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Preface

Motor driven systems account for about 40% of global electricity demand, i.e. 7400 TWh per year, and about 70 % of the industrial electricity consumption. This is the single largest end-use of electricity. Not only this, but motor systems offer still today large cost-effective efficiency improvement potential, calculated between 20% to 30%. This would significantly reduce greenhouse gas emissions at zero or even negative costs, as improvement measures in motor driven systems are generally cost-effective and have short pay-back time.

Motor driven systems will therefore play a key role in reducing CO2 emissions, increase the security of energy supply and improve the competitiveness of industry. If all the motor systems would be optimised energy cost savings would be US$100 - 146 billion per year. Yet energy efficiency investments are not yet priority in new plants or during refurbishments.

The eight international conference on **E**nergy **E**fficiency in **Mo**tor **D**riven **S**ystems (EEMODS) was organised in Rio de Janeiro from 28 to 30 October 2013, to discuss the newest developments in this field of energy efficiency in motor driven systems. This major international conference, which was previously been staged in Lisbon (1996), London (1999), Treviso (2002), Heidelberg (2005), Beijing (2007), Nantes (2009), Washington DC (2011) has been very successful in attracting an international and distinguished audience, representing a wide variety of stakeholders in policy implementation and development, manufacturing and promotion of energy-efficient motor systems, including key policy makers, equipment manufacturers, academia, and end-users.

The EEMODS conference has established itself as an influential and recognised international event where participants can discuss the latest developments and build international partnerships among stakeholders.

EEMODS'13 provided a forum to discuss and debate the latest developments in the impacts of electrical motor systems on energy and the environment, the policies and programmes adopted and planned, and the technical and commercial advances made in the dissemination and penetration of energy-efficient motor systems.

During the conference numerous studies on individual component (motors, pumps, compressors, fans) and on the consumption characterisation and the potential for improvement of energy efficiency of these systems have presented. Also policy actions in a variety of regions and countries have been presented.

For motors, most of the OECD countries and some developing countries have adopted mandatory efficiency requirements (one of the conference highlights was the Eco-Design Regulation in the EU), classification systems and motor selection database. The ISO energy management standard ISO 50001 another highlight on EEMODS, completing a task that was raised at the first EEMODS conference.

Other policy initiatives cover end-use equipment such as pumps, compressors, and fans, including again classification schemes and minimum efficiency requirements. Some of these initiatives are of a voluntary nature and they include: information dissemination, best practice, voluntary agreement, audit schemes, and financial and fiscal.

The EEMODs'13 Conference Proceedings contain the most up-to-date information on policies, programmes, science and technologies in motor systems.
All the papers have been peer reviewed by two independent experts.

IE3 Induction Motor designs with Aluminum and Copper rotor cage: a comparison

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Abstract

The aim of this study was to design three-phase induction motors with Aluminum and Copper cage, in the range 0.75÷22 kW, to fulfill the IE3 efficiency level according to typical performance and standard constraints. The proposed study has concerned TEFC, 400 V, 50 Hz, S1 duty three phase squirrel-cage induction motors only. The motors designs, with Al and Cu cage, have been optimized in order to reach the minimum efficiency level IE3 at lowest active material costs and satisfy the physical and performance constraints of the designs, that are the motor specifications. A suitable Optimization Procedure has been used that has allowed to find the "best design" by chancing the geometric dimensions of the stator and rotor shape, the stator winding and the stack length. The optimized designs with Aluminum and Copper cage have been compared and discussed.

Introduction

The new three phase induction motors classification scheme (EC Regulation Nr. 640/2009) has introduced two efficiency levels [1]: "high efficiency" IE2 and "premium efficiency" IE3, totally new for Europe and corresponding to the American "Nema Premium". Its coming dates open new settings for electric motors Manufacturers, which will have to adapt their production cycle and invest on development strategies for innovative and high efficient motors. The improvement of induction motor efficiency requires the use of innovative technological solutions [2] and the optimization of the motor design [3], keeping construction restrictions typically adopted for these motors classes. The use of die-cast Copper rotor cage [3,4,5,6] would result in attractive improvements in motor energy efficiency and could represent a valid alternative to traditional (and low cost) Aluminum cage.
This paper presents a study on new induction motor designs with Aluminum and Copper rotor specially developed to reach the IE3 efficiency level. A comparison on technical and economic aspects will be shown. Five motor sizes have been selected: 1.5 kW-6 pole, 3 kW-4 pole, 7.5 kW-4 pole, 15 kW-4 pole and 22 kW-2 pole, squirrel-cage, TEFC, 400 V, 50 Hz, S1 duty. Table I shows, for each size, the IE3 minimum efficiency levels according to the EC Regulation No. 640/2009.

Table I – The IE3 minimum efficiency levels for the considered motor sizes.

Rated power (kW)	Poles	Frame size	Efficiency IE3
1.5	6	100 L	82.5 %
3	4	100 L	87.7 %
7.5	4	132 M	90.4 %
15	4	160 L	92.1 %
22	2	180 M	92.7 %

The motors designs have been optimized in order to reach the minimum efficiency level IE3 at lowest active material cost and satisfy the physical and performance constraints of the designs, that are the motor specifications. The study does not take into account the costs for the die-casting and stamping processes, and the tooling cost. For the active material cost calculation, three different scenarios have been considered with different "Cu/Al" price ratio.
A suitable Optimization Procedure has been used [7,8] that has allowed to find the "best design" by chancing the geometric dimensions of the stator and rotor shape, the stator winding and the stack length, in order to obtain a final optimized design whose dimensions are consistent, when possible, with the standard commercial frames.
Motor performance have been evaluated by a "lumped parameter model". The adopted model takes into account magnetic saturation, skin effect on rotor parameters and thermal analysis. The validity of

the mathematical model has been verified by means of experimental tests on several three-phase induction motors.
The paper presents the results of the IE3 optimized designs, with Al and Cu cage; these solutions have been compared in terms of performance, active material costs and advantage in size (diameter/stack length) and total weight. Moreover it has been possible to verify if the Al and Cu technologies allow to go beyond IE3 efficiency level and fit with standard dimensions compatible with commercial housings.

Optimization and Design Procedure

The optimization procedure is synthesized in the flow-chart shown in Figure 1, where X represents the set of motor design variables and F(X) the objective function (active material cost) to minimize.
Starting from a "preliminary design" (Initial design), the optimization algorithm iteratively updates the set of design variables (X) and try to identify an "optimal" motor by making a trade-off between the different parameters of the machine.
The block "Motor Analysis" evaluates the motor performance, the objective function and the constraints values. The physical description of the motor is reduced to equivalent parameters such as resistance and inductances: the adopted model takes into account the influence of saturation on stator and rotor reactances and the influence of the skin effect on rotor parameters. The effects of the temperature on motor resistances are computed on the basis of a detailed "thermal network". The validity of the mathematical model has been verified by means of experimental tests on several three-phase induction motors.
The motors designs, with Al and Cu cage, have been optimized in order to reach the minimum efficiency level IE3 at lowest active material costs and satisfy the physical and performance constraints of the designs, that are the motor specifications.
The active material cost is defined as follows:

$$ACM = (Wfe*Cfe) + (Ws*Ccu_W) + (Wrc*Cm) \quad (€) \qquad (1)$$

where:

- Wfe weight of gross iron (kg)
- Ws weight of stator winding (kg)
- Wrc weight of rotor cage (kg)
- Cfe cost of premium steel (€/kg)
- Ccu_W cost of copper wire (€/kg)
- Cm cost of raw material for rotor cage (Al or Cu) (€/kg)

These costs do not take into account the die-casting process, the stamping process, the tooling and the structure costs.
In order to guarantee the goodness and feasibility of the optimized designs, several constrains have been introduced that concern:

- the rated efficiency (minimum efficiency level for IE3, Table I),
- the power factor,
- the starting performance (starting torque and starting current),
- the breakdown torque,
- the stator winding temperature rise and rotor bars temperature rise,
- the slot fill factor.

The values of these constraints have been fixed with reference to commercial motors of the same size of the investigated motors.
The considered design variables set is shown in Figure 2 and concerns the geometric dimensions of the stator and rotor shape (inner and outer stator diameters, tooth width, slot high), the stator winding (number of turns per phase, wire size) and the stack length. Each variable has been varied between an upper and a lower limit according to Manufacturers suggestions, in order to obtain a final optimized design whose dimensions are consistent, when possible, with standard commercial frames. One small and one big housing Company have been considered as reference. The dimensions (L and D in Figure 3) of their commercial housings (type B3) are shown in Tables II and III.

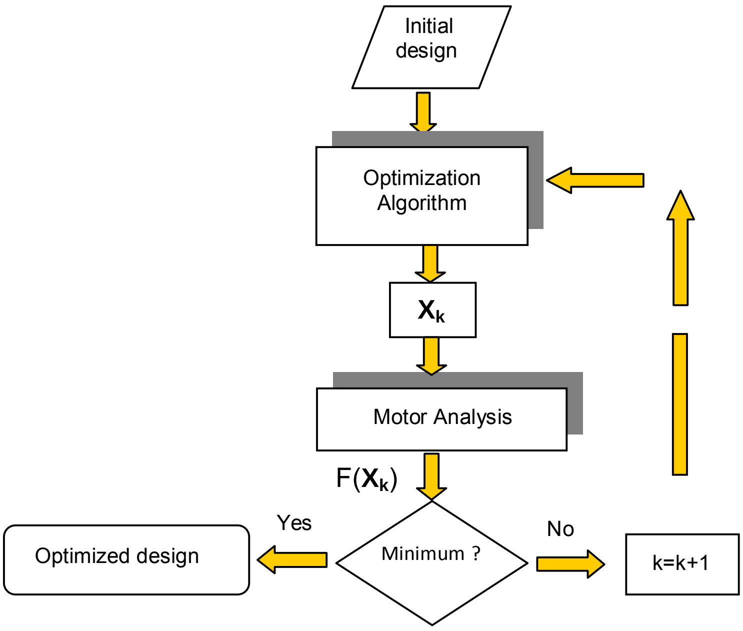

Figure 1 – Design optimization procedure.

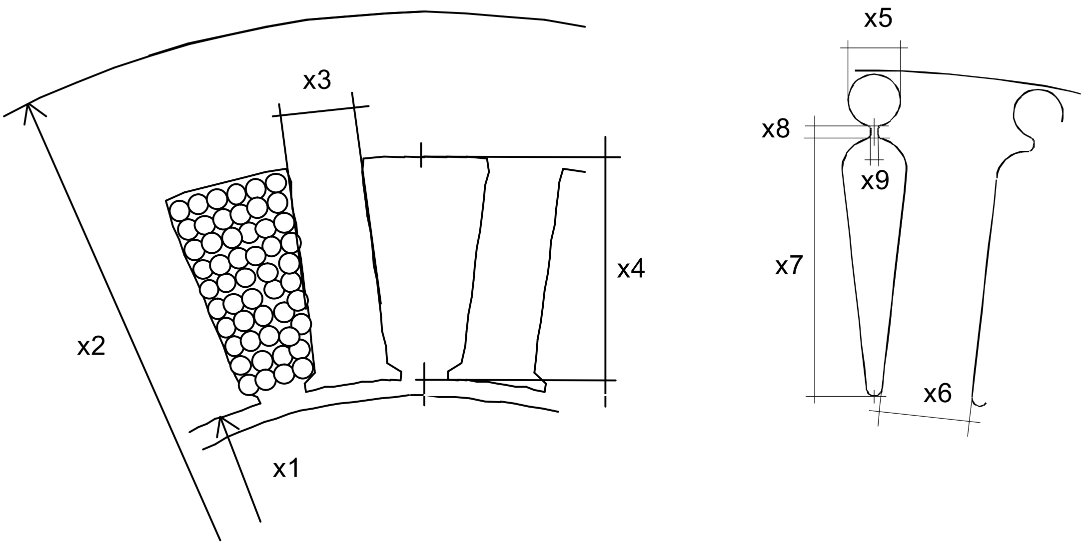

Figure 2 - Geometric design variables.

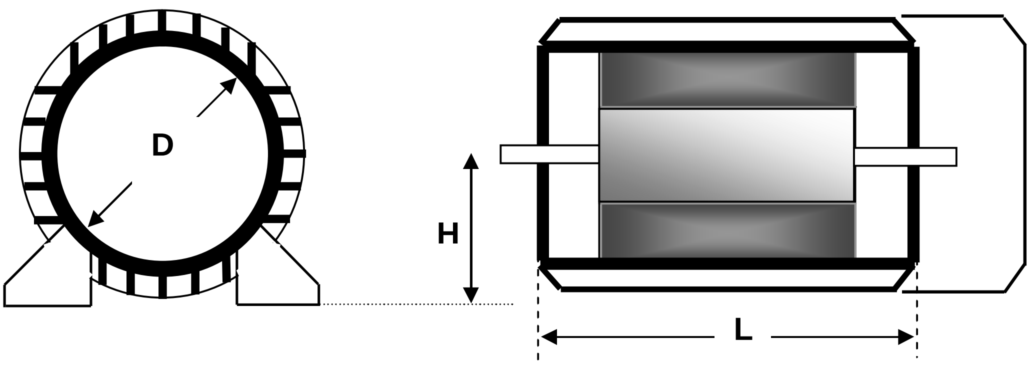

Figure 3 - Schematic commercial housing.

Tables II – Small Company commercial housing dimensions

Frame size	Length L (mm)	Inner diameter D (mm)
90 L	230	138
100 L	255	165
112 M	282	175
132 M	320	210
160 M	278	260
160 L	322	260
180 M	317	290
180 L	355	290
200 L	385	327

Tables III – Big Company commercial housing dimensions

Frame size	Length L (mm)	Inner diameter D (mm)
90 L	192	130
100 L	198	155
112 M	214	175
132 M	268	210
160 M	270	260
160 L	314	260
180 M	317	290
180 L	355	290
200 L	375	327

Design assumptions

The following design assumptions have been made. For each size, the motors with Al and Cu cage have the same:

- number of stator and rotor slots,
- air-gap length,
- slot fill factor,
- stator slot opening,
- rotor skewing,
- shaft diameter,
- winding distribution and "winding factor",
- stator slot insulation and thermal coefficients (for the thermal network)
- percentage for the Stray Losses calculation (2% the output power).

About the active materials, the following unit price have been imposed (2012):

- premium steel Cfe 0.91 (€/kg);
- raw material for Al cage Cm_Al 1.76 (€/kg);
- copper wire Ccu_W 15% higher than the cost of Cu raw material

The cost of raw material for the copper has been related to the aluminum one, and the following three Scenarios have been introduced by imposing a different "Cu/Al" price ratio:

Scenario 1 - $€_{CU}$ / $€_{AL}$ = 3.0

- raw material for Cu cage Cm_Cu = 5.28 (€/kg)
- copper wire Ccu_W = 6.07 (€/kg)

Scenario 2 - $€_{CU}$ / $€_{AL}$ = 3.5

- raw material for Cu cage Cm_Cu = 6.16 (€/kg)
- copper wire Ccu_W = 7.08 (€/kg)

Scenario 3 - $€_{CU} / €_{AL}$ = 4.0

- raw material for Cu cage Cm_Cu = 7.04 (€/kg)
- copper wire Ccu_W = 8.10 (€/kg).

The motors have been optimized with reference to the Scenario 2. The commercial “premium steel” 330-50 AP (0.5 mm thickness) has been chosen for the new designs, and the main magnetic characteristics are presented in the Table IV.

Tables IV – Magnetic characteristics of the “premium” steel 330-50AP (50 Hz)

B (T)	H (A/m)	Losses (W/kg)
1.0	121	1.31
1.5	946	2.86

Results

The results of the optimized designs are shown in the following Tables and Figures, that include the motor main dimensions, the motor performance and the active material weights and costs for the three Scenarios, calculated according to the (1); for each size, some comments have been included.

1.5 kW, 6 pole Motor

Table V shows the 1.5 kW, 6 pole motor main dimensions while Figure 4 shows losses, rated current and torque Ir, Tr, starting current and torque Ist, Tst, maximum torque Tmax, active material weights and costs.
Both designs have the same rated efficiency (82.5%) and the performance are quite similar and consistent with typical performance of a commercial Al motor of the same size.
In Table V it is important to highlight that the outer stator diameter of the Al motor allows to use commercial housing produced by a small company only and not the housings of the big company (Table III): in this case (*) a new (out of line) and more expansive housing is needed.
The Cu motor is compatible with all commercial housings (small and big company, see Table II and III) and presents an advantage in size (diameter/stack length) with a total weight reduction of about 9%. Moreover, the slots area are smaller respect the Al solution, with a reduction of about 16% for the stator slot and 24% for the rotor slot (and rotor bar). Although this significant reduction on the rotor slot area, the weight of the Cu rotor cage is twice over the Al cage and this is due to the different specific weight of the two metals.
The total copper weight in the Cu motor (stator winding and rotor cage) is about 48% higher than the copper weight (stator winding) in the Al motor.
The Cu cage motor is slightly more expensive, with an increase on the active material cost of 3 Euro for the Scenario 1 and about 6 for the Scenarios 3: this difference could be reduced if the Al motor needs a new (out of line) housing.

Tables V – 1.5 kW, 6 pole motor main dimensions

η = 82.5% (IE3)	Al	Cu
Stack length (mm)	130	126
Outer stator diameter (mm)	160 (*)	152
N. of turns x phase	342	342
Wire size (mm^2)	0.830	0.688
Stator slot area (mm^2)	81.9	68.5
Rotor slot area (mm^2)	50.2	38.0

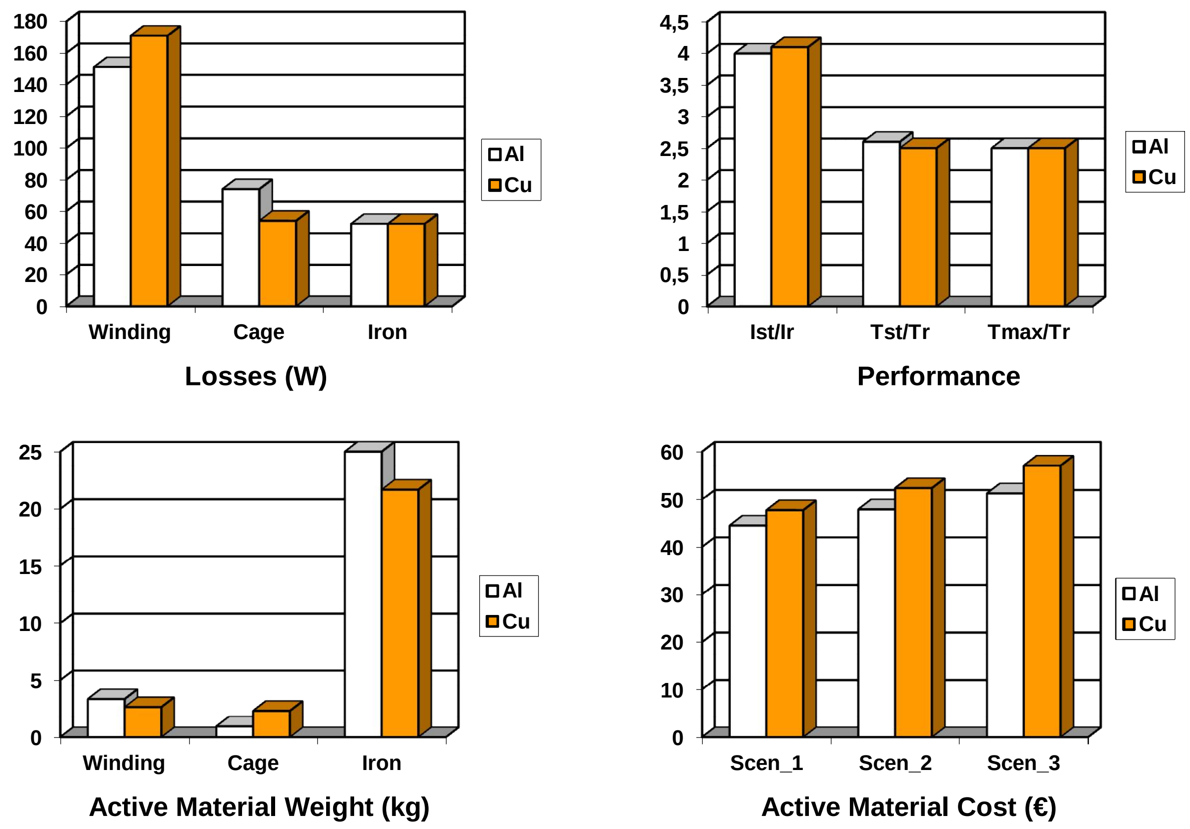

Figure 4 - 1.5 kW, 6 pole motor losses, performance and active material weights and costs.

3 kW, 4 pole Motor

Table VI shows the 3 kW, 4 pole motor main dimensions while Figure 5 shows losses, performance and active material weights and costs.
Both designs have the same rated efficiency (87.7%) and the performance are quite similar and consistent with typical performance of a commercial Al motor of the same size.
The outer stator diameters of both designs allow to use commercial housings produced by the small company only (see Table VI (*)).
The Cu motor presents an advantage in size (diameter/stack length) with a total weight reduction of about 6%. The comparison points out a significant reduction of stator and rotor slot area (rotor bar), for the Cu motor, of 18% and 37%. The total copper weight in the Cu motor (stator winding and rotor cage) is about 42% higher than the copper weight (stator winding) in the Al motor. The Cu cage motor is slightly more expensive, with an increase on the active material cost for all cases, in the range between 4 and 7 Euro.

Tables VI – 3 kW, 4 pole motor main dimensions

η = 87.7% (IE3)	Al	Cu
Stack length (mm)	155	150
Outer stator diameter (mm)	165 (*)	160 (*)
N. of turns x phase	186	186
Wire size (mm^2)	1.645	1.31
Stator slot area (mm^2)	125	102
Rotor slot area (mm^2)	93.8	58.6

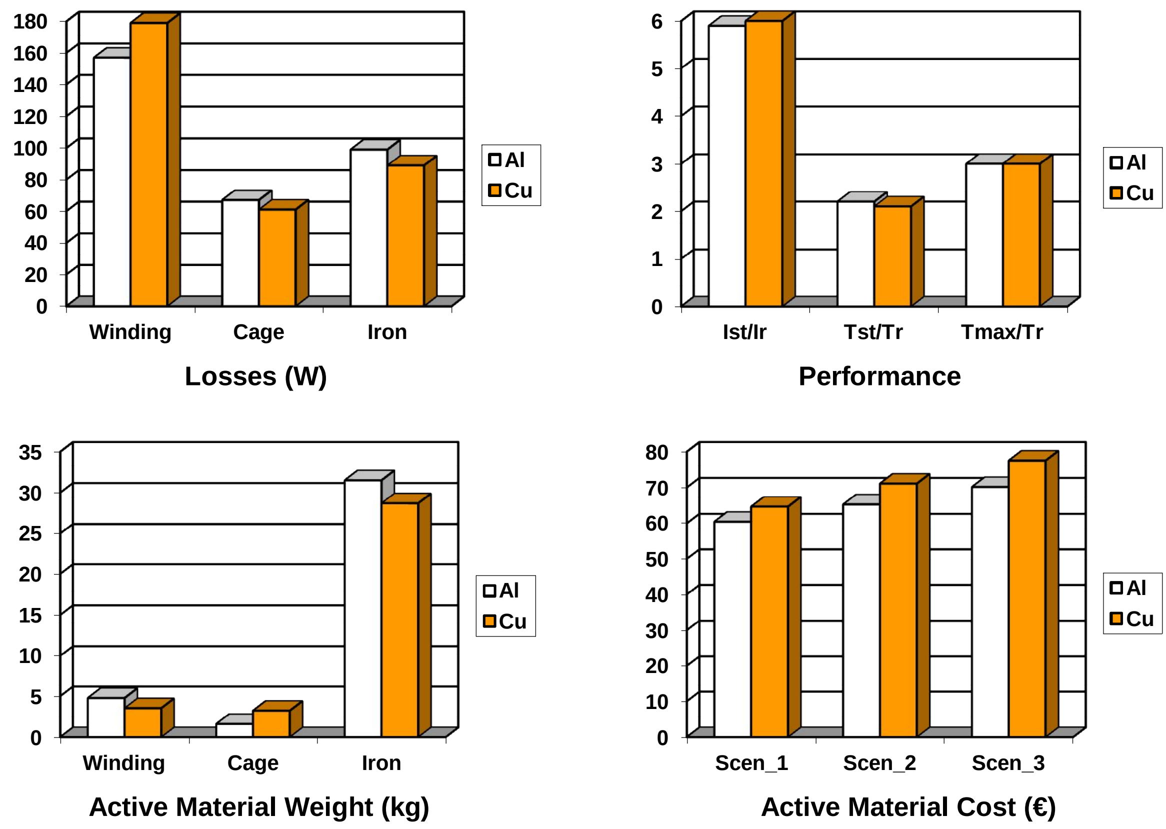

Figure 5 - 3 kW, 4 pole motor losses, performance and active material weights and costs.

7.5 kW, 4 pole Motor

Table VII shows the 7.5 kW, 4 pole motor main dimensions while Figure 6 shows losses, performance and active material weights and costs.
Both designs have the same rated efficiency (90.4) and the performance are quite similar and consistent with typical performance of a commercial Al motor of the same size.
Difficulty to go beyond IE3 with Al technology because of limitations in housing and inability to fit with standard dimensions for the small and big company. The outer stator diameter of the Al cage needs a new (out of line) and more expansive housing (Table VII (*)).
The Cu motor can use commercial housings produced by small and big company and presents an advantage in size (diameter/stack length) with a total weight reduction of about 9%: this percentage tends to increase when a bigger housing is used for the Al cage motor.
The slots area are smaller respect the Al solution, with a reduction of about 18% for the stator slot and 54% for the rotor slot (and rotor bars) but the weight of the Cu rotor cage is 50% higher than the Al cage. The total copper weight in the Cu motor (stator winding and rotor cage) is about 22% higher than the copper weight (stator winding) in the Al motor.
The Cu motor has an active material cost lower respect to the Al motor for the Scenario 1: for the other two cases the difference are very small. If the cost of the new housing for the Al motor is taken into account, the Cu motor is certainly more convenient (excluded the cost of die-casting process).

Tables VII – 7.5 kW, 4 pole motor main dimensions

η = 90.4 % (IE3)	Al	Cu
Stack length (mm)	200	190
Outer stator diameter (mm)	215 (*)	210
N. of turns x phase	114	108
Wire size (mm^2)	4.80	4.15
Stator slot area (mm^2)	205	168
Rotor slot area (mm^2)	115	52.5

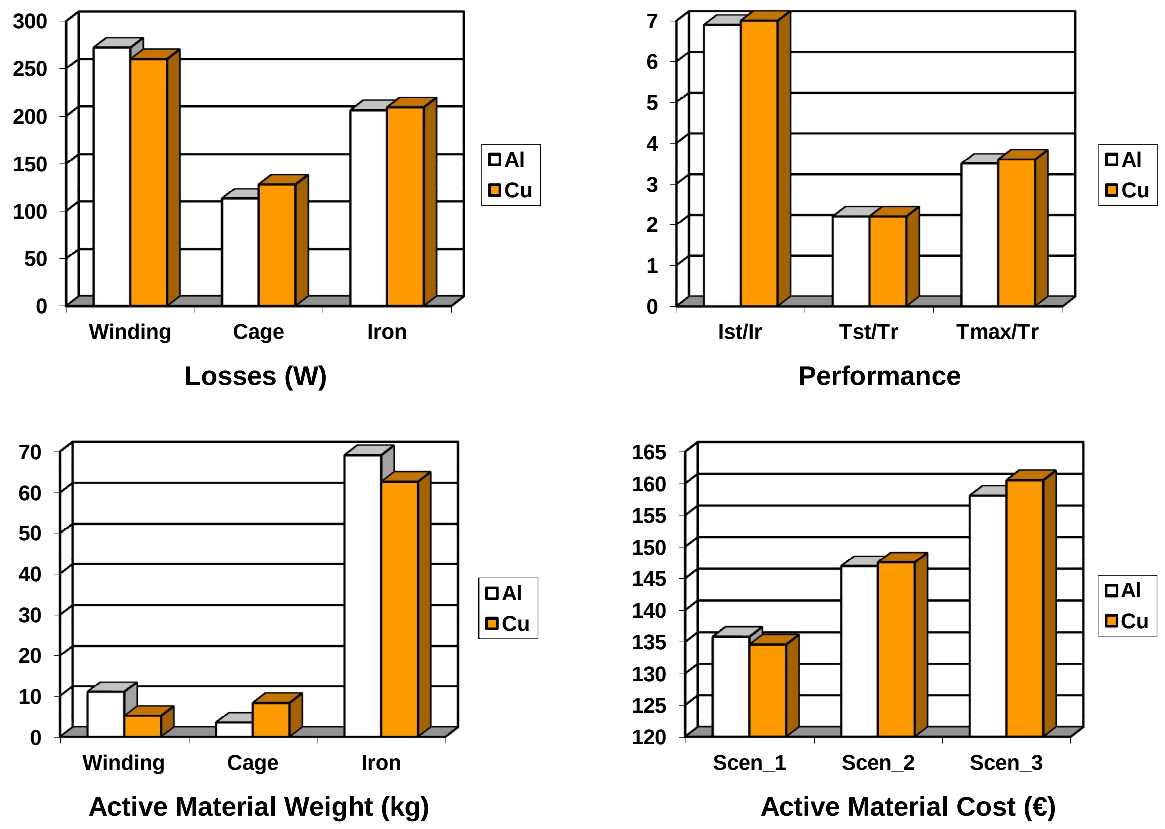

Figure 6 – 7.5 kW, 4 pole motor losses, performance and active material weights and costs.

15 kW, 4 pole double-cage Motor

Table VIII shows the 15 kW, 4 pole motor main dimensions while Figure 7 shows losses, performance and active material weights and costs.
Both designs have the same rated efficiency (92.1%) and the performance are quite similar and consistent with typical performance of a commercial Al motor of the same size.
Both designs can use commercial housings produced by small and big company.
The Cu motor presents an advantage in size (diameter/stack length) with a total weight reduction of about 11%.
The comparison points out a significant reduction of stator and rotor slot area (rotor bar) of about 18% and 37% respectively: the weight of the Cu rotor cage is twice over the Al cage.
The total copper weight in the Cu motor (stator winding and rotor cage) is about 13% higher than the copper weight (stator winding) in the Al motor.
The motor with copper cage allows a reduction on the active material cost in all cases, from 8 to 10 Euro (excluded the cost of die-casting process).

Tables VIII – 15 kW, 4 pole double cage motor main dimensions

η = 92.1% (IE3)		Al	Cu
Stack length	(mm)	225	215
Outer stator diameter	(mm)	255	245
N. of turns x phase		78	78
Wire size	(mm^2)	7.90	5.60
Stator slot area	(mm^2)	228	182
Rotor slot area	(mm^2)	83	65

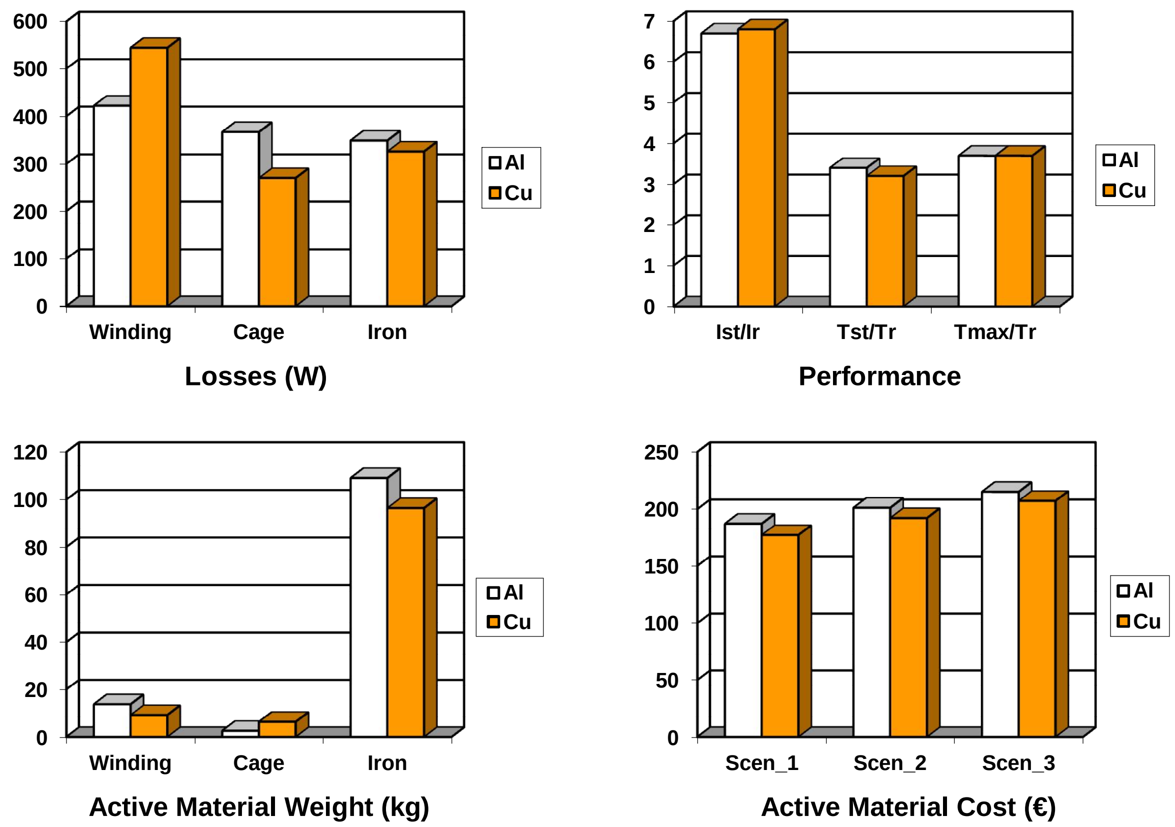

Figure 7 – 15 kW, 4 pole double cage motor losses, performance and active material weights and costs.

22 kW, 2 pole double-cage Motor

Table IX shows the 22 kW, 2 pole motor main dimensions while Figure 8 shows losses, performance and active material weights and costs.
Both designs have the same rated efficiency (92.7%) and the performance are quite similar and consistent with typical performance of a commercial Al motor of the same size.
The outer stator diameters of both designs allow to use commercial housings produced by small and big company.
The Cu motor presents an advantage in size (diameter/stack length) with a total weight reduction of about 8%. The reduction of stator and rotor slot area (rotor bar) are about 18% and 32% respectively and the weight of the Cu rotor cage is twice over the Al cage.
The total copper weight in the Cu motor (stator winding and rotor cage) and Al motor (stator winding) is equal, making the steel weight the difference to the benefit of copper rotor solution.
Moreover, the motor with copper cage allows a reduction on the active material cost in all cases of about 16 Euro (excluded the cost of die-casting process):

Tables IX – 22 kW, 4 pole double cage motor main dimensions

η = 92.7% (IE3)	Al	Cu
Stack length (mm)	215	205
Outer stator diameter (mm)	290	285
N. of turns x phase	84	84
Wire size (mm^2)	6.36	4.80
Stator slot area (mm^2)	200	164
Rotor slot area (mm^2)	122	83

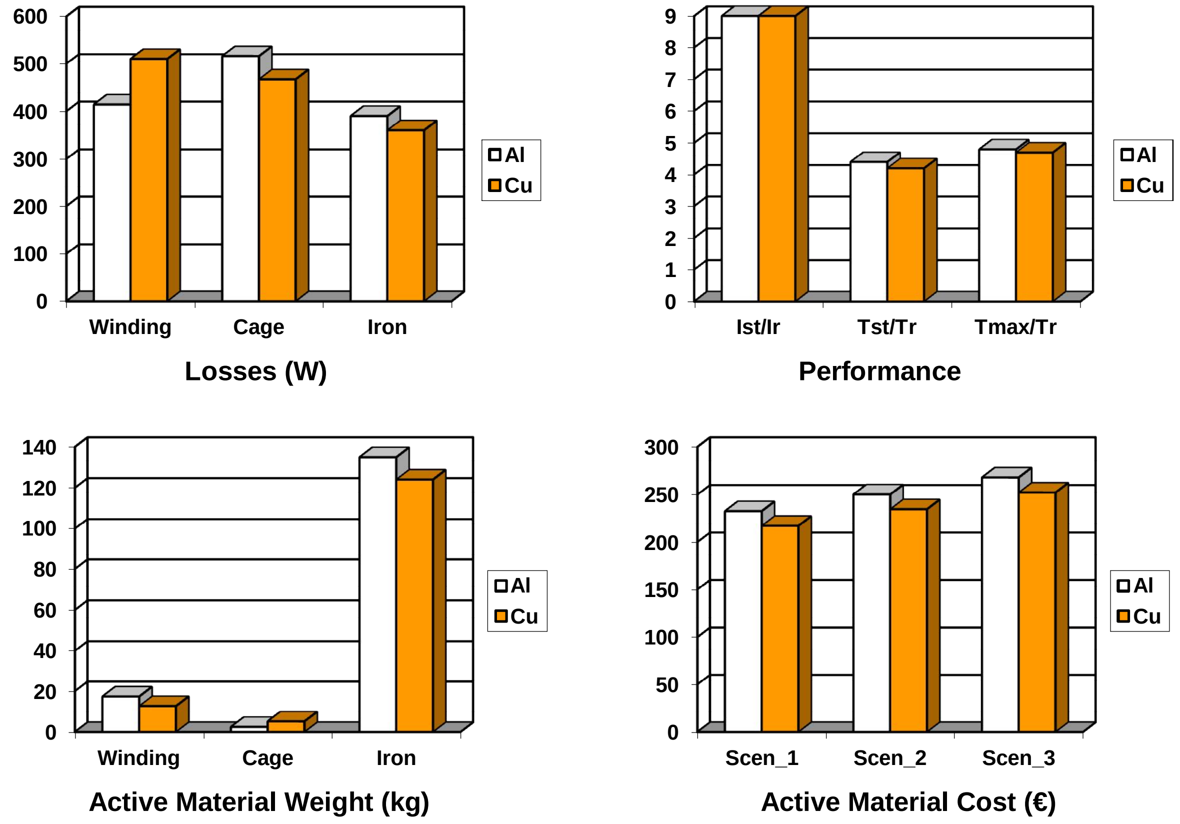

Figure 8 – 22 kW, 2 pole double cage motor losses, performance and active material weights and costs.

Conclusions

In conclusion, the following remarks could be pointed out.
The performance of the motors with Al and Cu cage are quite similar and consistent with typical performance of commercial Al motors of the same size.
The Cu motors present always an advantage in size (diameter/stack length) and total weight.
The total copper weight in the Cu motors (stator winding and rotor cage) is higher than the copper weight (stator winding) in the Al motors, difference reducing from small to large sizes (in case of 22 kW one, they are similar).
Difficulty to go beyond IE3 with Al technology because of limitations in housing and inability to fit with standard dimensions for the small and/or big company.
Table X shows the Cu rotor motors active material cost variations (in Euro and %) respect to Al rotor motors.
For the small sizes (1.5 and 3 kW), the Cu cage motors are slightly more expensive respect to the Al motor while for the 7.5 kW the difference on the active material cost is very small; this difference could be reduced if the Al motor needs a new (out of line) housing.
For the big sizes (15 and 22 kW), the Cu cage motors present active material costs lower than the IE3 Al motors for all Scenarios (excluded the cost of die-casting).
Copper rotor motors are proving a cost-effective way of meeting the new high efficiency IE4 standards.

Acknowledgments

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Tables X – Cu rotor motors active material cost variations (in Euro and %) respect to Al rotor motors

Motor Power (kW)	Scen_1		Scen_2		Scen_3	
1.5	+3.2 ∈	+7.2%	+4.5 ∈	+9.4%	+5.8∈	+11.3%
3	+4.2 ∈	+7.0%	+5.8 ∈	+8.9%	+7.4∈	+10.5%
7.5	-1.2 ∈	-1.0%	+0.6 ∈	+0.4%	+2.4∈	+1.5%
15	-9.9 ∈	-5.3%	-8.9 ∈	-4.4%	-7.8∈	-3.8%
22	-15.4∈	-6.6%	-15.5∈	-6.2%	-15.8∈	-5.9%

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DEVELOPMENT OF A THREE-PHASE ELECTROMAGNETIC DEVICE FOR THE EVALUATION OF THE MAGNETIC LOSSES IN ELECTRIC MOTORS' STATORS

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Abstract

Concerns about the environment, combined with the needs of meeting energy efficiency standards and obtaining lower costs in the manufacturing of electric motors, have made manufacturers more attentive to the performance of their products. One of the major factors affecting the efficiency of an electric motor is the loss portion that takes place in the magnetic core, which is typically constructed with laminated steel for electrical purposes. This paper describes the idea of a new test device that allows a better evaluation of the magnetic losses generated in the ferromagnetic core of the stator of rotating electrical machines.

Introduction

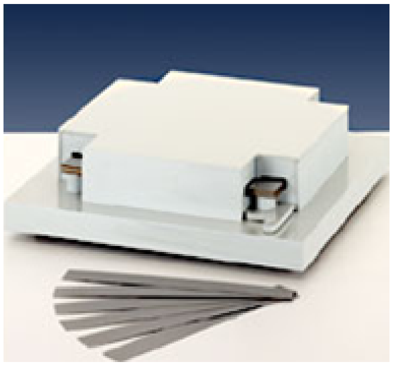
For the evaluation of magnetic losses in steel sheets, one of the most used methods is the Epstein frame test, because it is standardized, simple, fast and has good repeatability. But in some cases, the Epstein frame test results are incoherent with the actual motor core losses, because the best steel according to the Epstein frame may not always result in the lower motor core losses [1]. In the Epstein frame test, the lamination samples consist of rectangular strips, not being faithful to the geometry of the laminations of an electric motor. Moreover, the magnetic flux generated in the Epstein strips is only alternating, with no losses associated with the rotating field that exists in an electric motor. The proposed test device addresses the magnetic losses generated due to the geometry of the stator, which is formed by teeth and yoke. The power supply of the testing system enables the test specimen to experience the same flux characteristics of actual rotating electrical machines, allowing a better assessment of magnetic losses in steel sheets, because the test conditions are more faithful to the characteristics of a rotating electrical machine.

Development

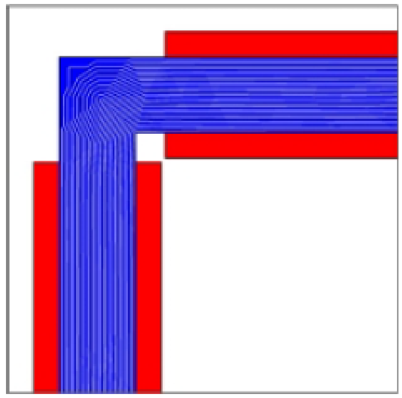
Currently there are several methods that are relatively well developed and generally accepted by the scientific community for the evaluation of losses in magnetic steel sheets for electrical purposes. Among them, the most common are the Epstein Frame, the Single Sheet and the Ring Coil.

A. Epstein Frame

Probably the most popular method, as already mentioned, the test with the Epstein frame (Figure 1a) is normally used for the characterization of steel sheets of rotating electrical machines and transformer cores. However, this test does not really represent electric motors. Its samples are in the form of rectangular strips and the magnetic flux applied to the samples is purely alternating (Figure 1b), without the rotating components found in a rotating electric machine.



a)



b)

Figure 1 - a) Commercial Epstein frame device [2], b) Magnetic flux distribution in the Epstein frame samples [3].

The Epstein frame test is used for the characterization of both grain oriented (GO) non grain oriented (NGO) electrical steel sheets.

B. Single Sheet Tester

The Single Sheet Tester has the same concept of the Epstein frame, but with the advantage of performing the test with only one sheet plate, thus simplifying the sample preparation. The sample in this case has a square form, in order to compensate the magnetic anisotropy generated in the steel plate lamination process, due to the rolling direction.

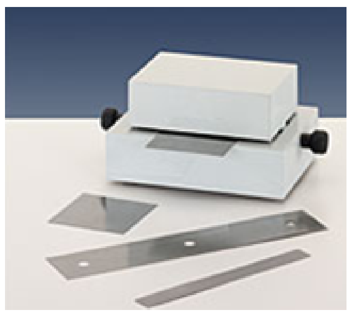


Figure 2 - Single Sheet Tester [2].

C. Ring Coil

The ring coil test is used to evaluate steel sheets in the form of toroidal core. In the case of rotating electrical machines, the stator, or, more precisely, the yoke, is the evaluated element (Figure 3a). The samples are wrapped by two coils, one comprising the primary and the other the secondary winding, so that the magnetic flux flows through the sample in the tangential direction (Figure 3b). In the case of a stator testing, the magnetic flux does not pass through the teeth, resulting in magnetic losses being generated in the yoke only. There is some uncertainty related to the precise amount of material that contributes to the generation of magnetic losses and in determining the mean magnetic path length, depending on the values of induction. Therefore, the results obtained with this test are generally used for comparative analyses, enabling a qualitative evaluation of lamination samples.

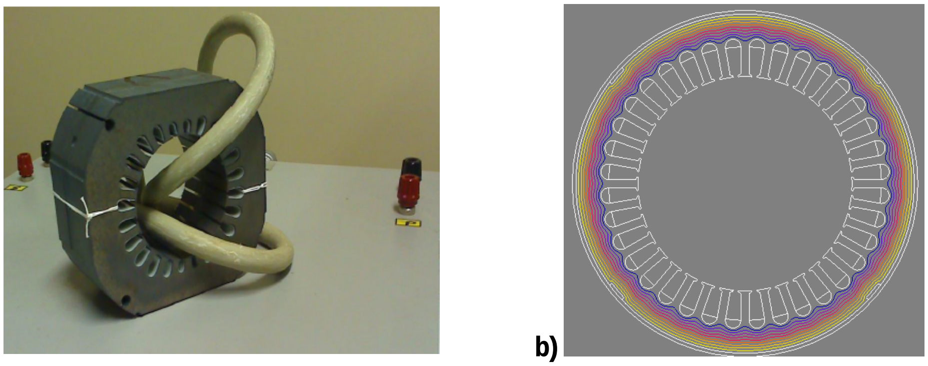
a)  b)

Figure 3 – a) Ring coil test for a stator sample [4], b) Magnetic flux distribution in the stator yoke during the ring coil test.

All the tests mentioned above have the common characteristic of applying only alternating magnetic field in the samples, not addressing the magnetic losses generated by the rotating fields that exist in actual rotating electrical machines. The magnetic losses generated in some parts of the electric motor, such as the region between the stator teeth and the yoke are neither evaluated by these traditional methods.

D. Three-phase electromagnetic device

The proposed method aims to provide a more faithful test system to the reality of a rotating electrical machine, evaluating the magnetic losses generated in the stator, taking into account the geometry of the laminations and the magnetic field rotating component. It was developed a three-phase electromagnetic device capable of generating a magnetic flux that really represents the magnetic flux of an electric motor. Unlike the Coil Ring test, the proposed device allows the evaluation of the total magnetic losses taking place the stator, which comprises those generated both in the yoke and in the teeth. The test device is designed to be in the place of the rotor (Figure 4), once that the intention is to evaluate the losses generated in the stator core.

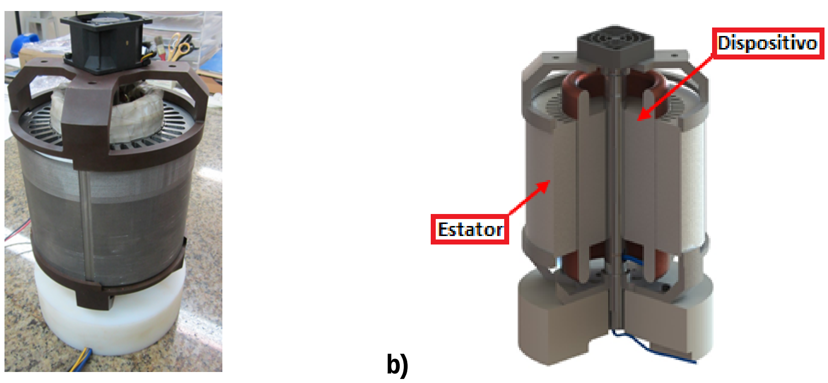
a)  b)

Figure 4 - a) Full test system with the stator sample in position, b) Cut view of the test system showing the test device in the rotor place.

Similarly to the tests previously mentioned, the developed device has two windings, one primary and one secondary winding, but the two windings are three-phase. The primary winding is responsible for generating the rotating magnetic field in the stator and measuring the total losses in the device (Joule losses and magnetic losses). The secondary winding is responsible for measuring the magnetic induction in the sample laminations. Figure 5 shows the flux distribution and the induction mapping in a typical motor core quarter.

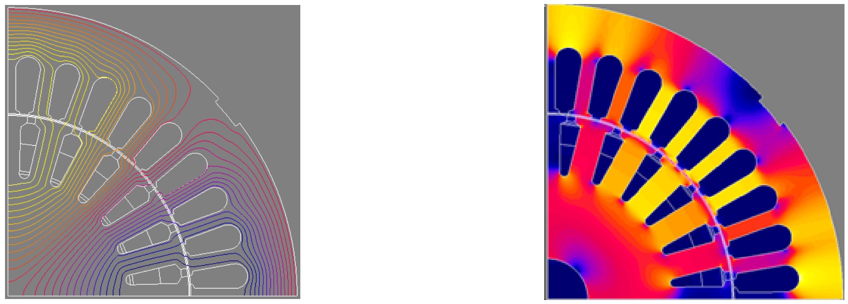


Figure 5 - Simulation of the proposed test. a) Distribution of flux lines, b) Mapping of the magnetic induction in ¼ of a typical electrical machine lamination.

The test consists in the generation and measurement of magnetic losses in the test system as a whole. During the test, the loss measurements embrace the sum of magnetic losses generated by the device and the stator. As the objective of the device is to evaluate the stator core losses only, it is necessary to subtract the magnetic losses generated by the electromagnetic device (rotor) from the total measured losses. The stator core losses are obtained by Equation 1.

$$P_{Est} = Pt_{ens} - P_{dis} \qquad \text{Eq.1}$$

Where:

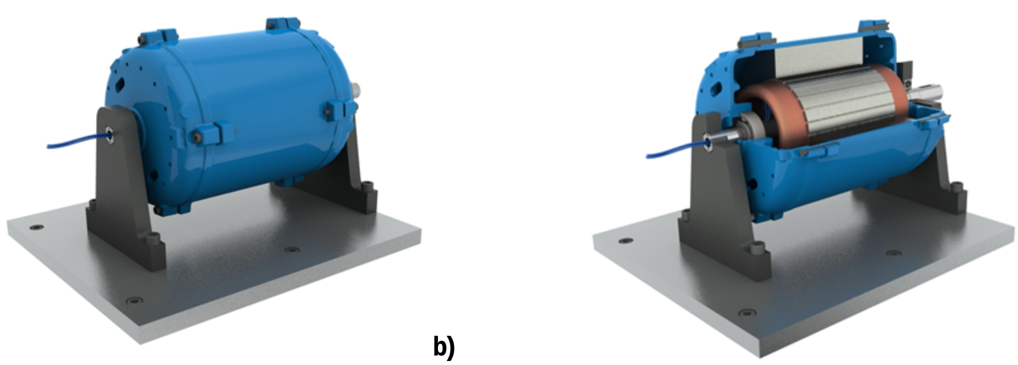
P_{Est} : Stator core losses, [W];

Pt_{ens} : Total magnetic losses measured during test, [W];

P_{dis} : Magnetic losses of the electromagnetic device (rotor), [W].

As the magnetic losses are measured by the primary winding, it is necessary to subtract from the measurement result the power absorbed due to the electrical resistance of the winding (Joule losses).

To obtain the magnetic losses of the device, a bench calibration bench was developed based on the principle that a laminated ring rotating in synchronous speed generates no magnetic losses, since there is no flux variation in the ring in this situation. For the calibration test, an equipment was designed to promote the rotation of a laminated ring (inserted in a frame) around the electromagnetic device (Figure 6).



a) **b)**

Figure 6 - a) External view of the calibration system, b) Internal view of the calibration device.

The electromagnetic device is supported in the calibration system through two bearings, which allow the frame to rotate around the electromagnetic device. Inside the frame, a ring made of laminated steel sheets encompasses the electromagnetic device. The synchronous speed of the calibrating ring will be imposed by a synchronous motor coupled to the shaft, which is fixed in the calibration system frame. When the primary winding is energized, it generates a magnetic field both in the ferromagnetic core of the device and in the calibration laminated ring (Figure 7). As the laminated ring is in synchronism with the magnetic field, the magnetic losses generated in the ring will be null.

a) b)

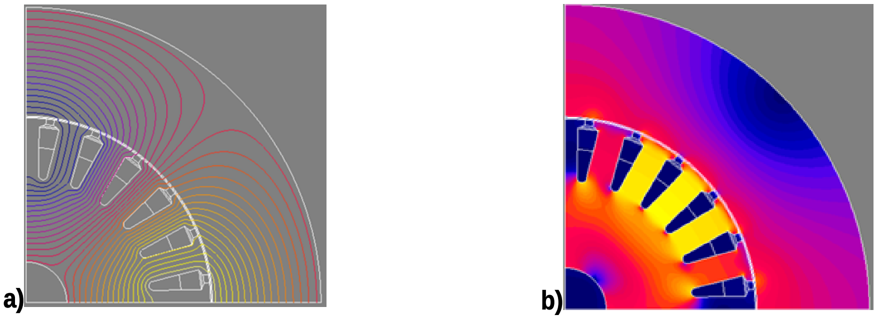


Figure 7 - Simulation of the calibration test. a) Distribution of magnetic flux in the device and in the calibration ring, b) Mapping of the magnetic induction in the device and in the calibration ring.

The core losses are related to the peak values of the magnetic induction in the teeth of the device, which can be measured through the secondary winding. To calculate the average magnetic induction in a pole of the the electromagnetic device, Equation 2 is used.

$$B_{med(t)} = \frac{1}{N_e \cdot K_b \cdot S} \int V_{a(t)} \cdot dt \qquad \text{Eq.2}$$

The magnetic induction calculated as per Equation 2 has a sinusoidal behavior, so the peak value of the magnetic induction is calculated by Equation 3.

$$B_{pk(t)} = B_{med(t)} \cdot \frac{\pi}{2} \qquad \text{Eq.3}$$

Where:

$B_{med(t)}$: Average magnetic induction as a function of time, [T];

$V_{a(t)}$: Phase voltage of the secondary winding as a function of time, [V];

N_e : Number of turns in one phase;

K_b : Winding factor;

S : Magnetic device cross section, [m^2];

$B_{pk(t)}$: Peak magnetic induction as a function of time, [T].

Experimental Results

A number of samples of the same magnetic material strips were manufactured, so that different tests and methods could be applied to characterize the silicon steels under evaluation (Figure 8), as follows: rectangular samples for the Epstein frame, stator laminations for the proposed electromagnetic device and full electric motors for no-load lab testing (classical procedure for determining core losses in electric motors). Samples were manufactured with supposedly equivalent silicon sheets provided by 3 different electrical steel suppliers, for comparative purposes.

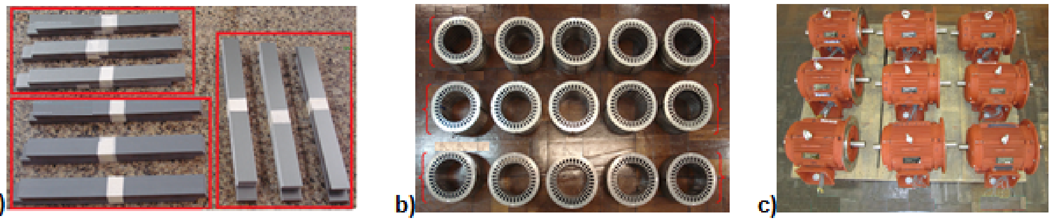


Figure 8 - Samples for the experimental analyses. a) Rectangular samples for the Epstein frame test, b) Stator samples for the proposed electromagnetic device test, c) Motor samples for the electrical lab tests.

In the Epstein frame test, the magnetic losses were assessed in four induction levels at 60 Hz. From the results obtained with this method (Table 1 and Figure 9), it is possible to classify "A" as the best and "B" as the worst supplier among the 3 evaluated ones.

Table 1 - Results obtained with the Epstein frame – 60Hz.

Magnetic Induction (T)	Supplier	Magnetic losses (W/kg)
0.8	A	1.367
	B	1.518
	C	1.502
1.0	A	1.991
	B	2.221
	C	2.177
1.2	A	2.747
	B	3.072
	C	2.980
1.5	A	4.259
	B	4.847
	C	4.563

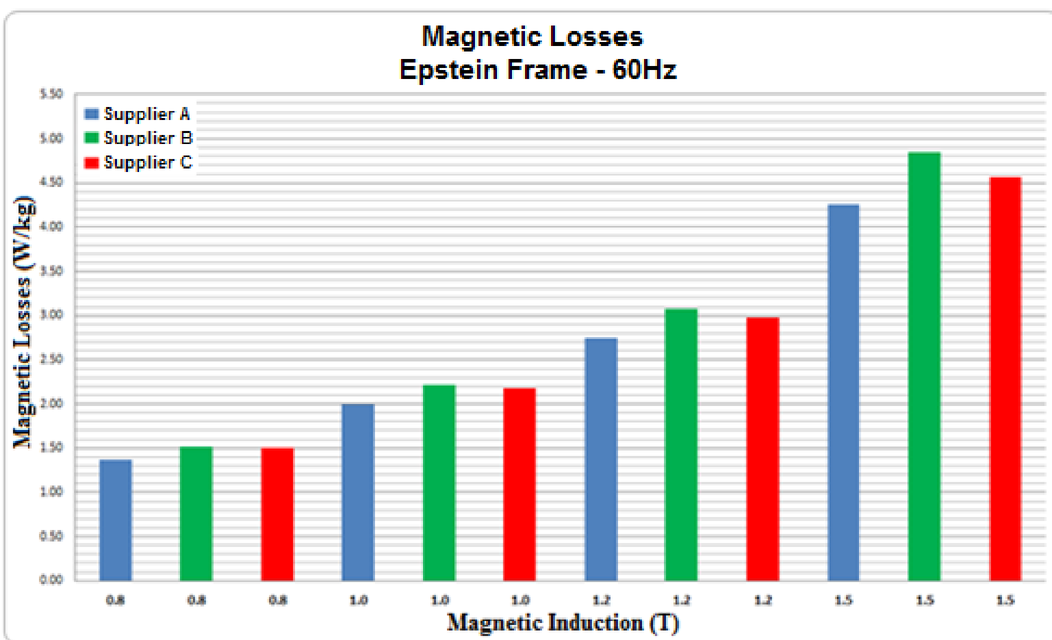


Figure 9 - Results obtained with the Epstein frame – 60Hz.

The test done with the proposed electromagnetic device followed the same steps of the Epstein frame test, that is, again 4 points of magnetic induction were evaluated at 60 Hz, however, different loss behaviors were observed in the two tests. The results obtained with the three-phase electromagnetic device are presented in Table 2 and Figure 10. It is possible to realize that now supplier "C" appears to be the best, while supplier "B" appears to be the worst of the 3 evaluated suppliers.

Table 2 - Results obtained with the three-phase electromagnetic device - 60Hz.

Magnetic Induction (T)	Supplier	Magnetic losses (W)
0.8	A	21.539
	B	21.933
	C	20.841
1	A	31.368
	B	32.475
	C	30.229
1.2	A	43.344
	B	44.914
	C	41.957
1.5	A	66.609
	B	69.283
	C	64.427

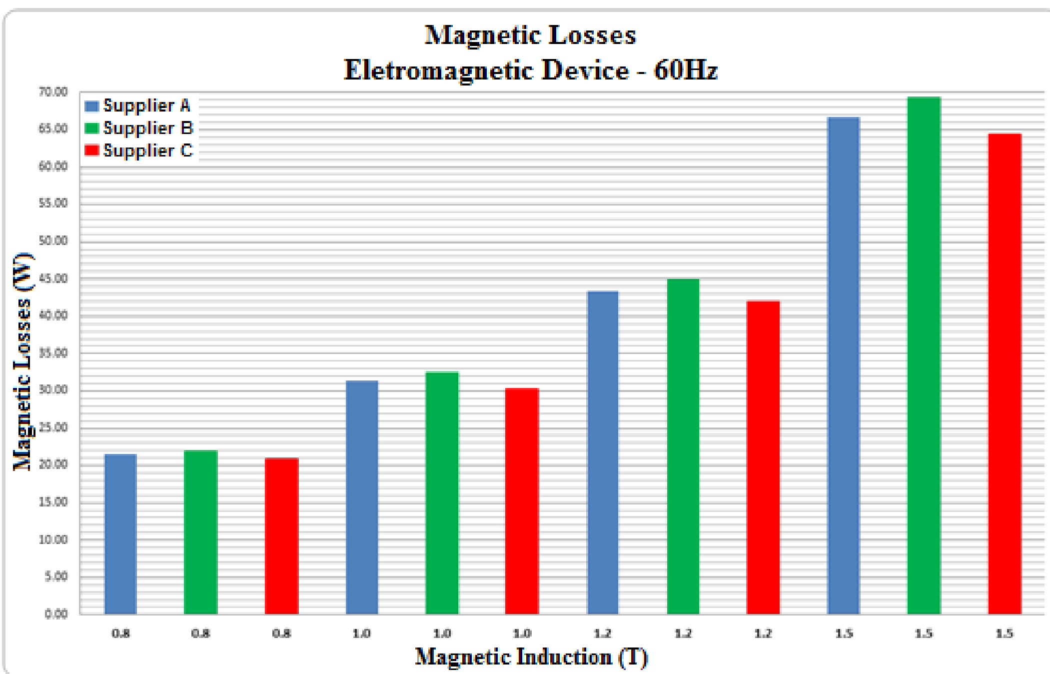


Figure 10 - Results obtained with the electromagnetic device three-phase - 60Hz.

In the tests performed with actual electric motors running at no-load, the magnetic losses were evaluated in the nominal flux condition of the motors (380 V / 60 Hz). Comparatively analysing the results obtained with the electric motors built with theoretically similar steels from three different suppliers (Table 3 and Figure 11), it is possible to notice that, the supplier "C" once more proved to be the best and supplier "B" the worst of the three investigated ones, in agreement with the results obtained with the proposed test method

Table 3 - Results obtained in the tests accomplished with full electric motors

Voltage (V)	Frequency (Hz)	Supplier	Magnetic losses (W)
380	60	A	127.80
		B	134.80
		C	123.60

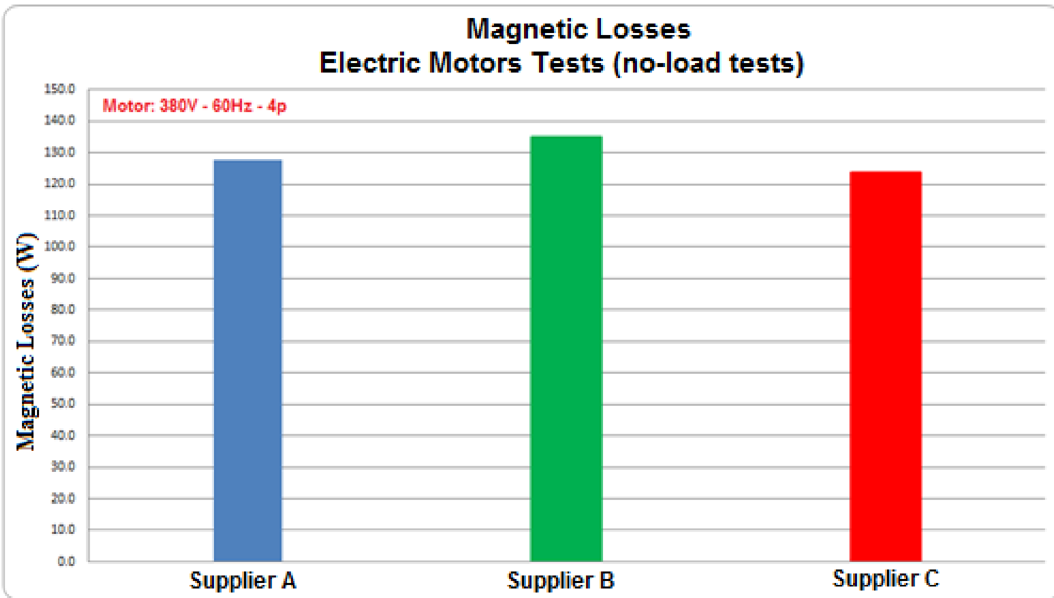


Figure 11 - Results obtained with actual electric motors (no-load tests).

In the Epstein frame, three groups of samples of a same strip from each supplier were tested. In the three-phase electromagnetic device, five stator stacks (with laminations taken from the same strip) were used for each supplier, and each sample was tested three times. For the no-load tests, three motors were built with each supplier' steel, and each motor was also tested three times. The results shown in the tables and graphs above comprise the average loss values found in these tests.

Conclusions

Observing the results of core loss measurements carried out using three different methods, it was possible to realize that the tests accomplished with full electric motors (no-load run) and the tests accomplished with the three-phase electromagnetic device proposed in this paper (stator stack samples) presented the same tendency and provided the same qualitative conclusions about the evaluated silicon electrical steels. These two methods rendered agreeing classifications among different suppliers of magnetic materials in a quality rank based on magnetic loss test results. The Epstein frame test, on the other hand, presented dissonant results relative to the other two testing methods.

The three-phase electromagnetic device built for the evaluation of magnetic losses in stators of rotating electrical machines allows a faithful assessment of the losses generated in the stator core of an electric motor, providing experimental results that match those coming out from traditional methods that are generally used for the evaluation of iron losses in actual motors.

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PWM effect on motor losses and temperature rise

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Abstract

Totally enclosed fan-cooled (TEFC) 37 kW class 130 (B) temperature rise 50 Hz induction motor loss measurement results in heat run tests with sinusoidal or PWM-supply are presented. The heat run tests are performed with 25 Hz, 40 Hz and 50 Hz points with 92 per cent of the load using different switching frequencies and modulation principles. Two equal-power frequency converters were used in the test, one with vector control and another with DTC control. In addition to the heat run measurement points, the drive efficiencies were also measured using speed – torque matrix of 16 measurement points. The motor temperature rise, losses as well as measurement accuracies in sinusoidal supply or PWM supply are analyzed and discussed. The uncertainty analysis shows that in the case of PWM signal, it is reasonable to analyze the uncertainty using the fundamental wave power accuracy.

Introduction

The introduction of energy efficiency regulations around the world has made the determination of losses and energy efficiency of the induction motor more and more important topic. Currently several IEC standards are under revision or under development. 60034-1: “Rotating electrical machines - Part 1: Rating and performance” [1] is under revision. In the next revision of the standard, also converter-fed machines are expected to get their efficiency classes. *Rotating electrical machines - Part 2-1: Standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles)* [2] is also under revision. The revision will have significant advances over the 1st edition such as single preferred test method for induction motors, order of tests and measurement points in the test are fixed and the minimum accuracy of the measurement instruments is increased. *60034-2-3: Rotating electrical machines - Part 2-3: Specific methods for determining losses and efficiency from tests for converter-fed AC machines* is under development and it is expected to be launched during 2013 as a technical specification. The Canadian Standards Association is developing the *CSA 838: Energy Efficiency Methods for Three-Phase Variable Frequency Drive Systems.* There is also the development of Eco design standard running. It specifies the energy efficiency requirements for complete drive modules (CDM) and power drive systems (PDS). This standard defines the IE classes and provides limits as well as test procedures for their classification. The voltage source converters have now been used almost during four decades, but just lately the converter efficiency has become an object of interest due to the standardisation process and energy efficiency level classifications.

At present, there exists an application guide IEC 60034-17: Cage induction motors when fed from converters [3] and IEC 60034-31: Guide for the selection and application of energy-efficient motors including variable-speed applications [4]. In [5], it is shown that different laboratories testing the same motor came up with very different results. The Round Robin test series proved that the loss tolerance of 15 % is reasonable. This shows that even the efficiency of grid connected machines is troublesome to determine accurately. In case of converter-fed machines pulse-width-modulated signals create extra challenge to the motor efficiency determination. The results of variable speed drives efficiency measurements of three collaborating research institutes are presented in [6]-[8]. The authors suggest that the efficiency of the VSD should be measured in an operating point matrix and presented by contour curves. The additional harmonic losses caused by PWM methods have been studied widely in the literature, e.g. in [9]-[15]. Still, there exists no generally accepted way to determine the additional harmonic losses. There are, of course, several problems related to defining the efficiency of the converter, the motor and the drive. For example, there is no standard modulation technology to be used and there is no standard control method to be used either. The DC-link level to be used has no standard etc. All of these have a significant impact on the efficiencies.

Heat run tests

As direct electrical and torque measurements very easily fail, heat run tests performed on electrical machines are extremely important both for manufacturers and users when the amount of losses are accurately defined. A manufacturer would like to have an optimally designed machine so that the product is competitive, while a user wants to be sure that the motor temperature at full load does not exceed the thermal limits of the insulation and thus have a negative impact on the motor lifetime.

A 37 kW industrial totally enclosed fan-cooled (TEFC) class 130 (B) temperature rise induction motor was used in the tests. The frame size of the motor is 225. The catalogue value of the efficiency for this motor is 93.6 % with a full load and 93.4 % with a 75 % load in a sinusoidal supply. Two equal-power frequency converters were used in the test, one with the DTC and another with the vector control. The vector controlled frequency converter uses symmetrical two-phase modulation, thus the switching frequency is 2/3 of the carrier frequency.

In the temperature test measurements, the motor temperatures with a sinusoidal supply and with a frequency converter supply were recorded. With the sinusoidal supply, the electrical input power of the motor, the rotational speed and the shaft torque were recorded by a 500 Nm Magtrol torque transducer TMHS 313. In the frequency converter use, the electrical input and output power of the converter were recorded by two Yokogawa PZ4000 power analyzers. In these measurements, a 10 second record length with 1 million samples at a 1 minute interval was used. At each operating point, the motor was running 540 minutes (nine hours) to obtain thermal equilibrium and correct slip. The electrical powers shown here are an average value of the last 30 samples. At the end of the measurement, the current and voltage were recorded with a 1 second time interval and a 1 µs sample time to perform the DFT analysis to obtain the fundamental voltage and current as well as to calculate the distortion. The temperature of the machine was recorded with Fluke Hydra reading the three pre-installed Pt-100 sensors located in the machine windings. One Pt-100 sensor was used to obtain the ambient temperature. LabView was used to gather the data to get the same time stamp for all values.

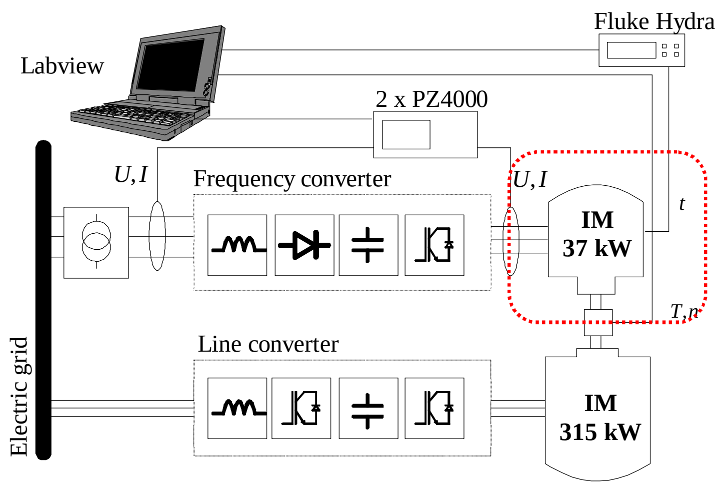

Figure 1. Measurement setup. The motor under test is marked with a dashed line square.

The sinusoidal supply tests were carried out with 25 Hz, 40 Hz and 50 Hz frequencies. A synchronous generator providing low THD was used to supply the motor with 25 Hz and 40 Hz sinusoidal voltages. Both converters were driven with a frequency reference.

25 Hz operating point

The input (terminal) phase voltage of the frequency converter was set to an RMS value of 230 V with a transformer. As a load, a DTC-controlled induction machine was used. The nominal load torque of the 37 kW induction machine is 239 Nm. The load value was set to 220 Nm resulting in 92 per cent of the nominal load torque. The temperature rises in Tables I, II and III are the average values of the three Pt-100 sensors located in the stator windings. The laboratory temperature was recorded with a

Pt-100 sensor and its value was subtracted from the results. During the temperature tests, the laboratory temperature varied between 25–28˚C.

The numerical results of the measurements are given in Table I. The THD values provided in the tables are calculated from the current. For the vector-controlled converter, the fundamental component of the voltage decreases, when the switching frequency is increasing. Thus, more fundamental wave power is needed to produce the required torque and speed. Although the fundamental voltage is decreasing, the fundamental current component is increasing, and thus, the voltage and current distortions decrease as the switching frequency is increased. The slip of the motor is at its highest value when the switching frequency is low and losses are high. This shows that the motor is behaving logically in the measurements.

Table I. Numerical results of the measurements at the 25 Hz operating point with sinusoidal and converter supply.

	Sinusoidal	Vector	Vector	Vector	DTC	DTC	DTC	DTC
f_{sw} [kHz]	-	1	4	8	1	2	3	3.75
U_{fund} [p.u.]	0.477	0.499	0.498	0.497	0.515	0.514	0.514	0.513
I_{fund} [p.u.]	0.933	0.931	0.935	0.936	0.918	0.925	0.919	0.919
I,RMS [A]	64.47	66.01	64.70	64.74	63.92	63.95	63.50	63.60
n [rpm]	729*	731	734	733	732	733	733	734
T [Nm]	219.7	220.4	220.2	220.3	220.7	221.7	220.1	219.9
P_{mech} [kW]	16.66	16.87	16.93	16.91	16.94	17.02	16.92	16.90
P_{out} [kW]	18.30	19.18	18.70	18.71	18.82	18.79	18.62	18.60
P_{in} [kW]	-	19.63	19.24	19.42	19.41	19.46	19.36	19.42
$P_{motor,loss}$ [kW]	1.64	2.31	1.77	1.80	1.88	1.77	1.70	1.70
THD_{50} [%]	1.34	21.7	2.48	2.36	1.96	1.58	1.08	1.52
t_{rise} [˚C]	62.7	86.1	68.8	67.1	72.6	68.3	65.8	65.2

*supply frequency 24.84 Hz

The THD values show considerable distortion when the vector control converter is used with a 1 kHz carrier frequency. The differences in the amount of harmonic components between 4 kHz and 8 kHz carrier frequencies are not significant. The DTC converter produces less distorted currents than the vector controlled converter. The temperature rise and loss rises versus sinusoidal supply are shown in Figure 2. The DTC converter optimizes the voltage to be slightly higher than in case of the vector controlled converter.

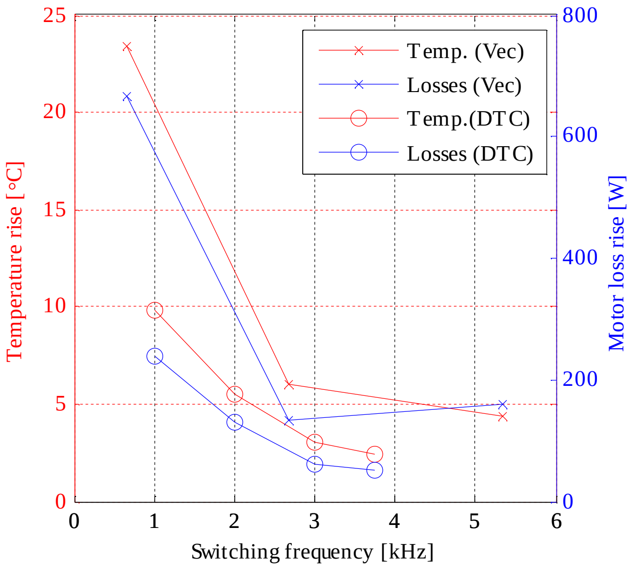

Figure 2. Extra temperature rise and loss changes compared with the 25 Hz sinusoidal supply as a function of the switching frequency. The load torque is set to 92 % of the motor nominal load.

The additional temperature rise and additional motor losses produced by a frequency converter are at their highest values when the switching frequency is low. The losses of the motor rise from 200 W up to 760 W depending on the switching frequency and the converter used. The temperature rise and loss curves do not exactly match in Figure 2. The temperature rise can be assumed to be a more reliable indicator of the motor losses than the direct power measurement. If we assume that the correct value of the measured torque is 220 Nm and the correct rotational speed is 732 rpm, the losses vary by 77 W, when the torque measurement has an error of 1 Nm and 100 W if the speed has an error of 1 rpm, respectively. The total motor losses at this operation point are around 1800 W, and consequently, the relative loss error can be very large. The largest difference in the additional losses produced by two different converters can be assumed to be the voltage fundamental wave amplitude. A higher voltage means a smaller current, and therefore, dominating resistive losses will decrease.

40 Hz operating point

At the 40 Hz operating point, the frequency converters are functioning in the normal operating range, and the motor power is 74 % of the nominal power. The sinusoidal voltage was produced by a synchronous generator. The THD_{50} value of the grid voltage is 0.65 % measured at the motor terminals. The numerical results of the measurements are given in Table II.

Table II. Numerical results of the measurements at the 40 Hz operating point with sinusoidal and converter supply.

	Sinusoidal	Vector	Vector	Vector	DTC	DTC	DTC	DTC
f_{sw} [kHz]	-	1	4	8	1	2	3	3.75
U_{fund} [p.u.]	0.795	0.795	0.793	0.792	0.818	0.822	0.822	0.817
I_{fund} [p.u.]	0.938	0.935	0.941	0.940	0.925	0.925	0.927	0.927
I,RMS [A]	64.8	65.6	65.0	65.2	64.1	64.0	64.0	64.0
n [rpm]	1185	1183	1183	1183	1184	1184	1184	1184
T [Nm]	219.0	219.1	218.9	219.2	219.0	219.2	219.0	219.0
P_{mech} [kW]	27.18	27.14	27.12	27.16	27.15	27.18	27.15	27.15
P_{out} [kW]	29.28	29.79	29.47	29.47	29.55	29.43	29.39	29.38
P_{in} [kW]	-	30.31	30.09	30.28	30.23	30.20	30.23	30.27
$P_{motor,loss}$ [kW]	2.1	2.65	2.35	2.31	2.4	2.25	2.24	2.23
THD_{50} [%]	0.80	18.03	3.33	3.38	2.77	1.68	1.30	1.74
t_{rise} [°C]	58.0	71.8	61.8	61.1	64.0	61.1	59.7	60.6

The numerical results show that the slip of the motor remains constant with all switching frequencies for both converters. When the motor is driven with the DTC, the slip of the motor is 1 min^{-1} smaller than when using the vector control. The reason for this is that the DTC converter drives the motor with a slightly higher flux density. The current distortion shows that the DTC modulation is capable of producing less distorted current than the symmetrical two-phase modulation. Similarly as at the 25 Hz operating point, the DTC is driving the motor with a higher voltage than the vector control. The less distorted, smaller current results in lower motor losses. The temperature rise values in Table III are not in an order that was assumed. The temperature rise of the motor fed by the DTC converter with 3 kHz is smaller than the temperature rise with the 3.75 kHz switching frequency. The results above support the results obtained at the 25 Hz operating point; the temperature rises of the motor are smaller when the DTC converter is used instead of the vector controlled converter. The temperature rise and loss changes compared with the 40 Hz sinusoidal supply as a function of switching frequency are shown in Figure 3.

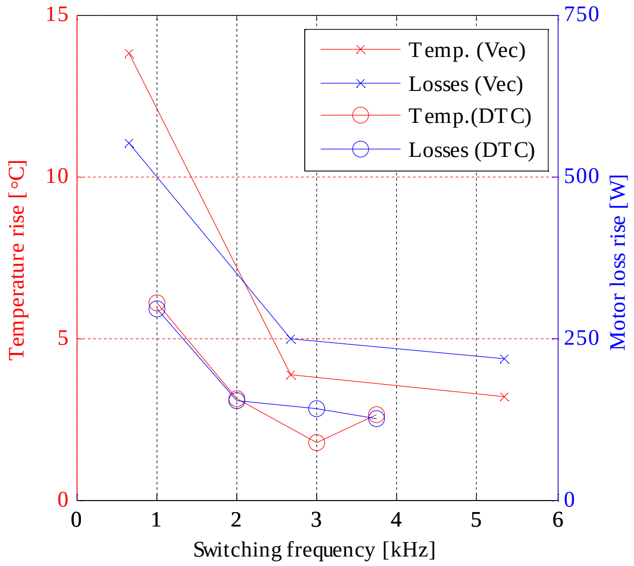

Figure 3. Extra temperature rise and loss changes with different PWM supplies compared with the 40 Hz sinusoidal supply as a function of switching frequency. The load torque is set to 92% of the motor nominal load.

The motor losses with the sinusoidal supply are 2100 W and the temperature rise is 58.0˚C. The motor losses at the 40 Hz point increase from 120 W to 600 W and the temperature rises from 3 to 14 degrees Celsius compared to the values in sinusoidal supply. Both quantities show that the loss increase produced by the frequency converter is slightly less than at the 25 Hz operating point. At the 40 Hz point, the motor is running cooler than at the 25 point, because the cooling of the motor is significantly improved.

50 Hz operating point

At the 50 Hz operating point, the same load and the switching frequencies were used as at the 25 Hz and 40 Hz points. The grid voltage with the THD_{50} value of 1.24 % was used instead of the generator. The numerical results of the measurements are given in Table III.

Table III. Numerical results of the measurements at the 50 Hz operating point with sinusoidal and converter supply.

	Sinusoidal	Vector	Vector	Vector	DTC	DTC	DTC	DTC
f_{sw} [kHz]	-	1	4	8	1	2	3	3.75
U_{fund} [p.u.]	0.999	0.926	0.919	0.922	0.922	0.914	0.906	0.914
I_{fund} [p.u.]	0.937	0.978	0.988	0.990	0.983	0.987	0.995	0.989
I,RMS [A]	64.9	68.5	68.4	68.2	68.4	68.3	68.9	68.7
n [rpm]	1484	1479	1482	1480	1479	1480	1479	1479
T [Nm]	219.7	219.5	219.5	219.9	218.9	218.6	218.6	218.2
P_{mech} [kW]	34.14	34.00	34.07	34.08	33.90	33.88	33.85	33.80
P_{out} [kW]	36.46	36.94	36.85	36.77	36.68	36.62	36.60	36.54
P_{in} [kW]	-	37.51	37.53	37.59	37.46	37.47	37.54	37.45
$P_{motor,loss}$ [kW]	2.32	2.94	2.78	2.69	2.78	2.74	2.75	2.74
THD_{50} [%]	2.52	15.47	3.44	3.77	2.57	2.70	2.34	2.99
t_{rise} [˚C]	59.2	71.5	66.2	63.8	67.8	66.1	66.4	65.7

At the 50 Hz operating point, the amplitude of the fundamental wave voltage of the vector- controlled vector controlled converter is larger than the one that the DTC converter is using to drive the motor. This is a result of different converter rectifier topologies. At the 25 Hz and 40 Hz operating points, the situation with the fundamental wave amplitude is the opposite. The current distortion of the DTC converter still remains smaller than the one obtained with the vector controlled converter.

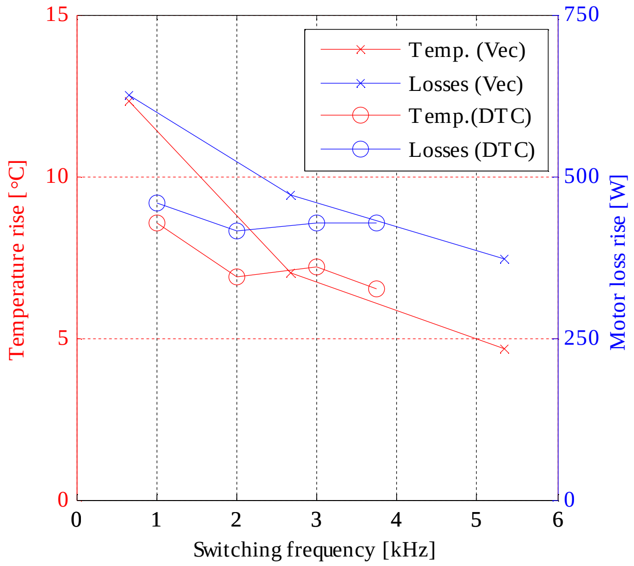

Figure 4. Extra temperature rise and loss changes compared with the 50 Hz sinusoidal supply as a function of switching frequency. The load torque is set to 92 % of the motor nominal torque.

The temperature rise results correspond well with the measured loss rises. The motor loss rises due to PWM modulation is a function of the rotational speed, the modulation method and the switching frequency.

Speed torque matrix

The 4 x 4 speed – torque matrix was measured after heating the motor to its normal operating temperate. All energy efficiency (flux optimization) control features were turned off and the frequency converters are driven with frequency references similarly as in the temperature rise tests. The vector converter carrier frequency is 4 kHz and the DTC converter switching frequency is 3 kHz. First, the efficiency in the nominal point was obtained and then in the load torque points in descending order. The different speeds were measured also in descending order. The results are given here as iso-efficiency contours.

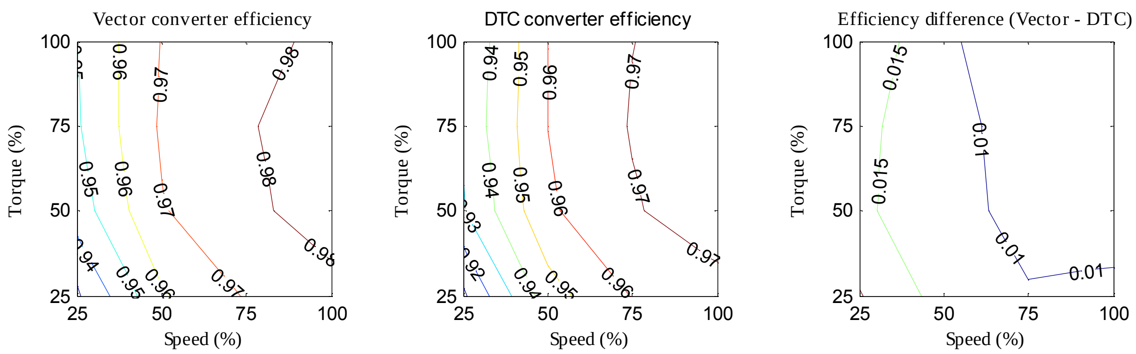

Figure 5. Converter efficiencies in speed – torque plane.

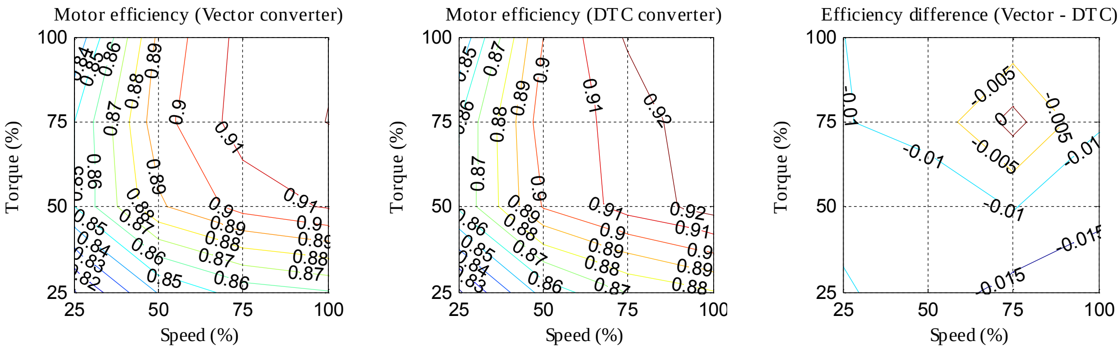

Figure 6. Motor efficiencies in speed – torque plane.

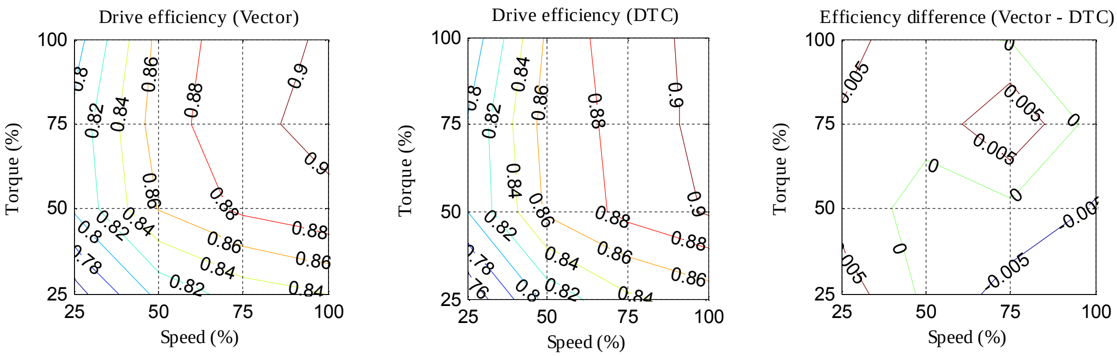

Figure 7. Drive efficiencies in speed – torque plane.

Although, the differences in temperature tests are well noticeable, when inspecting the drive efficiencies in speed – torque plane, the drives with these two different converters can considered to be equally efficient. The same conclusions can be drawn with both tests. In this case, the vector controlled frequency converter has lower losses than the DTC converter, but the motor losses are smaller when using the DTC converter. To obtain the results of the heat run tests takes several months, but the matrix measurements can be done in the single day. When the measurement series is planned, it has to keep in mind, what is the target of the measurements. When inspecting the frequency converters at system level, the matrix measurement is enough accurate, but in the frequency converter development the heat run test gives more reliable results.

Uncertainty analysis

The power measurement uncertainty in the case of PWM-voltage can be estimated using discrete Fourier transform (DFT) and calculate the power components at each frequency and refer these to manufacturer's data sheet to get the uncertainties with different frequency ranges. From the control engineering point of view, an electrical machine is a voltage-controlled current source. The losses of the motor are dependent on the amplitudes and frequencies of the current components. The voltage coupled to the machine terminal produces the current through the machine impedance. The different voltage waveforms produce different current waveforms, and the best way to analyze the current is its spectrum. Even when pulse-width-modulation is used, the fundamental wave is still transferring most of the electric power to the motor and further via the air gap to the motor shaft. The different control systems similarly as the same control system with different controller parameters have different voltage and current spectra, and therefore the electric power flowing through the drive can be in different frequency ranges. Figures 8 and 9 show the power spectrum estimates with these converters.

The figures have been compiled so that the results of current and voltage DFTs are multiplied by each other. The bars represent the sum of these power components with the given frequency ranges.

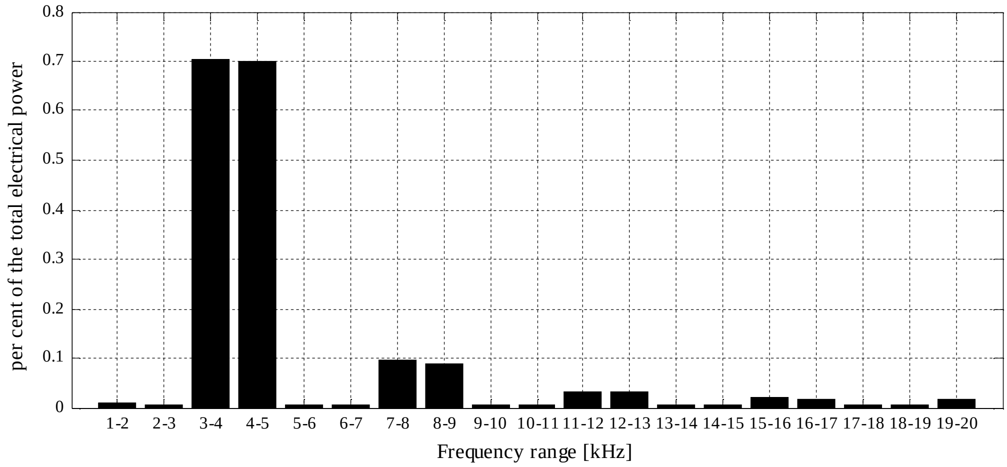

Figure 8. Vector-controlled inverter-fed induction motor electrical power as a function of frequency. The measured results are obtained with a 37 kW motor driven with a 50 Hz frequency reference. In the measurements, the carrier frequency is set to 4 kHz and the load torque is 92 per cent of the nominal load. The fundamental wave frequency carries 98.0 %, and the rest of the harmonic components under 1 kHz carry 0.26 % of the total power under 20 kHz.

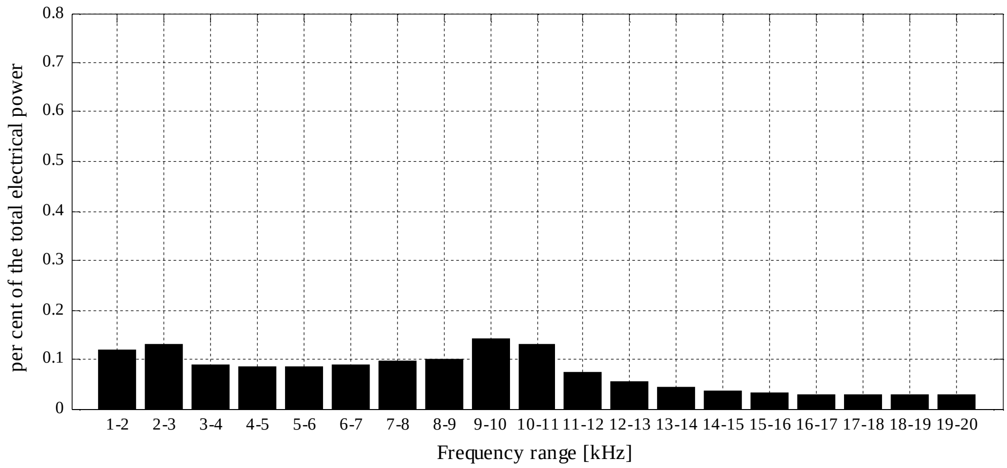

Figure 9. DTC inverter-fed induction motor electrical power as a function of frequency. The measured results are obtained with a 37 kW motor driven with a 50 Hz frequency reference and load is set to 92 per cent of the nominal torque. In the measurements, the average switching frequency is 3 kHz and the load torque is 92 per cent of the nominal load. The fundamental wave frequency carries 97.5 %, and the rest of the harmonic components under 1 kHz carry 0.4 % of the total power under 20 kHz. In the frequencies above 10 kHz, only 0.28 % of the total power is flowing through the drive.

The figures show that the electrical power distribution is different with different PWM supply conditions. The carrier frequency is clearly visible in the case of the PWM, but the switching frequency of the DTC cannot be seen from the figure. The power analyzer accuracy is given as a sum of the reading uncertainty and the measurement range uncertainty. The uncertainties considering the electrical equipment used in the measurements are shown in Table IV. The power measurement uncertainty of the power analyzers is given for sinusoidal signals with a unity power factor in the given frequency range. Additional uncertainties arise from the leading or lagging power factors and common-mode voltages in the measurement system. The torque transducer torque uncertainty is below ±0.1 % of rated torque. This error includes the linearity and hysteresis errors. The minimum speed detection of this high speed sensor is 1 rpm.

Table IV. Yokogawa PZ4000 power accuracy [16].

Frequency	Accuracy
DC	±(0.2% of reading + 0.1% of range)
0.1 Hz ≤ f ≤ 10 Hz	±(0.2% of reading + 0.05% of range)
10 Hz ≤ f ≤ 45 Hz	±(0.2% of reading + 0.025% of range)
45 Hz ≤ f ≤ 1 kHz	±(0.1% of reading + 0.025% of range)
1 kHz ≤ f ≤ 10 kHz	±(0.15% of reading + 0.04% of range)
10 kHz ≤ f ≤ 50 kHz	±(0.3% of reading + 0.05% of range)
Power factor error	
45 Hz ≤ f ≤ 66Hz	+ (0.15 tan φ)% of reading

Using the power spectrum, measurement instruments accuracies at given points and measurement results, we can compile a measurement uncertainty matrix that gives the uncertainties of the measurement results in each point of speed - torque matrix, Fig 10. On the left, the uncertainty of the vector controlled frequency converter measurement is given, in the center the corresponding motor measurement and on the right hand side the drive efficiency uncertainty. The error in input and output power measurements of the converter or motor is considered not to correlate. The uncertainty matrix of the DTC converter looks exactly the same as the one for the vector converter; because the overall power measurement uncertainty is ± (0.100149% reading + 0.0253% range) for the PWM signal from 0.1 Hz to 20 kHz. Thus, the uncertainty analysis can be simplified and it is possible to use the fundamental wave accuracy for the total active power and not making a remarkable error in the analysis.

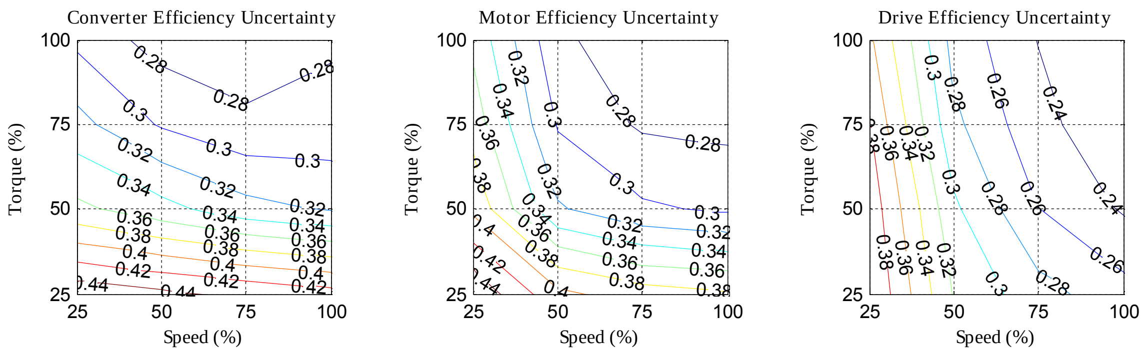

Figure 10. Uncertainties of the frequency converter, motor and drive efficiency determinations using measurements. The lines present the uncertainty in percentage units in speed – torque plane.

The uncertainties in the efficiencies are higher with smaller loads. In these measurements the uncertainties are quite high. If we compare the differences in figures 5.-7 and the uncertainty figures, we find out that the uncertainty is in all cases higher than the difference between these two drives.

Conclusions and discussion

The results here cannot be used to compare the different modulation methods or control systems performance because the parameterizations, estimations and realizations affect the results. Although, the heat run tests showed differences between the two converters driving the same motor. If we look at the loss rises at default switching frequencies, 4 kHz for the vector controlled converter and 3 kHz for the DTC converter. The motor loss rises for the vector controlled converter and the DTC converter were 8% and 4% at the 25 Hz point, 12% and 7% at the 40 Hz point and 20% and 19% at the 50 Hz point respectively, compared with the sinusoidal supply losses. According to this research, there is no general rule of thumb that can be used to obtain the effect of PWM on the motor losses. The motor temperature rises are directly proportional to the additional losses produced by the PWM in the motor.

The additional losses are a function of the rotational speed and the switching frequency. The iso-efficiency contours are a valuable tool to visualize and analyze the large number of measurement points and it is well justified when frequency converter driven systems are analyzed at system level.

Detailed analysis of electric power measurement uncertainty with PWM – signal is given. Here, the measurement instruments can be considered as basic level accuracy devices and the measurement instruments with similar accuracies are used in many motor labs around the world. It is well acceptable in case of PWM signals to use power analyzer accuracy at fundamental frequency to estimate the total uncertainty in the active power measurement. It should be kept in mind that, when low power level and low power factor points are measured the uncertainties may be reasonably higher than in the nominal point. The power factor error in the power measurement uncertainty analysis must not be neglected. In this case the frequency converter efficiency uncertainties vary from 0.28 to 0.44 percent units. According to these measurements the rated point efficiency of the vector control converter is (98.2±0.3)% and the rated point efficiency of the DTC converter efficiency is (97.4±0.3)%. The motor efficiency at the nominal point with sinusoidal supply is 93.6%, and 91.9% when driven with the vector controlled converter and 92.8% with the DTC converter with the same 0.3% uncertainty.

Although, the converter losses are different from each other, the total drive losses remain almost constant. In this case, the frequency converters' as well as the motor's efficiency differences are marginal. From the energy efficiency point of view, both these converters are almost equal. It should be kept in mind that the uncertainties of the direct input – output efficiency determination with high efficiency devices can be high. In engineering work, the temperature rise is a good indicator of motor losses, but it is motor specific and cannot be used to compare different motors. Also, the temperature rise gives only relative changes in the losses. The uncertainty of these measurements is greater than the differences between the drives. When same laboratory setup with the same instruments and data collection methods are used, the results are valid for comparison, but the uncertainty of the measurements should be inspected if the results are compared with the results obtained by another laboratories.

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Beyond IE4: Future Efficiency Improvements in Electric Motor Systems

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ABSTRACT

While motor system efficiency has improved significantly in recent years, there are a number of additional gains that can be expected in the future. This paper will cover some of these possible improvements with respect to both motors and drives. Motor system efficiency could easily be increased with components and technologies that exist today, but the market place is reluctant to accept the resulting increase in motor cost that would occur with such changes. Therefore, although all possible improvements are covered, the emphasis in this presentation is on identifying potential improvements that can be cost-effective and on making an estimate of when these improvements may be available in the marketplace. Of course, "cost-effective" depends not only on the cost of energy, which varies widely from place to place, but also on the way costs are accounted for within an organization.

Both motor and drive efficiency improvements will be reviewed, and the three major motor technologies (induction, permanent magnet (PM) and reluctance motors) will all be examined. Motor technology improvements cover both the design aspects of a motor and the materials that are available for constructing a motor. The drive improvement section also covers drive design and new drive components, as well as looking at novel ways to employ the drive to improve system efficiency.

BACKGROUND

The need to increase overall motor system efficiency has never been greater. With the rising costs of energy and the substantial concerns about global CO2 emissions, achieving the highest possible motor system efficiency has become a critical priority. It is worth stating that while this paper is focused on possible specific improvements to electric motors and motor drives, it is the whole systems approach that still has the largest untapped potential for efficiency gains in motor-driven applications. Approaches like applying variable speed operation to all processes that could benefit from variable speed; eliminating gearing and pulleys in mechanical systems like pumps and fans; and altering manufacturing processes so that they do not require so much energy input will yield far larger gains than can be achieved at the motor and drive level. However, cost-effective improvements in motor system efficiency also have significant promise and should be aggressively pursued.

CURRENT STATUS

When considering what constitutes a high efficiency motor, both the power rating and operating speed of the motor must be taken into account. Motor efficiency generally increases with larger sized motors and higher power levels. While a 1 KW machine may be considered very efficient at an 89 percent efficiency rating, a 50 KW machine would need to be 95 percent efficient to be considered highly efficient. Efficiency improves as motors get larger because motor torque increases directly with motor volume, while losses increase at a lower total rate.

Currently, motors that achieve efficiencies significantly higher than IE3 (or in the U.S., NEMA Premium) are available and more are being brought to market every year. These motors are generally based on permanent magnet (PM) or reluctance motor designs; however, properly designed induction motors using advanced materials can also achieve these higher efficiencies. These higher efficiency motors generally cost more than less efficient motors, but the payback times are often only 2 to 3 years. Even with such an attractive payback, the market has not yet embraced these motors in a substantial manner. However, the future holds a continuous stream of material, design and process improvements that will continue to make these motors more efficient and more attractive to the marketplace.

In looking at motor system efficiency improvements, the motor offers a bigger opportunity for efficiency improvements than the electronic drive. Current electronic drives are generally above 95 percent efficient and are often 96 to 97 percent efficient. Some of the newest drives even reach 98 percent and higher at full load operation, depending on their power rating. Given the inherent nature of power conversion devices, this leaves little room for further improvement. However, in some applications, new techniques such as energy recovery during deceleration could improve overall motor system efficiency.

Motors, however, have efficiencies in the low to mid nineties -- which is good, but could clearly be better, since higher efficiency motors already exist but generally have not been widely adopted by industry because of the upfront costs. All aspects of motor components can be improved, including soft magnetic materials, permanent magnets, windings, bearings and thermal conduction. Further advancements in motor design will also help increase motor efficiency -- and often at very low or no additional manufacturing costs.

EFFICIENCY IMPROVEMENTS IN MOTORS

Motor Materials

There are two main areas where cost-effective efficiency gains can be accomplished in motors: the materials that make up the motor and improvements in motor design. Important work is currently being conducted on improving all the materials that go into a motor, including;

(1) Soft magnetic materials, such as those used in laminations,
(2) Magnet materials,
(3) Conductors,
(4) Bearings and their lubrications, and
(5) Casing materials.

Each of these will be discussed in detail below.

Soft Magnetic Materials

Soft magnetic motor components undergoing improvements include:

- Lower loss lamination steels,
- High performance amorphous metals,
- Exotic alloys such as Cobalt alloys,
- Soft magnetic composites (SMC), such as oriented SMC material, and
- Nano-particle compositions.

Of these, the first two are likely to provide near-term motor performance benefits. Better processing of standard lamination steels is lowering the hysteresis losses of these steels. Work is being done on better steel-treating methods such as laser scribing, which reduces the overall steel loss.

While amorphous metals have been around many years, they have not been applied to motors due to geometry and manufacturing constraints. Recently, more interest has been devoted to this material with axial PM motor designs. The advantages of amorphous metals are low coercivity, high resistance to eddy currents, and a square hysteresis loop. The disadvantages of this material are low saturation flux and the fact that it is extremely hard to process into the shapes used in traditional radial motor designs.

With respect to pressed power soft magnetic composites, work is being done on new formulations and even on an oriented version with a permeability that approaches lamination steel in the preferred direction. The advantage of these soft magnetic composites is that complex shaped parts can be made with a low-cost pressing process. The disadvantages of traditional SMC materials include low permeability and high hysteresis losses. Numerous research institutions are working with iron or iron-cobalt nano-particle formulations to see how perfect a soft magnetic material can be made. This work is early and will take a number of years to reach commercial availability.

Magnet Materials

Regarding magnets, there is an abundance of work currently being conducted on advanced magnets. Opportunities include samarium iron nitride (SmFeN), cerium-based rare earth magnets, iron-cobalt, pure iron, nickel-iron, manganese and numerous nano-particle PM formulations, as well as others. Many of these are part of the U.S. Department of Energy REACT program. The previous examples are a list of work undertaken in the United States, and I am sure that in Europe, Japan, China and other countries there is a similar level of effort in PM development.

There is also a lot of work being done on magnets that are currently commercially available. Neodymium iron boron magnets continue to have increased energy product, higher stable temperature limits, and minimized use of expensive alloying elements. With respect to ferrite magnets, new higher energy product formulations are being developed, along with higher coercivity versions. Even Alnico is being studied to see if its coercivity can be increased without decreasing the Br. With all this work being conducted on both new and existing magnet materials, there is a high probability that new and improved magnet choices will be available to the motor designer of the future.

Several of these developments plan to have sample magnets available this year, and with some of these programs there is a rather clear path between laboratory development and medium to large scale commercial production. I think it will be likely that we will see enhanced magnets being sold in the commercial marketplace within 5 years.

Conductors

Conductors have potential for improving efficiency though the use of rectangular conductors (which are currently being used in motors built by GM and Remy for the automobile industry), flat wire, and foil conductors. Each of these is likely to see greater usage in the near future. Progress is also being made in better insulation coatings for conductors leading to higher temperature operation and higher breakdown voltages. More distant possibilities include carbon nanotube conducting wire and high temperature superconductors. While superconducting wire has been used in some very large motors, I expect to see this technology being applied more commonly in motors down to 375 Kilowatts and maybe as low as a 100 Kilowatts, as the attractive features of this wire increase and the costs significantly decrease.

Bearings and their Lubricants

The mechanical rotating losses from the motor bearings are being addressed with better bearing designs, advanced materials such as ceramic balls, and lower friction lubrications. In the more distant future, magnetic bearings and fluid bearings may be deployed more commonly in the motor market.

Casing Materials

An area that could see significant improvement is one that is often overlooked. This is casing and potting materials which yield better thermal conductivity for the motor. These are being perfected so that heat can escape more easily from the motor, resulting in a more reliable and more efficient motor as a result of lower winding temperatures.

Design Improvements for More Efficient Motors

With respect to motor design, there are copper rotor induction motors, improved switched reluctance motors and a variety of new permanent magnet (PM) motor topologies all vying for a portion of the overall motor market.

It is well-accepted that permanent magnet motors can achieve higher motor efficiencies than induction motors because of the reduction of losses in the rotor. In addition, the rated efficiency of a permanent magnet motor is specified with the assumption it will be operated from an electronic drive, so its rated efficiency performance can actually be achieved in real world applications. However, permanent magnet motors in the past have cost more than induction motors, due to the cost of the magnet materials used in these motors. This is especially a concern at the present time since many high performance permanent magnet motors rely on rare earth permanent magnet materials, which are experiencing unprecedented price swings and supply concerns.

PM motors come in many configurations and currently the interior permanent magnet (IPM) motor leads the industry in performance with respect to power density and efficiency. There are also many new PM geometries being developed such as radial hub motors, permanent magnet axial motors, and transverse flux motors. Some PM motor designs can effectively use low-cost ferrite magnets. These designs can achieve the efficiency of rare earth PM motors while maintaining attractive manufacturing costs. However, their power density is not as high as rare earth PM motors.

Switched or synchronous reluctance motors are also being improved, and some of them meet or exceed IE4 efficiency requirements. These motors also have minimal rotor losses compared to induction motors. They are taking advantage of better design techniques, and better lamination materials have reduced the noise problems that have plagued this motor in the past. Because the motor and drive must be carefully matched, they are sold as a complete package of motor and drive. The use of standard commercial drives is not an option for reluctance motors.

To achieve IE4 efficiencies and above with induction motors, copper rotor technology most likely needs to be utilized, as well as better lamination steels and optimized design. This pushes the cost of these motors higher than standard induction motors, but they can still be operated directly from the line for fixed speed applications. Given the inherent rotor conduction losses, it is unclear just how much more efficiency can be achieved with the basic induction motor design.

Sources of Motors Losses

Motor losses can be divided into categories as to where they occur and what mechanism is responsible for the loss. The first loss area is conduction losses in the motor conductors. Induction motors have conduction losses in both the rotor and the stator. PM and reluctance motors only have conduction losses in the stator. Conduction losses generally dominate the efficiency performance of a motor when the motor is operated at lower speeds. Iron losses occur in all motor types in both the stator and the rotor. However, surface mounted PM motors can have so little rotor iron loss that it can be ignored. Iron losses generally set the efficiency performance at high speeds. The third category of losses is frictional losses that are mainly due to bearings but in larger motors can also be due to windage. These losses are dependent on motor speed. To achieve a broad flat efficiency curve, both conduction and iron losses must be addressed and kept at a low value. Motor losses are summarized in Table 1 below.

Conduction losses – torque-related losses	**Location**
Coil I^2R losses	stator
Speed losses – speed-related losses	
Iron losses – hysteresis and eddy currents	stator and rotor
Frictional losses – bearings and windage	rotor
Other – torque and speed related	
Excess losses – hysteresis and eddy currents	stator and rotor

Table 1: Motor Loss Summary

It is difficult to fairly compare motor technologies in a direct manner; however, the graphic given below (Figure 1) does indicate the relative sources of losses in each of these motor types. The left hand scale is an approximate percentage loss number for a 1 kilowatt motor.

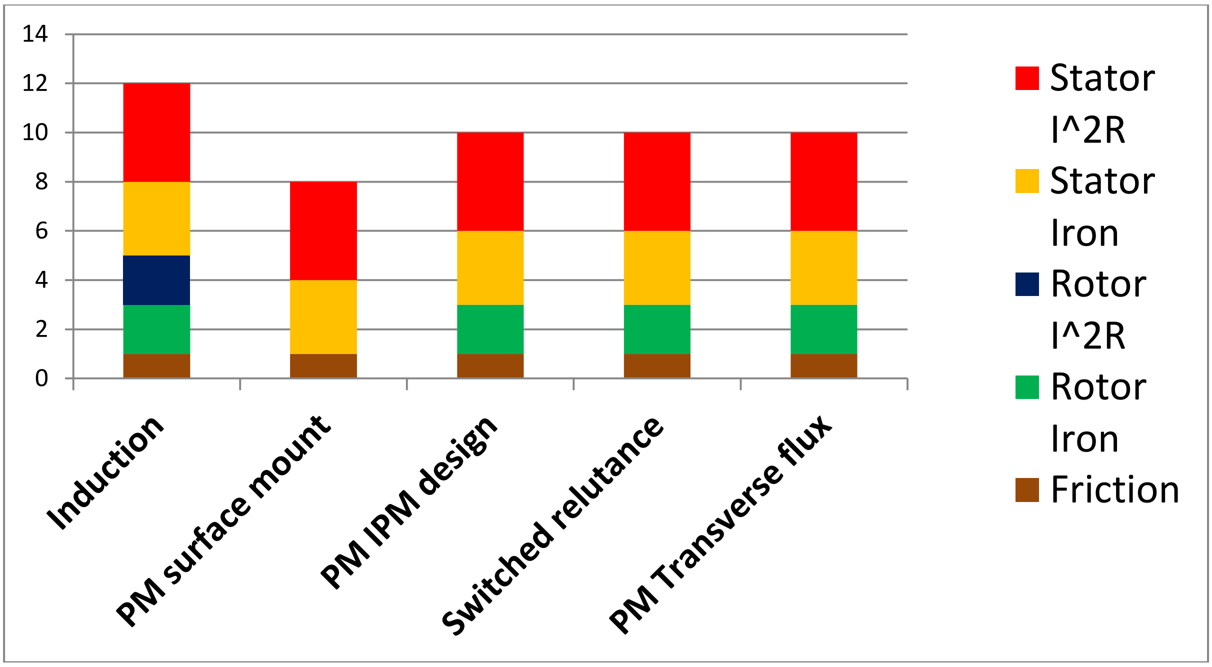

Figure 1: Approximate percent relative loss in induction, PM and reluctance motors (1 kW)

EFFICIENCY IMPROVEMENTS IN DRIVES

Looking at the electronic drive or inverter for the motor, a similar long list of improvements can be forecast. The improvements can be divided into the following three categories: improved components, new designs, and improvements in software and application techniques. For motor drives, higher efficiency means cooler running and more compact drives. Most of the improvements in the electronics used by motor drives are not solely driven by the motor drive industry. They are mostly driven by the needs of the solar power, electric automotive, and the power supply industries -- all of which are seeing rapid market expansion. Especially in the automotive industry, the history of improving overall performance while driving costs lower is legendary, and one would expect to see significant improvement in the cost/performance ratio for all aspects of motor drives.

Improved Components for Drives

Better components for electronic drives include:

(1) Active power semiconductors such as IGBT's, MOSFETs, GaN and SiC components,
(2) Power supply conversion components used in internal power supplies,
(3) Lower power processors, and
(4) Lower loss passive components like inductors and capacitors.

Currently, gallium nitride and silicon carbide are competing for a spot in the general purpose motor drive designs. Both of these materials make devices that can provide higher efficiency drives since they both have lower switching losses than IGBT's, which are the standard device for currently produced motor drives. The advantages of SiC and GaN include both lower switching losses and higher switching speeds, which allow smaller and lighter passive power components. The issue with both of these technologies is that the cost of the device is many times the cost of an equivalent power IGBT device. Predictions are that these devices will rapidly decrease in cost and increase in performance to make them much more attractive.

IGBT's and power FETs made from standard silicon will also improve in their performance in the same time frame, making it a very difficult call to determine which power technology will dominate the market. Most likely, each device technology will be applied in certain market segments, and we will see a greater diversity of types and features in motor drives.

Not only is there a revolution going on in the power semiconductors for motor drives, but there are similar developments in the other components used in these drives. All the components such as internal power supplies, microprocessors, inductors and capacitors are improving in both performance and cost. This is especially true for inductors, as better magnetic core materials are leading to inductors with significantly lower power losses. Microprocessors are becoming even more powerful in terms of processing capabilities, at the same time that their power consumption is decreasing. This is driven by the rapid trend to mobile devices such as cell phones and portable computing. It goes without saying that the cost of these devices is also decreasing.

Design Improvements for More Efficient Drives

With respect to new and improved electronic designs, new bridgeless rectification designs, such as those from International Rectifier or from Optimum Power Conversion (Cuk design), as well as others, represent a great opportunity for efficiency gains. A typical motor drive takes AC line power and rectifies it to produce DC power, which is then chopped in order to make the controlled motor currents that are necessary to operate the motor. These new designs eliminate at least one stage of rectification loss, helping to boost overall drive efficiency. Typical rectification loss results in a line voltage drop of about 1.5 volts; with low voltage line inputs (240 volts), this can result in approximately a 0.5 percent total efficiency loss. Saving half of this with bridgeless rectification certainly makes sense in many cases.

The power to operate the motor drive internal circuitry is also being addressed. While the motor may only be run for part of the day, the drive is usually powered on 24/7. By reducing the standby power consumption of the motor drive, overall system power consumption is reduced.

Software and Control Techniques

Software and control techniques can also be applied to help improve system efficiency. These include such approaches as:

- Varying DC link bus voltage with motor speed and load to reduce overall switching losses,
- Voltage boosting to operate at higher voltages and lower currents, thereby reducing conduction losses, and
- Power factor correction to prevent excessive loss in the power lines feeding the inverter.

This extra power line loss when not using a power factor-corrected drive is often ignored, since the power losses occur in the AC lines feeding the motor drive and are not measured in typical motor system efficiency tests.

Finally, some of the new motor drive electronic designs allow for power flow back from the motor and into the power line. These four-quadrant type designs could be used to recover power when the motor is decelerating and to supply it back to the power grid, rather than to dissipate it in the motor drive or motor. In certain applications where there is significant starting and stopping of the motor, this type of operation could further improve system efficiency.

CONCLUSION

Most of the possible improvements discussed in this paper apply to all motor designs. The exceptions are that permanent magnet improvements only help PM motors, foil windings only apply to designs that can use bobbin style windings, and high temperature superconductors only apply to very large motors. For motors, the largest efficiency gains will most likely be in PM and reluctance motors from improved permanent magnet materials, improved laminations, better thermally conducting case materials, and reduced bearing friction. For drives, the most gains will be in new bridgeless topologies, better power devices, and improved low power system components.

While specific predictions of the future are often fraught with difficulties, I am willing to take the risk and place some possible time frames on the developments discussed above as to when they may become cost-effective and have reasonable market presence. The tables below cover the improvements in both motors and drives that have been covered in this paper. The time frames have been divided into 3 categories; within 3 years, 3 to 6 years out and more than 6 years in the future. Some advancements straddle these ranges and get put into two of the periods. Again, the criteria for this prediction is when the improvement is cost effective and has generally been adopted for use in industrial applications.

Motor improvements:

Topic - Laminations	Less than 3 years out	3 to 6 years out	Greater than 6 years out
Improved traditional laminations	X	X	
Amorphous metals	X	X	
Cobalt and exotic alloys		X	X
Soft magnetic composites		X	
Nano-particle materials			X

Table 2: Motor lamination materials

Topic – PM materials	Less than 3 years out	3 to 6 years out	Greater than 6 years out
Iron Nitride formulations		X	
Cerium compositions			X
Iron or Iron cobalt		X	
Minimized rare earth		X	
Improved ferrites	X		
Nano-composites			X

Table 3: Permanent magnet improvements

Topic – Other motor materials	Less than 3 years out	3 to 6 years out	Greater than 6 years out
Conductors - normal	X	X	
High temp superconductors		X	X
Bearings	X	X	
Casing thermal materials	X	X	

Table 4: Other motor materials

Topic – Motor design	Less than 3 years out	3 to 6 years out	Greater than 6 years out
Enhanced Induction	X	X	
PM Radial	X		
PM Axial	X	X	
Reluctance	X	X	
PM Transverse flux		X	X

Table 5: Motor design improvements

Drive improvements:

Topic – Power semiconductors	Less than 3 years out	3 to 6 years out	Greater than 6 years out
IGBT's	X	X	
MOSFETs	X	X	
GaN Gallium nitride		X	X
SiC Silicon carbide		X	X

Table 6: Power semiconductors

Topic – Other drive components	Less than 3 years out	3 to 6 years out	Greater than 6 years out
Inductors, low loss	X	X	
Capacitors, high current capable		X	X
Low power processors	X	X	
Better internal power supplies	X		

Table 7: Other drive components

Topic – Drive design	Less than 3 years out	3 to 6 years out	Greater than 6 years out
Bridgeless designs	X	X	
Capacitive coupled designs		X	X
DC link voltage control		X	
Voltage boosting		X	
Power factor correction	X	X	
4 Quadrant operation		X	X

Table 8: Drive design and operation

Combining all the above improvements and then applying these to a 3.75 kilowatt motor, and then consulting my crystal ball, I will venture the following predictions for what is in store for improvements to this size motor 3 and 6 years from now. This is presented first in the Table 9 below and then in the graphic in Figure 2. This figure shows the current IE3 and IE4 efficiency requirements versus motor size as well as my predictions for future 3.75 kilowatt motors. In addition, I have extended the 6 year out curve to all motor sizes.

Efficiency (percent)	Motor	Drive	System	Improvement
• Today's motor (standard)	90	95	85.5	0 %
• Today's motor (best practice)	93	96	89.3	3.8 %
• 3 Years estimate motor	95	97	92.1	6.6 %
• 6 Years estimate motor	96	98	94.1	8.6 %

Table 9: Efficiency prediction for 3.75 kW motor

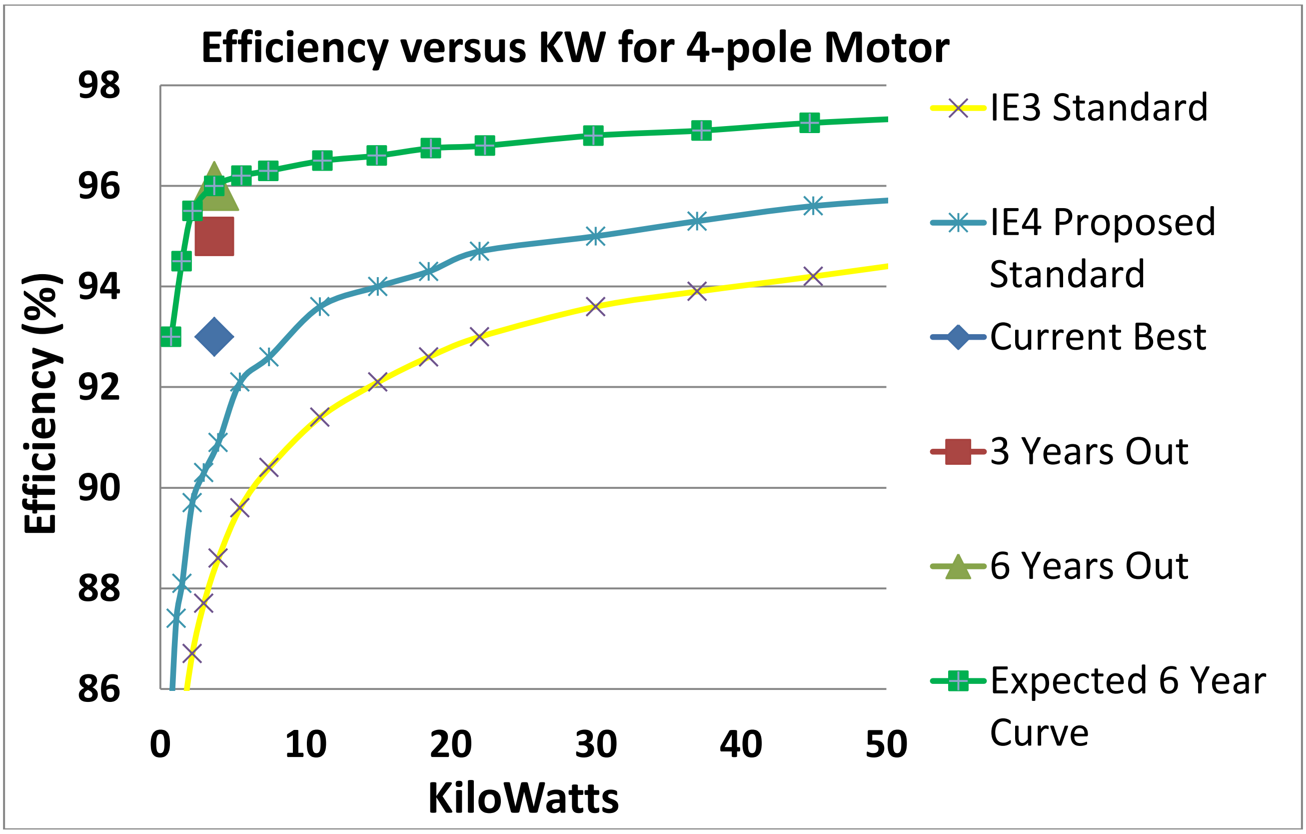

Figure 2: Motor Efficiency versus motor size with 3.75 kW motor projections

With all these possibilities for improvements in both motor and drives, the future is bright for significant continued increases in overall motor-driven system efficiency.

Significant efficiency improvements are coming!!!

Three-Phase Induction Motor Preliminar Design Assisted by CAD Software based on Brazilian Standards

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Abstract

Energy efficiency of electric motors is a challenge for the national industry in many countries, although their efficiency has been increased gradually over the years. This paper deals a computer-aided tool for the design of N-type (similar NEMA B-type) three-phase Induction Motor (IM). Such tool will bring flexibility for the design engineer during the project development. The software has the following main objectives: 1) to analyze the input data parameters of the IM project, according to Brazilian technical standards (NBR) 17094-1:2008 and 15623-1:2008, printed by the Brazilian Standards Organization (ABNT); 2) to design an IM with all electrical specificity, based on a known project method; 3) to evaluate the designed motor's performance with the same methodology. The program has a friendly graphical user interface (GUI) and it was developed by using the GUI development environment tool from MATLAB®. This paper also describes the logic programming through flowcharts and equations. The software main purpose is to produce a computer-aided tool for designing IM at the first conception step. It will evaluate the performance of the project (no built) and seek alternatives to improve its efficiency before the motor`s assembly. Knowing that the Brazilian standards requirements induce to achieve higher levels of efficiency (equivalent for other national standards) in an IM design, their technical features will be taking into account, and probably it may change the previously used IM design method. Changes on the methodology shall be highlighted in the paper.

1. Introduction

The energy efficiency of electric motors is one of the biggest challenges for the national industry in several countries, e.g. Brazil, USA and EU countries. In recent years, these countries have reviewed the minimum efficiency levels of motors [1] [2] [3], believing in the gradually increase of energy efficiency, which are already shown experimentally in [4] [5] and also theoretically [6]. It is observed in this challenge the opportunity to improve the design tools, commonly used in an electric motor design.

Brazilian standards require some necessary values for the induction motor design, as well as NEMA and IEC standards. These standards deal with the input parameters to be specified at the beginning of the design, such as: rated voltage, service factor, insulation class [7], minimum or maximum values like: torque, starting torque, casing (frame type), relation between the starting apparent power and rated power [8] and the minimum efficiency level [3] [9].

The proposed software evaluates the design process during some of these limiting design parameters, not for all, but the sufficient to achieve the main purpose of the design engineer. The software was developed in MATLAB ® and it fulfills the analytical approach of induction motor design, using the already known techniques presented in [7]. The software does not verify the typical parameter values like: flux density and current density, usually verified in numerical technique such as finite element or other. The motivation of this work is to provide a tool, which can carry out a fast evaluation, but not necessarily the final solution to the project [10].

2. Brazilian Technical Standards

The main Brazilian standards which have importance in the induction motor design are the standards described in [8] and [9]. In [9] are presented the standard dimensions for rotary electrical machines, like: the relation between the frame sizes and the height of end shaft (H), the diameter of the rotor shaft and the recommended rated power in kW. The relation between the frame sizes and the height of end shaft (H) is presented on [9].

Among the standard horsepower ratings of electrical motors in the range from 1 hp to 50 hp, the recommended power rates are 0.75 kW (1 hp), 1.1 kW (1.5 hp), 1.5 kW (2 hp), 1.8 kW (2.5 hp), 2.2 kW (3 hp), 3 kW (4 hp), 3.7 kW (5 hp), 4 kW (5.5 hp), 4.5 kW (6 hp) , 5.5 kW (7.5 hp), 6.3 kW (8.5 hp), 7.5 kW (10 hp), 10 kW (13.5 hp), 11 kW (15 hp), 13 kW (17.5 hp), 15 kW (20 hp), 17 kW (22.8 hp) 18.5 kW (25 hp), 20 kW (26.8 hp), 22 kW (30 hp), 25 kW (33.5 hp), 30 kW (40 hp), 32 kW (43 hp) and 37 kW (50 hp). It is important to point out that the table recommends power rate values up to 1000 kW (1340 hp). The standard shaft diameters have the following values in mm: 7, 9, 11, 14, 16, 18, 19, 22, 24, 28, 32, 38, 42, 48, 55, 60, 66, 70, 75, 80, 85, 90, 95, 100 and 110.

In [8] are presented, the motor duty cycles (S1 to S10, where S1 is the continuous duty), the supply voltages (220 V, 380 V or 440 V), the supply frequency of 60 Hz for products to be commercialized in Brazil, the motor design (N, H and D), which is similar to NEMA motor design (B, C and D), minimum values for starting torque (in pu), locked rotor KVA (limits for inrush current) and maximum torque (in pu). The minimum starting torque and maximum torque are function of the rated motor power, the number of poles and the motor design (N, H). For the motor design D, it is standardized only the starting torque at a fixed value of 2.75 pu.

The locked rotor KVA is given by the following expression, where S_p is the starting apparent power, P_n is the rated power, I_p/I_n is the starting current in pu, η is the efficiency at full load and PF is the power factor at full load. The standard shows the maximum values for the ratio S_p/P_n (only for the motor design N and H), depending on the motor's rated power.

$$\frac{S_p}{P_n} = \frac{I_p/I_n}{\eta \cdot FP} \tag{1}$$

The standard distinguishes the motors with star/delta starter (NY and HY). These motors feature the same characteristics given for the categories N and H. The only the standard recommendation is that the starting torque in pu should have 25% of the value for categories N and H. Moreover, the mechanical load should be reduced, since the starting torque could be insufficient for its own starting.

The standard specifies when and how the service factor should be different than one ($\neq$1). If the motor design project agrees with the rising temperature limits of the standard, they must have the unit service factor (=1). Otherwise, it is necessary to specify a service factor greater than one (>1). For electric motors with the power rates from 0.75 kW (1 hp) to 150 kW (200 hp), the service factor it can be modified to 1.15. Fractional motors vary this modification between the values of 1.15 and 1.4. In case of a higher overload capability, it is recommended to use a standardized motor with a rated power higher than the original.

In [8] is displayed, the minimum efficiency levels for induction motors. The values are standardized according to the motor rated power and its synchronous speed. One section of the standard table is shown in Figure 1. The recommendation of the reference temperature for the appropriate insulation class (temperature correction of resistance) is also standardized, even if there are no references on this temperature in high-efficiency motors. The standard also provides a match between the frame size, the rated power and the machine synchronous speed. This correspondence is restricted to induction motors IP44, IP54 or IP55, thermal class B or F, motor design N, 60 Hz frequency, low voltage and height of end shaft between 63 mm and 355 mm, in continuous duty.

Rated power		Synchronous rotation (rpm)	
kW	cv	3600	1800
		Frame	
0,37	0,5	63	71
0,55	0,75	71	71
0,75	1	71	80
1,1	1,5	80	80
1,5	2	80	90S
2,2	3	90S	90L
3	4	90L	100L
3,7	5	100L	100L
4,5	6	112M	112M
5,5	7,5	112M	112M
7,5	10	132S	132S

Figure 1 – Relationship between rated power, synchronous rotation speed and frame sizes [8]

3. Design Methodology for Induction Motor

The used design methodology is described in [7]. The design algorithm is shown in Fig. 3.

3.1 Stator core sizing

This methodology is based on output coefficient design concept, which gives the inner stator diameter calculation (D_{is}).

$$D_{is} = \sqrt[3]{\frac{2p_1}{\pi\lambda}\frac{1}{C_0}\frac{p_1}{f_1}\frac{K_E P_n}{PF \cdot \eta}} \tag{2}$$

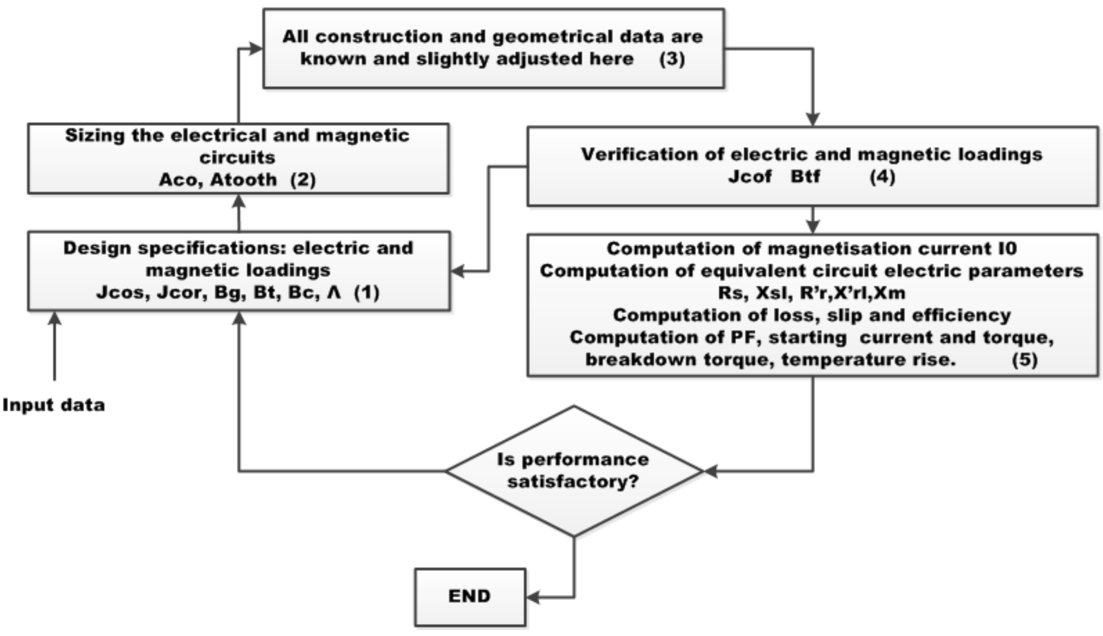

Figure 2 – Design algorithm [7]

For equation 2, it is necessary to define the number of pole pairs (p_1), the ratio between the stack length and the pole pitch (λ),the Esson's constant (C_0), the emf coefficient (K_E) and the input parameters (P_n , PF , η e f_1). The Esson's constant is a function of the number of poles, the apparent power.

From the teeth saturation coefficient ($1+K_{st}$), the voltage form factor (K_f) and the flux density shape factor (α_i) are specified. Together the winding factor (K_{w1}) and the airgap flux density (B_g) , determines the specific stator current load (A_1).

$$A_1 = \frac{C_0}{K_f \cdot \alpha_i \cdot K_{w1} \cdot \pi^2 \cdot B_g} \tag{3}$$

With all the above calculated values, others stator settings are required such as: the design current density ($J_{\cos}$), the slot fill factor (K_{fill}), the tooth flux density (B_{ts}), stator back iron flux density (B_{cs}) stator slot height (h_s), the core radial height (h_{cs}) and finally the outer stator diameter (D_{out}).

For stator slot sizing, it should be computed the stator slot opening (b_{os}), the height of the stator slot opening (h_{os}), the wedge height (h_w), the slot upper width (b_{s2}), the slot lower width (b_{s1}) and the tooth width (b_{ts}). The tooth width, for manufacturing reasons, should not be less than 3.5 mm. This slot is called semi closed trapezoidal slot.

3.1.1 Stator winding

Knowing the number of stator slots (N_s) from the number stator slots per pole (q), the winding type (double layer chorded winding or single layer) is defined. The calculation of the number of turns per slot is given in the following:

$$W_1 = \frac{K_E \cdot V_{1ph}}{4 \cdot K_f \cdot K_{w1} \cdot f_1 \cdot \phi_g} \tag{4}$$

where (V_{1ph}) is the phase voltage and (ϕ_g) is the air-gap flux.

The number of conductors per slot (n_s) is given by:

$$n_s = \frac{a_1 \cdot W_1}{p_1 \cdot q} \tag{5}$$

where (a_1) is the number of paths in parallel, such parameter may be $a_1 \geq 1$.

Therefore, the magnetic wire cross section is calculated from the rated current (I_{1n})

$$A_{\cos} = \frac{I_{1n}}{a_1 \cdot J_{\cos}} \tag{6}$$

3.2 Rotor core sizing

For the number of rotor slots (N_r) should be chosen avoiding the alignment between the rotor and stator teeth, thus minimizing the reluctance torque. The designer's expertise is very important at this moment. In general the number of stator slots must be different from the number of rotor slots. The rounded semi-closed rotor slot can be found high efficiency motors. [7]

Since the magnetomotive force (MMF) in the stator and rotor do not have equal magnitudes, it is possible to calculate the values of rotor bar current (I_b) from a relationship between the mmf of the rotor and the stator.

$$K_I = \frac{FMM_r}{FMM_s} = \frac{I_b \cdot N_r}{2 \cdot m \cdot W_1 \cdot K_{w1} \cdot I_{1n}} \approx 0.8 \cdot PF \tag{7}$$

From the rotor bar current, the end ring current can be computed (I_{er}), and with the current density in the rotor bar (J_b), the rotor slot area is determined (A_b). Linking the end ring current with the current density in the end ring (J_{er}), we obtain end ring cross section.

$$A_{b,er} = \frac{I_{b,er}}{J_{b,er}} \tag{8}$$

The design is accomplished by calculating the air gap length (g) (should not be less than 0.35 mm for manufacturing reasons [7]), rotor diameter (D_{re}), the rotor tooth flux density (b_{tr}), the upper slot diameter (d_1), the lower slot diameter (d_2), slot height (h_r),the height of the rotor slot opening (h_{or}) and rotor slot opening (b_{or}).

3.3 Application of Brazilians standards in design methodology

Figure 4 shows the moment where the generated design data will be handled by the Brazilian standard requirements.

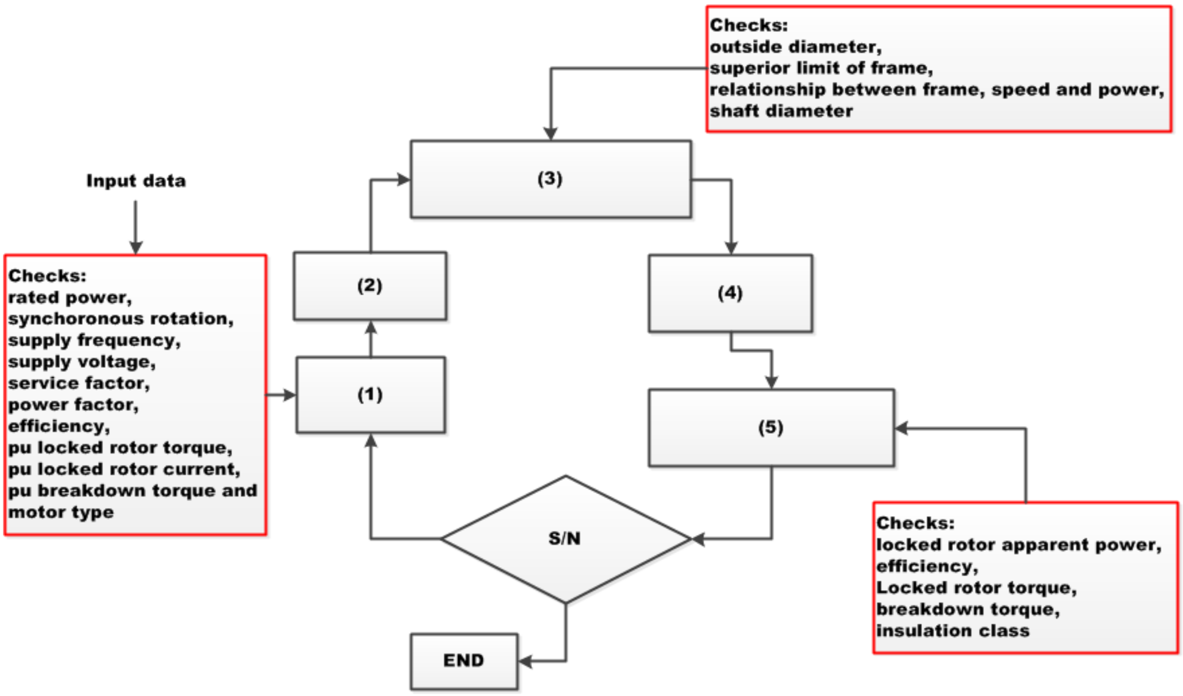

Figure 3 – Design algorithm taking into account the highlighted requirements of the Brazilian Standards

The step number five (see Fig. 4) is related to motor performance and uses the IM equivalent circuit with calculated parameters from the design data [7]. After the calculation of the equivalent circuit parameters, locked rotor KVA, efficiency, locked rotor torque, breakdown torque and the rising temperature are checked.

4. CAD (Computer Aided-Design) Software

The developed software has a sequential simple and structure, where the steps are described in flowcharts in this section. The first flowchart shown in Figure 4, presents the first part of the software that is the verification of input data by some requirements shown in section 2.

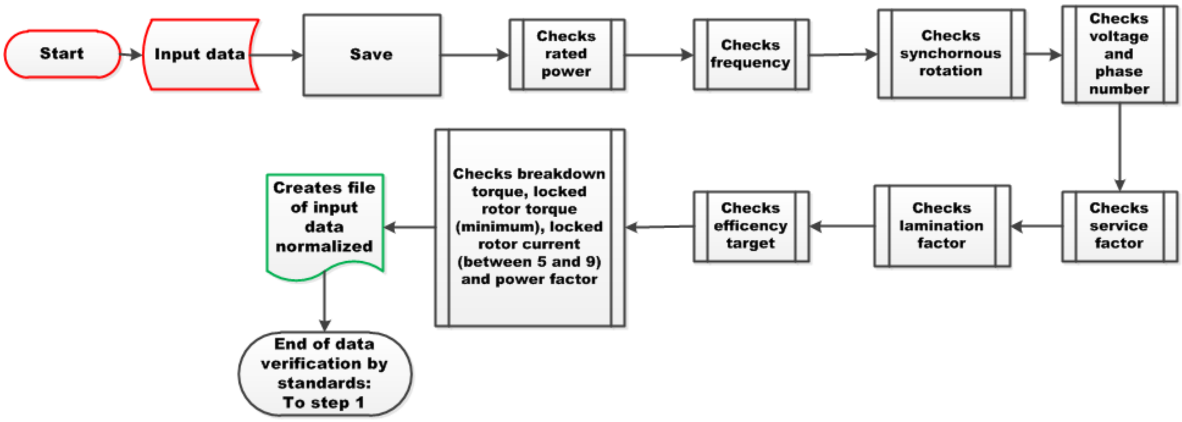

Figure 4 – Standards input data verification

In Figures 6 and 7 are shown the steps 1, 2, 3 and 4, as in Figure 3. Figure 5 introduces the equivalents process of the stator and winding sizing and Figure 6 introduces rotor and squirrel-cage/end-ring sizing.

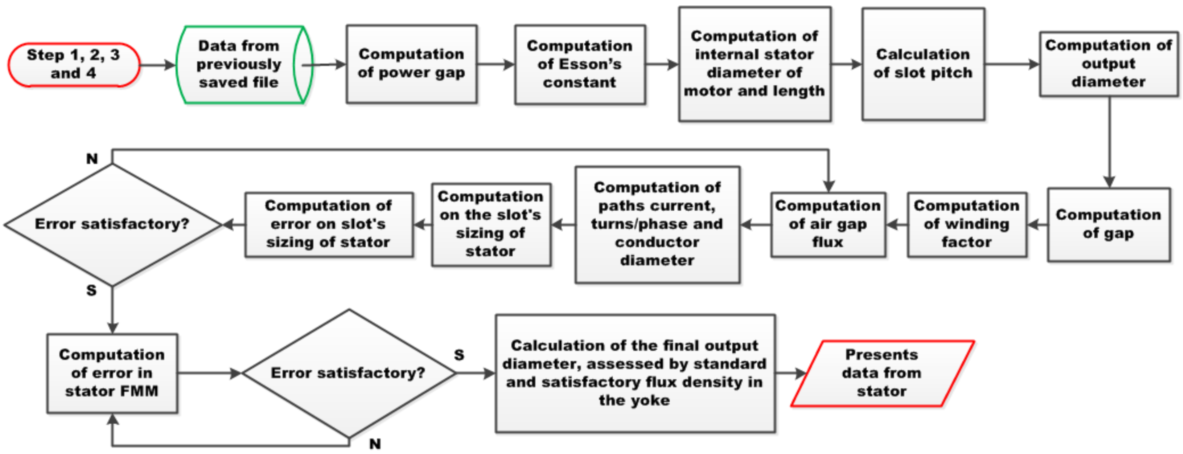

Figure 5 – Step 1, 2, 3 e 4 – Part 1 – Stator Sizing

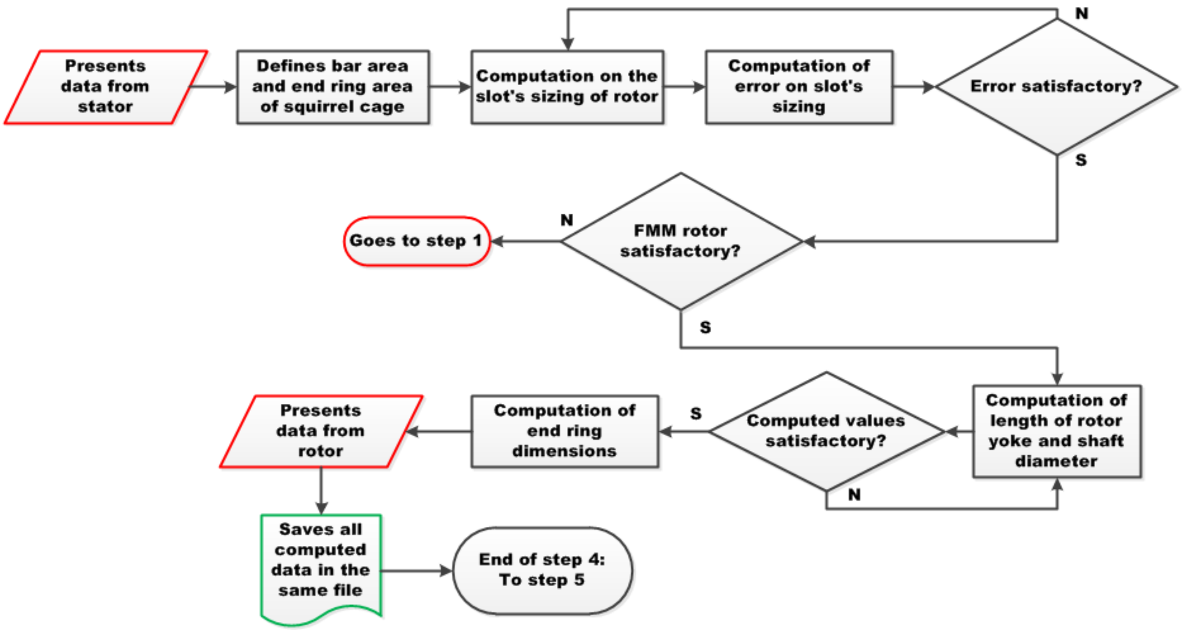

Figure 6 – Step 1, 2, 3 e 4 – Part 2 – Rotor Sizing

The last step of the software (step 5) is displayed in Figure 7. In this step are carried out the performance calculations. Moreover, these calculations are in agreement with the standards utilized in this work.

The software has a window user interaction, showing design information and sets the required inputs to the project. Several screens were designed for the various stages of the project. This was created in efforts to make the software more user friendly for new our infrequent users. This paper will not display all the developed windows, so that only the main windows are presented.

Figure 8 shows the main input data window. All the windows were developed in Portuguese language. The input data are: rated power, synchronous rotation, supply frequency, supply voltage, phase number, service factor, lamination factor, and the target parameters are: power factor, efficiency, locked rotor torque, breakdown torque and locked rotor current.

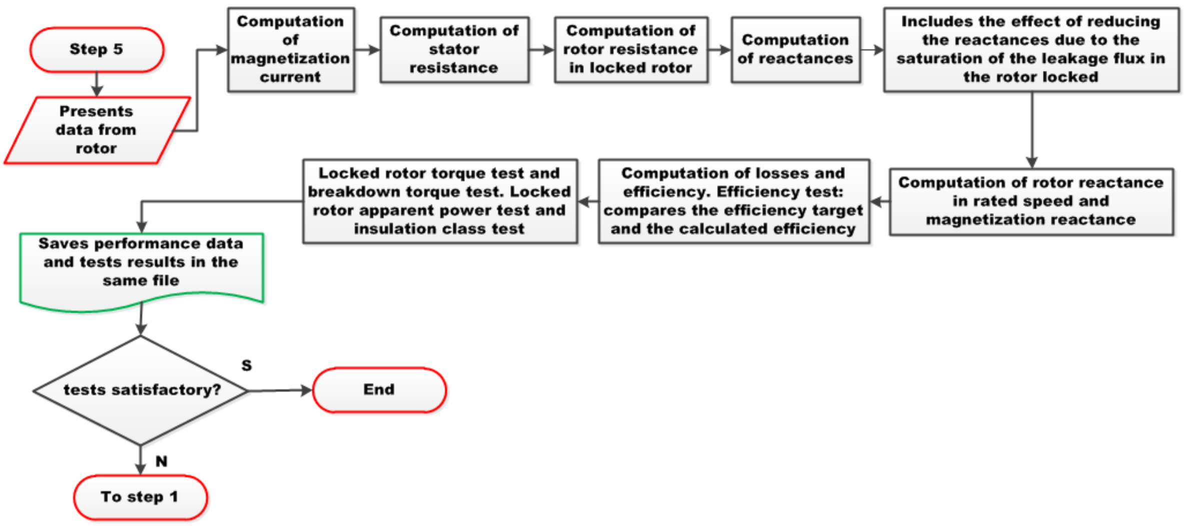

Figure 7 – Step 5 – Motor performances.

Figure 8 – Main window

Figure 9 shows the stator results window. Furthermore, it presents several sizing results, like: stator slot, teeth, output diameter and internal stator diameter

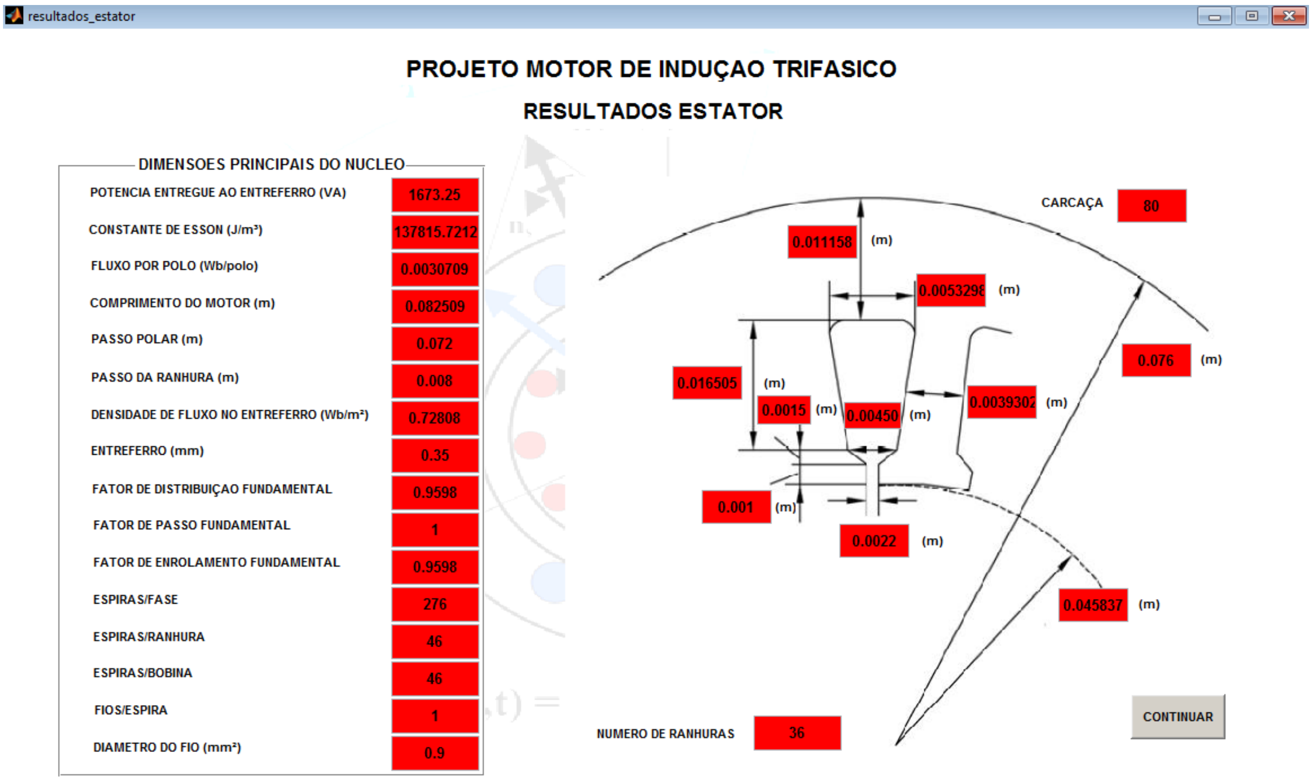

Figure 9 –Stator results window

Figure 10 presents the rotor sizing result window. It shows several sizing results, like: slot rotor, shaft diameter, internal rotor diameter and the bar/end ring sizing.

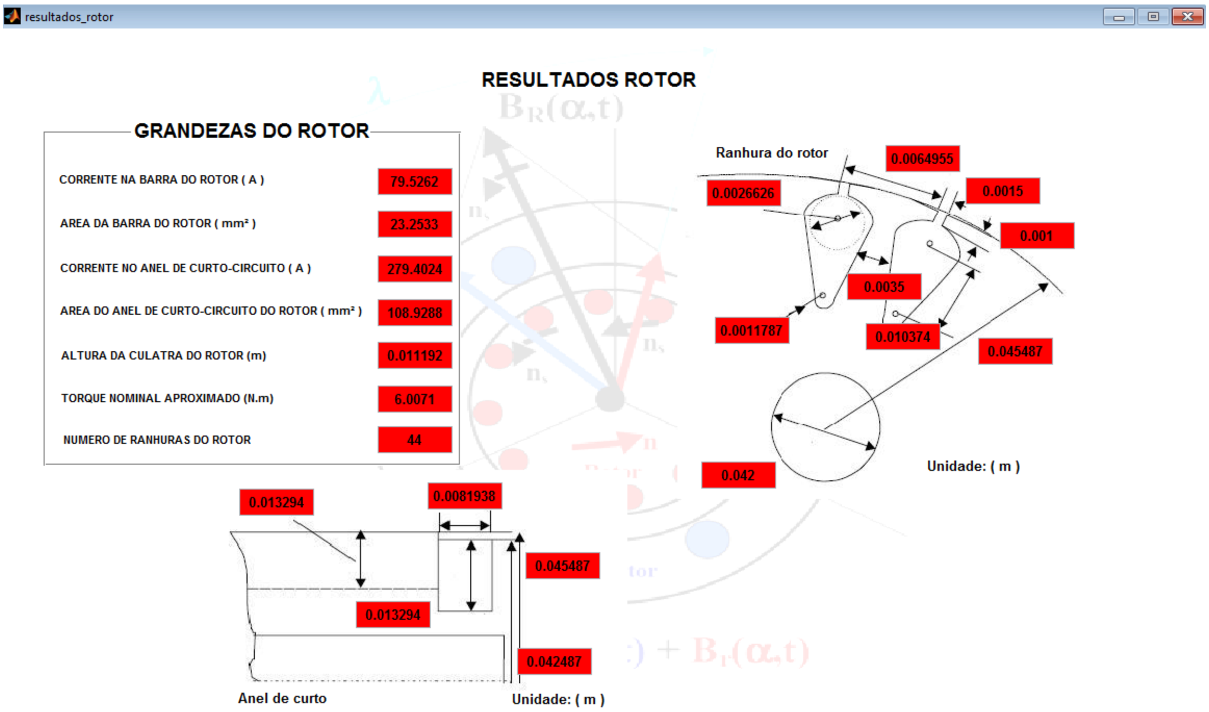

Figure 10 –Rotor results window

All computed motor design data are stored in a spreadsheet and the performance test results as well.

5. Design

This section aims to introduce CAD design of an induction motor with 1.5 hp, 380 V, design N (similar to NEMA design B), 4 poles, 60 Hz, unit service factor load, targeted efficiency 81.5%, targeted power factor 0.79, 1.9 pu locked rotor torque and 2 pu breakdown torque. The ferromagnetic core should be made of steel-silicon alloy (3.5%) with thickness of 0.5 mm. The stator winding has 3 slots/pole/phase, full pitch coils, without currents path in parallel, fill factor 40% and 1.5 aspect ratio. According to [8] the motor must have frame size type 80.

The flux density in the air gap around should be around 0.7 T, the tooth flux density between 1.5 T and 1.65 T and the back core flux density between 1.4 T and 1.7 T. Insulation class is B, however it is a high-efficiency motor with a reference temperature of 80º C [7]. The bar skewing is equivalent to the rotor slot pitch length. The current density in the stator winding is 4.5 A/mm² and current density in the rotor bars is 3.4 A/mm².

Analyzing only the stator winding, it can be seen that motor design has the important properties shown in Table 1. It can be verified that the performance tests were satisfactory, but for the purpose motor design only the efficiency is introduced in Table 1.

Increasing the number of paths current to reduce area of the coil conductor (without modifying the slot area), is likely to increase the motor efficiency. The modified data in the design are shown in Table 2. The new fill factor value is 0.56 and it is set the number of current paths equal to 2.

After the slot sizing (keeping the slot area constant), the Table 2 shows the resizing of the motor winding (increasing the path currents in parallel), resulting in a better efficient.

This section describes the software versatility to obtain the motor sizing and subsequent adjustments were necessary to improve the design requirements, especially in the improved efficiency as shown in Table 2.

Table 1 – Winding design results

Winding parameters	Calculated values
W_1	276
n_s	46
N_b	46
n_{cond}	1
d_{cond}	0.9 mm
a_1	1
K_{fill}	0.4
A_{slot}	73.2 mm²
η	83.3%

Table 2 – Modified winding design results

Winding parameters	Calculated values
W_1	552
n_s	92
N_b	92
n_{cond}	1
d_{cond}	0.75 mm
a_1	2
K_{fill}	0.56
A_{slot}	73.2 mm²
η	84.8%

6. Conclusions

The paper introduces that the constructive aspects of the induction motor using a CAD tool is interesting, fast and serves like an initial step to improve the machine design, consequently, the efficiency. The software does not exclude other techniques, which can refine de design, e.g. finite element methods, being its main advantage.

It is highlighted that such techniques improve the efficiency without extra tooling costs is important after use of software. Since just the number of paths current was increased, without changing the area of the stator slot, the increase on number of turns/phase reduces the conductor area, increasing the wire cost in the motor construction. Since the price/km for second calculated wire (see table 2) is 20% less than the price/km of the first calculated wire (0.9 mm diameter) and the first calculated wire coil/phase length is 114 m (276 turns/phase), the cost of copper increases 60% because the coil length is 228 m (552 turns/phase). Furthermore, the software allows testing different motor techniques, such as: increase of the motor length, which should also increase the motor efficiency [5].

A future software upgrade will include the parameter of minimum torque as recommended in the Brazilian standard [8]. The minimum torque is developed from the torque-speed curve of an induction motor. Another software improvement is to provide the software to downloading on a website and an English-language version.

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A STUDY ON THE INFLUENCE OF THE BASE ON THE DYNAMIC PERFORMANCE OF AN INVERTER-FED MOTOR

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Abstract

Impact and vibration are mechanical effects that often accelerate the failure mechanisms of industrial machinery and equipment. It is therefore indispensable to minimize or control these effects in order to avoid premature failures in motor driven systems. In this context, the supporting base of an electric motor plays an important role as regards keeping the normalized vibration levels complied with in the factory production stage. The bases used by motor manufacturers are normally of the rigid type (according to IEC 60034-14 and NEMA MG1 Part 7 standard) and reproducing this condition in actual plant operation is a challenge. As a result, severe vibration effects, such as resonance, are likely to occur in the field. Based on these concepts, this paper proposes an experimental methodology using modal analysis and ODS (Operating Deflection Shapes) techniques to compare and understand the differences between a rigid and a flexible base, and how this difference could lead to resonance problems in variable speed motor applications. A standard industrial motor driven by a frequency inverter was used with two types of operating bases, namely a rigid one and an ordinary (neither rigid per the international standards nor exactly flexible) one. The experimental results show that the ordinary (non-specified) base introduce a number of natural frequencies in the mounting fit (motor plus base) that may lead to high vibration levels in operation regimes with speed variation, compromising the expected motor service life.

Introduction

When a structural natural frequency coincides with the frequency of the motor operating speed, high vibrations of machinery, structures and foundations can occur and cause machinery or structural damage, resulting in loss of production and expensive repair [2]. In this context, the specification of the base where an electric motor will operate is extremely important, once that the main boundary conditions that define the first natural frequencies of a horizontal electric motor are exactly those related to the fixing of his feet [3].

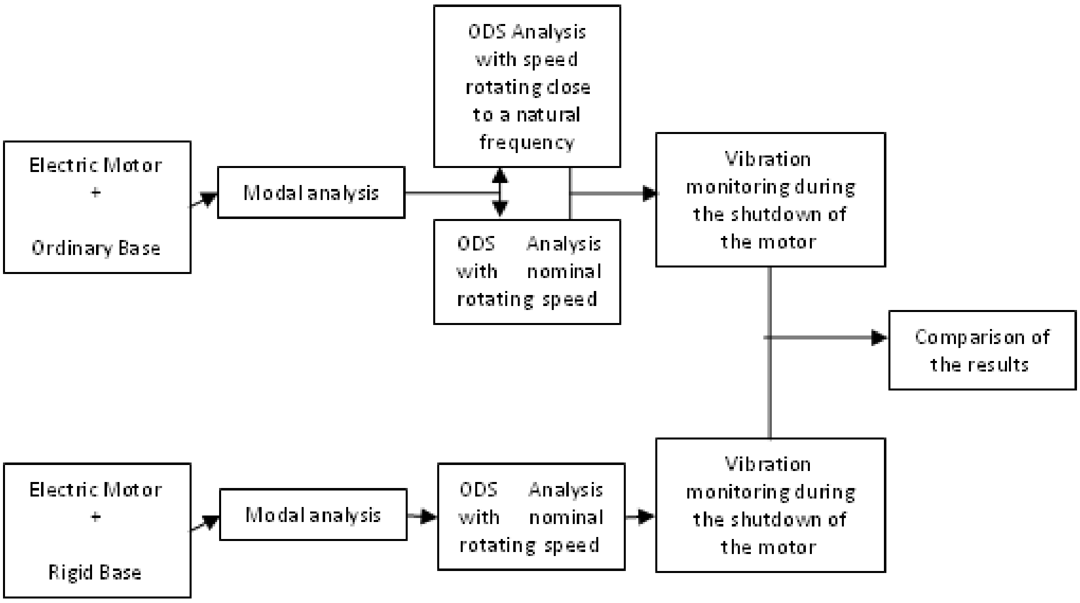
These arguments are corroborated by some standards, such as IEC 60034-14, NEMA MG1 Part 7 and API 541. The mentioned IEC and NEMA standards, for example, define that vibration testing of electric motors should be done both in free suspension and fixed on a rigid and massive base. Such conditions aim at ensuring a minimum distance between natural frequencies and external influences, because besides the fact that the vibration of an electric motor is closely linked to the mounting, the results shall be reproducible to provide comparable measurements.

The use of an inadequate base to fix the motor can result in the proximity between natural frequencies of the test arrangement and the operational frequency of the motor, increasing the vibration levels due the resonance phenomenon and consequently reducing the motor service life [2], [3], [6]. This condition becomes more critical when a VSD (Variable Speed Drive) is used, because, in this case there is not only one operation frequency, but a range of operation frequencies that should be avoided.

This paper focuses the problem that an inadequate base introduces in the operation of electric motors driven by VSD. Two operating bases were used with the same electric motor of 30 kW, 2 poles, 60 Hz operating at no load with nominal rotation speed of 3600 rpm (60 Hz). One of them follows the IEC 60034-14 and NEMA MG1 Part 7 specifications in the whole motor operation range and is therefore referred to as rigid base. The other one is a common structure that does not follow any standardized specification and is therefore referred to as ordinary base. Both test arrangements, base plus motor, were dynamically characterized and their behaviors were compared. For this purpose, conventional and advanced techniques of vibration measurements such as modal and ODS analyses were used. The adopted methodology, as well the obtained results, is shown hereafter.

Methodology

The study methodology followed the flowchart below:



The following vibration measuring equipments were used: a Bruel & Kjaer Pulse 3560C, four channels plus two ENDVECO accelerometers 752A12, and a lap-top using the ME'scope ODS software.

Supporting Bases

According to IEC 60034-14 and NEMA MG1 Part 7 standards, a base can be considered rigid when the maximum vibration velocity measured in the horizontal and vertical directions on the machine feet does not exceed 25% of the maximum velocity measured at the adjacent bearing housing in the same measurement direction. This requirement ensures that natural frequencies of the complete test arrangement do not coincide with: ±10% of the rotational frequency of the machine, ±5% of twice the rotational frequency, or ±5% of once and twice the electrical line frequency. For the rigid base used in this study, the maximum foot to bearing vibration velocity ratio for any operation speed (from 3600 rpm down to zero speed) was 10%. Figure 1a shows the rigid base. The other base was chosen not to satisfy the standards specifications for rigid base on purpose. Figure 1b shows the ordinary base used in this study.

a) Rigid base according to IEC 60034-14. b) Ordinary base.

Figure 1: Bases used in the experimental measurements.

Modal Analysis

The modal analysis consists in exciting a structure with an impulsive or any other arbitrary force, and using a force transducer to acquire this excitation signal at the same time as acceleration transducers strategically positioned at chosen points of the structure acquire the resulting response signals. With the acquisition of both the acceleration (response) and the force (excitation) signals, it is possible to obtain the amplitude and phase differences between them and, afterwards, by means of mathematic treatment, get the mode shapes and corresponding natural frequencies of the structure. In this study, the same distribution pattern, accelerometers, and applied force location were used in both test arrangements (motor fixed on rigid base and motor fixed on ordinary base). The red vectors in Figure 2 indicate the direction and position of the two accelerometers used to measure each response point of the discretized structure, and the little blue hammer indicates the direction and position of the applied impulsive force (fixed impulsive force mode).

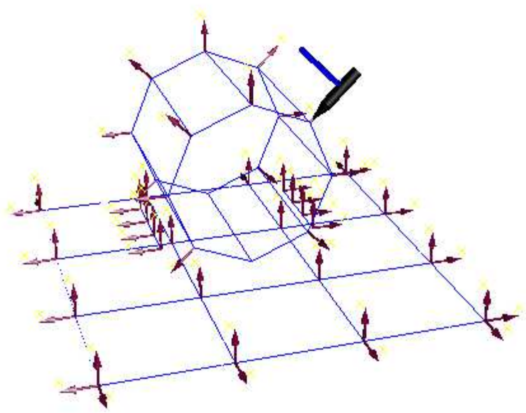


Figure 2: Acquisition points of the response and excitation signals for the modal analyses.

ODS Analysis

The ODS analysis consists of mapping the structures under consideration, performing vibration measurements on two points at the same time. One point is always fixed. The vibration measurement will report, in each frequency, the considered point amplitude and phase difference relative to the reference point. Plotting together the measurement results obtained in all points of the structure geometry, taking into account the amplitudes and phase differences relative to the reference point, provides the structure deformation shape when it vibrates in a specific frequency. Figure 3 shows the ODS project used with both supporting bases. The red vectors indicate the direction and position of the accelerometers, the reference accelerometer is highlighted.

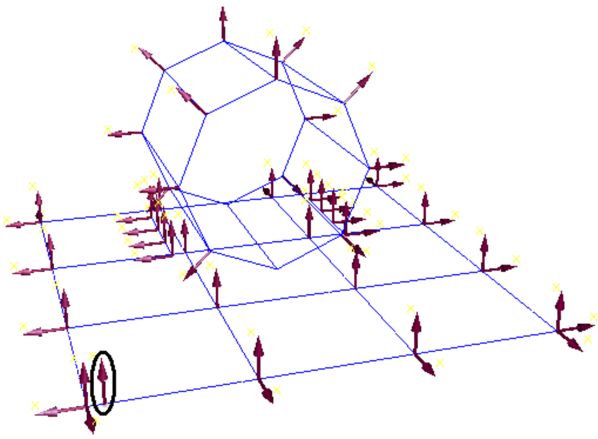


Figure 3: Acquisition points for the ODS analyses.

Vibration monitoring during the shutdown of the motor

This test consists in making the motor run at rated speed (or above), and then shutting it down, letting it stop spontaneously. As there is always a residual unbalance in the motor's rotor (as allowed by standards such as ISO 1940-1), and, as it is known, the unbalance produces an excitation (force) only at the motor rotation frequency, there will be a small excitation of the test arrangement following the mechanical rotation frequency, as the motor gradually decelerates. In order to increase the excitation source (unbalance), the shaft key was removed (the rotor is normally balanced with half key, according to standards specifications). During the motor deceleration vibration measurements are done in time steps, generating a plot called waterfall that shows the response spectrum at each time step.

Results

The modal analysis showed that the first natural frequency of the motor fixed on rigid base is 193 Hz, well above the range specified by IEC 60034-14 and Nema MG1 Part 7 standards. This reveals the little influence of the rigid base on the vibratory response of the motor in operation condition up to rated speed. Figure 4 shows the mode shape of the motor mounted on the ordinary base, with natural frequency at 50 Hz, within the operating range of the VSD driven motor. It can be observed that the ordinary base is deforming due to its low stiffness. High vibration levels are thus expected when the motor operate at 3000 rpm, since this operating frequency will coincide with a natural frequency of the test arrangement, causing the resonance phenomenon.

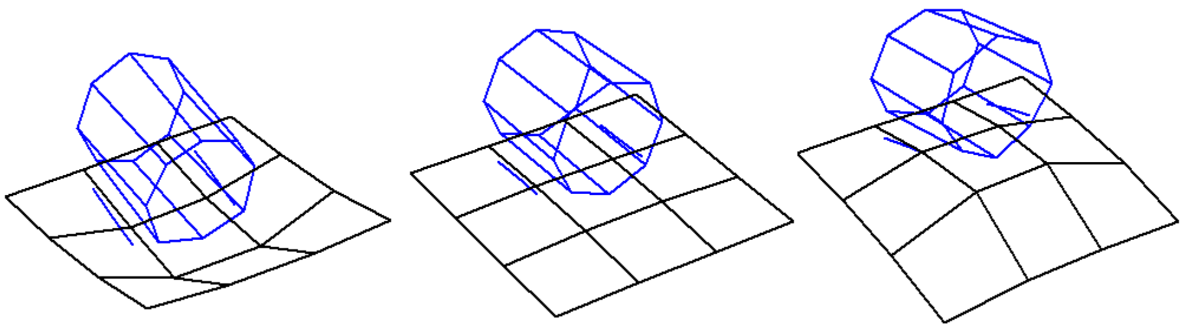


Figure 4: First mode shape of the motor on the ordinary base (natural frequency at 50 Hz).

The ODS analysis of the motor fixed on rigid base was performed at 3000 rpm (50 Hz) and at the nominal speed (3600 rpm or 60 Hz). It can be observed the low amplitude motor movement, as expected, due to the rotor residual unbalance, at both mechanical operation frequencies (50 Hz and 60 Hz), while the base remains practically static in both situations (Figure 5 and Figure 6).

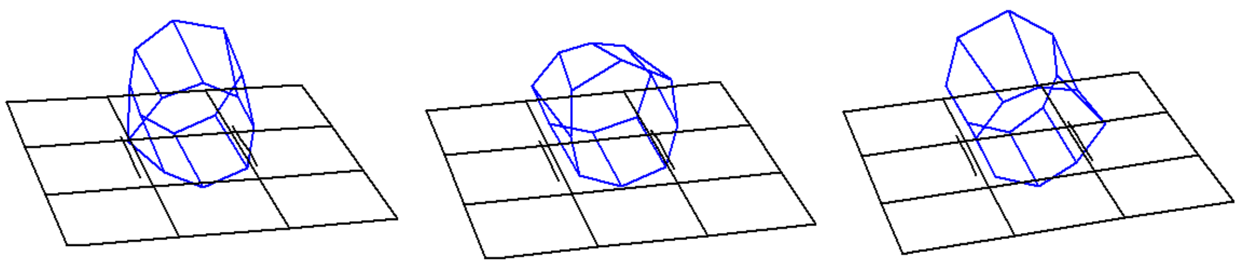


Figure 5: ODS analysis of the motor fixed on rigid base (analysis done at 50 Hz with the motor rotating at 3000 rpm).

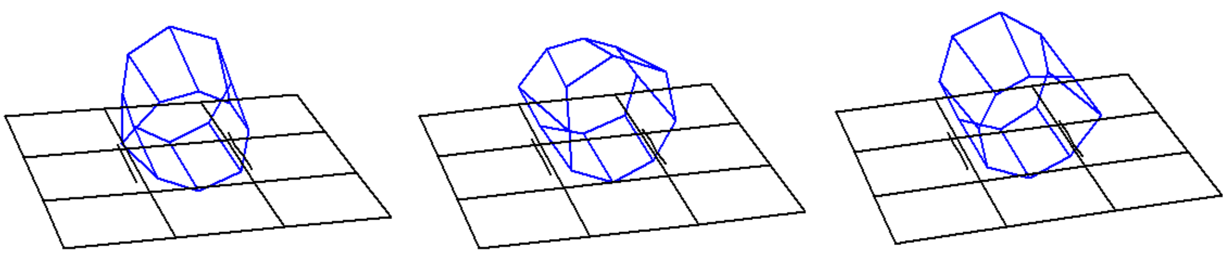


Figure 6: ODS analysis of the motor fixed on rigid base (analysis done at 60 Hz with the motor rotating at 3600 rpm).

To evidence the resonance phenomenon and to compare the measurements got with the motor fixed on the two bases, the ODS analyses of the motor fixed on the ordinary base was also performed at 3000 rpm and 3600 rpm, once that a natural frequency was identified at 50 Hz in this case. Looking at Figure 7 it is clear that the deformation of the base with the motor operating at 50 Hz is similar to the modal shape found at 50 Hz (Figure 4), confirming the hypothesis that the motor would have vibration problems if operated at 3000 rpm.

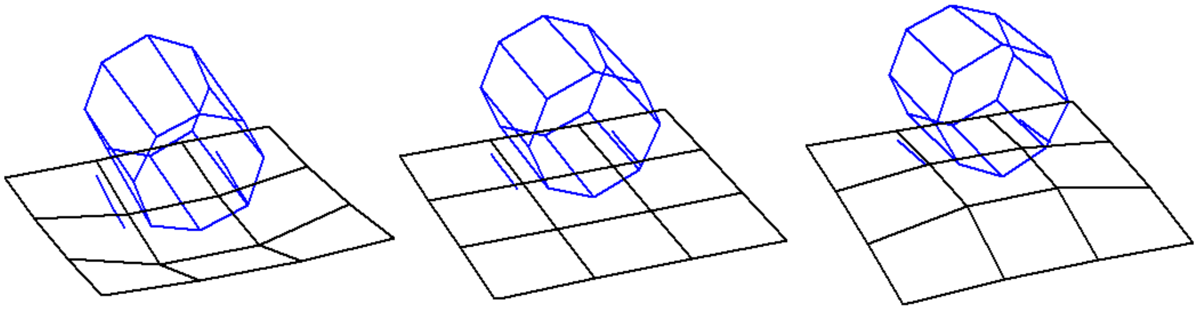


Figure 7: ODS analysis of the motor fixed on the ordinary base (analysis done at 50 Hz with the motor rotating at 3000 rpm).

Figure 8 presents the deformation of the test arrangement at 60 Hz with the motor operating at 3600 rpm. It can be observed that the arrangement deformation is still close to the modal shape found at 50 Hz, however with low amplitude, since the operating excitation no more coincides with the natural frequency.

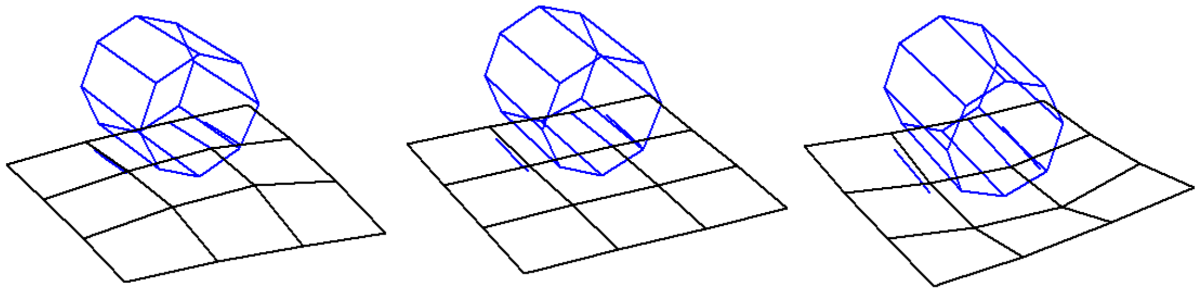


Figure 8: ODS analysis of the motor fixed on the ordinary base (analysis done at 60 Hz with the motor rotating at 3600 rpm).

IEC 60034-14 standard establishes that the maximum vibration level for an electric motor similar to the one used in this paper, fixed on a rigid base, is 1,8 mm/s rms. Table 1 presents the horizontal and vertical effective vibration values measured on the drive end (DE) and non-drive end (NDE) bearings of the motor, when fixed on the rigid base and on the ordinary base, for 3000 rpm and 3600 rpm operation. The vibration in the axial direction of the motor is not being shown, because of its very low level.

Table 1: Motor vibration measured values

Effective vibration [mm/s rms]								
Measured direction	Rigid base				Ordinary base			
	3000 rpm		3600 rpm		3000 rpm		3600 rpm	
	DE	NDE	DE	NDE	DE	NDE	DE	NDE
Horizontal	1,53	1,46	1,27	1,22	1,94	1,05	1,82	0,938
Vertical	0,745	0,398	0,644	0,4	6,75	24,7	1,71	3,14

Comparing the two mounting conditions, one can notice that limits indicated by the standards are satisfied only for the motor fixed on the rigid base. The highest vibration value was measured in the vertical direction on the non-drive end of the motor fixed on the ordinary base. This result could be expected, once that it is in this direction that the highest base deformation occurs, according to the natural vibration mode shape at 50 Hz, as presented on Figure 4.

Figure 9 shows the Frequency Response Function (FRF) curves measured on the motor non-drive end in both mounting conditions. These curves evidence the response amplification when the motor is fixed on the ordinary base, justifying the high vibration levels found.

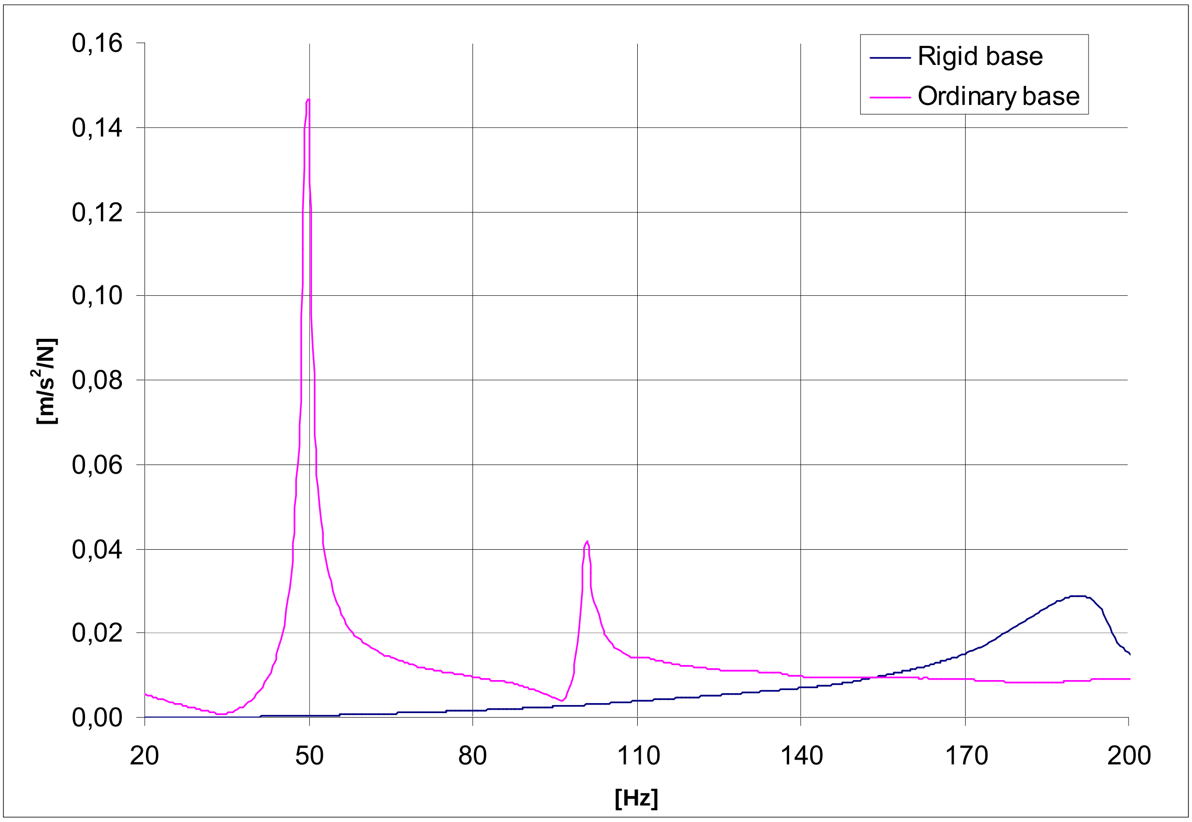
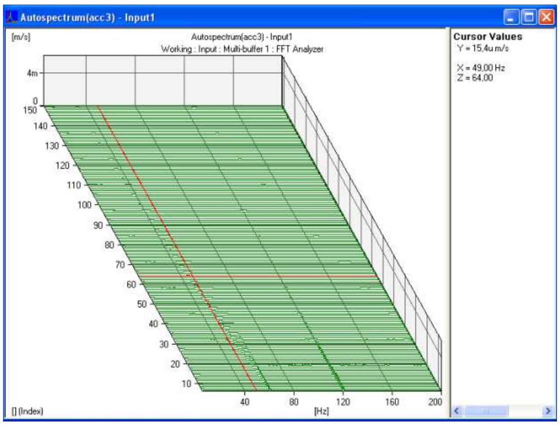
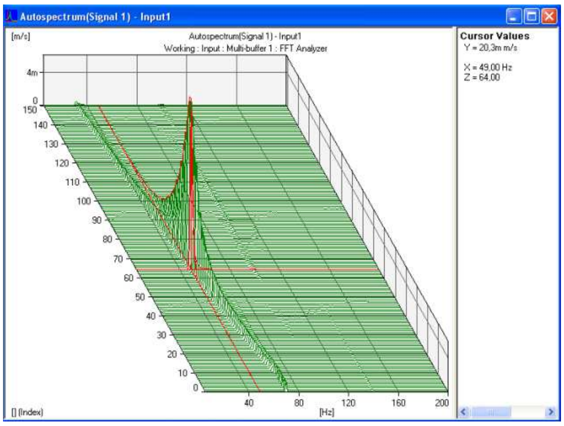


Figure 9: FRF curves extracted from modal analyses

The influence of the natural frequency of the motor fixed on the ordinary base within the operating range of the motor driven by VSD can be easily observed when the vibration in the vertical direction is monitored during motor shutdown. Figure 10 shows this measurement with the motor installed on both bases, for comparative purposes. In the case of the rigid base, it cannot be noticed any amplification during the rotation decrease (Figure 10a). In the case of the ordinary base, however, it is clear the amplification caused when the effect of residual motor unbalance goes from 50 Hz downwards. To facilitate the analysis, the graphs shown in Figure 10 are in the same amplitude scale.



a) Waterfall graph of the motor fixed on the rigid base during shutdown – no amplification is noticed at all.



b) Waterfall graph of the motor fixed on the ordinary base during shutdown, evidencing the amplification at 50 Hz.

Figure 10: Vibration monitoring in vertical direction during motor shutdown

Table 2 presents the measured vibration levels when the motor was rotating at 50 Hz on both bases.

Table 2: Vibration values measured during shutdown with the motor rotating at 3000 rpm

Vibration [mm/s rms]	
Rigid base	Ordinary base
0,0154	20,3

From the analysis presented, it is expected that the motor fixed on ordinary base and operating at 3000 rpm with VSD has its service life reduced due to the very high levels of vibration.

Discussion

Drawing an analogy between this work and practical applications, it can be expected that high and sometimes catastrophic amplification of vibration may occur in the field if the fixing base of the rotating machine is designed without regard to the dynamic behavior of the complete arrangement of the coupled machines plus their operation bases. Nowadays it is very common to use VSD to vary the speed of electric motors, increasing the efficiency of production processes. This is the case of some types of compressors and centrifugal pumps [7]. Not less common are the vibration problems caused by equipment installed on inadequate operating bases, which often stop the production process, either by machine damage or emergency repairs, compromising significantly such processes.

In this paper, standards of vibration acceptance criteria for electric motors manufacturing were used as reference, with emphasis on IEC 60034-14 and NEMA MG1 Part 7. However, these standards cannot be used for evaluation of installed motors on actual applications. For these specific cases there is DIN 4024-1, which focuses on the proper design of foundations for operating conditions of rotating equipment. The goal of DIN 4024-1 is to provide the machinery supporting base designer with guidelines to prevent the occurrence of unacceptable vibration levels in the field, which can cause damage to machines and their foundations, for both static and dynamic loads.

Conclusion

By means of ODS and modal analyses it was possible to identify the existence of a natural frequency in an ordinary base plus motor assembly within the operating range of the motor. A high vibration level in the vertical direction was detected when the motor operated on this base. The higher vibration in that direction can be attributed to the resonance condition and to the mode shape, which has high vertical deformation. When the same measurements were taken with the motor mounted on a rigid base, it was not perceived any natural frequencies within the motor operating range and the vibration levels remained within the levels stated by standards throughout the speed range, what can be explained by the huge mass and stiffness of the base. The behavior observed with the ordinary base assembly may be the explanation of many vibration problems in the field that compromise the efficiency of production processes, in which the aim of the use of VSD is exactly the reduction of unnecessary losses.

It can be concluded that to ensure low levels of vibration, in order not to compromise the motor service life, the base on which it is installed must be correctly designed so that the natural frequencies of the arrangement be kept well away from the motor operating frequency. Special care should be taken with motors that are driven by VSD, since these normally operate within a speed range and, therefore, not only one operating frequency but a whole frequency band should be avoided. To achieve this goal it was suggested to use DIN 4021-1.

The ODS and modal analyses have proven to be important tools to identify and understand the phenomena that cause increased levels of vibration in electric motor applications. If correctly used, these tools can help solving problems and thus ensure a smooth operation of the whole drive system, preventing premature failures.

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Assessment of prospects of prescribing super-premium efficiency levels with induction motor technology

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Abstract

Premium efficiency standards for certain induction motors have become mandatory in the US since December 19 2010. Although motors rated above premium efficiency levels can be found on the market today, there are some concern about the benefits of imposing higher efficiency levels above premium efficiency level. The perception is that the induction motor technology cannot cost-effectively support the goal to achieve efficiency levels above premium efficiency and that any such regulatory effort would be counter-productive. A market survey of motors above premium level is presented and analyzed. The data analyzed price and stated efficiency information. The analysis includes both induction motor and permanent magnet motors that are marketed as super-premium efficiency motors. The prospect of prescribing higher efficiency standards for induction motors is assessed from the technological and economic points of view using the concept of viability curves.

Introduction

Premium efficiency (per NEMA MG-1 Table 12-12) standards for certain electric motors have become mandatory in the US since December 19 2010. The US Department of Energy is mandated by law to determine if there is need to set higher standards than the one currently in effect within 24 months of coming into effect of a current standard. At the time of writing this paper, the Department is conducting a study to make such determination. The next possible efficiency level is the so-called super-premium efficiency level, an equivalent of which is the IE-4 level which is dedicated to advanced motor technologies such as permanent magnet (PM) motors. Although some motors rated above premium efficiency levels can be found on the market, there is a general perception that the induction motor technology cannot support the goal to achieve efficiency levels above premium efficiency both technologically and cost-wise. Manufacturers and Energy Efficiency Advocates have expressed concerns and have suggested that efforts should be directed towards alternative measures such as system efficiency improvement, development of advanced technologies such as permanent magnet (PM) motors and widening of scope to cover hither-to uncovered induction motors. Such concerns may be plausible, as the US and Canada, being early adopters of minimum efficiency performance standards (MEPS) are probably at the upper end of the induction motor efficiency spectrum for regulatory purposes. However, super-premium induction motors have been on the market for a long time, with products from several manufacturers. It is therefore timely to assess their impact in the market within the current debate of whether to increase efficiency standards above premium efficiency levels.

The goal of this paper is to discuss the feasibility and challenges of setting super-premium efficiency standards for induction motors. In this paper, a survey of current products above premium level are presented and analyzed. The analysis includes both induction motor and other technologies being marketed as super-premium efficiency products. The prospect of prescribing higher efficiency levels for induction motors would be assessed from the technological and economic points of view using the concept of viability curves.

Minimum Efficiency Performance Standards

It is estimated that the current market of electric motors is represented by about 300 million units in use worldwide; a consumption of 7,400 TWh/year (which is between 40 to 50% of total electricity production); motor shipments of about 30 million units per year, and a repair market of another 90 million units/year [1]-[3]. Today induction motors (IM) will remain the most dominant type of motors in industry.

The efficiency of electrical motors in the market has been increased during the last two decades as a result of a combination of public policy, higher energy costs and consumer awareness. The effectiveness of public policy through MEPS is well recognized globally. Currently, there are MEPS in at least a dozen countries, including US, Canada, China, Korea, Brazil, Chile, Australia and New Zealand. For example, in the European Union, IE2 efficiency level has been in effect since June 2011. In January 2015 motors rated 7.5kW to 375kW are expected to meet IE3 level or IE2 level if fitted with a variable frequency drive and in 2017, motors rated 0.75kW to 375kW are expected to meet IE3 level or IE2 level if fitted with VFD. For comparison purposes, IE3 and IE2 efficiency levels are equivalent to NEMA Premium and EPACT efficiency levels found in NEMA MG-1 Table 12-12 and Table 12-11 [4] respectively (EPACT stands for Energy Policy and Conservation Act – the 1992 law that mandated MEPS for certain induction motors sold in the US). In addition to the countries that already have MEPS in place, several other countries are contemplating adopting standards. The strategy for implementing MEPS policies is similar around the world; the major differences being in the timing, affected products and methods of efficiency evaluation. Also, most countries start at relatively lower efficiency levels and gradually move towards higher levels.

Market Survey of Existing High Efficiency Motors

Figure 3 shows the full load efficiency levels of some electric motors (induction and PM motors) that are currently available on the US market. The data was pulled from seven manufacturer catalogues and marketing material and is displayed as dots on the plot. Also displayed are the NEMA Premium MG 12-12 efficiency levels as well as the proposed IE-4 efficiency level, which would likely be considered a super-premium level. According to [5] the IE-4 super-premium level can hardly be achieved with induction motors. Others have expressed similar opinion in various forums. A look at the efficiency levels displayed in Figure 1 indicates that the IE-4 level may have already been reached in some cases or exceeded in some categories for some induction and also for PM motors; at least on the face value of the data available in manufacturer catalogues. However, being guided by competition, manufacturers' brochure data may likely be overly optimistic and the question of whether these published values can be substantiated through testing is another matter. It is true, though that there are induction motors on the market today that are at least one NEMA efficiency band above premium and the experience of the authors is that some of these motors have met or exceeded the stated nameplate efficiency levels through IEEE 112B testing.

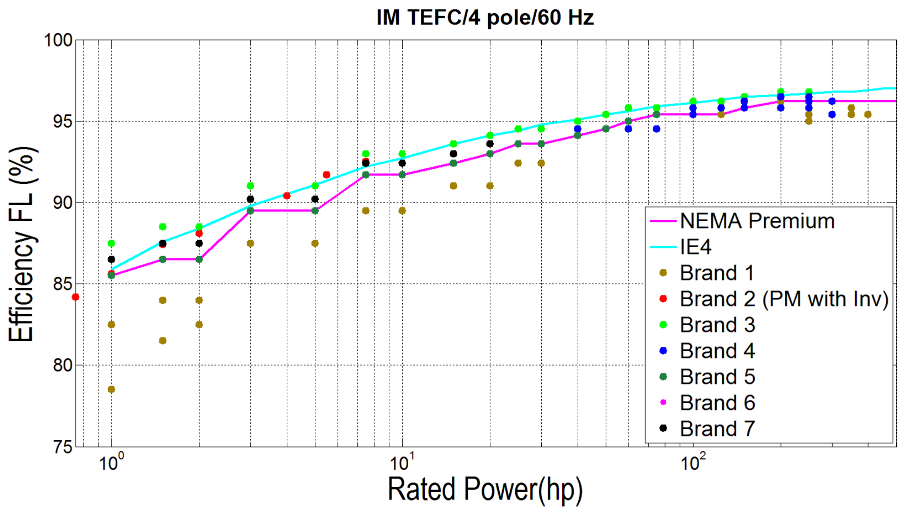

Figure 1 – Full Load Efficiency for Three-Phase Induction and PM Motors/4 pole/60Hz (US Market)

The market survey also compiled motor price information from the seven manufactures for the corresponding products featured in Figure 1. The list prices were discounted using each manufacturer's suggestions to arrive at a given price per motor for that manufacturer. The discount suggested ranged between 40 to 45% and was consistent with some actual purchases recently made by the authors. The average taken of the seven manufacturers constituted the average US market price for each motor and was used in the calculation. Fig 2 shows the price per kW of motors from two manufacturers. The premium motor is from manufacturer (brand) 5 and super premium is from manufacturer brand 3. Even though these are products from two different manufacturers, the price premium is clearly visible. The inverse trend is also logical, since as the machine size increases, the active volume is properly utilized. The average prices from all manufacturers are shown in Fig 3. Here we see that some of the prices of premium and super-premium coincide.

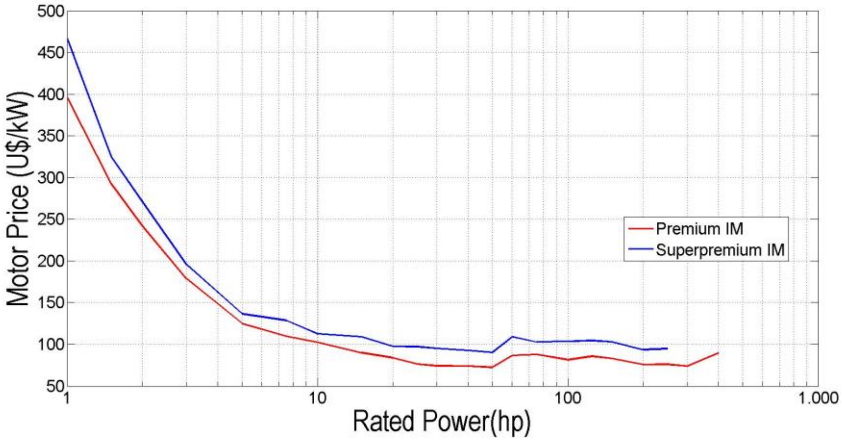

Figure 2 - US Market (Discount 40% Superpremium, 45% Premium)

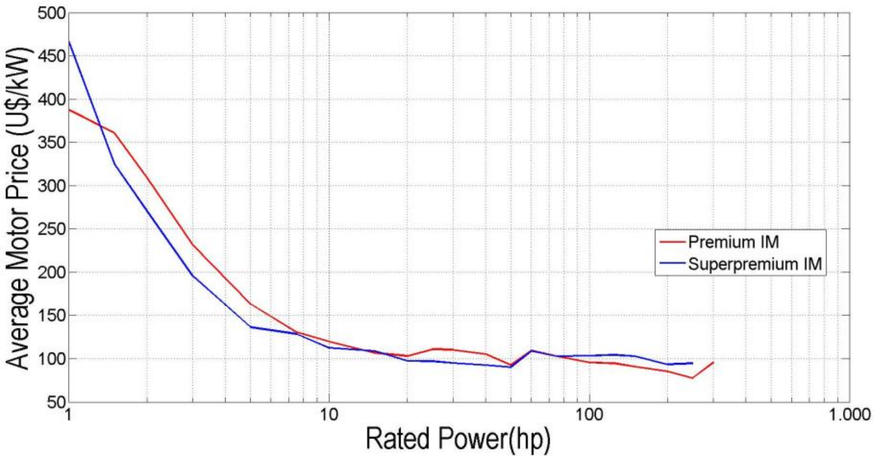

Figure 3 - US Market Average (Discount 40% Superpremium, 45% in Average Premium Motors)

Economic Considerations

The process of motor efficiency improvement is associated with an increase in manufacturing cost and subsequently the motor's acquisition cost. This is expected to happen since the reduction of the losses in all categories is typically obtained with the use of more and/or better materials that are more expensive and other technologies that may require some additional investment. Policy makers are mindful of this, since assessing potential cost and impacts is an essential step during the MEPS rule making process.

The key steps used in the US rule making process are shown in Fig 4. In figure 4 NOPR means "notice of proposed rule-making" and it is the document (or means) by which the Department of Energy (DOE) communicates its intentions to make rules and what processes and timelines it has followed so far or plans follow. The preliminary analyses step of figure 4 is further detailed in Figure 5 [7]. At this step all the important engineering analyses and life cycle cost analyses as well as various impact factors are analyzed in detail by regulators. These analyses are beyond the scope of this paper. The volume of information required to perform such analyses is not only tremendous but beyond the reach of the authors. Therefore, no attempt is made to perform any complicated analyses, similar to what would have been required under a rule-making effort. The authors' intent is to use very simple evaluation techniques to present an alternative perspective in order to discuss the subject at hand.

Figure 4 – Key steps of US Rule making

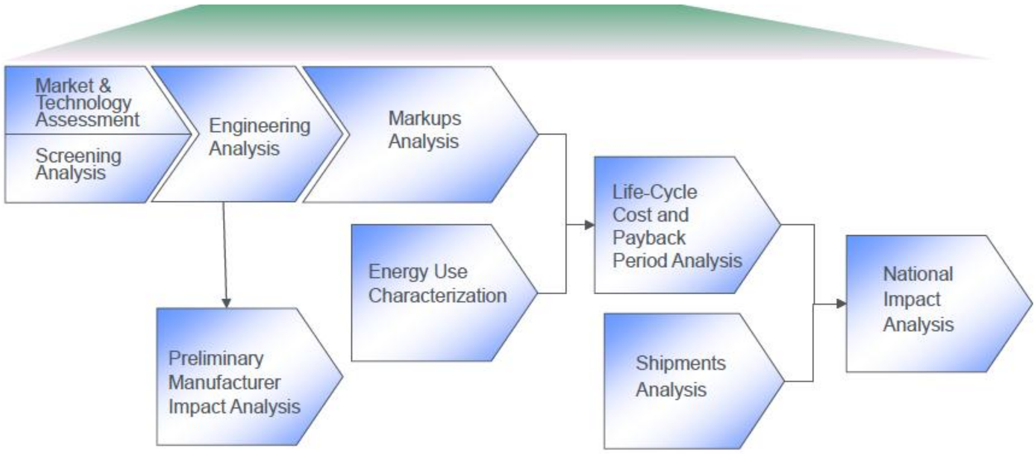

Figure 5 – Steps of Preliminary Analyses [7]

A. Life Cycle Costs

The initial cost of the motor is typically less than 2 % of the machine's life cycle cost (*LCC*) while energy costs take up close to 98%. The most important components of the LCC of a motor include the initial cost (*I*), the cost of energy consumed (*E*), Operation and Maintenance cost (*O&M*), and the Residual (*Res*) costs.

$$LCC = E + O\&M + Res \qquad (1)$$

Motor electrical energy consumption is easily the most significant aspect of total lifecycle costs, which is why efficiency improvements are important. The energy calculation depends on the operation characteristics of the motor as shown in (2):

$$E = \frac{P_{nom} \times L \times C \times H}{\eta} \qquad (2)$$

where L is load of motor expressed as % of the rated load, P_{nom} in kW, H is running working hours, η is efficiency and C is the energy cost (U$/kWh). It should be noted that the total energy consumption may vary throughout the life cycle of the motor, primarily as a consequence of energy cost escalations. Other factors that create variations in the total energy consumption include variations in run-hours motor load. In survey of US industrial motors recently carried, it was found that about 29% of the motors operating in the facilities were carrying less than 50% load [8]. The distribution of motor load from that survey is presented in Figure 6. The motors were rated 50hp, 75hp, 100hp and 150hp. For these motors the average load was found between 59%-76% (average of 68%). Figure 7 shows typical average operating load and run-hours of electric motors in the European Union (EU), the United States (US) and Brazil (BR) for different rated power ranges, as published other studies. It is evident that the average values in Fig 6 and 7 are consistent for the respective motor categories

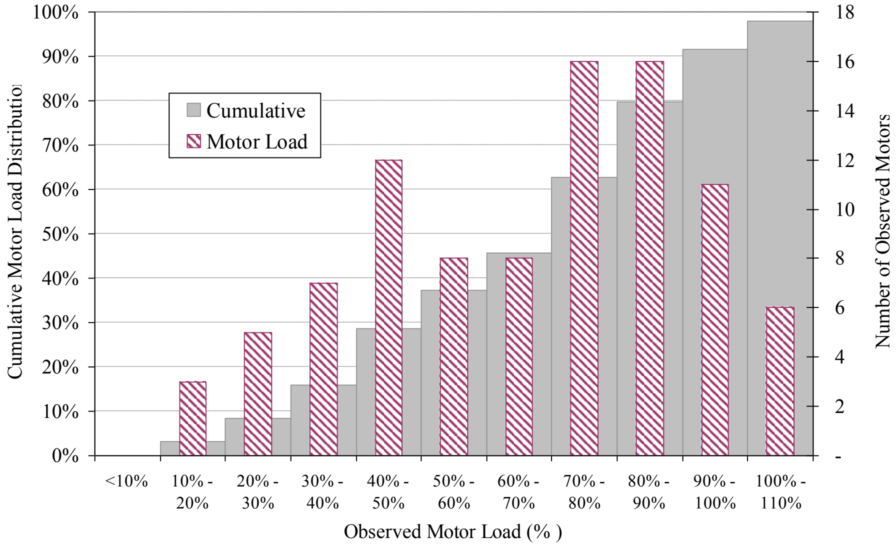

Fig 6: Operating load of 100 surveyed motors rated 50hp-150hp in US industry [8]

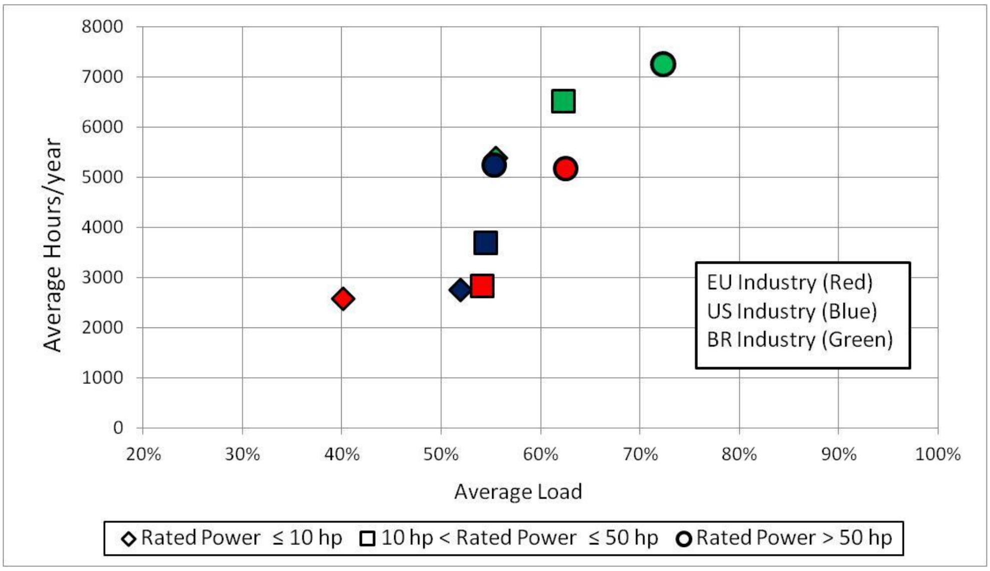

Figure 7: Average operation points for electric motors in the Industry of the US, EU and Brazil

B. Viability Analysis

From the perspective of the motor user, the most common method used in the assessment of the viability of a replacement of an existing (or failed) motor with higher efficiency motor, is the Simple Payback Method, which compares the investment cost (cost of the installation) and the energy savings. The result is a period of time, in years, when the investment will be recovered. This period can be compared to acceptable criteria and decision is made. The method however ignores all costs and savings occurring after the payback period and it also ignores the time-value of money.

An alternative evaluation method is the Net Savings (*NS*) method [9], which takes into account the time-value of money. The method can be expressed as in (3) [9]:

$$NS = \sum_{t=1}^{n} \Delta E \left(\frac{1+e}{1+d}\right)^{t} - \sum_{t=0}^{N} \frac{\Delta I}{(1+d)^{t}} \qquad (3)$$

where *d* is the discount rate, e is the escalation rate of the energy cost, which estimates the increase of the cost of energy in time above the inflation rate, t is the time period in years, *n* is the total life of the motor in years.

The first term of the equation (3) represents the energy saved during the life cycle of the motor (*n*, in years), with the values brought to the present time. The second term is the difference between the investment required to purchase/install the motors with different efficiency levels, it is usually simplified by a simple subtraction, since the investment is made in the present time (see equation 4). Obviously, if the result of the expression is equal to or greater than zero, the efficiency improvement project is viable and if less than zero, it is non-viable. NS equals zero is the viability limit for the project. Equation (3) can be simplified as shown in (4) by considering NS = 0:

$$P_{nom}LCH\left(\frac{1}{\eta_{Higher}}-\frac{1}{\eta_{Lower}}\right)\sum_{t=1}^{n}\left(\frac{1+e}{1+d}\right)^{t} = I_{Higher}-I_{Lower} \quad (4)$$

Note that in (4) ΔE is expanded, following (2). The expression in (4) can be represented in a graphic form for a given motor, with the parameters Load (L) and Annual Operating Hours (H) as variables, in order to visualize the effect of the efficiency improvement for the whole range of operation characteristics of the motor under analysis. The result of this approach is shown in Figure 8, where the limit of viability is represented by a curve that limits the economic viability of the proposed efficiency improvement. This curve can be referred to as a viability curve.

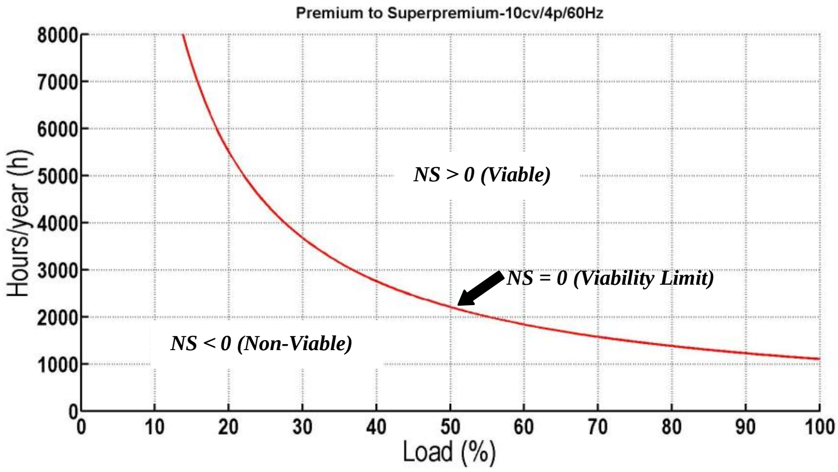

Figure 8: Viability curve for a motor efficiency improvement

(n=12 years, C = 0.0718U$/kWh, d=3%, e=2%)

Using the concept of viability curves, Figures 9 to 12 are presented to show the results of simulations regarding an increase from Premium to IE4 (Super-premium) efficiency levels in the US market. The following parameters were used:

- discount rate, *d*=3%, a recommended value used in [9] to evaluate federal energy efficiency programs
- electricity price escalation rate *e*=2% of elevation above the inflation during the period of study
- cost of electricity *C*= 0,072 U$/kWh, US industry average
- period of life of the machine, *n* =10 years (for motors 1-1.5hp), *n* =12 years (for motors 2-15hp), *n* =15 years (for motors 20 to 150hp), and *n* =20 years (for motors above 150hp) [9]
- Average motor prices for the US market compiled from market survey.

Superposed in Figures 9-12 are the average operating load characteristics data (Load and hours of operation) shown in Fig 7 for electric motors in US, EU and BR industry. Also included are viability curves for simulated price variations (price premium) for a super-premium motor in relation to the actual premium efficiency motor price. In other words the possible price of a super-premium efficiency motor is allowed to vary by the percentages indicated on the plots. The viability curve is then plotted for this price variation. The actual market price is also shown (red curve). For example, the price premium of a super-premium 1.5hp, 4-pole motor as shown in Fig 9 is about 11.8% and that of the 15hp motor is about 21.9% (Fig 10).

The application of the viability curve is based on the premise that if a user could not justify a move to a super-premium efficiency for a given motor, based on the current application conditions and tolerable price-premium then the investment is probably not reasonable. The application conditions used for this study are the industry average operating conditions in the US, EU and BR.

The use of viability curve as an indicator of feasibility is also premised on the fact that, in the event that regulations are put into place to move the market to super-premium level, there is no indication that the current market prices would change significantly or the motor operating conditions would change.

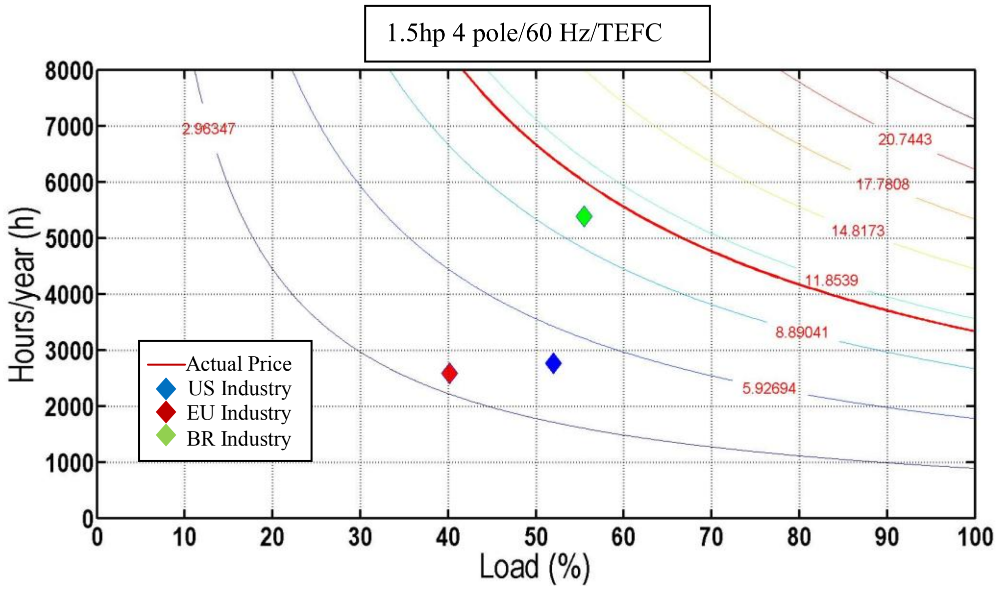

Figure 9: Viability curve of premium to super-premium for a 1.5hp/4 pole/60 Hz motor

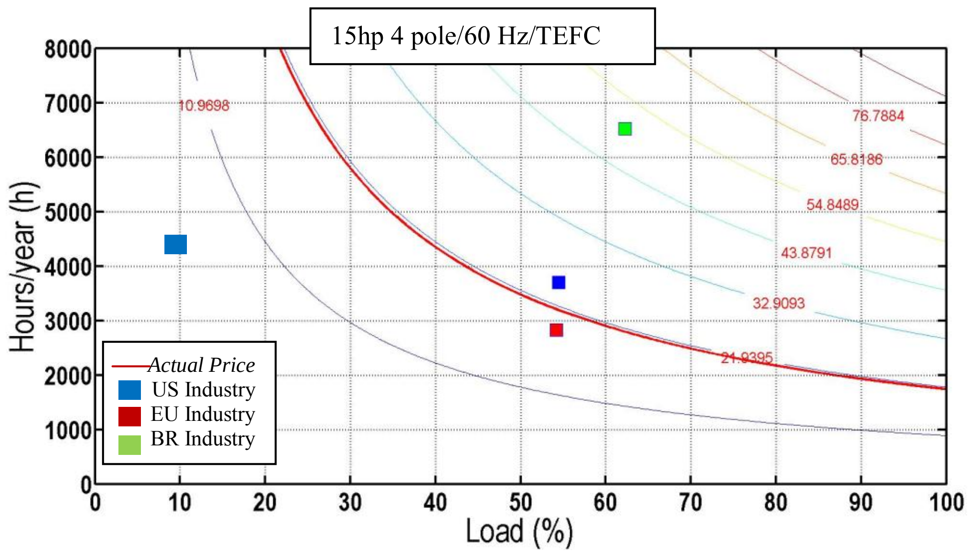

Figure 10: Viability curve of premium to super-premium for a 15hp/4 pole/60 Hz motor

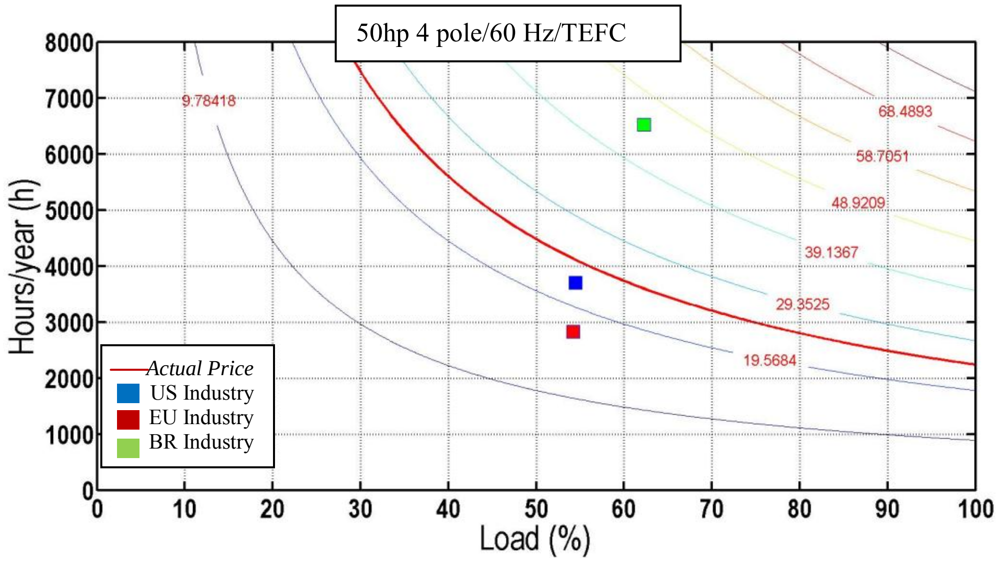

Figure 11: Viability curve increase from premium to super-premium of a 50hp/4 pole/60 Hz motor

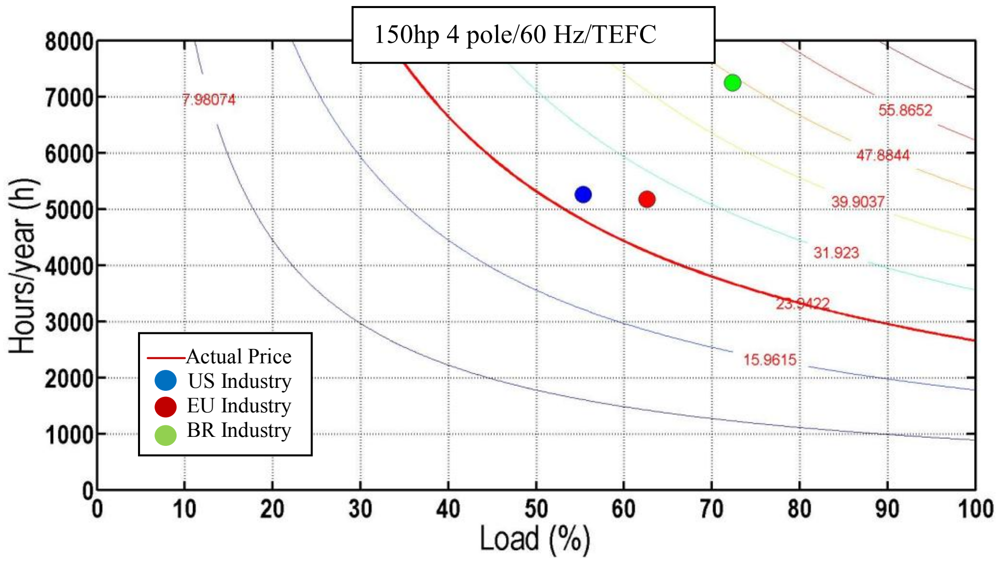

Figure 12: Viability curve of Premium to Super-premium level for a 150hp/4 pole/60 Hz motor

The simulation for 1.5hp motor (Figure 9) shows that even at the current price 12% premium makes it not viable, given the operating load and run-hours of the three regions. For efficiency improvement to be viable, the price premium should be between 3 to 6%. For the 15hp and 50hp (Figures 10 and 11) viability, the industry can tolerate a price premium of less than 20%. The current price premium cannot be supported in EU and US regions. For the 150hp motor (Figure 12), the actual price is suitable for the average operation points for all regions.

C. Efficiency Cost Relationship

As mentioned earlier, the market survey also compiled motor price information from manufacturers. Motor pricing is an interesting phenomenon that is influenced by many factors including competition. The prices used in this study are not from actual purchases and are subject to inaccuracies. Motor manufacturers deal with the major distribution outlets such as Motion, Allied, Kaman and Grainger differently than they deal with small mom-and-pop motor repair shops that distribute motors. Manufacturers also deal directly with large companies with large fleet of motors. Therefore motor prices can vary significantly depending on the type, vendor, location, etc. The prices used in this study are discounted list prices from manufacturer catalogues.

An alternative way of presenting the data is to compare the price premium versus the loss reduction (efficiency increase) as shown in Figure 13-15. The colored dots are market prices of specific motors whose functional isocost curves are on the same plot. The isocost curve is defined by the various input combinations of price variation and loss reduction that result in the same life cycle cost. If the dot is to the left of the curve, then the price variation and the associated loss reduction will lead to an increase in LCC (not good!).

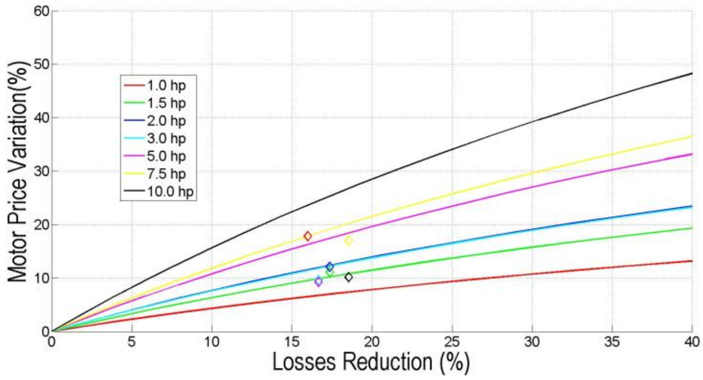

Figure 13: Price variation above Premium (Load = 52%, Hours = 2759)

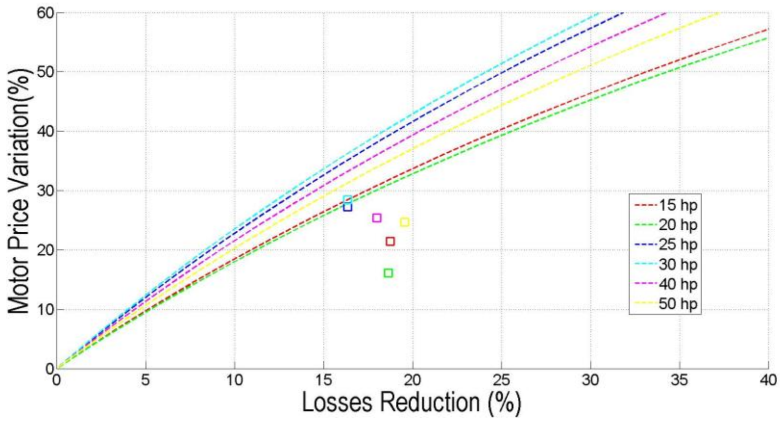

Figure 14: Price variation above Premium (Load = 54.5%, Hours = 3700)

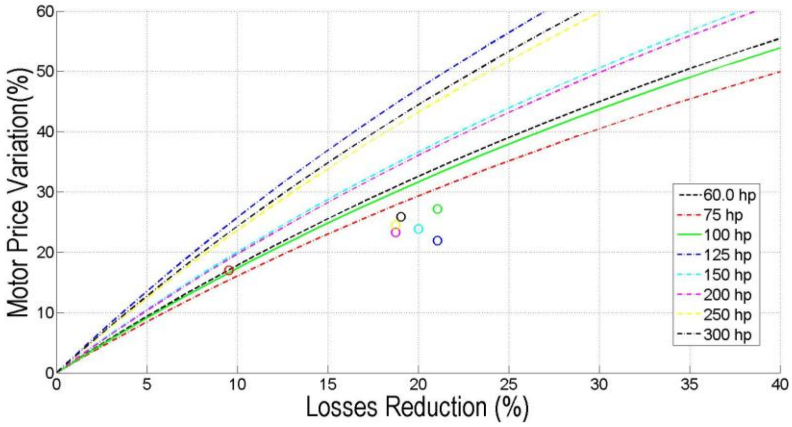

Figure 15: Price variation above Premium (Load = 55.3%, Hours = 5256)

The plots in Fig 13-15 show that the slope of the isocost curve is smaller for smaller motors (rated power < 10hp) than that for larger motors, which means that larger reduction of losses reduction will create relatively smaller price variations to maintain the same LCC. This is due to the higher price/rated kW for smaller motors (Figure 2) and the fact that they have lower annual run hours and lower average loads (Figure 7). The actual superpremium motors plotted as dots in the Figures confirm that the small motors (1 hp and 1.5 hp, red and green dots in Figure 13) are to the left of their respective isocost curves and will induce increase in the LCC.

Technology Considerations

The induction motor efficiency improvement is achieved by the reduction of losses through design and manufacturing. The motor losses are joule losses in the stator and rotor, iron losses, friction and windage losses and stray losses. Detailed description of these losses and steps to reduce them is readily found in literature. In this section we provide a brief review of some technological considerations for achieving higher efficiency.

A. Motor Losses

In order to raise the efficiency, at least one of five losses in the motor must be reduced. For the majority of industrial motors rated 1-200hp, the average losses per machine rating are as presented in Fig 16 and typical range of component losses are in Table I. Due to standardized requirements, there is limited room for variations and losses must often be reduced in all categories in order to increase efficiency. Industrial induction motors are required to meet minimum limits on locked-rotor, pull-up, and breakdown torques, maximum limit on the locked rotor current, as well as other requirements on starting and stall times. These performance requirements impose limitations on achievable efficiencies for a given volume of machine.

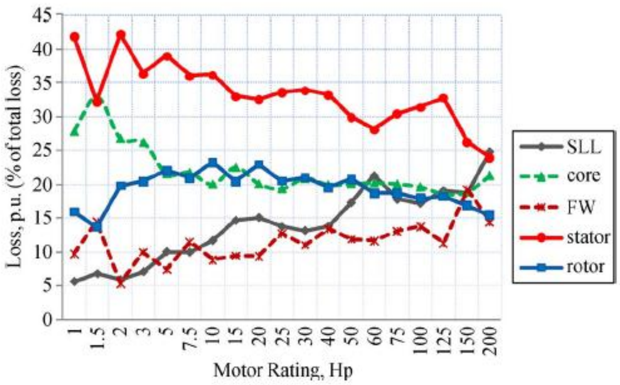

Fig. 16: Average per unit induction motor losses versus rating [10]

Table I : Typical Losses for Industrial Induction Motors [10]

Loss Component	Percent of Total Loss
Stator Joule Loss	25% to 45%
Rotor Joule Loss	15% to 25%
Iron (core) Loss	20% to 35%
Friction and Windage Loss	5% to 15%
Stray Load Loss	5% to 20%

Figure 17 shows the trend in the reduction of losses from the Standard Motor to Super premium compiled from data published in [11]. It can be noted that almost all the losses have appeared to have stabilized in the pattern of decrease as we move from premium to super premium motors. The reduction in rotor losses is due to the use of copper rotor technology, which may lead to a slight increase in the stator losses.

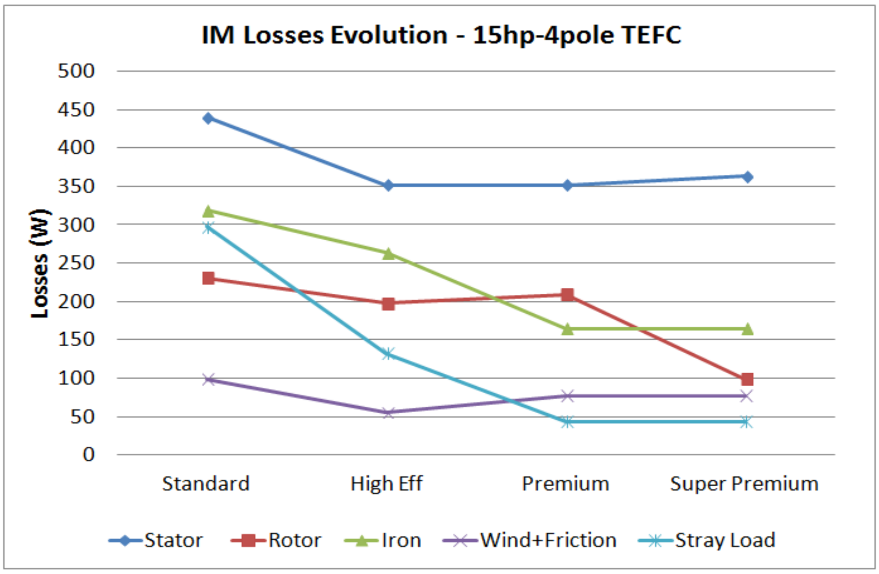

Figure 17: Evolution of the Losses in a 15hp/4 pole/TEFC Induction Motor

B. Copper Rotor Technology

Induction motors with die-cast copper rotors are often touted as the route to super-premium efficiency. This is because of recent improvements in copper rotor die-casting technology and subsequent appearance of products on the market in 1hp to 20hp ratings. These motors had nameplate efficiency above NEMA Premium levels. Recently some manufacturers in China have developed motors with copper rotors that are at least two NEMA efficiency bands above premium efficiency. Due to the high melting point of copper, die life is significantly short, and copper die-casting can potentially result in prohibitive costs for a manufacturer. So far only a few manufacturers are pursuing this technology for industrial motors. Nevertheless, the renewed interest presents a significant opportunity for the design and manufacturing of high efficiency induction machines. However, there is no indication that more manufacturers would pursue copper rotor technology if efficiency levels are raised to super-premium levels. This is because many of the products currently offered as super premium motors are in fact die-cast aluminum rotor products.

Fig. 18: Die-cast copper rotor for induction motor

In other words, it is possible to design super premium induction motors with identical or superior performance to copper rotor motors and the key deciding factor would most likely be cost. This is especially true because the short die life of copper die-casting tends to tilt the economics towards the relatively cheaper, time tested aluminum die casting that has significantly longer tooling life.

C. Stack Lengthening

Motor manufacturers have used different approaches to increase efficiency. The most preferred method is one that leads to minimal cost while meeting all performance requirements. One of these approaches is stack lengthening, which has recently been analyzed in [12]. The method was applied to various commercially manufactured motors to demonstrate the effectiveness of axial core lengthening for motors that have originally been optimized for different parameters. Figure 19 shows the results of core lengthening on the overall losses of the analyzed motors. The maximum loss reduction achieved was about 7% for the 7.5kW aluminum rotor motor. Using the plot of Fig 13, no more than 12% price premium can be tolerated. Although this price premium is close to the current market price the increase in efficiency may be practically too modest. The larger motors (56 kW) analyzed were found not suitable for further efficiency improvement using the stack lengthening technique.

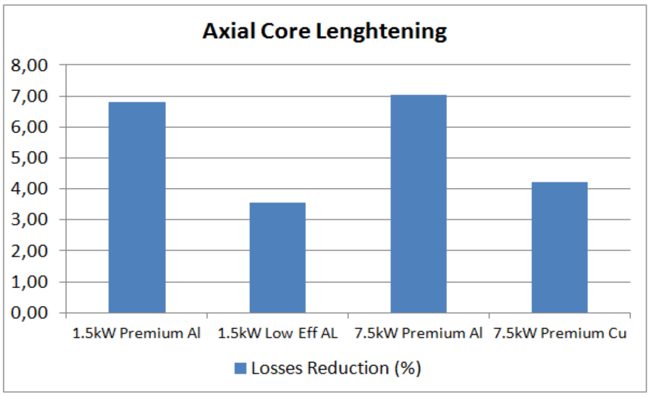

Figure 19: Losses reduction for axial core lengthening

The study concluded that only modest gains are possible with the stack lengthening approach. For the possibility of significant efficiency improvement, a complete redesign is required and this may or may not require significant re-tooling.

D. Locked Rotor Performance

Induction motors must meet certain standardized performance requirements and fit into specific dimensional frames. Each commercial or industrial induction motor can therefore be defined by a specific electro-dimensional parameter package. Locked rotor current (LRA) and torque (LRT) are among standardized performance parameters for induction motors. The LRA can be approximated from equation (5):

$$I_{st} = \frac{V_s}{Z_{st}} \quad (5)$$

where I_{st} is the starting current and Z_{st} is the starting impedance of the motor at slip of one. It has been shown that the efficiency improvement or the move from premium to super-premium efficiency impedance would be decreased to decrease losses. However, rotor resistance and reactance cannot be decreased with a free hand. In particular, a decrease in rotor resistance may lead to decrease in LRT. In general, lower impedance has potential to increase locked rotor current, which has wider implications for power system operation and switchgear operation. Any possible increase in LRA has to be mitigated at the expense of increased cost of the motor. The deep bar effect can be utilized to improve the locked rotor torque, as seen especially in the copper rotor designs. This has potential to increase active material usage and cost. To the extent that locked rotor current limits remain stringently fixed and higher values are not under consideration, it would be challenging and costly to significantly improve efficiency of induction machines without violating the set limits.

Efficiency Testing Considerations

Efficiency tests should be capable of differentiating between nominal efficiency levels and should be able to properly distinguish between the efficiency classes. The loss segregation method is the recommended method for efficiency measurement. The loss segregation method is well described in the applicable standards and in literature. The accuracy of the loss segregation test method and lingering issues with the determination of stray load loss have been the subject of various papers. Stray load loss is acknowledged the “wild card” in motor efficiency measurement. The loss is determined from the residuals of the apparent total loss in (6) through regression analysis. At high efficiencies loss segregation is particularly challenging, as the difference between input and output power diminishes. Mathematically, it can be shown that, the percentage error of the apparent power may be much larger than that of either the power input or output. The error compounds even much more if both power output and power input are large quantities, which is characteristic of large motors.

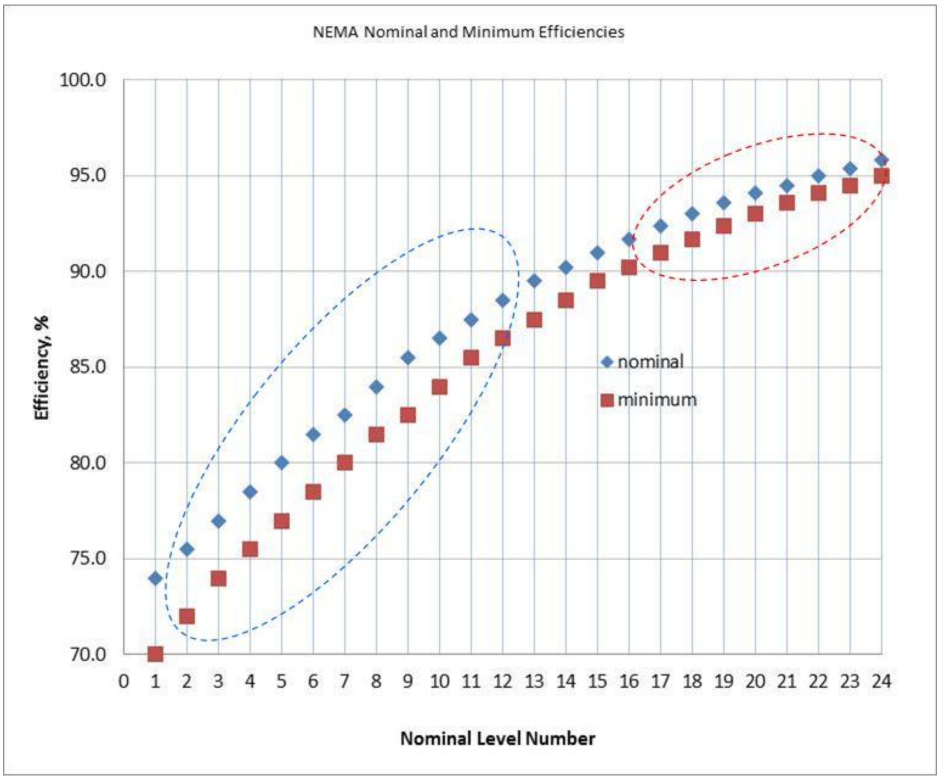

Figure 20: Nominal and minimum efficiency levels

Secondly, at high efficiencies the absolute difference between the efficiency bands become smaller and smaller and test differentiation becomes more difficult. This is especially true for larger motors and can be visually seen in Fig 20. For a nominal efficiency of 90.2%, the minimum is 88.5% a difference of 1.7%. At the higher end of 96.8% nominal, the minimum is 96.2%, a difference of 0.6%. This may be larger than intra lab tolerance but close to or perhaps exceed inter-lab tolerances. The latter may be an important factor in enforcement, especially when lab results are in dispute.

$P_{app} = P_{in} - P_{out}$ (6)

Conclusion

A survey and analysis of induction motors available in the market was carried out, comparing their prices and stated nameplate efficiency in order to evaluate the effect of prescribing super-premium efficiency levels for induction motor. The paper carried out motor energy use analysis, using the concept of viability curves. The findings indicate that application of super-premium motors is viable from the operational standpoint for some motors and not for others. This makes prescribing higher efficiency over the entire range of 1-500hp more challenging. For the lower horsepower motors, their relatively high price/kW tends to put them outside the viability limits corresponding to the average operation point in industry. Most large motors could meet the viability criteria since this analysis is mostly based on energy consumption economics and the economics for larger motors are typically favorable due to high energy consumption and higher run hours.

As motor size increases, efficiency increases. At high efficiencies, test differentiation becomes more critically important but also more challenging and those factors must be considered.

From the technological standpoint, the copper rotor technology is still being used by a few manufacturers for super premium small motors up to 20hp. However, most of the recent products are with die-cast aluminum rotors. Line start permanent magnet motors are increasingly becoming available on the market in normal distribution channels. From the survey, it can be seen that the efficiencies of these motors are not markedly higher than induction motors.

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Reconditioning techniques of electrical machines aiming the preservation of original efficiency

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Abstract

Efficiency of reconditioned motors is of interest since in addition to the number of new machines purchased and installed by the industry every year; nearly the same number of motors is repaired and reemployed. A literature review of rewound low and medium voltage motors is discussed.The efficiency of a rewound motor is found to increase, decrease or even remain the same following a rewinding operation based upon the actual practices employed. It is nevertheless shown that a carefully monitored rewinding procedure can indeed allow a replication of the efficiency of the original motor. This applies to a single as well as to multiple rewinds. The stator core (iron and stray losses) treatment including the actual procedure of removing the winding and the new winding details are found to be the key factors that influence a reconditioned motor efficiency. Of these, while removal of the winding is related to procedural delicacy, operator experience, correct temperature limits, etc., and while the new winding details are related to the motor operation and customer expectations, the real uncertainty lies in the stator core properties. This is thus studied further in detail. Stator cores of motors that are to be rewound are thus tested with various core loss test methods and at various locations to determine their suitability for reuse. Red flags such as losses exceeding acceptable limits, existence of localized hot spots and temperature rise of the core when exceeding acceptable limits are studied and remedies to address those are listed. Various stator core loss test methods like, EASA (Electrical Apparatus Service Organization) Loop Test, Phenix & Lexseco automated stator core loss test systems and Electromagnetic Core Imperfection Detector are reviewed and discussed. Of these, the first three are further investigated with the help of measurements and their differences documented. Recommendations are provided in establishing a pass fail criteria for preserving, restacking or replacing a stator core. This is identified as the key topic in preserving the efficiency of a reconditioned motor. The efficiency improvement opportunity is also shown to be made possible through a redistribution of the losses during rewinding and making the maximum efficiency occur at the actual operating point (load) of the motor. The paper discusses the economics of repair cost versus a new machine acquisition. Statistical data that illustrate the number/rating of motors that are repaired in Brazil every year and how this picture is evolving is provided for illustration purposes.

1. Introduction

This section provides background regarding the need and past experiences on the rewinding topic [1-33].

1.1 Motor repair statistics (in Brazil)

Around 21% of electricity in Brazil is consumed by industrial motors, which corresponds to 92 TWh/year [38]. In a 5% growth scenario, Brazil has an increase of 525 MW of new motors yearly. Also, it is estimated that around 250 MW of electric machines are repaired every year. For the case of large machines, for every 6 or 7 new electric machine, one old machine is repaired. The costs of an electric machine repair for such large machines are usually from 65% to 75% to that of a new machine. However, the key reason behind a repair decision is the reduced delivery time, usually of 6 to 8 weeks for a big machine repair as compared to 6 to 7 months for a new one. In such instances, usually efficiency isn't the main concern involved during reconditioning procedure. Depending on the procedure taken, 1% to 5% of the original efficiency of one electric machine can be lost during reconditioning if not done properly [37]. So, for an amount of 250 MW of reconditioned machines yearly, 2.5MW to 12.5 MW could be permanently lost, until machine replacement, after the next 10 to 20 years. This represents a cumulative increase of losses of 22 GWh to 110 GWh a year.

1.2 Efficiency opportunity through rewinding

In the industry, nearly 70% of the electricity is consumed by some type of motor-driven systems [1] most of whom employ induction motors. *In addition to the new machines purchased and installed by the industry every year, nearly the same number of motors is repaired and reemployed [3].* According to American Council for an Energy Efficient Economy (ACEE), some 1/3rd to 1/4th of all repaired motors may be rewound and the repaired motor numbers could be as high as 4/5th of all installations. As a result, even a small improvement in the efficiency of an existing induction motor will lead to significant energy savings and environmental benefits. In the European Union, a 1.5% increase in the energy efficiency of the electrical machines would produce electricity savings of over $2 billion per year [2] and contribute 2.75% to the reduction of CO2 emissions as agreed under the Kyoto Protocol.

Many motors are designed for best efficiency at or near full load. Through tests it has been observed that the standard motors achieved their maximum efficiency near rated load and suffered an appreciable decline in efficiency as the load is reduced. The high-efficiency motors on the other hand achieved their peak efficiency at approximately **75%** of rated load and maintained a high efficiency over a wider range of load than did the standard [3]. Typically half of all motors in the U.S. operate at less than 60% of rated load, and a third below 50% [3, 5]. *Thus the rewinding of a motor allows this unique opportunity to rewind the motor in a way so that the new distribution of losses could lead to the best efficiency at the actual operating point of the motor [26, 28].*

Dependaning on the age and vintage of the insulation system that is being replaced it is often possible to increase the operating efficiency and thermal class rating of the rewind. Advancements in insulating materials and manufacturing processes facilitate these gains. Improvements to resins, slot liners, insulating tapes and advances in coil manufacturing processes contribute to provide higher dielectrics, improved thermal transfer and increases in the conductor fill factor.

1.3 Rewinding or a new motor decision

The decision to go for a rewound or to have a new motor installed is a complex one and is defined by many factors. The state of degradation of a motor, availability of budgets by either the procurement (new motor) or service/maintenance entities (a rewound motor), time criticality, any prevalent or upcoming efficiency regulations, expectations from an actual rewound procedure are some of these factors. With the efficiency regulations getting tougher, flow of cheaper new motors from low cost countries, the cross-over rating, at which a new motor would make economic sense over a rewound motor keep increasing. Having said this, the de-facto regime is still rewinding, especially in developing countries. Estimates vary on what should be right motor rating for this choice with estimates varying from a few HP to 10's of HP.

1.4 Impact of loss redistribution

The efficiency of a rewound motor is found to increase, decrease or even remain the same following a rewinding operation based upon the actual practices employed. It is nevertheless shown in literature that a carefully monitored rewinding procedure can indeed allow a replication of the efficiency of the original motor. This applies to a single as well as to multiple rewinds. In addition, it is also debatable that the significant efficiency improvements claimed by certain rewinding techniques e.g. unity-plus, in fact result in an improvement in the power factor and not in the efficiency. The efficiency improvement opportunity is also shown to be made possible through a redistribution of the losses during rewinding and making the maximum efficiency occur at the actual operating point (load) of the motor in question.

The total power loss in a machine is normally divided up into the component parts of a stator-conductor loss, rotor-conductor loss, core loss, windage and friction losses, and stray load loss. The proportions of these component losses change with the machine size and the pole number with small machines having the stator-conductor loss as their dominant loss.

The stator core (iron and stray losses) treatment including the actual procedure of removing the winding and the new winding details are found to be the key factors that influence a reconditioned motor efficiency. Of these, while removal of the winding is related to procedural delicacy, operator experience, correct temperature limits, etc., and while the new winding details are related to the motor operation and customer expectations, the real uncertainty lies in the stator core properties

1.5 Test procedure

The possibility of new measurements is investigated. It is found that to have any interpretable results the efficiency measurements needed are: (Using IEEE-112B test method or similar)

1. Test on a newly manufactured machine
2. Repeatability test on this newly manufactured machine
3. Test after first rewinding
4. Test after 2nd rewinding
5. Test on an identical but old machine
6. Test after a rewinding operation on this old machine

For validation purposes of the tests for the older machine that has been in service to the new motor one must also verify that no design or material changes have occurred. This is sometimes impossible based upon the age of the older motor.

To isolate the influence of the burnout and stripping of the stator core, core loss tests should be performed using the same test method for the following:

1. Perform core loss test on new stator core before winding
2. Repeat test on new stator core
3. Repeat core loss test on stator core in frame after winding
4. Test stator core after burnout and stripping of winding
5. Repeat test on stator core after rewinding
6. Repeat steps (4) and (5) for second rewind of stator

Hence, at the very least 6 motor performance and core loss tests are needed. The tests on the older machine are necessary, since, a rewinding operation is usually performed on an older motor which already has some deterioration to its core losses. The drop in efficiency for such motors is not only due to rewinding but also due to the natural aging of the core.

1.6 The stator core losses

Stator core iron loss is traditionally segregated into two major categories:

- Hysteresis Losses
- Eddy Current Losses

The remaining unexplainable losses of the total core loss are bundled as anomalous losses. Hysteresis loss is a heat loss caused by the magnetic properties of the material. When a material such as an armature core is in a magnetic field, the magnetic domains of the core tend to line up with the magnetic field. In the stator of an electric machine, the magnetic field keeps changing direction. The continuous movement of the magnetic domains, as they try to align themselves with the magnetic field, produces molecular friction, which is the hysteresis loss. Both eddy and hysteresis losses are explained by the hysteresis loop in figure 1. The right side of the loop represents the energy required to establish the magnetic field on the positive slope of the AC waveform. The graph to the left represents the energy required to collapse the magnetic field on the negative slope of the AC waveform. The area between the two curves is proportional to total losses in the electrical steel and is dissipated in the form of heat. When the hysteresis loop is traced with DC input, the energy enveloped by the loop represents the hysteresis loss.

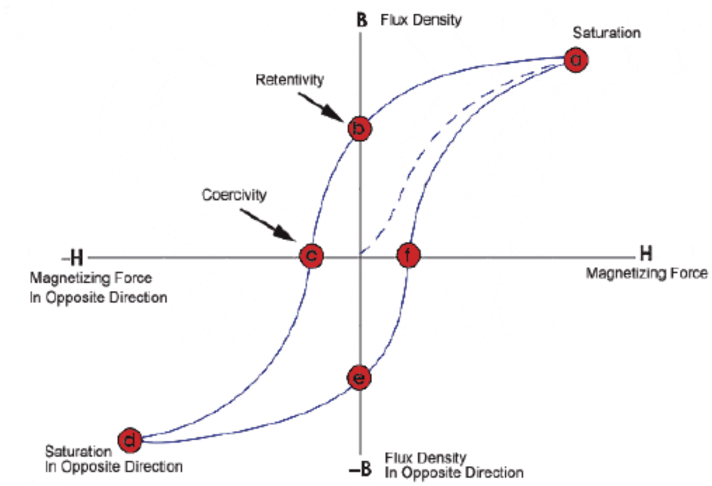

Figure 1: Hysteresis Loop

Eddy Current losses are defined as circulating currents that occur as a result of the magnetic field produced in the lamination. Circulating eddy currents flow perpendicular to the main flux field and are proportional to the cross sectional area of the laminate conductor (fig. 2). Using thinner laminations minimizes circulating eddy currents and associated losses. Increasing the silicon/aluminum content increases the resistivity and reduces the eddy-current losses. However, this is usually employed in larger machines. Eddy current losses are directly proportional to the square of the frequency, peak flux density and thickness of the lamination. They are inversely proportional to the resistivity of the material.

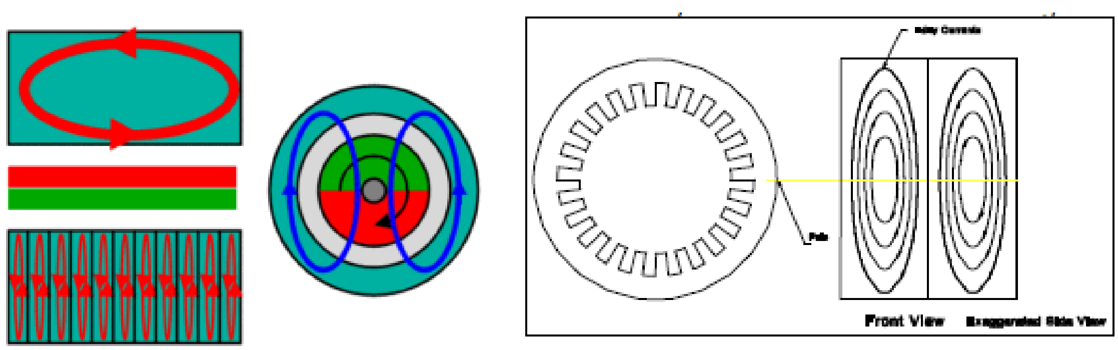

Figure 2: Eddy Current Diagrams

Eddy current losses increase between laminations when the inter-laminar insulation begins to break down (fig. 3). The circulating eddy currents in the individual lamination couples with adjacent laminations and increases the effective loss. The eddy current, hysteresis and anomalous losses are dissipated in the form of heat.

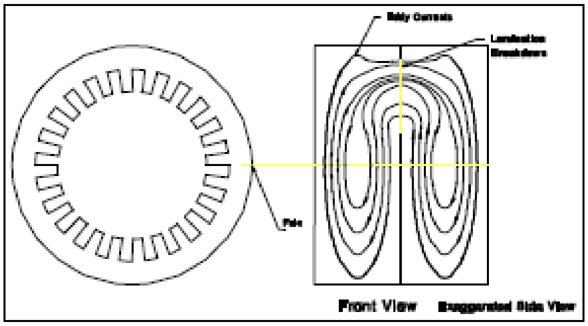

Figure 3: Eddy Current Inter-Laminar Flow

The summation of all these losses comprises the W/lb. loss in the stator core.

1.6.1 Influence of temperature

All the components of iron losses as well as the permeability are impacted by temperatures, a key parameter in motor stator rewinding procedure. In [35] it is shown that the permeability increases with temperature until the knee of the curve, then it decreases. The variation of the magnetic characteristics with temperature can be explained by the decrease of the magnetocrystalline anisotropy, the magnetostatic energy and the saturation magnetization with the increase of temperature. For a given flux density, iron losses are influenced by the operating temperature. The losses decrease with an increasing temperature. This is due to the fact that resistivity increases with temperature and hence the eddy current losses decrease. A rise of the temperature from 20 to 80 degrees (Epstein test) could give a loss density decrease of 3% [34].

1.6.2 Influence of other parameters

In [36] details are provided of how the various other parameters like punching, welding, laser cutting, etc. influence the iron losses. The spread in material properties of the sourced materials (lamination rolls) as well as the spread in loss figures as interpreted by different measurement techniques (specified by standards and otherwise) is also documented in detail.

1.7 Earlier findings

It is the “conventional wisdom” that a rewound motor’s efficiency is deteriorated with each rewind, due to core damage incurred during the rewinding process. Estimates vary, ranging from no loss to 5 percentage points lower per rewind [27]. Rewinding electric motors requires the removal of the original winding, which is normally very solidly located by a synthetic varnish. The process of removing the winding for a random wound stator requires the cutting-off of one of the two end windings, the heating of the stator in an oven to at least 350ºC to soften and burn off the varnish, then the mechanical withdrawal of the remaining winding and finally, the cleaning up of the stator core. The heating of the core may damage the inter-lamination insulation, increasing iron loss if the burnout temperature is too high. The mechanical removal of the winding and the cleaning up of the slots may also cause inter-laminar short circuits, which give rise not only to increased core loss but also to increased stray load loss since most of this loss occurs in stator and rotor teeth at the air gap surface [14]. Various studies looking at rewinding efficiency have revealed contrasting results [26, 28]. It has been shown that the loss figure after rewinding is less than 1% [4], about 1% [5], 2% [6], or up to 6% [7] of the efficiency. It is also found that each rewind would result in a 1% loss for multiple rewinds. The opposing view is that, a little or negligible loss [8]–[11] in the efficiency or even an improvement [12] may occur. The majority of the rewind studies were based on the small machines, which emphasizes one aspect of the loss.

2. Stator Core Loss Tests

The stator core (iron and stray losses) treatment including the actual procedure of removing the winding and the new winding details are found to be the key factors that influence a reconditioned motor efficiency. Of these, while removal of the winding is related to procedural delicacy, operator experience, correct temperature limits, etc., and while the new winding details are related to the motor operation and customer expectations, the real uncertainty lies in the stator core properties. This is thus studied further in detail. Stator cores of motors that are to be rewound are thus tested to determine their suitability for reuse.

2.1 Suitability of the stator core

Stator core loss tests are performed in the motor repair industry to determine the suitability of a stator core for reuse. For a typical repair/recondition the motor or generator is disassembled and the rotor is removed. The wound stator is subjected to a series of electrical tests to determine if any dielectric impairment to the electrical windings is present. If the windings exhibit acceptable readings for resistance, megohm, (megohm readings may be low but acceptable due to contamination) and surge tests the wound stator assembly is typically reconditioned.

During reconditioning a stator core loss test is performed to determine if the stator core has excessive core loss or hot spots. There are various ways of doing this as reported in the literature [3-12]. If the stator core exhibits excessive core loss (typical core loss of about 4 W/lb to 6 W/lb) the stator core should be evaluated further to determine if this is typical or if core plate erosion in the back iron is the cause. The repair facility may attempt to clear localized hot spots and retest.

If dielectric impairments to the electrical windings are present the stator is core loss tested as above to determine if it be reused. If the stator core loss tests are acceptable the stator is placed in a burnout oven (650 °F - 700 °F) to remove the insulation and resin securing the electrical windings in the stator core. After the insulation has been burned the windings are stripped from the stator core. The stator core is retested for core loss to insure the inter-laminar core plate insulation was not impaired. General standard for the industry is that core loss in W/lb. did not increase pre and post burnout by more than 10%. Typical results for the increase in core losses are 1% to 2%.

2.2 Stator Core Loss Testing:

Stator core loss tests are performed to determine if any of the following conditions exist:

1. Stator core loss in W/lb. exceeds acceptable limits.
2. If the Stator core exhibits localized hot spots.
3. If the Stator core temperature rise exceeds acceptable limits.

Stator core loses in W/lb. are generally reflective of the ASTM (American Society for Testing and Materials) grade of electrical steel and condition of the inter-laminar core plate specifically in the back iron of the stator core. General industry standard for maximum core loss values are 4 W/lb to 6 W/lb. If the stator core measures above this limit the stator core should be replaced or un-stacked and the laminations recoated with an inorganic core plate.

Localized hot spots are an indication of circulating eddy currents resulting from a lack of inter-laminar insulation. Hot spots are defined as any region of the stator exhibiting a 10 °C or 18 °F temperature rise above the stabilized stator core temperature during an extended core loss or over saturation test. Extended 30 minute core loss tests are the preferred method in the motor repair industry. If the hot spot is localized it can generally be cleared by one of the following methods:

1. Bumping the stator core to separate the laminations in the affected region and application of an oxidious inorganic coating or similar.
2. Fanning the laminations out and application of an inorganic coating.
3. Machining the surface of the stator in the region of the hot spot.

If the hot spot covers a larger region it can sometimes be cleared by baking the stator core at 350 °F and applying an inorganic coating while the laminations are thermally expanded. The stator core is allowed to cool and retested.

2.3 Stator Core Loss Test Methods:

Stator core losses can be measured by one of three methods in the motor repair industry (see Fig. 4).

1. The EASA loop test.
2. Commercial stator core testers such as Lexseco and Phenix.
3. An EL CID (Electromagnetic Core Imperfection Detector)

Figure 4: Picture of the EASA Loop Test and commercial core loss testers.

The EASA loop test is typically conducted at a magnetization level of 85,000 lines of flux per square inch or 1.32 Tesla. This is accomplished by applying 9 ampere turns of excitation per inch based on the mean stator core diameter. To determine the number of loop turns based on this requirement using a fixed single phase AC source voltage supply the number of turns required for the test loop can be calculated and current estimated. (Ampere - Turns = π X D X H). Commercial core loss testers test at the same magnetization level, 85 K lines/in², as the EASA loop test using a single turn. The same calculations apply as earlier and the required test voltage can be calculated based on a single turn. The required current can be calculated based on the diameter of the stator and a constant equating the requirements to achieve an excitation level of 9 ampere turns per inch for the mean stator core diameter Because a single turn is used the required current for the test is much higher.

Both the EASA loop test and commercial core loss testers can be used to detect hot spots. This is accomplished by extending the duration of the core loss test typically to thirty minutes. Temperature profiles should be taken every five minutes with an infrared camera. The prescribed maximum hot spot allowance is 10 °C or 18 °F. The hot spot should be removed and the stator core retested.

An alternative method, EL CID (Electromagnetic Core Imperfection Detector), to detect faults in the inter-lamination core insulation was developed by the Central Electrical Research Laboratory of the UK. Instead of the previous full flux working level the newer method uses only a small fraction of rated excitation to generate fault currents within the core body which are sensed by a pick-up coil. This avoids the testing problems usually found with high excitation, yet still gives an accurate indication of damaged areas along tooth tips and walls, as well as possible sub-surface damage.

The EL CID equipment tests a core for faults by exciting the core using a toroidal winding to produce a ring flux similar to the conventional method (see figure 5 below), but only to 4% of its normal working level of excitation. A sensing head is then passed over the surface of the core to detect magnetically the presence of fault currents themselves rather than the heating effect they produce. The power required is low enough to be within the capacity of standard workshop outlets for quite large machines. Only 2 to 3 KVA of test power is required to test for an alternator that could be as large as several 100 MW.

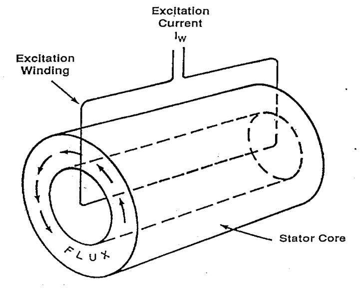

Figure 5: Core Excitation Winding and Flux Path

2.4 Test results

To characterize the different core loss test results discussed above for a certain 800 HP, 4160 V, 4 Pole frame stator assembly with the winding removed was studied with the different test methods used at various locations. Results are provided in Table 1

Table 1: Stator Core Loss Test Results

Parameter	EASA Loop- RBI Test Report	Phenix - RBI Test Report	Lexseco - RSZ Test Report	Lexseco - RLP Test Report	Phenix - RLP Test Report	Lexseco - MCO *(1) Test Report	Lexseco - MCO *(2) Test Report	Lexseco - MPC Test Report	Phenix - MPC Test Report
Vsc	130.00	8.63	14.60	11.60	8.59	16.10	15.90	12.30	8.50
Amps	10.30	187.00	161.30	160.00	188.00	208.00	167.00	164.50	188.20
KVA Input	1339.00	1614.37	2354.98	1856.00	1614.92	3348.80	2655.30	2023.35	1599.70
KW Measured	910.00	961.00	1473.00	1264.00	1500.00	2120.00	1781.00	1312.00	954.00
KW Calculated	910.00	944.89	1495.41	1286.21	938.27	2159.98	1802.95	1260.55	927.83
PF - Meas.	0.68	0.59	0.64	0.69	0.58	0.65	0.68	0.62	0.58
Stator Weight	677.02	679.76	665.91	677.31	679.76	675.58	675.58	675.00	679.00
Meas. W/lb.	1.34	1.41	2.21	1.90	2.21	3.14	2.64	1.94	1.41
Cal. W/lb.	1.34	1.39	2.25	1.90	1.38	3.20	2.67	1.87	1.37

Notes:
Phenix - RLP Calculated KW at .93 PF actual PF was 0.581
Lexseco - MCO *(1) Test Report Actual measured current was 174.1 Amps
Lexseco - MCO *(2) Test Report Actual measured current was 133.8 Amps

As can be seen from Table I, the EASA loop test and Phenix core loss test produced comparable results. Both use regulated power supplies that provide sinusoidal waveforms to the test coil and produce near sinusoidal waveforms with minimal ordered harmonics during the core loss test. The core loss test is performed at 85 kilo lines/in² or 1.32 Tesla. With minimal ordered harmonics the measured watts lost is reflective of the fundamental waveform.

The Lexseco tester uses a saturable core reactor as an input power supply to regulate current during the core loss test. The voltage and current input waveforms are not sinusoidal and have significant ordered harmonics. The core loss test is performed at 85 kilo lines /in² or 1.32 Tesla based on the fundamental waveform. The ordered harmonics increase losses in the core that are in addition to those produced at 85 kilo lines/in². This results in a higher W/lb. result when compared to the EASA loop or Phenix core loss test. In order to evaluate how the harmonics are influencing flux density a Fourier analysis was completed on the voltage and current waveforms. The associated phase angle of the harmonics to the fundamental waveform was evaluated to determine if they are additive and creating higher flux density or additional loses comparable to those produced by a VFD. It should be noted that 3rd order harmonics are not typical in a 3-phase motor.

Based on the Fourier analysis the total harmonic distortion produced by the Lexseco tester is contributing to higher losses in the stator core during the core loss test and is in addition to those produced by the fundamental waveform at 85 kilo lines/in². This results in a higher W/lb. core loss value, as can be seen from Table I. The resulting W/lb. core loss will not be linear/scalable for larger and smaller stators. The smaller the stator core the greater the difference will be between the test methods. This occurs as a result of the amount of saturation the reactor is operated at to test a smaller stator core. The IPS Cleveland Lexseco core loss tester has a 300 KVA saturable core reactor. 1.2KVA was required for the core loss measurement on the test stator. Operating the reactor in a significantly saturated mode produces higher harmonics in addition to the fundamental waveforms. This is because of saturation of the core that causes non-linear behavior and thus higher harmonics. The reactor will approach a sine wave output only at rated load. Due to the different test methods core loss results for the EASA loop and Phenix core loss test will not be comparable to or linear/scalable to the Lexseco core loss test results.

2.5 Observations

The three core loss test methods (EASA, Phenix and Lexseco) reviewed in this study do not reflect the actual core loss the motor or generator will incur during operation. The only reliable means to make this determination is to complete an IEEE - 112B segregation of losses test. Testing at 85 kilo lines/in² of flux density in the back iron is a good average for comparisons but is not representative of the actual flux produced by the winding and associated influence of the rotor. Typical design flux densities can range from 65 kilo lines/in² to 110 kilo lines/in².

Each of the three core loss test methods is a reliable means to determine if stator core degradation occurred pre and post burnout. They provide a reliable method to check for localized hot spots and total stator core temperature rise as a result of inter-laminar insulation breakdown, specifically in the back iron during an extended core loss test. They also provide a reliable way to evaluate duplicate stator cores from the same design or model number series if tested with the same test method.

In order to establish a maximum W/lb. core loss test result the following variables would need to be taken into account.

1. Electrical steel type, grade, thickness.
2. Influences of stacking factor, welds and method of capture in the frame.
3. Actual flux density that the stator will operate at.
4. Winding data is required to determine Bc flux density for a full flux test.
5. Actual operating temperature rise
6. Method of core loss test.

Each of these factors should be considered when establishing an acceptable maximum value for W/lb. core loss. Based on these variables it is extremely difficult to establish a generic pass fail criteria in W/lb. for the EASA loop, Phenix or Lexseco core loss test.

2.6 Pass-fail criteria recommendations

The authors propose to establish a pass fail criteria for preserving, restacking or replacing a stator core based on the following criterion.

1. If a known value for core loss in W/lb. can be derived across a statistically significant population of identical stator cores a maximum watts/lb core loss can be established using +/- 2 standard deviations of the population. This assumes the same test method will be employed for all core loss tests.
2. Conduct an independent study of existing core loss test results to determine if a confidence level can be established to set a maximum acceptable core loss value using any of the three test methods. i.e. - 6.0 W/lb.
3. Perform an extended core loss test at 85 kilo lines/in² for a minimum of 30 minutes or until the stator core's thermal rate of rise is less than 1 °F for a ten minute period. Minimum extended core loss test time is 30 minutes.
4. Check the back iron and base of the slot cell cavity using an infrared camera every 5 minutes and record temperature gradients. Review for localized hot spots. Hot spots are defined as any region of the stator exhibiting a 10 °C or 18 °F temperature rise above the stabilized stator core temperature during an extended core loss test.

3. Conclusions

This paper provides some insight into the topic of rewinding motors, especially in relevance to stator core losses. By taking Brazil as an example developing country, it is mentioned that the repair motor market share (in MW) is half of that of new motors commissioned every year, even if the cost of repair could be 65-70% as compared to that of a new machine. Rewinding also provides an opportunity of improving the efficiency of a motor, if done properly by redistributing the motor losses. The importance of measurements is emphasised. Since the core may be affected through burnout or stripping during the motor rewinding process, adequate knowledge of core losses is thus necessary. This in turn depends upon core loss test methods, which have been discussed in detail.

Three methods for measuring core losses are studied (EASA, Phenix and Lexseco) through detailed experimentation. Results on a certain 800 HP motor are provided. Each of the three core loss test methods is a reliable means to determine if stator core degradation occurred pre and post burnout. It is nevertheless found that based upon the particular test method, the core losses would be different, primarily dependent upon the power supply of the employed equipment. It is thus necessary that the old motor and the rewound motor is measured with the same test equipment, as otherwise discrepancies may occur. The differences increase as the core gets deeper into saturation. Since the EASE loop and Phenix employ a similar power supply, the results from these two tests are closer and will not be comparable to or linear/scalable to the Lexseco core loss test results. Various factors should be considered when establishing an acceptable maximum value for W/lb. core loss, thus making it extremely difficult to establish a generic pass fail criteria in W/lb. Still, the authors do propose to establish a pass fail criteria for preserving, restacking or replacing a stator core, the key being have consistency in the core loss test method.

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Motor Efficiency: A Critical Comparison of Laboratory Motor Capability Measurement with Operating Estimation Techniques in the Field

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Abstract

Good motor management programs include seeking ways to capitalize on energy saving opportunities, like replacing currently installed motors by higher-efficiency ones, or improving the operating condition such that the motor will operate at higher efficiency. The starting point of such programs is an understanding of motors' operating efficiencies. The means of measuring motor efficiency is defined in IEC 60034-2, but its requirements can only be met in a laboratory. Operating efficiencies of motors in the field differ from their nameplate information due to reasons external to the motor – i.e. motor application; and internal ones – such as motor condition. The picture becomes more complex once one considers the different accuracy of existing field-friendly efficiency estimation methods.

The core information sought by motor users in terms of energy savings is obtained by comparing the operating efficiency of a motor in the field with the one of a replacement motor running under those same conditions. This paper addresses the challenges of achieving such a comparison. It demonstrates that employing accurate efficiency estimation methods is critical. Equally important is the understanding of the impact that power quality, loading, the motor repair history and field-maintenance practices have on a motor's operating efficiency. This paper concludes that good motor management requires knowledgeable professionals using adequate tools and enforcing best practices for motor usage and maintenance in the field, as well as for their repair and reconditioning off-site.

I. INTRODUCTION

Installing only highest-efficiency motors in the hope of achieving optimal efficiency is at most only a partial solution. The environment in which these motors run, the plant's maintenance practices and each motor's repair history are equally important, but frequently neglected. An efficiency-oriented motor management program is part of an overall Life Cycle Management (LCM) approach: where components such as bearings, seals and lubrication are identified based on functional needs as a part of a particular driven application, where correcting of power quality issues are pursued for their global efficiency and economic benefit to the whole plant, and where improvement of a motor's operating efficiency will also increase its lifetime. These benefits can only be reached by heightening motor user's awareness to the importance of combining an integrated design from a system and not solely a component perspective with maintenance procedures that take advantage of active condition monitoring. Only then will companies get closer to their potential of a realized smaller, and not only hypothetical environmental footprint.

Robustness, simplicity and low maintenance requirements make the three-phase induction motor (IM) the most commonly used motor in industrial applications, being responsible for the majority of electrical consumption in U.S. industry [1]. Consequently, the IM is a prime target for efficiency improvement programs. This paper presents the system variables external to this motor type, as well as the conditions internal to it that affect its operating efficiency. Furthermore it discusses existing methods to measure and to estimate motor efficiency. Finally, the paper suggests how education, tools and best practices ought to be combined into a high quality efficiency-oriented motor management program, allowing the user to profit from an integrated system analysis.

II. INDUCTION MOTOR LOSS DISTRIBUTION

This paper discusses the impact on efficiency of IMs under various conditions. In order to follow these concepts, it is critical to understand the basics of the five physical loss components of an induction motor in terms of their physical meaning and how these are modeled in the equivalent circuit of Fig. 1. The reactances X_{ls} and X_{lr} represent the stray stator and rotor reactances, and X_M the magnetizing reactance.

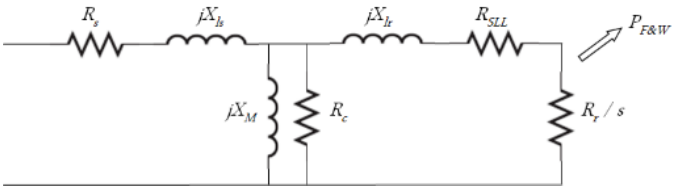


Fig. 1. Equivalent circuit of IM including five loss components.

The losses are modeled as follows: The resistance R_c models the core losses P_c which vary in proportion to the square of the voltage applied to the stator, R_{SLL} represents stray load losses P_{stray} which change in proportion to the square of load, and $P_{F\&W}$ represents the friction and windage loss which is nearly constant for line-operated motors. The conductive losses of the stator P_{I2Rs} change in proportion to the stator resistance R_s and the square of the stator currents. The resistance R_r/s can be split in two parts: R_r is the rotor cage resistance responsible for the rotor conductive losses P_{I2Rr} which vary in proportion to the square of the load, and the remaining

$$R_r \frac{1-s}{s}, \quad (1)$$

which models the power delivered to the shaft.

Fig. 2 shows how the total motor losses $P_{total\ loss}$ is composed of these five loss components for a typical induction motor and how the proportions of the individual losses change as a function of load. Although P_{core} and $P_{F\&W}$ show slight variations with load, IEC 60034 and IEEE 112 consider them to be load-independent, which is why their sum is called constant losses, P_{const}.

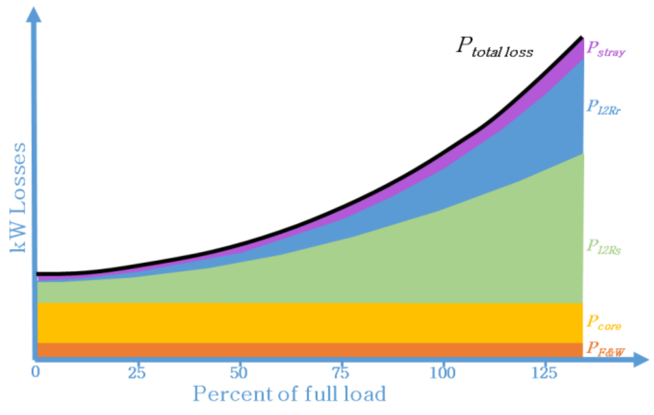


Fig. 2. Typical loss distribution and total losses as a function of load.

III. EXTERNAL VARIABLES – MOTOR CAPABILITY VS. MOTOR OPERATION

This section of the paper discusses circumstances external to the motor that cause it to operate at efficiencies different than nameplate. The motor is the center-piece of a chain of three links: Power Quality, Motor and Load. Varying the power quality or load away from nominal values will change the operating efficiency.

A. Power Quality

The power quality for an IM is determined by 3 different voltage properties.

1) Voltage Level

Fig. 3 shows how variation of voltage level for motor changes its operation in terms of starting and break-down torque, starting current and full load current. Efficiency and power factor changes are a result of non-linear behaviors caused by particular motor designs.

The traces of this figure are to be understood only as a typical behavior, with their particular shape varying from one motor design to another. Note that the graph implies the motor to be running at full load.

Motor temperature will drop as long as the overvoltage levels are in the range where efficiency increases. Such mild overvoltages will extend insulation and lubrication lifetimes, thus raising a motor's expected life.

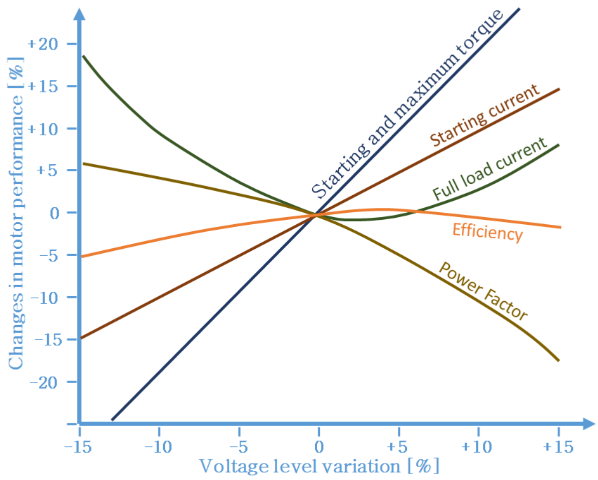
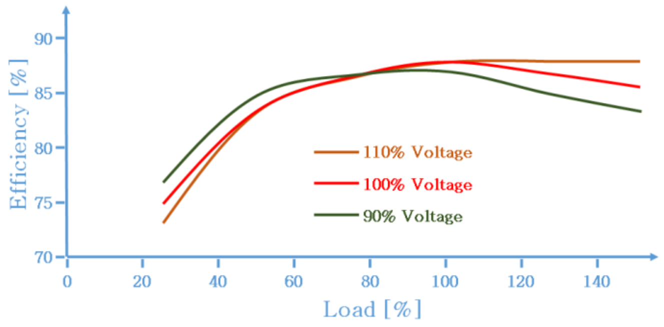


Fig. 3. Efficiency, PF, starting current and FL current vs. Voltage level.

Motors in industry rarely run at full load [2], slightly complicating the evaluation of efficiency. Fig. 4 shows how a 50hp and a 100hp motor's efficiency changing for over- and under-voltage conditions as a function of load.

A motor's efficiency will rise at very low loads for a drop in voltage level because P_{core} is proportional to the square of voltage, which is the dominant loss at low loads (Fig. 2). At higher loads, the behavior reverses: Rotor and stator currents are reduced with slight over-voltages, causing a bigger drop in stator and rotor P_{I2R}, which become the dominant losses. This explains the benefit of operating a motor under slight over-voltage conditions for high loads.

Predicting whether a motor's efficiency will react more strongly to voltage variation levels at lower or higher load is impossible since it depends on the particular design. The 50hp motor's efficiency in Fig.4 reacts more strongly to variations in voltage level at low loads, while the 100hp reacts more strongly at higher loads.



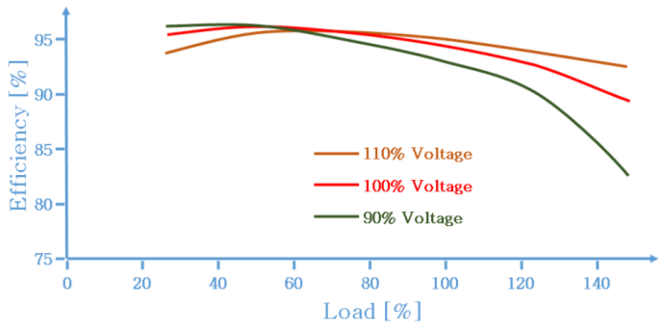


Fig. 4. Efficiency vs. load of a 50hp motor (top) and a 100hp motor (bottom) at 110%, 100% and 90% voltage level [3].

2) Voltage Balance

Almost all voltage busses experience some voltage unbalance. Von Jouanne et al. point out in [4] that one third of the distribution voltage busses in the USA have more than one percent voltage unbalance, and two percent of the busses run with more than three percent of voltage unbalance. Unless it is actively managed by a plant's engineering, voltage unbalance at lower voltage busses inside of the plant will typically be higher than what is supplied by the distribution company. A relatively slight amount of voltage unbalance typically creates strongly unbalanced currents in the stator, adding significant heat to the rotor. P_{I2R} losses in stator and rotor rise, increasing the motor's operating temperature, lowering its lifetime and causing a drop in efficiency.

The IEC and NEMA worlds differ in how they deal with voltage balance [5], causing frequent debates between motor scientists and motor users. IEC quantifies unbalance with defining *VUF* as the ratio of negative sequence voltage divided by positive sequence voltage. NEMA calculates voltage unbalance as V_{unb} directly from line-line voltage level readings by dividing the largest voltage difference from a line-line reading to the average line-line reading, divided by the average line-line reading. Both methods have advantages. *VUF* is scientifically accurate in describing the amount of voltage that causes losses to the motor, while the strength of V_{unb} resides in the ease of calculation – a handheld voltage meter and a calculator suffice.

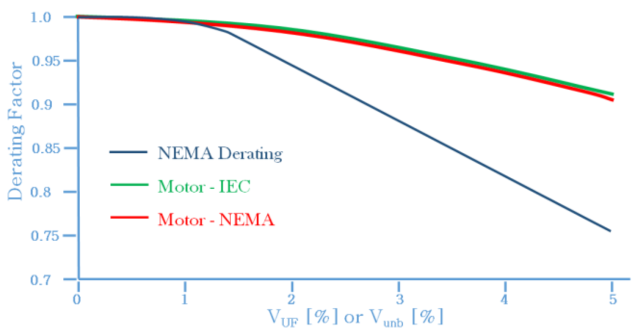


Fig. 5. NEMA Derating factor, and IEC and NEMA true deratings of a 5hp 4-pole TEFC motor [5].

Fig. 5 is the result of a study by Springer et al. [5], where one particular 5hp motor was subject to varying amounts of voltage unbalance, and the load was regulated such that the highest temperature of the motor's insulation was equal to the temperature running with zero unbalance and full load. The study concludes that:

1. The "knee" of the NEMA derating curve at 1% unbalance doesn't match the motor's behavior.
2. The NEMA derating factor curve [6] is significantly too aggressive for this particular motor.
3. The same number-result of *VUF* and V_{unb} describe very similar operating conditions – arguing that discussions of *VUF* vs. V_{unb} may not be very meaningful, since the results barely differ.

Wallace et al. investigated the effect load and voltage unbalance had on a 50hp, 100hp and 300hp motor on efficiency by subjecting them to 0% and 2.5% voltage unbalance at various load points [3].

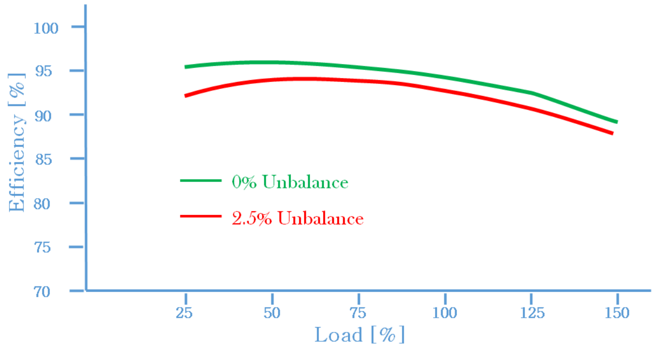


Fig. 6. Efficiency vs. load of a 100hp 4-pole motor for 0% and 2.5% unbalance [3].

The 100hp motor showed a marked decrease in efficiency, as displayed in Fig. 6. However, the authors note that even though the voltage unbalances caused significant current unbalances for all three motors, "*Surprisingly, in spite of these current unbalances, the efficiencies of the 300hp and 50hp motors are virtually unaffected from the balanced case*". In conclusion, it is clear that voltage unbalance can have a very detrimental effect reducing motor efficiency and life expectancy. It is not possible, however, to derive any type of derating curve that would be suitable and accurate for all motors, since particular motor designs affect the sensitivity of reaction to a particular amount of voltage unbalance. For more information on voltage unbalance and its effect on motors, refer to [7-8].

3) Voltage Distortion

Voltage distortions are the root-cause for additional currents in the stator and the rotor. These currents cause additional heat, raise the motor temperature and drop the operating efficiency. Similar to NEMA's voltage unbalanced derating factor, [6] also specifies a derating factor shown in Fig. 7 applicable to the harmonic components of the distortions, defining the harmonic voltage factor *HVF* according to (2).

$$HVF = \sqrt{\sum_{n=5}^{\infty} \frac{V_n^2}{n}} , \qquad (2)$$

Dissimilar motor designs will react differently to the same amount of *HVF*, rendering unbalance and distortion derating graphs inaccurate. Nevertheless, they remain a useful tool for the motor user, since they give a guideline for how to deal with substandard power quality, which is sometimes an unavoidable condition.

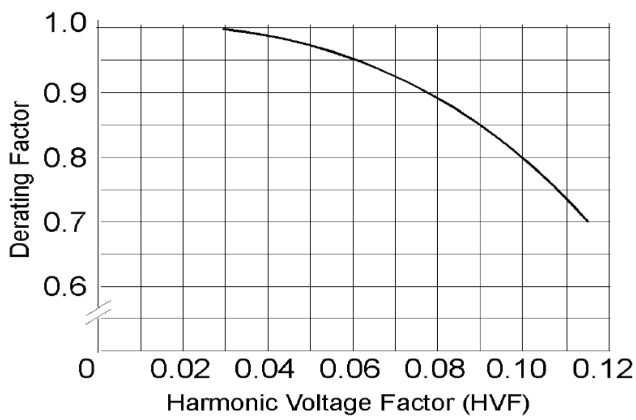


Fig. 7. NEMA Harmonic derating factor [6].

Agamloh et al. investigated the effect of Total Harmonic Distortion (*THD*) on the efficiency of a 10hp motor. Different than *HVF, THD* is defined as the square root of the sum of the squares of the amplitudes of all harmonic components, divided by the fundamental frequency. As the levels of V_{THD} rise, harmonic currents in the motor will rise as well, lowering the operating efficiency, as expected. However, the super-imposition principle cannot be applied because of nonlinearities. Assuming that a particular amount of distortion will add a certain amount of kW losses to a motor's operation, regardless of the load, would have led to a different graph than Fig. 8. Applying the superposition principle would have resulted in the distance between *negligible THD* and *12% THD* being reduced in proportion to the load. This research shows that motors running at higher loads are disproportionally burdened with additional heating caused by distortion.

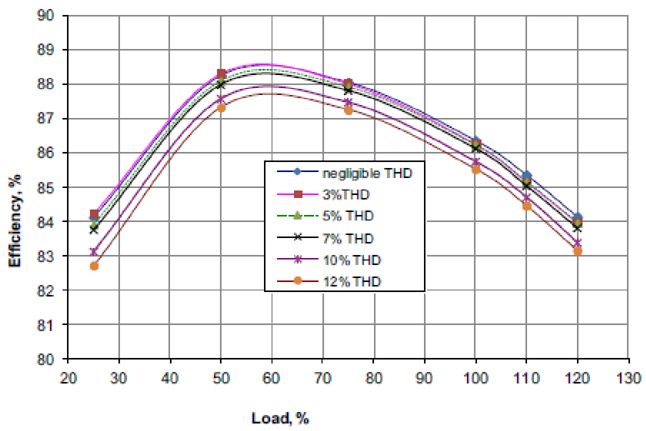


Fig. 8. Efficiency of a 10hp motor as a function of load for various amounts of THD [9].

B. Load

Agamloh compiled results of the "100-motor study" and evaluated the effect of partial-loading [2], where it shows that about a third of the motors were running with loads below 50% (Fig. 9).

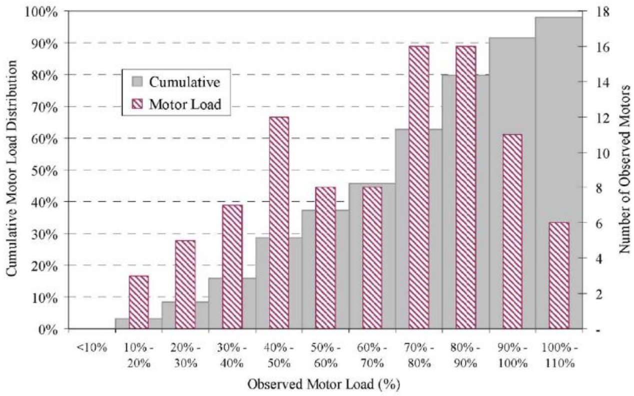


Fig. 9. Percentage of motors vs. load [%] – distribution of "100-motor study" [2]

It is well-known that a motor's efficiency changes as a function of load level. Fig. 10 shows an additional important fact: various motor designs have different shapes to their efficiency curves. The nameplate efficiency of Motor B is nearly one percent higher than Motor A, seemingly making it the better choice. Running at low loads, however, Motor A will outperform Motor B and its higher nameplate efficiency by a wide margin.

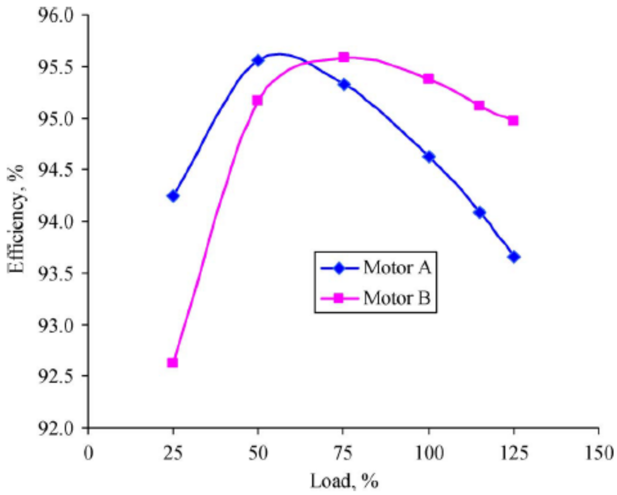


Fig. 10. Efficiency vs. load for two different 75hp 4-pole motors [2].

IV. INTERNAL VARIABLES – MOTOR CONDITION

This segment deals with a discussion of internal reasons about how the IM affects efficiency. First, it discusses differences in nameplate efficiency and the true efficiency of new motors in mint condition, and then it evaluates root causes that will affect each of the five losses.

A. Nameplate Efficiencies – Expected Accuracies

A typical unexpected source of inaccuracies in terms of efficiency resides in the difference between the nameplate efficiency of a particular motor and the true rated efficiency if that motor is tested in accordance with IEC 60034-2 or IEEE 112B.

[6] states in chapter 12.58.2 that "(efficiency) shall be identified on the nameplate by a nominal efficiency (…) which shall be not greater than the average efficiency of a large population of motors of the same design". This implies that a number of motors may have rated efficiencies below those shown on the nameplate. Furthermore, it requires that any motor's losses, under rated conditions, do

not exceed 120% of the losses as calculated by the nameplate efficiency. This means that a motor with a nameplate efficiency of 90% could have an efficiency as low as 88%.

B. I^2R_{stator}

Stator losses P_{I2Rs} are prevalent losses at high loads, and less important at low loads. While the motor's load point largely defines the magnitude of the current, the stator resistance is a result of the design of the motor. Most IE3 motors' R_s will be lower than comparable IE1 motors', hence contributing lower P_{I2Rs}.

Random-wound motors with a higher slot fill-factor will result in a lower stator resistance, thus a more efficient motor. Sometimes, it is possible for repairers to raise the slot-fill from the original machine-wound design resulting in a more efficient motor than the mint condition. However, it is also feasible that a low-quality repair will have lowered the slot-fill factor, raising the motor's stator resistance and lowering its efficiency [10]. Motor end-users should keep a database of their motors' R_s, to verify that P_{I2Rs} didn't rise as a result of a low quality repair. EASA's best practices require that "*The winding should maintain the same electrical characteristics as the original*" [11], while [12] goes further, stating that "*The resistance of the windings may not be increased*."

C. Friction and Windage

The $P_{F\&W}$ losses have two components: friction and windage. Friction losses are caused by bearings and – where used – friction from contacting seals. The choice of the highest class in bearing efficiencies can reduce the friction losses to half the value of standard designs, as depicted in Fig. 11 [13].

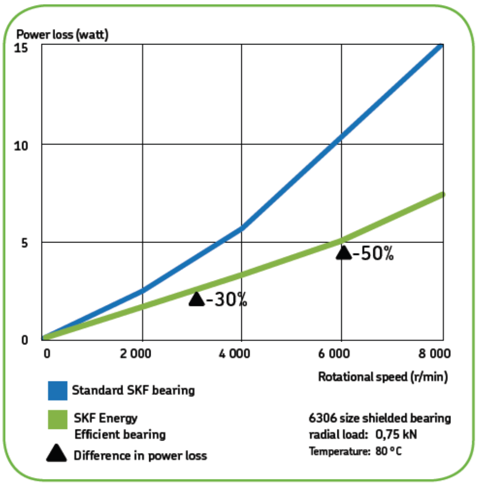


Fig. 11. Power loss simulation results for SKF Energy Efficient deep groove ball bearings compared to standard SKF bearings.

Over-lubrication and using the wrong lubricant are frequent problems in industry. In addition to raising bearing temperature, which results in reducing lubrication and bearing life considerably, this practice increases friction losses, thus lowering a motor's operating efficiency. Motor users' maintenance programs should include education and proper procedures to avoid this common problem.

Windage losses of higher efficiency motors are typically lower since higher efficiency motors produce lower losses, hence needing smaller fans to dissipate the heat.

D. Core Loss

Core losses of a motor in mint condition depend on the geometry of the stator, the quality of the steel and the thickness of the stator laminations. Core losses of a used motor may be significantly higher due to a variety of reasons. Laminations may be shorted due to previous rotor-rub or stator insulation failures, creating hotspots as depicted in the infrared picture in Fig. 12.

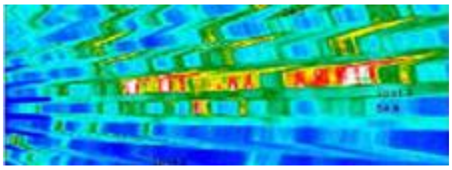


Fig. 12. Infrared picture of a stator bore during core-loss test showing multiple hotspots.

Another scenario that can raise core losses is a motor repair that used a burn-out oven without properly functioning temperature regulation. Overheating the stator laminations causes irreversible damage to the steel, increasing P_{core} significantly. Best practice repairs require the performance of two core-loss tests: One prior to repair, which assesses whether the core is in sufficiently good condition to warrant a repair at all. The second core-loss test is performed after repair, verifying that the core hasn't been damaged by the repair itself.

E. I^2R_{rotor}

Rotor conductive losses P_{I2Rr} are fundamentally a motor design issue. However, die-cast rotors may have porosity, or manufactured motors with multiple broken bars will run with higher slip, hence operate with higher P_{I2Rr} and at lower efficiencies. Care must be taken by the repairer when re-barring manufactured rotors to not change the rotor cage resistance R_r. Differences in R_r will result in either drops in efficiency, or in lower start-up torque capabilities.

F. Stray Load Loss

The stray load losses of a motor should not change significantly. Lathing the rotor and increasing airgap size is viewed as a bad repair practice. A larger airgap will change the stray load losses significantly, and also raise stator currents and P_{I2Rs}. A repaired motor with longer end-turn windings will have higher P_{stray}. Motor designs using magnetic wedges have become more common. Replacing magnetic wedges with non-magnetic ones will also raise P_{stray}. However, higher stray load losses due to motor repair are not a frequent problem.

V. OPERATING EFFICIENCY ESTIMATION METHODS

This part of the paper compares the most frequently used methods for obtaining an operating efficiency number. The shaft torque-speed method is the reference because it is not an estimation but correctly measures the operating efficiency. The efficiency estimation methods used in the field are called Nameplate, Slip, Current, Statistical, Airgap and Statistical-Airgap. They are discussed in terms of their accuracies and levels of intrusion. The last segment discusses a method by which the most accurate method, the Statistical-Airgap efficiency estimation method, can be further refined by performing an additional No-Load measurement.

A. Shaft Torque-Speed Measurement

The shaft torque-speed method is a direct measurement of the operating efficiency of a motor in the field. It requires the installation of a torque-speed transducer on the motor's output shaft, and taking data from this instrument in synchronicity with electrical input power to the motor. However, the high accuracy of this method is outweighed by the extremely high level of intrusiveness, as it requires installation of a torque-speed transducer for each motor to be tested.

B. Nameplate Estimation Method

This method is the most trivial, least intrusive and consequently usually also very inaccurate. It is based on the assumption that the machine nameplate is accurate (Fig. 10), that it always operates at nominal efficiency, regardless of loading (Fig. 9), voltage condition (Figs. 6 and 8), and that the motor is in pristine condition (see previous section of this paper "Internal Variables – Motor Condition"). These assumptions are unrealistic, rendering the Nameplate estimation method nearly useless for efficiency studies.

C. Slip Estimation Method

This method requires measurement of input power and speed. The efficiency is estimated as follows,

$$\eta_{est.slip}[\%] = \frac{P_{NP} \cdot slip[\%]}{P_{in}} \quad , \qquad (3)$$

where P_{NP} is the nameplate power of the motor, and P_{in} is the input power.

It assumes the percentage of output power of the motor is equal to the percentage of nameplate slip. Errors for this estimation method are caused by the condition of the rotor cage, voltage level and nameplate slip accuracy. The full-load slip of a motor with broken bars, or excessive amounts of porosity is significantly higher than the nameplate. Cages in bad condition will overestimate the output power, potentially leading to efficiency estimates higher than 100%. The torque-speed curve of induction motors is proportional to the square of the voltages. Voltage levels above 105% are preferred by many motor users, since motors tend to operate at lower temperatures under these conditions (Fig. 3). A 5% overvoltage will skew the operating slip-line upwards by 10%. A motor running with an efficiency of 92% will display an efficiency estimate of 82% if using the slip method. An additional source of errors from this efficiency estimate is the accuracy of the nameplate slip itself. Nameplate speeds are rarely equal to a motor's full-load speed. The accuracy of nameplate speed for [6] design motors only requires it to be within ±20% of the slip.

D. Current Estimation Method

The efficiency estimate using the current method has similarities to the slip method in that it measures the input power and estimates the output power based on one measurement – in this case the stator current.

$$\eta_{est.curr.}[\%] = \frac{P_{NP} \cdot curr.[\%]}{P_{in}} \quad , \qquad (4)$$

The most significant sources of error to the efficiency estimate using the current method are percentage load, nameplate inaccuracies, and voltage level.

An induction motor's current level while operating at low loads is significantly larger than the percentage load, as shown in Fig. 13. This effect will result in efficiency estimates far in excess of 100% for motors running at low loads.

The current-based efficiency estimate is also very susceptible to voltage level variations. Motors commonly operating at overvoltage conditions will result in a low efficiency estimate when running at high loads.

Nameplate current levels allow for inaccuracies since variability of identical motors can be significant. [6] allows for nameplate current to differ from full load by as much as 10%. This error will affect the load estimate to the same proportion, hence distort the efficiency estimate by up to 10%.

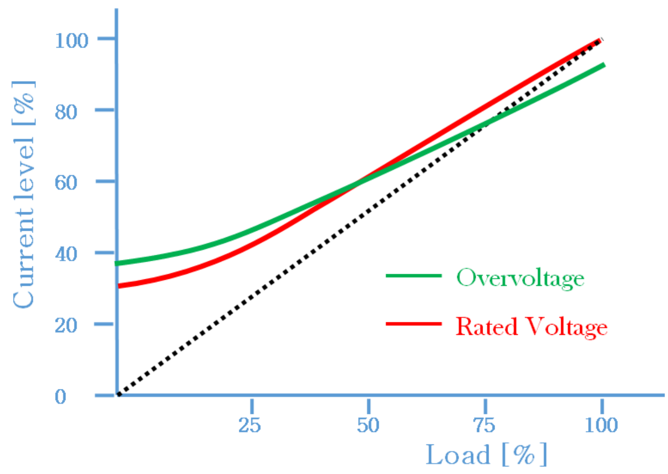


Fig. 13. Current level vs. load level for rated and over-voltage.

E. Statistical Estimation Method

Statistical methods combine measured data of IMs with empirical equations derived for groups of motors. An example of such a method is entering the measured stator current, operating speed and input power, and nameplate speed and current. The program has knowledge of typical stator resistances, friction and windage, core and stray load losses. Combining this data with empirical knowledge, the program estimates the operating efficiency.

Inaccuracies similar to those identified with the previous methods apply with this approach, since deviations of nameplate information compared with the actual performance of the machine are to be expected.

F. Airgap Torque Estimation Method

This method calculates an efficiency estimate resulting in an output power estimate divided by the input power measurement. The output power estimate results from the multiplication of speed times a torque estimate as shown in (5). The torque calculation utilizes (6), which has been implemented widely for VFD torque control of induction motors [14]. Stator resistance of the motor must be known.

$$\eta_{est.trq} = \frac{2 \cdot \pi \cdot T_{airgap} \cdot speed}{P_{in}} , \qquad (5)$$

$$T_{airgap} = \frac{3P}{4}(\lambda_d \cdot i_q - \lambda_q \cdot i_d) , \qquad (6)$$

T_{airgap} represents the airgap torque, P the number of poles of the motor, λ the instantaneous flux, i the instantaneous current and the subindices $_{d,q}$ the direct and quadrature axes according to Park's equations. Investigations by Hsu [15] and Kueck et al. [16] expect this to be the most accurate efficiency estimation method of the ones listed this far. Being nearly impervious to nameplate inaccuracies and calculating the airgap torque accurately even for variations of voltage level, balances and distortions, it is a far superior alternative to the previously mentioned estimation methods.

The airgap torque estimation method calculates P_{I2Rs} and P_{I2Rr} accurately, which are the prevalent losses at higher load points as seen in Fig. 2. The main error sources of this method are that $P_{F\&W}$, P_{core}, and P_{stray} are not accounted for. The resulting overestimation of operating efficiency is more severe, the lower the load of the motor, where the unaccounted $P_{const.}$ is prevalent.

G. Statistical-Airgap Method

Adding a statistical evaluation to the airgap torque estimation method enhances the accuracy of the efficiency estimation significantly, by including a knowledge-based estimate of $P_{const.}$ and P_{stray} as a function of motor rating, nameplate speed and voltage level. Adding current signature based speed measurements as published in [17] enhances field-friendliness significantly since physical proximity to the motor is not required any longer.

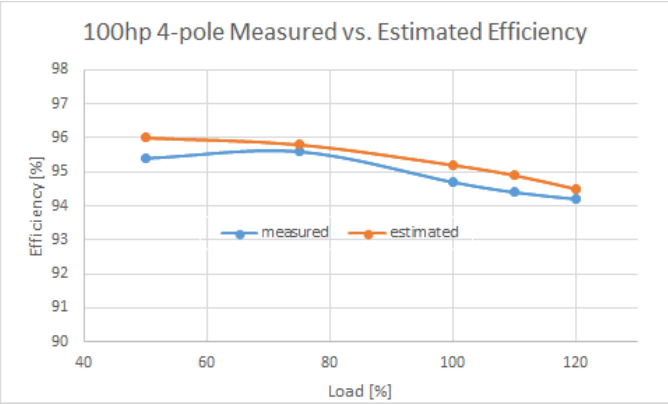


Fig. 14. Comparison of measured efficiency and Statistical-Airgap efficiency estimate vs. load for a 100hp motor.

These enhancements were introduced to the standard airgap efficiency estimation method, and are available as a commercial instrument [18]. The Northwest Energy Efficiency Alliance funded a major study of available efficiency estimation instruments which was performed on the dynamometer of the EPRI-funded Motor Systems Resource Facility. The report of the study is publicly available [19].

The results of this study showed that combining the benefits of the statistical method with the airgap efficiency estimate method leads to results that are significantly more accurate than using the airgap torque estimate alone. The executive summary of this study recommends that "*Based on accuracy, lack of intrusion, ease of use*" the instrument using the combined Statistical-Airgap method "*is the best overall choice.*"

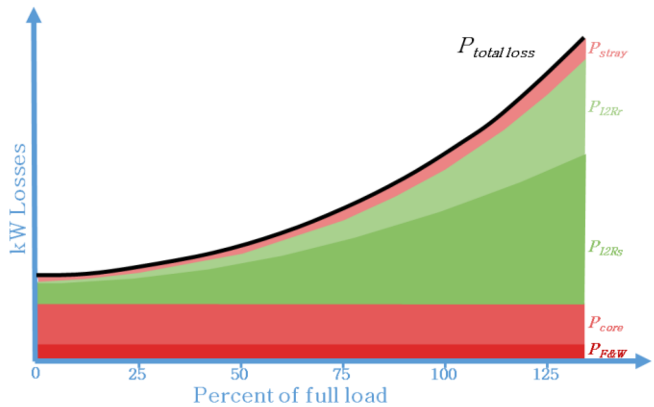


Fig. 15. Accurately considered losses (green) and statistically estimated losses (red) as a function of load for Statistical-Airgap estimation.

The green portions of the loss distribution vs. load of Fig. 15 display the losses that are calculated accurately with the Statistical-Airgap method. The losses in red are estimated based on statistical knowledge. The difference between a reasonable expectation for $P_{F\&W}$ or P_{core} and the real values for this particular motor is the main source of error for this method. Likely sources for these errors are enumerated in the Internal Variables section of this paper.

H. No-Load Corrected Statistical-Airgap Method

Refining the Statistical-Airgap method, which further diminishes the remaining inaccuracies, is achievable by adding a no-load (uncoupled) test to the preceding data. Under no-load conditions, P_{I2Rr} and P_{stray} are equal to zero. The no-load input power is equal to $P_{const.}$ plus the no-load P_{I2Rs}, which can easily be calculated out of stator currents and line-line resistances.

Subtracting P_{I2Rs} from the measured no-load input power P_{in0} results in an accurate P_{const} , as long as voltage unbalance and voltage distortion are small, leaving P_{stray} to be the only losses that are statistically estimated.

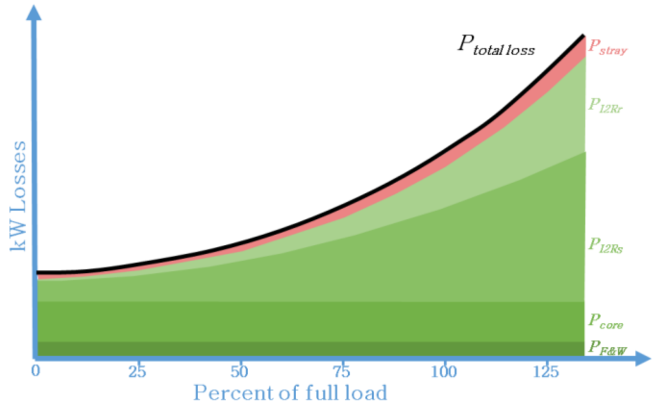


Fig. 16. Accurately considered losses (green) and statistically estimated losses (red) as a function of load for No-Load corrected Statistical-Airgap estimation.

This further refinement of what [19] calls the leading efficiency estimation method will significantly reduce the size of the remaining unknown losses. However, uncoupling a motor introduces a very high level of intrusion that is only rarely acceptable. One scenario where uncoupling is necessary is when a motor is about to be exchanged, for example, because it is suspected of being inefficient. In that case, it is advisable to uncouple first, measure the no-load losses and calculate the No-Load corrected Statistical-Airgap efficiency estimate. This will help verify that the decision to replace this particular motor is the correct one.

The main sources of inaccuracies of the No-load corrected Statistical-Airgap method are differences between P_{stray} of the motor compared to its statistical expectation, and additional losses introduced during the no-load test due to voltage unbalances and distortions.

VI. CONCLUSION

This paper analyzes areas that are required for successful efficiency-oriented motor management programs. Not only must motor nameplate efficiencies be considered, but also the factors internal and external to the motor that cause its operating efficiency to differ from its nameplate. Power quality and load impact the operating efficiency as well as a motor’s repair history and the plant’s maintenance practices. Furthermore, the paper discusses the requirements for measuring operating efficiency in the field and evaluates efficiency estimation alternatives, balancing their respective accuracies with their levels of intrusiveness.

Integrating these components into a high-quality, efficiency-oriented motor management program results in a list of requirements. The decision to exchange a motor for a more efficient one hinges primarily on the motor’s operating efficiency, setting a high bar for the accuracy of its measurement/estimation. Before making a decision of which method to employ, one must consider demands of minimum accuracies and allowable levels of intrusion. Evaluating how a motor’s power quality and load impact its capabilities is the next step. This requires education in motor efficiency matters, which must also include the benefits of implementing best practices for in-plant motor maintenance as well as for off-site motor reconditioning and repair. Optimal lubrication and alignment procedures need to be in place and verified to maximize a motor’s operating efficiencies. Efficiency-oriented motor management also requires the best results in motor reconditioning or repair. Close collaboration with the motor repair facility ensures that it upgrades standard-efficiency bearings with high efficiency ones and that it follows a minimum of best practices for motor repair [10]. An alternative to such an active partnership is a careful choice of the motor repair facility, trusting that third party certifications like [20] provide education to the repair facility and enforce higher standards which lead to consistent and superior quality.

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The effect of power quality on induction motor operation

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Abstract

Experimental tests were carried out to determine how induction motors operate under abnormal voltage conditions such as over voltage, under voltage, voltage unbalance, voltage distortion, single-phasing. The results for several motors are compared in terms of efficiency and over-current conditions and the motors ability to ride through the condition with minimal interruption. The differences in the performance of the motors are highlighted. The motors tested comprise integral horsepower three phase motors of EPACT and Premium design as well as single phase motors. It was verified that distortion levels of about 8%THD have negligible effect on the operation of both the integral and single phase motors. Modest amounts of voltage unbalance and momentary single-phasing conditions can also be tolerable under certain conditions.

Introduction

Induction motors are often subjected to power quality issues that are inherent in industrial power supplies. It is known that adverse power quality (PQ) conditions detrimentally affect the performance of induction motors. Several papers have been published that discuss the effect power quality abnormalities such as voltage unbalance, under-voltage and over voltage, voltage distortion on the operation of induction motors. Recently, there has been an increasing discussion on transforming the transmission grid into an intelligent or smart grid. The ultimate goal of smart grid is to improve reliability of electric energy delivery and usage. Several techniques have been proposed by different stakeholders to look at specific aspects of the problem. Some of these techniques being applied or considered under the smart grid concept include conservation voltage reduction (CVR) [1] and single-phase reclosing. These techniques would have unintended power quality effects on the operation of induction motors.

This paper presents an overview of power quality effects on induction motor operation. Experimental results and analysis are presented to quantify the effects of voltage abnormalities, distortion and single-phasing of induction motors in a smart grid environment. The PQ investigations relate to both EPACT and Premium motor designs. (For reference, EPACT stands for Energy Policy and Conservation Act – the 1992 law that mandated minimum efficiency standards for certain induction motors sold in the US. Efficiency levels for EPACT can be found in NEMA MG-1 Table 12-11 and Premium efficiency levels are in Table 12-12 [2]). A derating factor is suggested to mitigate the major power quality abnormalities.

Smart Grid and End-use Power Quality

Conservation voltage reduction (CVR) is a technique that is employed by electric utilities to reduce energy consumption of loads by reducing the voltage of distribution feeders. A recent study that assessed the impact of CVR reported that up to 3% reduction in energy is achievable on a national scale in the United States [1]. The CVR techniques are becoming more important in the era of smart-grid and a number of utilities have at one point in time implemented this. Since voltage is reduced to the load induction motor loads are affected.

Another technique under the smart grid concept is the use of automatic reclosers. Under smart grid, there is an increasing tendency to interrupt and reclose only lines that are faulted and to ensure that un-faulted phases remained operational. This means that three phase loads on distribution feeder such as induction motors are subjected to single-phasing, during the operation of these devices. Although the effect of sustained single-phasing is discussed in literature, momentary interruptions caused by recloser operation are inherently different and their effect on motor operation needs to be evaluated.

In addition to the above mentioned techniques from the utility perspective, there are other influences on power quality from the utilization perspective such as increased penetration of non-linear loads that create significant voltage distortion. Distortion in the power supply of induction motors can cause adverse operational problems.

Power Quality Abnormality Definitions

A. Voltage Unbalance

There are different types of voltage unbalance and they have been well defined in literature. The most useful definition is in (1):

$$V_{un} = \frac{max\ \left(\left|V_{ab} - V_{avg}\right|, \left|V_{bc} - V_{avg}\right|, \left|V_{ca} - V_{avg}\right|\right)}{V_{avg}} \times 100 \qquad (1)$$

where V_{unb} is the percentage voltage unbalance, V_{ab}, V_{bc}, V_{ca} *are line voltages and* V_{avg} is the average of the three line voltages. Another definition in terms of the negative and positive sequence voltages is given by:

$$V_{unf} = \frac{V_2}{V_1} \times 100 \qquad (2)$$

where V_{unf} is the voltage unbalance factor, V_1 is positive sequence voltage, V_2, is the negative sequence voltage. In (2) if the voltages V_1 and V_2 are expressed with their phase angles, the ratio becomes the complex unbalance factor.

B. Voltage Distortion

Voltage distortion is a consequence of time harmonic content in the power supply, which causes harmonic voltages, currents, harmonic fields and torques that are present alongside their fundamental quantities. Some of the harmonic voltages (such as harmonic orders 5, 11...) have phase sequence opposite to the fundamental and they create fields that rotate in the opposite direction to the fundamental field while those with the same phase sequence as the fundamental (such as 7, 13,...) create fields that rotate in the same direction as the fundamental. The zero sequence harmonics are also known as the triplen harmonics and they do not create rotating fields in the motor as their components are all in phase and cancel out in a typical star connected three phase system.

The total harmonic distortion (THD) and harmonic voltage factor (HVF) can be used to describe and quantify voltage distortion. The THD is defined as:

$$THD_V = \sqrt{\frac{\Sigma V_h{}^2}{V_1{}^2}} \times 100\%, \quad h = 2, 3\ldots \qquad (3)$$

where V_1 is the fundamental voltage and V_h is the harmonic voltage and the HVF is also defined as [2]

$$HVF = \sqrt{\sum_{n=5}^{n=\infty} \frac{(V_n)^2}{n}} \qquad (4)$$

C. Single Phasing

Single-phasing is a term attributed to a condition where one phase of a three-phase system is opened either on the source side or load side. The loss of a phase could be caused by, among other things, a blown fuse, damaged switchgear, bad contact, open cable, bad cable terminal lug, etc. With respect to the transformer that feeds the load, two types of single phasing can be distinguished – primary and secondary single-phasing, with the latter presenting a more severe condition in terms of the high currents that flow through the motor load. In general, the loss of a phase in a three phase system is an extreme form of voltage unbalance.

Experimental Setup to Investigate Power Quality Effects

The experimental setups used to investigate various power quality effects are provided below in the subsequent subsections. More detailed descriptions can be found in [3]-[5].

A. Voltage Magnitude Deviation and Unbalance Test Setup

The setup used to investigate voltage magnitude deviations is shown in Fig 1. The test motors were set up, aligned and loaded with a dynamometer until the temperature of the motor did not change by more than 1^0C within a 30 minute period. After the stable temperature was achieved, different levels of voltage deviations were applied with the help an auto transformer.

Fig 1: A 1hp motor setup to investigate unbalance effects

TABLE I
Line Voltages for Unbalance at 460V

Target Unbalance, %	1.00%	1.50%	2.00%	2.50%	3.00%	3.50%	4.00%	4.50%	5.00%
Voltage 1 (V)	457.7	456.6	455.4	454.3	453.1	452	450.8	449.7	448.5
Voltage 2 (V)	457.7	456.6	455.4	454.3	453.1	452	450.8	449.7	448.5
Voltage 3 (V)	464.6	466.9	469.2	471.5	473.8	476.1	478.4	480.7	483
Average Line Voltage (V)	460	460	460	460	460	460	460	460	460

The tests were based on the utilization voltage and deviations from the nominal utilization voltage of the electric motors. The motors investigated were subjected to abnormal voltage conditions within ±10% of their nominal rating in 5% step increments. For a 460V nominal motor voltage, the test points were 414V, 437V, 460V, 483V and 506V. In addition to the voltage magnitude variations, voltage unbalance from 1% up to 5% in 0.5% increments was also introduced. Table 1 shows the applied line voltages for the nominal 460V condition for various unbalances ranging from 1% to 5%. Similar tables of applied voltages were developed for 414V, 437V, 483V and 506V. Therefore the test motors were subjected to a combination of under/over voltages and unbalance.

The tests for voltage deviations were completed with four motors - two three-phase 50hp motors, one of which is energy efficiency design and the other is premium efficiency design; and two three-phase 1hp motors, one of which is energy efficiency design and the other is premium efficiency design.

B. Voltage Distortion Test Setup

The setup used to investigate voltage distortion sought to evaluate distortions ejected into the power supply by a variable frequency drive (VFD) source. The main setup consisted of a 50hp motor connected to a VFD and a line reactor. This 50hp motor system served as the source of injection of harmonics onto the bus of the test motor, which is connected to the same bus. The loading on the 50hp injection motor was varied to change the levels of harmonic content and voltage THD from under 2% to approximately 8%. Thus the injected harmonics would mimic a practical scenario in a plant, where a larger motor operating with a VFD may be injecting harmonics onto a bus on which a line connected motor is operating.

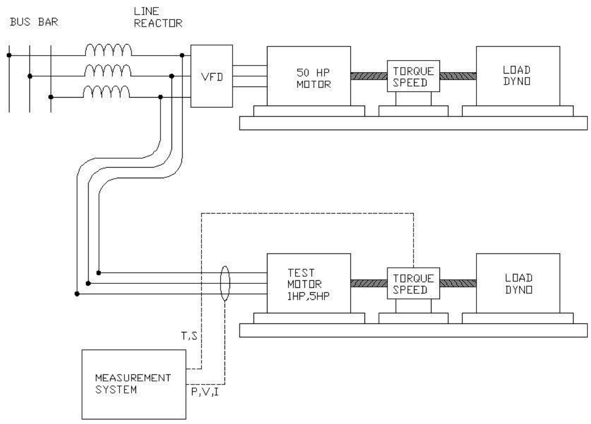


Fig 2: A test setup to investigate voltage distortion effects

Fig 2 shows the primary test setup used for the tests and Table II shows the spectrum of the injected harmonics, indicating the measured voltage THDs achieved with the 50hp injection motor carrying the loads specified in the Table.

TABLE II

HARMONIC VOLTAGES AT 460V

Harmonics Order	Magnitude, V			
1	458.7	458.8	458.0	457.3
3	2.9	1.5	1.1	0.8
5	5.3	14.9	25.6	28.2
7	2.6	8.6	9.1	10.2
9	0.7	1.2	0.3	0.5
11	3.5	9.3	14.8	15.9
13	3.3	6.5	10.8	12.0
15	0.2	0.8	0.6	0.4
17	1.5	5.1	5.8	6.4
19	0.7	4.3	5.9	6.3
21	0.0	0.4	0.9	0.6
23	0.4	3.5	4.3	4.4
25	0.1	3.3	5.1	4.9
Total THD-v, %	**1.8**	**4.9**	**7.5**	**8.2**
50hp Injection Motor Load, %	**0**	**50**	**100**	**115**

As shown in Table II, the 5th harmonic had the highest magnitude but the 7th, 11th and 13th also have reasonable magnitudes.

The tests were conducted after motors achieved thermal stability. After thermal stability was achieved the harmonic injection motor was loaded to specified loads corresponding to approximately 2%, 5%, 7.5% and 8% THD levels and the data points were taken. The tests motors for this setup include two 5hp motors and two 1hp motors, of which each rating is made up of one premium efficiency design and an energy efficient design. Three single phase motors were also tested. They include a 0.25hp permanent split capacitor motor, a 1hp capacitor start induction run motor and 1.5hp double capacitor motor. The selection of the polyphase motors was partly based on what is readily available in the laboratory, with the only criteria being that one be premium efficiency and the other standard efficiency of the same rating. The single-phase motors were also selected based on availability, with the criteria that each basic configuration type is included in the investigations.

In addition to the setup described in Fig 2, this paper includes results of another setup, whereby the test motor was supplied with power from a programmable power supply with predefined harmonic content; only the 5th and the 7th order harmonics were included in the spectrum. The test motor for this test was a 10hp 4-pole motor.

C. Single-phasing Test Setup

The general schematic of the test setup to investigate single-phasing is provided in Fig 3. The induction motor under investigation, M1, is connected to the power source through a distribution transformer. The three types of transformer connection for the primary and secondary windings used for the investigations are indicated in Fig 3. Also, the typical Y (Wye) and Δ (Delta) connections of polyphase induction motors was investigated. The goal of the tests is to determine conditions under which a motor is able to ride through single-phasing.

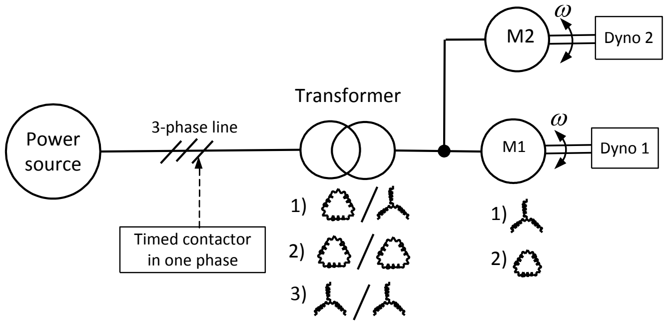


Fig 3: General schematic to investigate single-phasing

The test motors for this setup include a 1hp, 2hp, 5hp and two 10hp motors. The test motors have different winding connections (Y or Δ). As shown in Fig 3, a second motor, M2 is connected on the same bus, in some experiments to investigate grouped single phasing. The test motor is loaded while the power supply line of the motor is interrupted from the primary side of the transformer, in order to simulate single-phasing. A Labview data acquisition system was programmed and used to pulse a contactor to open and close during operation of the motor. The contactor initially opens and after 0.2s the contactor closes momentarily for about 50ms and re-opens. After 10s, the contactor is again momentarily closed and re-opened and finally the third operation is carried out after 13s. The 50ms duration of the pulse for closing the contactor was chosen to simulate the condition that clearing the fault was unsuccessful. This operation sequence (0.2s-10s-13s) is typical sequence used in a utility distribution system.

Results of Voltage Deviations and Unbalance Tests

The experimental results for the voltage deviation tests are discussed in the following subsections.

A. Voltage Magnitude Deviation

Fig 4 shows the response of 50hp motors to over/under voltage conditions and Fig 5 shows a similar plot for the 1hp motors. These tests also serve as the baseline test for each motor for the purposes of comparing with unbalanced voltage operation. The baseline test was done by loading the motor at full load with a dynamometer and changing the applied voltage to a specified level while the loading of the dynamometer remained unchanged.

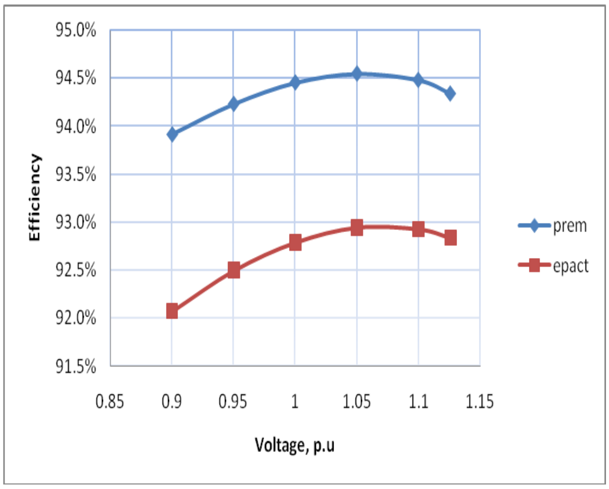


Fig 4: 50hp motors voltage magnitude deviation test

In general, the efficiency dropped at lower voltages and increased at higher voltages. The 50hp premium and EPACT motors were both most efficient at voltages at approximately 1.05pu. Beyond this point the efficiency started to drop. The key difference in the characteristics is that, while the 50hp premium motor efficiency changed by approximately 0.5% point within the range from 0.9pu volts to the 1.05pu volts, where the peak efficiency was attained, the 50hp EPACT motor changed by nearly 1% point in the same interval. This means overvoltage condition may be relatively more beneficial, in terms of energy efficiency, to the EPACT design than the premium motor. On the other hand it can also be said that the EPACT design is less tolerant to under voltage conditions than the premium, as the latter maintained a relatively flat efficiency profile even during under voltage conditions.

The trend described above is also followed by the 1hp EPACT motor. However, the efficiency of the 1hp premium motor showed a different characteristic as shown in Fig 5. The efficiency of this motor was fairly flat for the under voltage condition up to about rated voltage, and then efficiency dropped after that point. Note that one differentiating feature of this motor is that it is a die-cast copper rotor motor while all other motors are of aluminum rotor construction. Additional tests are required to further characterize this motor in order to determine if the observed characteristic was due to the rotor construction or otherwise. According to the result obtained it can be seen that the 1hp copper rotor premium motor can tolerate up to 10% under voltage without drop in efficiency. However, it has a more drastic drop in efficiency during overvoltage conditions. On the other hand, in terms of the impact on operational efficiency the EPACT 1hp design may be more tolerant to over voltages and less tolerant to under voltages.

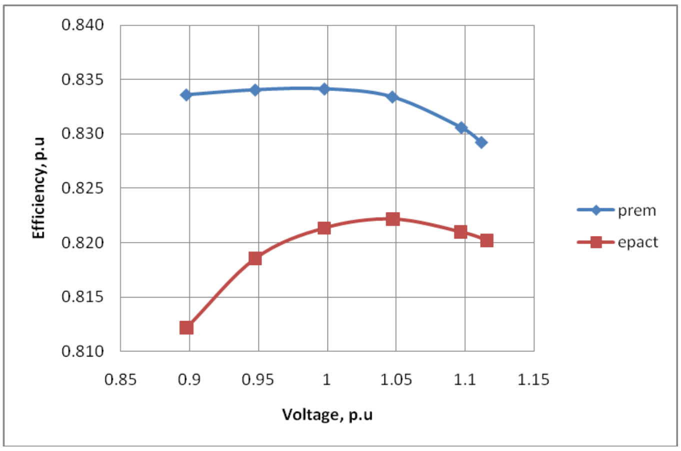


Fig 5: 1hp motors voltage magnitude deviation test

B. Voltage Unbalance

In the voltage unbalance tests the motors were operated on different combinations of over voltage and under voltage according to values that were defined *apriori* (an example is in Table 1).

Fig 6-9 show the efficiency profile of 50hp and 1hp EPACT and premium motors to unbalanced operation with over/under voltage conditions. The efficiency of all the motors decreased with increase in unbalance. Also, unbalance levels of up to 1.5% have negligible effect if the motor is operated at rated voltage. Furthermore, for unbalance up to 5% the motor efficiency generally reduced by about 1 to 3% with the lower end being applicable to the premium motors while the upper end is attributable to the EPACT motors.

For a given unbalance operating at a higher voltage level (nominal voltage and above) tends to give a better efficiency performance (flatter profile) than operating at a lower voltage level (below nominal voltage). This observation may not hold true for the copper rotor motor. Further investigations are required for the copper rotor motor in order to confirm its behavior.

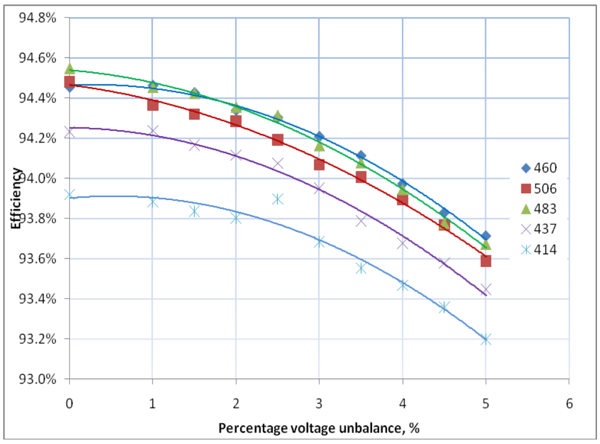


Fig 6: 50hp Premium motor eff. versus unbalance

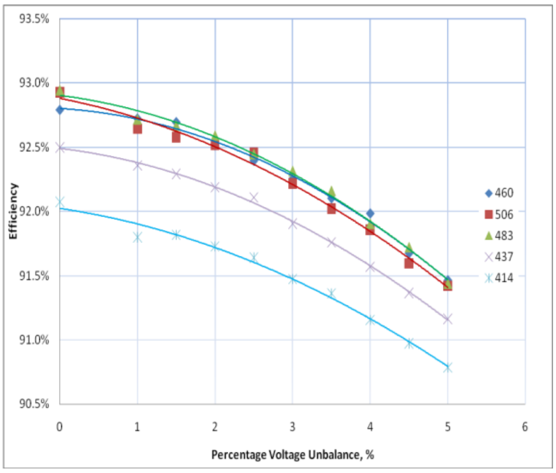


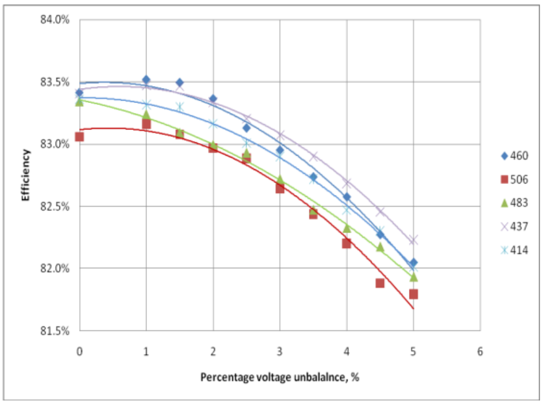
Fig 7: 50hp Epact motor eff. versus unbalance

Over Current Effects

The primary effect of the unbalance is the high current in some phases of the motor that may cause additional joule losses and heating effects on motor operation. The maximum per unit current in a phase during unbalance operation was calculated per (3) to demonstrate this effect:

$$I_{pu} = \frac{max\ (I_a,\ I_b,\ I_c)}{I_{FL}} \qquad (3)$$

where I_{pu} is the per unit current, I_a, I_b, I_c *are line currents and* I_{FL} is the nominal (full load) motor current. The plots of per unit current are shown in Fig 10-11. The plots of per unit current for the higher voltages generally coincide with that of the nominal 460V. From the efficiency standpoint, it can be observed that up to 5% unbalance could be manageable if the user would tolerate the associated 1-3% points degradation of motor efficiency. However, the unbalanced currents in one or more phases may exceed desired values. If the maximum per unit current allowable is taken as 1.25 pu, then several conclusions can be drawn. For example, with an under voltage of 414V, only approximately 3% unbalance can be tolerated. In fact, in the case of the 1hp motors, the maximum unbalance that can be tolerated for even the nominal voltage level is approximately 3.5% for the EPACT motor and 2.5% for the Premium motor.



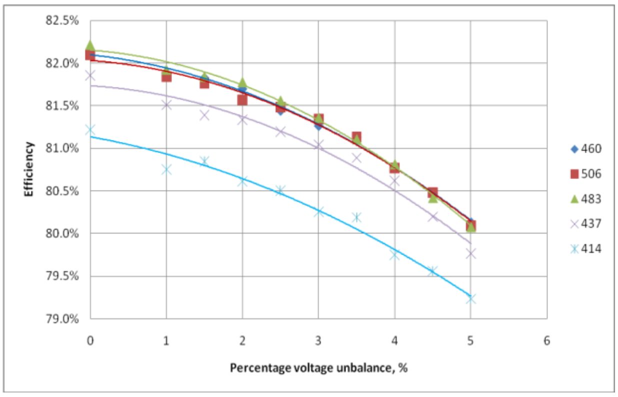
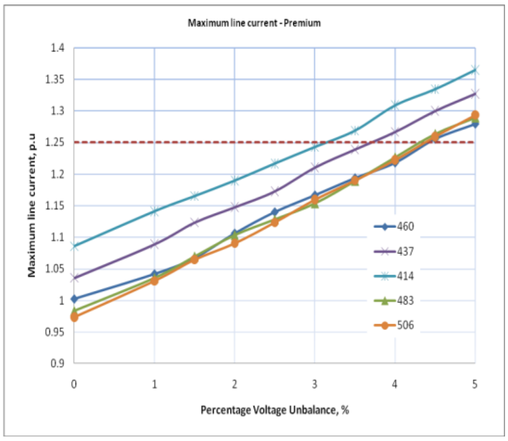


Fig 8: 1hp Premium motor eff. versus unbalance Fig 9: 1hp EPACT motor eff. versus unbalance

The maximum allowable current was set at 1.25 p.u, because this value is often used in the sizing of motor separate overload device, according to the NEC 430.32 A(1) for most standard motors [6]. For other non-standard motors, a more stringent value of 1.15pu is applied in the code. This means that practically no voltage unbalance could be tolerated for such motors during under voltage conditions without tripping the motor protective overload devices. However, if the motor is operated at a reduced load, say 75%, the per unit current is much less.



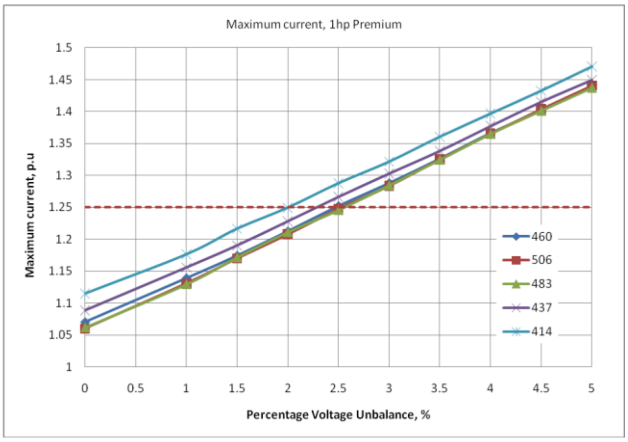


Fig 10: 50hp Premium motor max. line current Fig 11: 1hp Premium motor max. line current

Derating

It has been suggested that when motors are operating under unbalanced conditions, they must be de-rated in order to mitigate the undesirable effects. NEMA MG-1 [2] provides a derating curve for motors operating under unbalanced voltage conditions. Several other approaches for derating have been suggested, including derating based on current, loss, heating. The two main practically useful approaches for derating are current approach and horsepower approach. In the current approach, a limit is placed on the full load current, while in the horsepower approach, a limit is placed on the horsepower.

During the voltage unbalance tests, current based derating was investigated. The motor load was reduced to ensure that the unbalance did not result in current in any phase that exceeded the rated full load amperes (FLA). The ratio of the resulting shaft horsepower to the nominal is considered as the derating factor. Fig 12 depicts the motor derating with a limit on motor amperage and the NEMA derating curve side by side. As shown in this figure, the derating with a limit on motor amperage results in a lower curve than the NEMA curve and is linear from zero to five percentage unbalance. As shown in Fig 13, with the motor amps limited to the nominal current, the motor efficiency is slightly higher than it would have been without a limit imposed on the motor amps. The slight increase in efficiency may be explained by the absence of the additional overheating produced in the phases with excessive currents created by the unbalance.

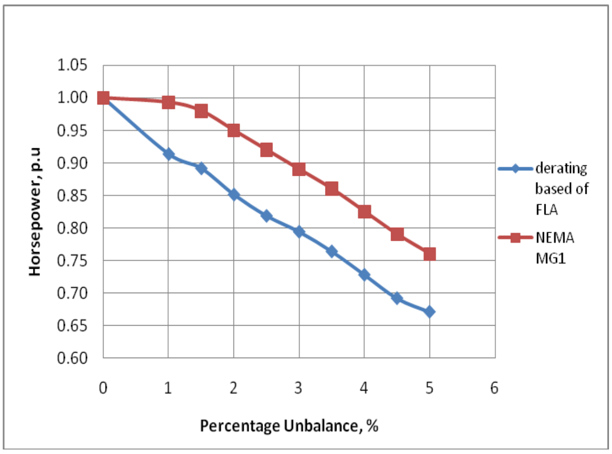


Fig 12: 50hp Premium motor derating

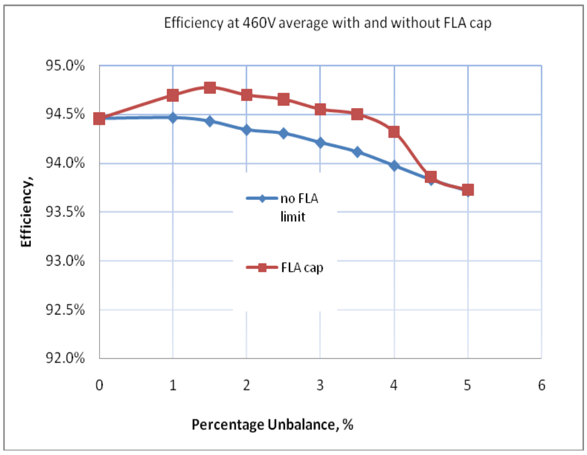


Fig 13: 50hp Premium motor derating efficiency

It should also be noted that the above means of de-rating tends to under load the motor, as restricting the maximum current to nominal in the highest phase might lead to significant reduction in other phases and underutilization of the machine.

Results of Voltage Distortion Tests

A. VFD Injected Harmonics

Figs 14-15 show a plot of motor efficiency as a function of voltage THD for the 5hp premium and the 1.5hp double capacitor single phase motor. In all cases, it is evident that the efficiencies remain fairly flat and that the voltage distortion levels of up to 8% had a negligible impact on the efficiency. As shown in the plots, the 8% THD point appears to be the point where the efficiency begins to drop slightly.

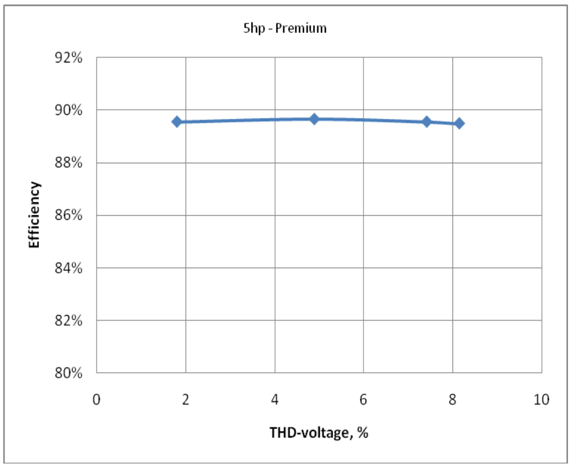


Fig 14: 5hp Premium motor efficiency vs THD

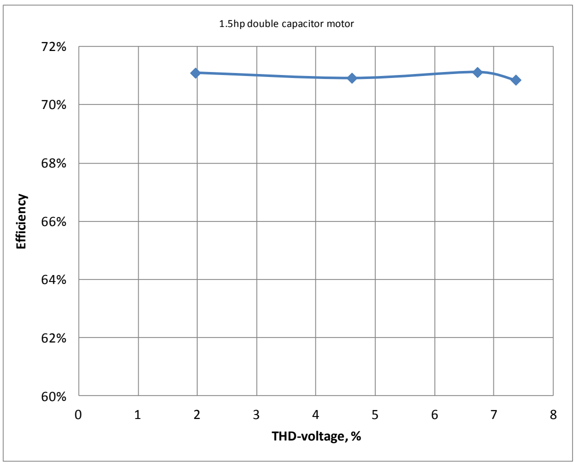


Fig 15: 1.5hp 1-phase CSCR motor efficiency vs THD

The trend reported in Fig 14-15 are typical for all the cases investigated. In particular, all the single-phase motors, including the permanent split capacitor, double capacitor and capacitor start induction run motors behaved identical way as the integral horsepower motors. It can be conclusively stated that levels of THD up to 8% have minimal effect on the motor efficiency of single phase and three phase motors. Furthermore, there is no noticeable difference between EPACT and premium efficiency motors with respect to their performance with voltage distortion. Within the distortion levels up to 8% injected from VFD sources, the efficiency of the motors did not change and it is hereby also implied that steady state thermal conditions of these motors would likewise be unchanged.

B. Harmonics from Programmable Power Supply

In the test with programmable power source, THD levels up to 12% were injected into the power supply of the induction motor. The motor losses were segregated using the IEEE 112B. Additional details can be found in [4]. Fig 16 shows the full load efficiency as a function of THD. In this plot, it is seen that the efficiency barely changed within the range of 0 to 7% THD, but rapidly began to change at 10% and 12%. This finding is totally consistent with the tests with VFD injected harmonics.
The stray load loss (SLL) of the motor for various THD levels is presented in Fig 17. It is worth to note that noticeable differences occur only at higher loads. Also, while the 10% and 12% THDs have higher SLL than the lower THD levels, there is no clear distinction for the lower THDs. Interestingly, the 7% THD has the lowest SLL. Although additional losses associated with the time harmonic currents may affect the value of the SLL, it is apparent that the trend observed here may be due to the consideration of SLL as a residual loss rather than the effect of voltage distortion. There is no evidence in the findings to conclusively suggest that up to 8% THD, the value of the SLL is dependent on the distortion.

Regarding the conventional losses, it was observed that they increased as the THD level increased although the increase was modest for the lower THDs with gradual build up towards the 12%. The friction and windage losses remained constant.

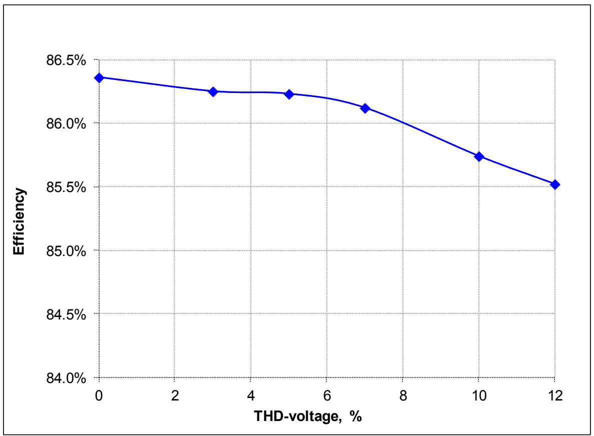


Fig 16: Efficiency of 10hp motor with %THD

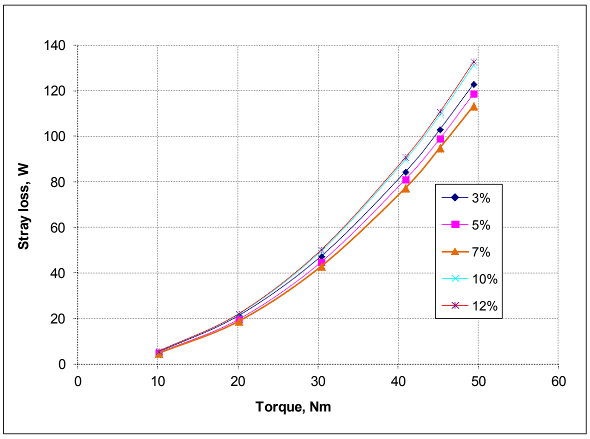


Fig 17: Stray loss of 10hp motor with %THD

Results of Single-phasing Tests

In this section some results of motors subjected to the single phasing sequence of 0.2s-10s-13s are presented. Some of the motors investigated stalled under certain conditions and did not stall under other conditions. Other motors did not stall at all under any condition. None of the motors stalled when subjected to the first operational sequence of 0.2s. This means that motors on a feeder would not be adversely affected if the recloser is able to successfully reenergize the feeder during the first operation. Other factors affecting motor operation during single phasing are reviewed below.

A. Effect of Motor Load on Single-Phasing Ride Through

In general, at full load, some motors stalled while others did not stall. However, at 75% load and below, none of the motors stalled. This indicates that lightly loaded motors could potentially ride through the single phasing condition described above.

Fig 18-19 show the 5hp and 1hp motors speed versus time plots during single-phasing. Although the 5hp motor stalled at full load, it was able to ride through the 50% load point. For the 1hp motor which did not stall at any condition, the dip in speed reduced as the load reduced.

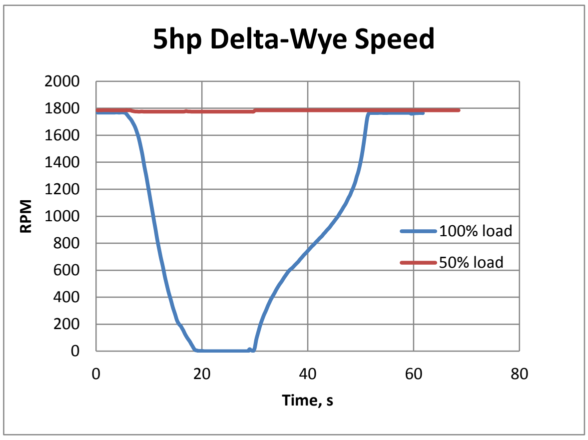


Fig 18: 5hp motor speed during single-phasing

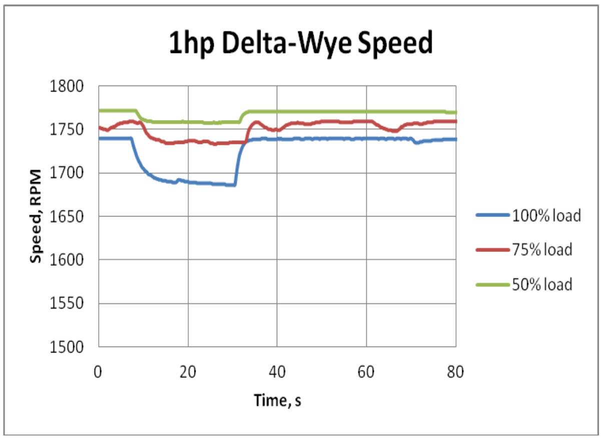


Fig 19: 1hp D-Y speed with load: 0.2s-10s-13s

The dependence on loading conditions of the motor can be explained from two points of view. During single-phasing the ability of the motor to develop the required torque to match the load torque is hampered due to changes in mmf and flux distribution in the machine. Three phase sources enable the motor to draw three phase currents to develop a rotating magnetic field while single phase currents produce a pulsating magnetic field. The loss of a phase disturbs the flux distribution in the motor and diminishes its ability to develop the necessary torque. Also, as mentioned previously, the voltage unbalance created as a result of the loss of phase can be resolved into positive and negative sequence voltages and there are fields associated with the sequences. The negative sequence torque counteracts that of the positive sequence, leading to overall reduction of the motor torque to match the load. Therefore, the loading of the motor is critical during single phasing.

During single phasing, in an attempt to generate enough electromagnetic torque to match the load, the currents in the motor significantly increased. The current profile during single phasing of the 1hp motor is shown in Figs 20 -21 for the D-D and D-Y transformer connections. These current profiles are typical for other motors on the same transformer connection. Theoretically the currents that are above nominal are at least 2pu. On the other hand, the D/Y connection produces currents in the secondary phases that are all higher than the nominal current. One of them is at least 2pu of the nominal or higher. Analytically, the magnitudes and phases can be determined using the method of symmetrical components and sequence impedance networks as can be found in literature.

The high currents lead to sharp rise in the temperature of the motor. In particular, the large negative sequence currents produce heating that is associated with single phasing. Throughout the experiment, the change in temperature did not exceed 10^0C above the temperature of the motor at the time of the single phasing.

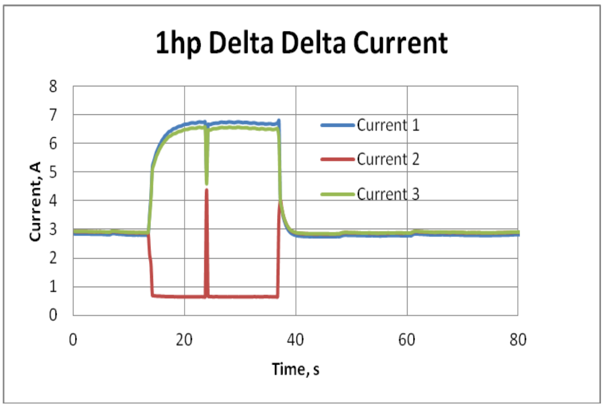


Fig 20: 1hp D-D current 0.2s-10s-13s

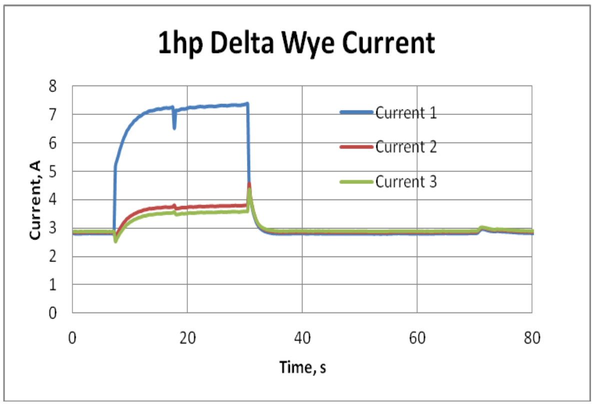


Fig 21: 1hp D-Y rms current 0.2s-10s-13s

B. Effect of Transformer Connection on Single-Phasing Ride Through

Next to the dependence on load, the transformer connection has a profound impact on the ability of a motor to ride through and not stall during recloser-induced single phasing. Fig 22 shows the speed of the 10hp Delta motor on full load during single phasing. It can be seen that the speed dipped slightly for the case of D-D connection but the motor totally stalled in the case of D-Y transformer connection.

For the 5hp motor, although the motor stalled under both D-D and D-Y transformer connections some differences in the characteristics are evident in Fig 23. In this figure the primary difference is on the motor starting profile, as the motor accelerates from stall conditions at the end of the complete cycle. The motor connection appears to be an influencing factor in this case and will be discussed in the next section.

All other things being equal, it can be suggested that the motors operating on D-Y connected transformer tend to be more susceptible to stall during the reclosing cycle than those on the D-D connected transformer. This is especially true if the motor has Delta connected windings, since as we shall note in the subsequent section, Y connected motors are relatively more vulnerable to single-phasing.

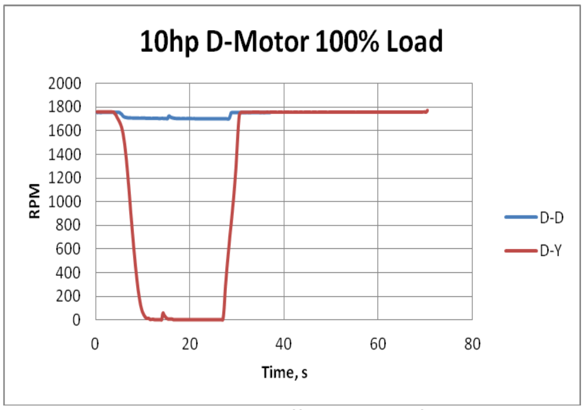


Fig 22: 10hp D-motor on different transformers

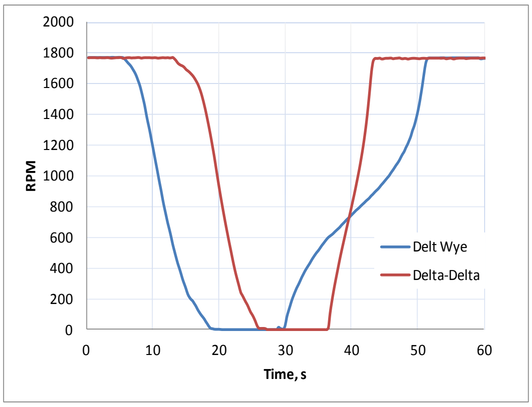


Fig 23: 5hp motor speed during single-phasing

The influence of the transformer connection can be explained from two perspectives; first by observing the current profiles in Fig 20-21 and also from the interaction of phases during the phase loss. During single phasing the high currents in the phases produce significant voltage drop that diminishes the voltage available to develop torque. Since motor torque is proportional to the square of voltage, this situation is even more severe for the Y connected motor, where the voltage across the winding phase is lower and voltage drop is high. In addition, the Delta connection has the property of electrically interconnected phases and during the loss of one phase, there is a possibility to "recreate" the lost phase through voltage division, even if the resulting voltage is much lower in magnitude. With the Y connection, such opportunities are limited, although the chances are fairly high, when phase to phase loads, such as motor loads are connected.

C. Effect of Motor Connection on Single-Phasing Ride Through

It appears that the stator winding connection of the motor affects the stall conditions for a given transformer connection. The 1hp and 2hp motors did not stall under any of the conditions tested. On the other hand the 5hp motor stalled on both transformer connections as shown in Fig 23. It must be noted here that both the 1hp and 2hp motors have Delta connected windings while the 5hp motor had a Star connected winding. Also at full load, the 10hp Y- motor and 10hp D-motors both stalled under the D-Y transformer connection. However, on the D-D transformer connection the 10hp Y-motor again stalled, while the 10hp Delta connected motor did not stall.

Having already noted, that the D-D transformer connection tends to be more favorable for a motor to ride through recloser operation, it is important to remark that all Y-connected motors (5hp and 10hp-Y) stalled under full load on this connection while all the D-connected motors (1hp, 2hp, 10hp-D) were able to ride through without stalling. It can therefore be concluded that the Y-connected motor is more susceptible to stall during single phasing. Here again, the tendency of the Delta connected motors to ride through the recloser single phasing can be explained by the enhanced capability of the Delta to develop relatively higher torque during single phasing.

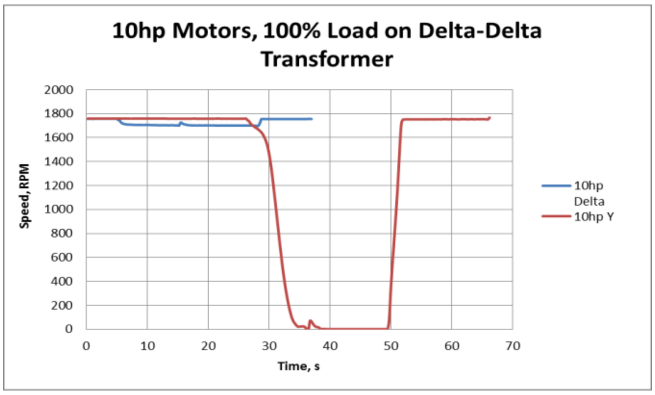


Fig 24: 10hp Y and D motors on D-D transformer

D. Summary on Single-Phasing Ride Through

A loss of phase does not necessarily make the voltage of the affected phase zero. However, in order to compensate for the lost phase, other phases must carry higher currents, thereby creating voltage drop which further reduces the voltages, increases slip leading to further increase in current of the healthy phases. Through back feed interactions from the connected load, in this case the back emf of the motor, the phase voltages of the affected phase can be re-energized in such a way that a phase angle is sustained with the other phases. In that case, the affected phase voltages do not collapse into phase and the motor does not stall. The motor stalls when the voltages of the affected phase are forced into phase. It was observed that the factors that determined whether a motor stalled include the reclosing cycle (or open duration), load the motor is carrying, the motor winding connection, transformer connection and whether there is a secondary motor connected in parallel. It must be noted that in all cases, none of the motors stalled when subjected to the first operational sequence of 0.2s. This means that motors on a feeder would not be adversely affected if the recloser is able to successfully reenergize the feeder during the first operation.

Derating of Motors for Power Quality Conditions

The derating of motors during adverse power quality conditions is often suggested. Various methods are applied in industry. From the foregoing experiments it appears that when the motor carries a load of 75%, it is able to ride through single-phasing without adverse effects. With a load of 75%, per unit current during voltage unbalance will be within normal limits. Therefore, it appears that a possible rule of thumb for derating for motors under severe adverse power quality conditions would be 75% load. While this paper is not advocating under loading motors, it may well be a reasonable suggestion, especially with the fact that most industrial motors are designed with the peak efficiency occurring at a load close to 75%.

Conclusion

This paper has presented the effect of power quality conditions on the operation of induction motors. Voltage deviations and unbalance, voltage distortion and single phasing effects are discussed.

With respect to voltage magnitude deviations and unbalance, some differences were observed between EPACT and Premium design motors. For example, while the 50hp premium motor efficiency changed by approximately 0.5% point within the range from 0.9pu volts to the 1.05pu volts, the 50hp EPACT motor changed by nearly 1% point in the same interval. This means overvoltage condition may be relatively more beneficial, in terms of energy efficiency, to the EPACT design than the premium.

Under unbalanced voltage operation the efficiency of all the motors decreased with increase in unbalance. Unbalance levels of up to 1.5% have negligible effect, especially if the motor is operated at rated voltage. Furthermore, for unbalances up to 5% the motor efficiency generally reduced by about 1 to 3% with the lower end being applicable to the premium motors while the upper end is attributable to the EPACT designs. Because of motor protection issues, the maximum unbalance that can be tolerated is limited by the maximum allowable per unit current. For example, in the case of the 1hp motors, the maximum unbalance that can be tolerated at nominal voltage level is approximately 3.5% for the EPACT motor and 2.5% for the Premium motor.

With respect to voltage distortion, it can be concluded that, distortion levels at or below 8% do not detrimentally affect the induction motor efficiency. This finding is applicable to EPACT and Premium integral horsepower motors as well as single phase motors. The finding is also applicable to whether the harmonics was generated through laboratory controlled power supply or from common bus non-linear load sources.

For induction motors subjected to momentary single phasing sequences typical of utility recloser operations, such as a 0.2s-10s-13s sequence, it can be concluded that if the motor is carrying a load of 75% or less, it should be able to ride through the sequence. Also, all motors, should be able to ride through the first fault clearing operation of 0.2s regardless of load or transformer connection or motor connection. This means that motors on a feeder would not be adversely affected if the recloser is able to successfully reenergize the feeder during the first operation. For other scenarios, motors would stall under certain conditions and would not stall under other conditions. The factors that determined whether a motor stalled include the reclosing cycle (or open duration), load the motor is carrying, the motor winding connection, transformer connection and whether there is a secondary motor connected in parallel.

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Highly efficient industrial 11-kW permanent magnet synchronous motor without rare-earth metals

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Abstract

We have developed a highly efficient 11-kW permanent magnet synchronous motor without using magnetic material containing rare-earth metals such as neodymium and dysprosium. The motor uses a double-rotor axial gap structure and amorphous cores to use low-magnetic ferrite magnets. To increase capacity, we also developed (1) a core with stratified amorphous metals that enable the motor to exhibit low-loss and be relatively easier to manufacture, (2) a stator that has expansive heat transferring areas for ensuring a sufficient cooling performance, (3) a high-strength resin for stabilizing a stator against large counter torque and thermal stress, and (4) a design method using 3-D magnetic, heat transfer, and stress analyses for the double-rotor axial gap motor. Compared to conventional motors of the same class, our motor is smaller and exhibits an energy efficiency of approx. 93%, which fulfills the highest standard of IE4 in the efficiency guideline set out by the International Electrotechnical Commission (IEC).

1 Introduction

Due to increasing social awareness of environment issues, such as global warming, there has been a growing interest in technology that increases the efficiency of electrical equipment. Therefore, the International Electrotechnical Commission (IEC) has set standards of industrial motor efficiency, namely IE1 (Standard-Efficiency), IE2 (High-Efficiency), and IE3 (Premium-Efficiency) [1]. Furthermore, higher efficiency standards, such as IE4 (Super-Premium Efficiency) and IE5 are now under consideration. Thus, we predict that motor efficiency will improve further.

A permanent magnet synchronous motor (PMM) with a rare-earth magnet exhibiting a high energy product (BH_{max}) is known to improve motor efficiency. However, although greater efficiency of motors using rare-earth magnets is actively being pursued, there is a growing need to recycle rare-earth magnets or to substitute them with more abundant materials.

Under these circumstances, motors without rare-earth magnets, such as induction motor (IM), switched reluctance motor (SRM), synchronous reluctance motor (SynRM), and PMM with ferrite magnets have been attracting attention. However, since these motors have both advantages and disadvantages, it is important to choose the appropriate motor for the situation.

We previously developed a small and highly efficient PMM with ferrite magnets for industrial use [2]-[6], which would be beneficial in terms of motor size, efficiency, and noise. This motor effectively uses low-magnetic ferrite material with amorphous magnetic metal (AMM) with which iron loss can be decreased and field magnetic flux increased due to the double-rotor axial gap structure. The iron loss of AMM is 1/10 that of traditional silicon steel sheets, namely 35A300, widely used in motors. As a result, the double-rotor axial gap structure allows a greater amount of ferrite magnet to be used; thus, producing more field magnetic flux than that of the traditional radial gap structure in relatively flat motors.

Amorphous metal has five times higher tensile strength than silicon steel sheets; however, they are also brittle, which makes them difficult to be stamped or cut into shape. Thus, a motor using AMM has not yet been put to practical use. Nevertheless, we addressed this issue by applying AMM to a double-rotor axial gap structure having a core with relatively simple geometry. In fact, we have already demonstrated the effectiveness of this simple structure using a 150-W fan motor and found that it would be possible to fabricate a small and highly efficiency motor [2][4].

Increasing the capacity is important to apply the motor for many applications. However, many problems arise due to expansion of motor size and increased electromagnetic force and temperature. Additionally, as far as we know, there is little practical case and few reports for the large-capacity double-rotor axial gap motor. Our goal for this study was to fabricate such a small and highly efficient industrial motor requiring higher capacity using the structure mentioned above.

In this paper, we discuss the problems to increase both efficiency and capacity in motors with ferrite magnets, solutions to those problems and test results of prototype machine.

2 Solutions for rare-earth less motor and problems in increasing capacity

2-1 Double-rotor axial gap motor with amorphous metal cores

Figure 1 compares a conventional and our developed motor structure. The conventional motor has a radial-gap structure with a cylindrical stator and rotor, as shown in Figure 1a). Laminated silicon steel sheets and rare-earth magnets are also used for the stator and rotor, respectively. On the other hand, the developed motor has a double-rotor axial gap structure with two disk-shaped rotors and a cylindrical stator, as shown in Fig. 1b). Similarly, AMM cores and ferrite magnets without rare-earth metals, such as neodymium and dysprosium, are used for the stator and rotors, respectively.

Figure 2 illustrates the methods of increasing efficiency in our developed motor. Motor efficiency can be expressed as

$$\text{Motor efficiency} = \text{Output (Torque} \times \text{Rotating Speed)} / \text{Input (Output + Losses)} \quad (1)$$

The output is obtained from the product of torque and rotating speed. The input is the sum of the output and losses of iron, copper, mechanical, and stray. In the Eq. (1), the developed motor improves efficiency by increasing torque and decreasing these losses.

Figure 2a) is a conceptual diagram showing how torque is increased with the double-rotor axial-gap structure. The torque increases according to the facing area between the rotors and stator (Gap area). The gap area of a radial-gap structure increases with the axial length of motor (L) and outer diameter of magnet (Dr). On the other hand, the gap area of an axial-gap structure increases with the square of the outer diameter of magnet (Da). This relationship leads to higher torque with the axial-gap structure than that of the radial-gap structure in a relatively short L, making increasing the torque of the motor possible.

Figure 2b) shows the reduction effect of iron loss by applying the AMM core. Amorphous magnetic metal is a foil shaped non-crystal alloy with 30-micro-meter thickness produced by rapidly cooling raw alloy materials, such as iron, from a melted state to solid state. Such a disordered atomic structure of AMM leads to lower hysteresis loss than that of traditional silicon steel sheets with a crystal structure. Moreover, eddy current loss of AMM can be fairly suppressed by forming it with appropriate core structure. As a whole, it is possible to drastically decrease motor loss by using an AMM core.

With the above technologies, the developed motor with ferrite magnets is smaller and higher in efficiency.

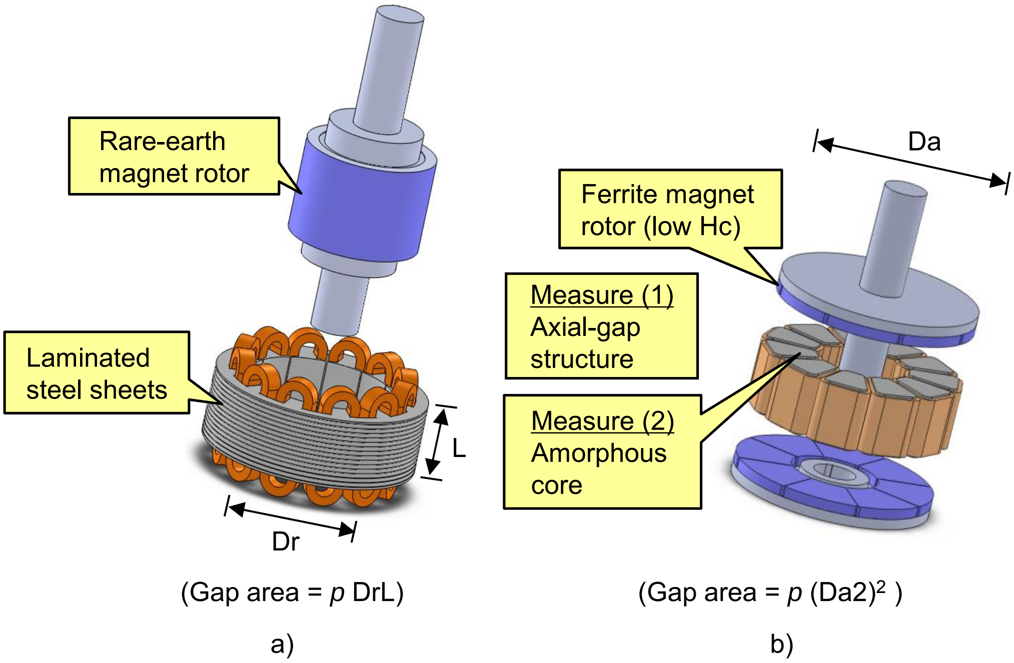

Figure 1: Motor structure: a) Conventional motor structure, b) Developed motor structure

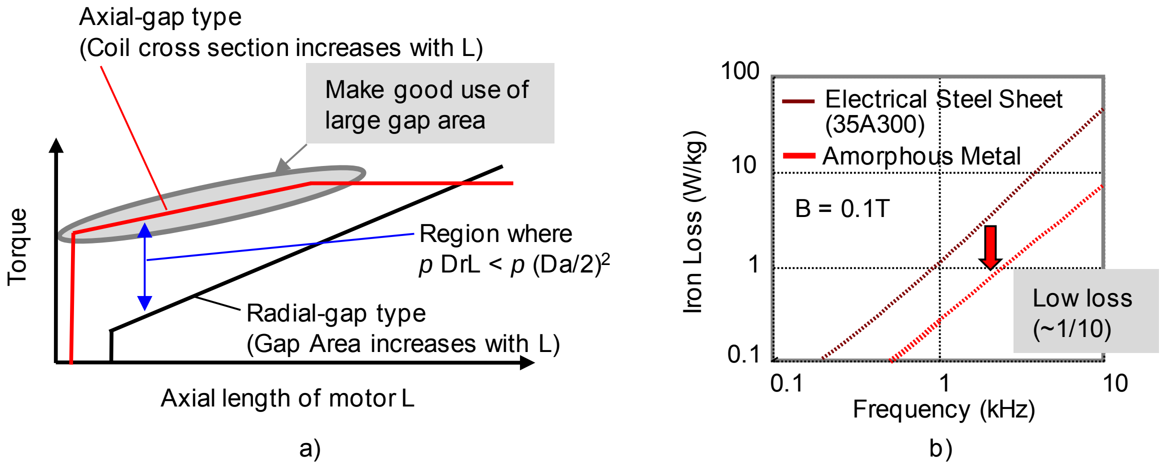

Figure 2: Development concept: a) Increasing torque, b) Decreasing losses

2-2 Problems in increasing capacity

Figure 3a) is a cross-section of the developed motor's configuration, and Figure 3b) is a schematic of the double-rotor axial gap structure of the motor.

The stator consists of circumferentially placed coils and cores, housing, and resin, as shown in Figure 3a), where the resin serves to stabilize the stator. A rotor consists of circumferentially placed ferrite magnets, a back yoke, and yoke, where the magnets are magnetized parallel to the axis and two rotors are coupled to a common shaft through each yoke.

The schematic shows the directions of magnetic flux. There are axial magnetic fluxes in the cores and circumferential ones in the back yokes.

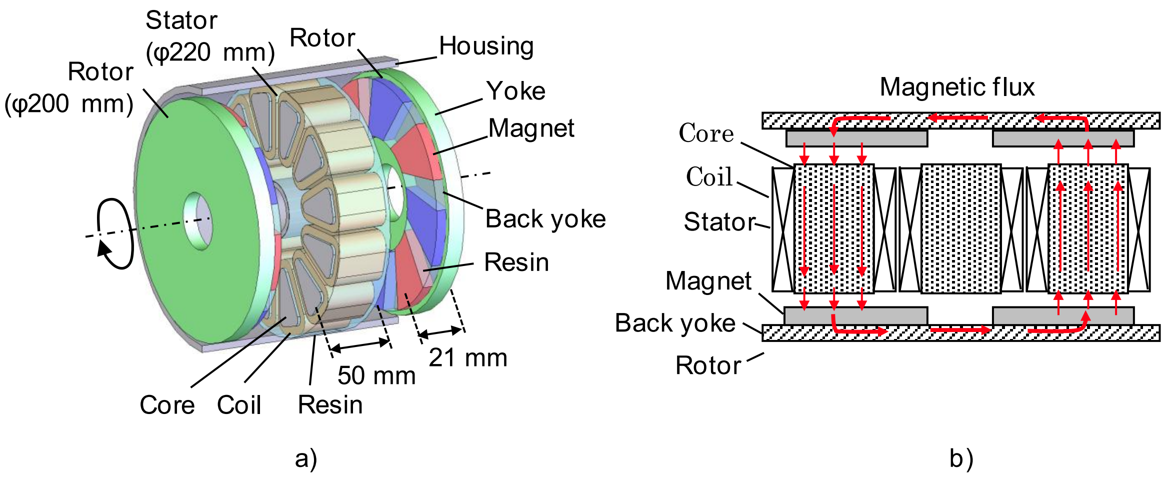

Figure 3: Developed motor configuration: a) Cross-section, b) Schematic

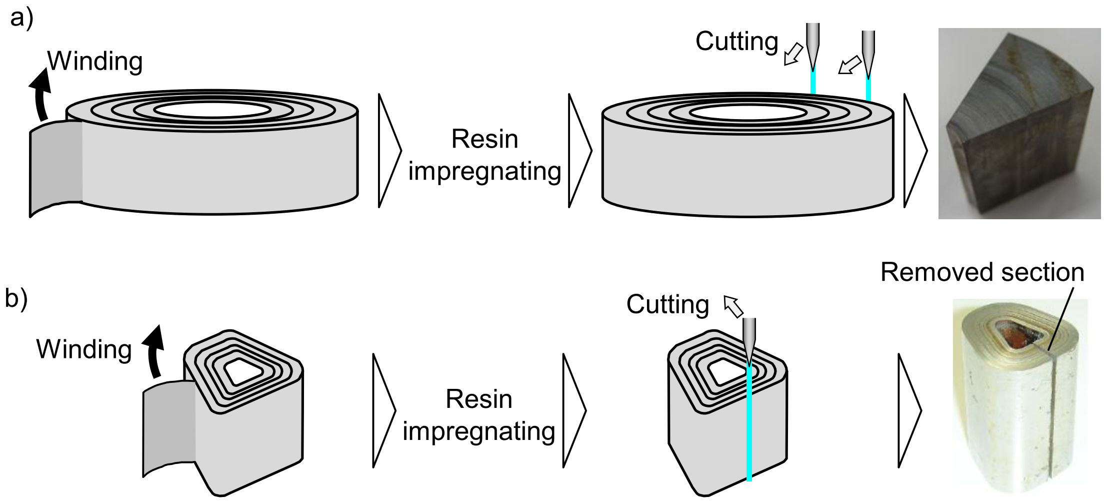

Figure 4: Production processes and structures of amorphous cores: a) Cut core, b) Wound core

Problem-1 Amorphous core to decrease eddy current loss and manufacture cost

Although it is necessary to laminate AMM perpendicular to the rotation axis to prevent an eddy current to axial magnetic fluxes, the stronger tensile strength and brittleness of AMM make it difficult to apply amorphous metals with traditional stamping technology. Therefore, it is important to form the amorphous core as simple as possible.

Two types of previously developed AMM core structures and those production processes are shown in Figure 4. These production processes consist of three steps, that are 1)winding of amorphous sheet, 2)bounding by resin, and 3)cutting a resin-impregnated AMM. In case of the cut core, the amorphous sheet is wound cylindrically. After being bounded by resin, the wounded core is cut radially to form the trapezoidal stator core, where a laser or water jet process is used to cut a strongly laminated AMM core. These cutting processes require an expensive equipment and longer machining time. On the other hand, because amorphous sheet is wound as trapezoidal shape, the wound core is possible to decrease cutting area. However, it needs at least one removed section to prevent an eddy current flow along winding direction of amorphous sheet.

Although both cores are well designed to decrease cutting area, it is impossible to rid the cutting area completely. When the motor capacity is designed to increase, the cutting time increases in proportion to the cutting area depending on core size. Also, these cores require a longer time for impregnation. Therefore, we developed an AMM core structure that exhibits low iron loss and low production cost.

Problem-2 Stable motor structure for cooling and strength

In our double-rotor axial gap motor, the stator can be stabilized by resin whose thermal conductivity and mechanical strength are generally less than that of metals.

Figure 5 shows a conceptual diagram of heat dissipation and forces occurring in the stator in our double-rotor axial gap motor. Figure 5a) illustrates the heat dissipation paths from a coil. Because the motor is equipped with an outer fan, several fins are placed on the outer surface of the housing for cooling by forced convection with fan-generated wind. With this structure, heat generated at a coil, which is the main loss source, radiates peripherally through the resin.

Figure 5b) shows the forces occurring in the stator. The forces are electromagnetic and thermal stress. The electromagnetic force mainly caused by counter torque (circumferential direction) and thermal stress caused by temperature changes and different linear expansion coefficients with different materials in the motor. Under such various stresses, the resin must be strong enough to stabilize the stator.

To solve the above problems, we developed a cooling structure for a double-rotor axial gap stator and a high-strength resin. We also applied three-dimensional finite element analyses (3-D FEAs) to design the motor by taking into account temperature and stress distribution.

2-3 Motor design

Goals of motor design

Table 1 lists the targeted motor design specifications. The targeted rated power is 11-kW (3000 r/min, 35 Nm), corresponding to two poles of an induction motor. The targeted motor volume is smaller than conventional induction motors using a bracket number of 160M, and the targeted efficiency is higher than 92.9% (IE4). The targeted temperature increase at the coils is lower than 75 K, corresponding to the maximum temperature increase of class B insulation. The insulation class is equal to a conventional induction motor.

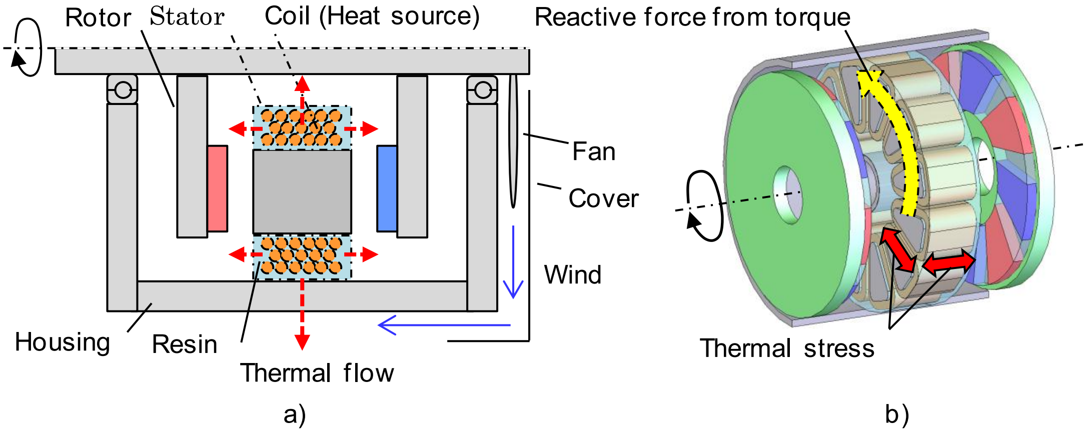

Figure 5: Conceptual diagram of heat dissipation and forces acting on stator: a) Heat dissipation from coils, b) Forces occurring in stator

Table 1: Specifications of targeted motor design

Parameter	Target
Capacity	11 kW (3,000 r/min, 35 Nm)
Volume	≦Bracket number 160M
Efficiency	≧92.9% (IE4)
Temperature increase	≦75 K (Class B insulation)

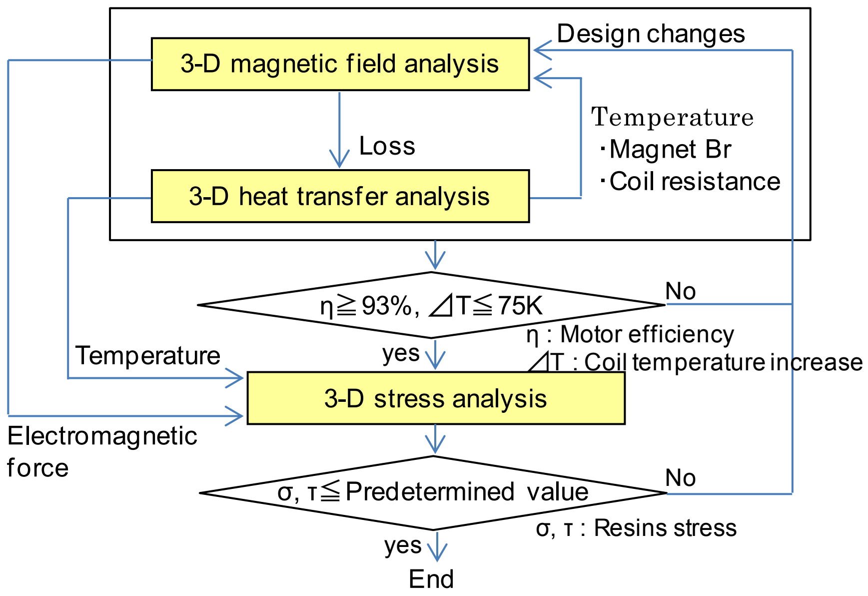

Figure 6: Design flow

Method for motor design

We initially studied the AMM core structure, stator structure, and resin separately as the basic structure of our double-rotor axial gap motor, which is discussed in the next chapter, of which the core and motor structure are shown in Fig. 3a).

Next, we designed the motor based on this basic structure. The design flow is shown in Fig. 6. It consists of 3-D magnetic field, 3-D heat transfer, and 3-D stress analyses, which allow us to predict distributions of magnetic field, temperature increase, and stresses more precisely, respectively. It starts with the 3-D magnetic field analysis that gives torque, losses, and forces in the motor. Then, using the losses as input condition, the 3-D heat transfer analysis gives the temperature distribution.

The temperature of the coils and magnets obtained from 3-D heat transfer analysis is fed back into the magnetic field analysis's inputs such as the magnets' Residual Flux Density (Br) and coil resistance. As a whole, the motor efficiency (η) and temperature increase of the coils (⊿T) can be calculated. If η and ⊿T do not satisfy the targeted value, we re-design the motor structure and re-calculate accordingly. Otherwise, using the distribution of magnetic force and temperature as an input condition, 3-D stress analysis gives the stress distribution in resin. If the stresses do not satisfy the predetermined values, we re-design the motor structure. The predetermined values mentioned above are determined based on the reduction factor of strength such as temperature characteristics and long-term degradation.

3 Basic structure for high capacity

3-1 AMM core

Figure 7 shows the developed AMM stratified core and manufacturing equipment. The AMM core is manufactured by laminating reed-shaped AMMs (Figure 7a)). The manufacturing equipment consists of transport and press systems (Figure 7b)). The tridimensional core shape is produced with different widths of reed-shaped AMMs by gradually changing the cutting distance of the amorphous tape. Therefore, it is possible to manufacture AMM cores with arbitrary cross-sections, and even an AMM core with curvature(R) in its four corners can be manufactured easily (Fig. 7c)).

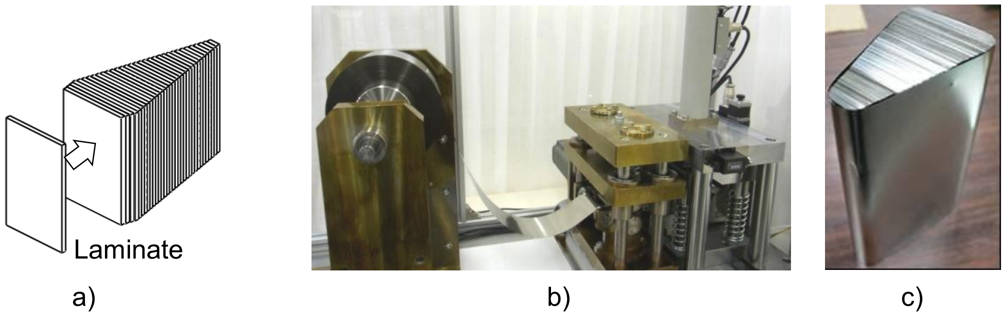

Figure 7: Developed core and manufacturing equipment: a) AMM stratified core, b) manufacturing equipment, c) test core

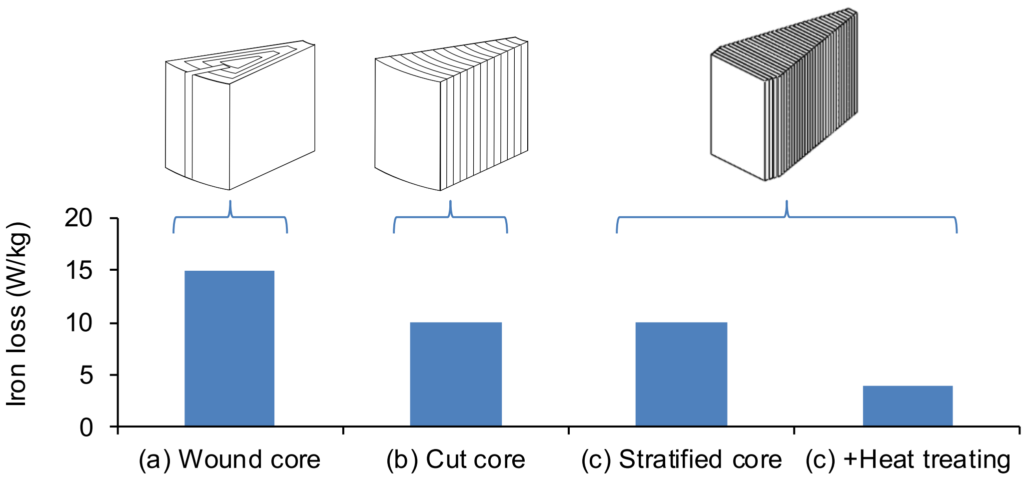

Figure 8: Measurement results of iron loss @1 T, 400 Hz

Figure 8 compares the measurement results of iron loss obtained using the Epstein method. The measurement condition was 1 T, 400 Hz. Compared to the wound core, the cut core and AMM stratified core exhibited almost 30% smaller iron loss. Similarly, compared to the non heat-treated AMM stratified core, a heat-treated core exhibited about 60% smaller iron loss. Therefore, we confirmed the following results. 1) The AMM stratified core is able to achieve far lower loss characteristics, 2) the dies of the press system have a longer life-span because the cutting load is very small, and 3) the cycle time is short enough for commercial production by automation of the equipment. Based on the findings above, we believe that the AMM stratified core is the optimum structure.

3-2 Stator structure for cooling

Figure 9 shows a 3-D heat transfer analysis model. The model consists of a finite element mesh model (Figure 9a)) and an equivalent circuit model (Figure 9b)). The mesh model is obtained by adding a resin, a shaft and bearings to the magnetic field analysis model. Also, as shown in the equivalent circuit model, nodes for spatial regions, such as the air gap between the rotor and a stator and one between a shaft and the stator, are added to consider the heat transfer between air and other components. The heat transfer coefficients for heat convection, which depends on flow velocity, are set on surfaces in contact with outside air.

The heat transfer analysis is conducted as follows. First, we clarify heat radiation pathways from the coils using the motor in Fig. 3. The pathways consist of (i) one from the outer periphery of the stator to the housing, (ii) one from the stator surface facing the air gap to a rotor and (iii) one from the inner periphery of the stator to the shaft.

Figure 10 shows the calculation results of 3-D heat transfer analysis. Figure 10(a) shows rate of heat flow from the stator. The heat flow of pathway (i) accounts for 85.8% of the total heat dissipation. Figure 10(b) shows temperature distribution of the stator surface. On the pathway (i), the heat is transferred from coils to housing through insulator such as bobbin and mold resin. Because of the smaller thermal conductivity of them, it seems that large temperature gradient between coils and housing occurs. Therefore, decreasing thermal resistance between the coils and housing is effective for improving cooling performance. In response to this, we propose three types of a stator structures (A, B, C: combination of A and B) to increase heat transferring areas; thus, average thermal conductivity between coils and housing.

Figure 11 compares the calculation results of the temperature increase of the coils for each stator structure. Compared to the original structure, the temperature reduction effects of the above-mentioned structures are as follows: structure-A: -31%, structure-B: -51%, and structure-C: -56%. We used structure-C as a basic stator structure based on the results described above.

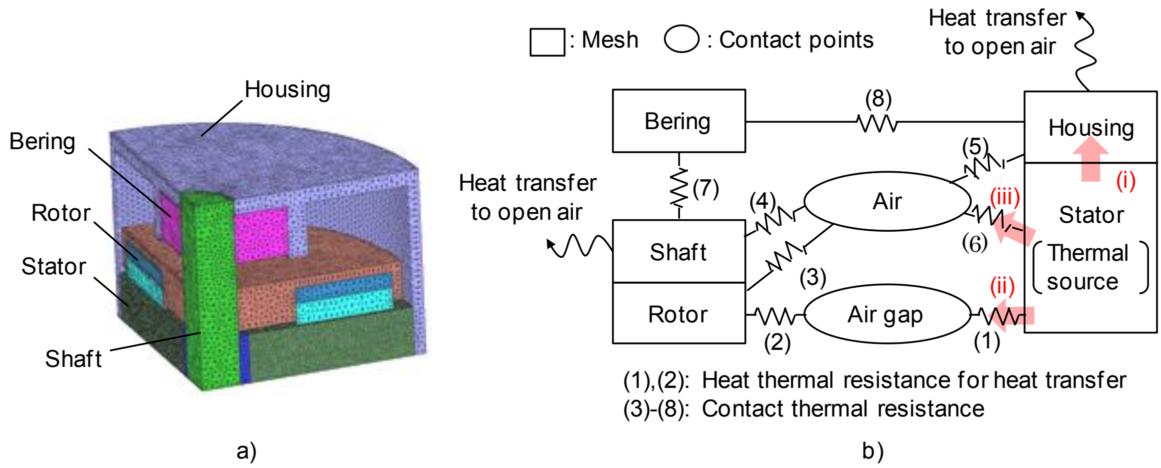

Figure 9: Three-dimensional heat-transfer analysis model: a) Mesh model, b) Equivalent circuit model

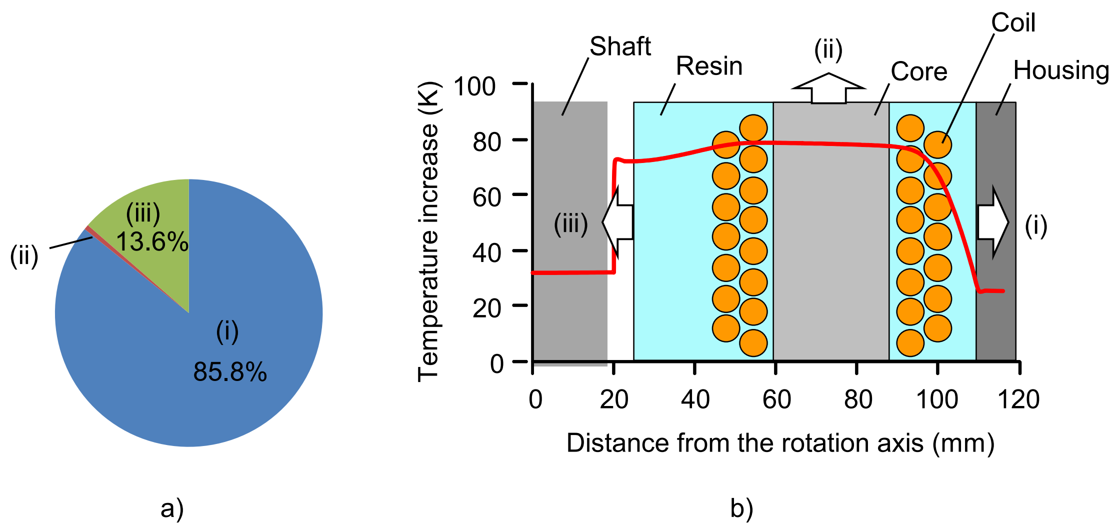

Figure 10: 3-D heat transfer analysis results: a) Percentage of heat flow from stator, b) Temperature distribution of the stator surface.

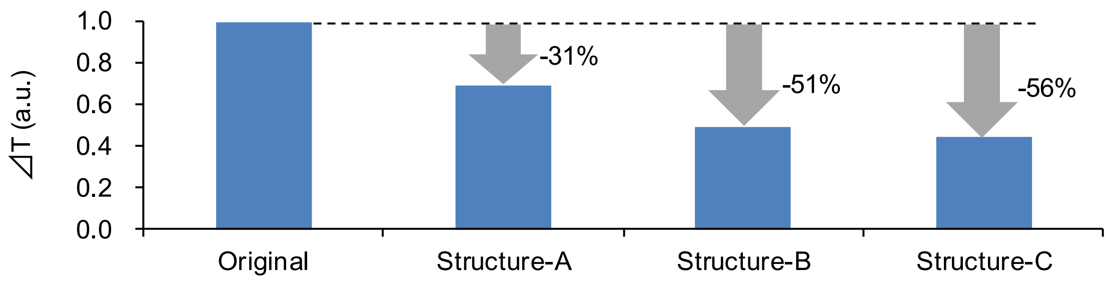

Figure 11: Calculation results of cooling system

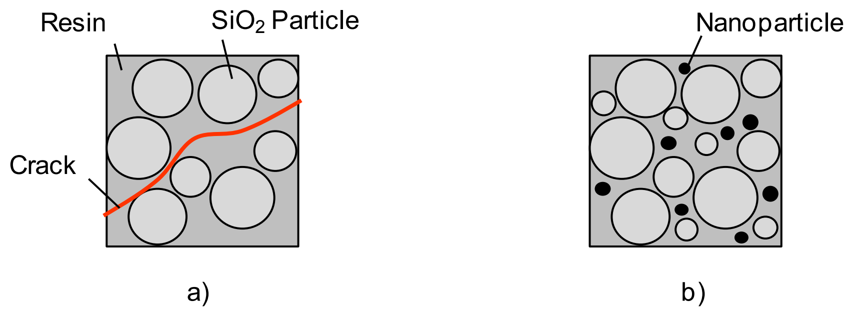

Figure 12: Conceptual diagram of a) Conventional resin, b) Developed resin

3-3 Mold resin

Figure 12 shows conceptual diagrams of the developed resin to improve fracture toughness. In comparison to a conventional epoxy-based resin, the developed resin, which consists of nano-scale rubber fillers of less than a few hundred nanometers in diameter, effectively prevents the occurrence of cracks in a resin. As a result, it provides almost 1.5 times higher fracture toughness than that of conventional resin, as well as optimal flexural strength, thermal conductivity, and formability for motor use by controlling other resin parameters such as compounding ratio and particle size distribution.

4 Trial motor

4-1 Development of a trial motor

We designed a trial motor according to the design flow in Fig. 6. The difference between the motor shown in Figure 3 and that in Figure 6 is the trial motor's stator axial length, 50 mm for the former and 84 mm for the latter, which was due to a design change of coils. Other dimensions, such as outer diameter of ferrite magnets, are the same as those in Figure 3.

Figure 13 shows the calculation results of the trial motor at rated condition (11-kW, 3,000 r/min, 35 Nm). Figure 13a) shows the distribution of magnetic flux density. Compared to the saturated magnetic flux density on the linear region of the magnetization curve (BH curve) of the AMM, the average magnetic flux density in amorphous cores was far smaller, at 0.6 T. Figure 13b) shows that the temperature increase of coils was 64 K, which is smaller than the targeted temperature increase of 75 K (Class B insulation), and there were small temperature differences between each coils which could make evaluating the heat-resistance temperature of a coil possible based on its average temperature. As shown in Figure 13c), tensile stress was sufficiently smaller than the predetermined value, and though not shown here, we confirmed that the shear stress on the outer periphery of the stator is smaller than that of the predetermined value. As a result, we presume that the developed resin can stabilize the stator and prevent internal cracks or shear peeling from the housing.

Figure 14 shows photos of the trial motor. The axial length of the trial motor was reduced to approximately 2/3 that of the conventional induction motor, as shown in Figure 14a). Also, as can be seen in Figure 14b), the twelve AMM stratified cores of the stator are stabilized by the resin. Two rotors with ferrite magnets and a cooling fan are shown in Figure 14c). To improve strength against centrifugal force, integrated ring-shaped magnets are used with reinforcing resin covering the outer periphery of the magnet to prevent the magnets from scattering.

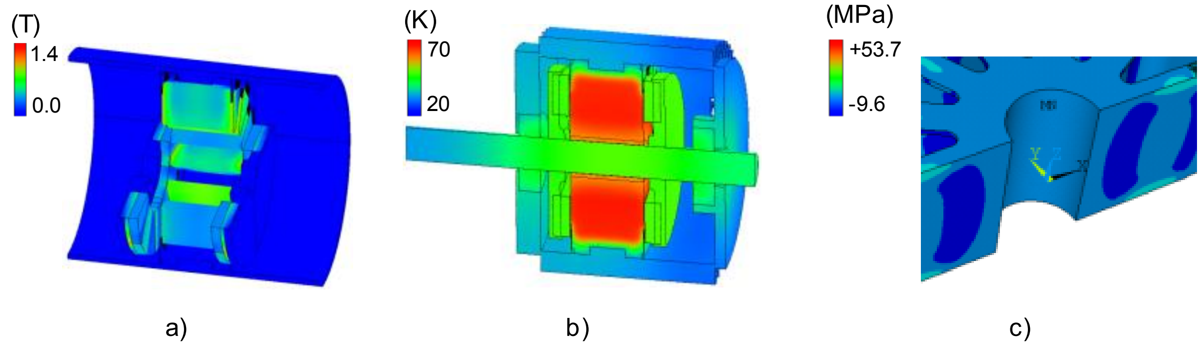

Figure 13: Calculation results of trial motor: a) Magnetic flux density, b) Temperature increase, c) maximum principal stress

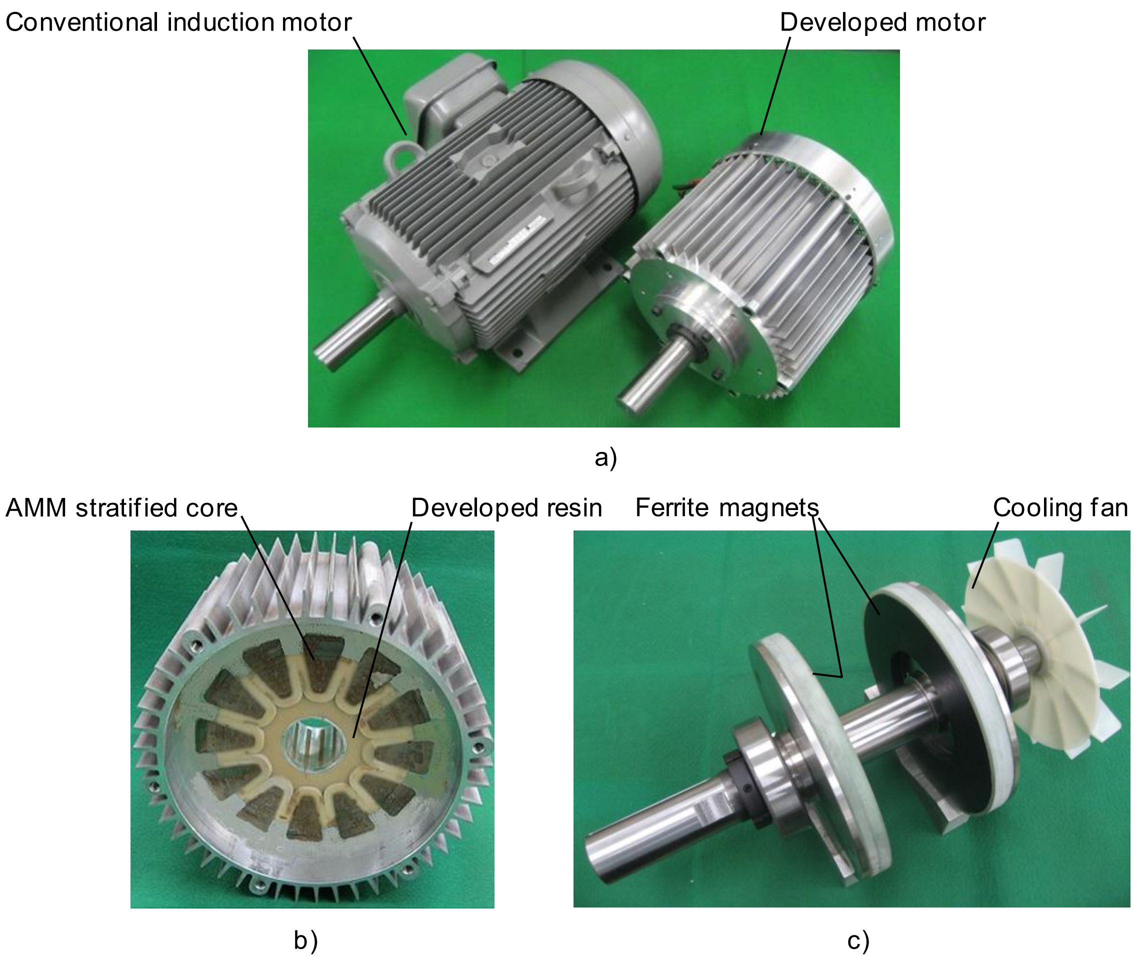

Figure 14: Photos of test motor: a) Overview, b) Stator, c) Rotor

4-2 Test results

Figure 15 shows the measurement results of the motor characteristics. Figure 15a) shows the calculated and measured torque output as a function of the input current. Even though the torque showed a saturating tendency at the high input current region, which is caused by the effect of leaded current phase, the measured values agreed well with the calculated values. Regarding the heat run test results at the rated output condition shown in Figure 15b), the temperature of a coil converged in about 3 hours. The increase of coil temperature was lower than the targeted value of 75 K, by 5 K, and its measured trend agreed well with the calculated one. Finally, Figure 15c) shows motor efficiency as a function of the relative load torque of rated 35 Nm, as well as the efficiency of a conventional induction motor and standard values of IEC (IE1-IE4). The developed motor exhibited high efficiency of 93% in the range of 50 to 100% load torque, and reached 93.1% at rated load torque, satisfying IE4 (92.9%).

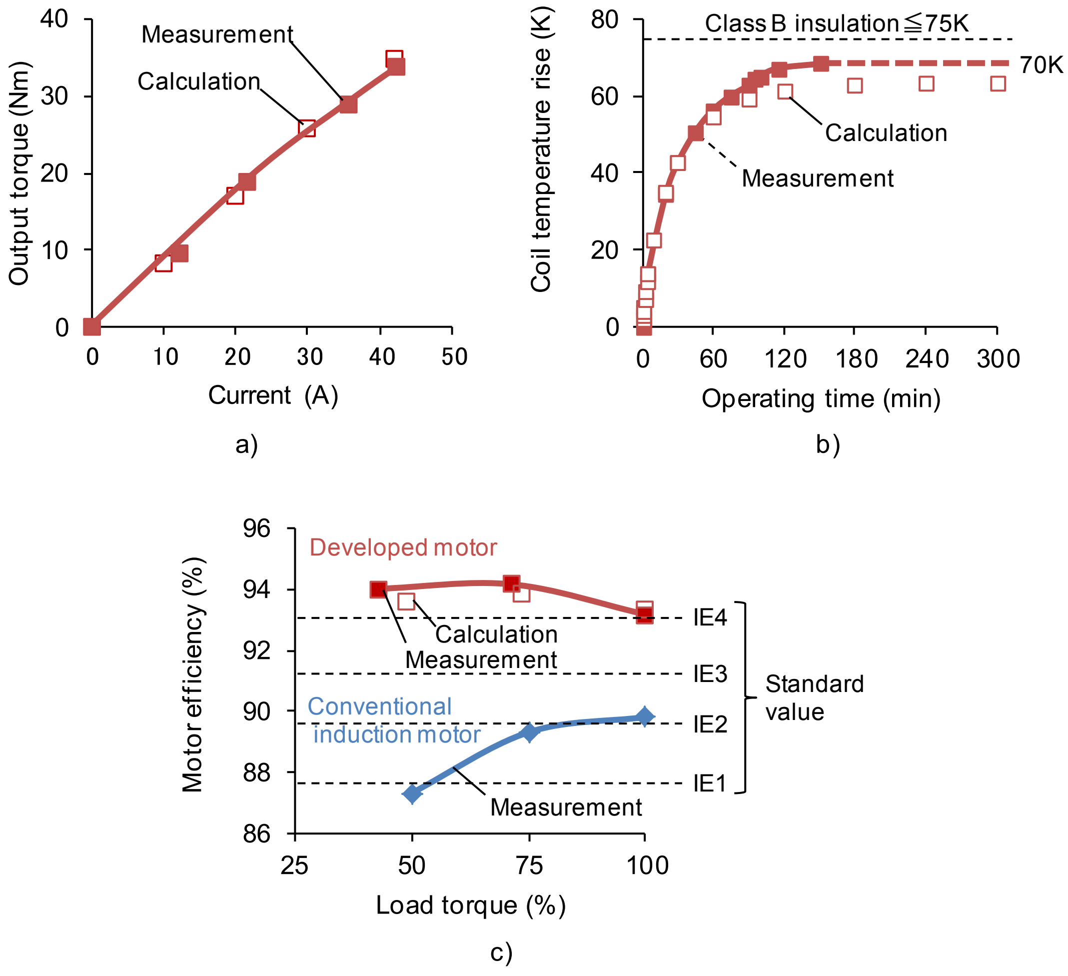

Figure 15: Motor test results: a) Current-torque characteristics, b) Temperature increase test, c) Motor efficiency

5 Conclusion

We discussed technologies for increasing the capacity of a small and highly efficient double-rotor axial gap motor that uses an AMM core stator and ferrite magnet rotors without rare-earth metals. We explained the design concept, AMM cores, cooling and structural systems, and motor test results. The key points and results are as follows.

1) The newly developed AMM stratified core satisfies low iron loss and low production cost. The core provides equal or less iron loss than that of previously developed AMM cores, even without the resin impregnation process and laser or water-jet cutting process, which could lead to high production cost.

2) Despite the far lower thermal conductivity of resin than metal materials, we revealed that most of the heat generated in a coil is transferred to the housing through the resin, as demonstrated in our 3-D heat transfer model, where as much as 86% of the total heat flow is conveyed from the coils to the housing. The developed stator, which reduces thermal resistance between coils and the housing, exhibited 31-56% lower temperature increase in the same model.

3) The developed resin, which contains nanometer-scale rubber fillers, exhibited almost 1.5 times higher fracture toughness compared to conventional resin. The developed resin can stabilize a stator without allowing internal cracks or shear peeling from the housing.

4) Our 11-kW industrial motor, based on the above technologies, is smaller than conventional induction motors and exhibits an energy efficiency of 93.1%, which fulfills the highest standard of IE4 in IEC.

We explained the development results of our 11-kW motor with a rated speed of 3,000 r/min, corresponding to a two-pole induction motor. We have already demonstrated an IE4-11kW motor with a rated speed 1,800r/min, which corresponds to a four-pole induction motor in our laboratory. We are planning to conduct long-term reliability assessment and explore the potential for the developed motor to be expanded to other capacities and applications.

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STATOR WINDING INTERTURNS SHORT CIRCUIT FAULT DETECTION IN A THREE PHASE INDUCTION MOTOR DRIVEN BY FREQUENCY CONVERTER USING NEURAL NETWORKS

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Abstract

This work is the application of a Multilayer Perceptron Artificial Neural Network (MLP ANN) to detect early inter turn short-circuit faults in a three phase converter fed induction motor. The quantity used to analyze the problem is the stator current or, more specifically, the harmonic contend of its frequency spectrum, also called current signature. The analysis through the current signature is a non-invasive method and can be embedded in the frequency converter, what is a great advantage. The dataset used to training and to validate the ANN is obtained using a test bench that allows to apply different levels of inter turn short-circuits in the machine. It is observed that the fault motor dataset and healthy motor dataset are difficult to separate due the nonlinear character, which demands a large computational effort to choose an appropriate MLP topology. The MLP is trained by two different algorithms (the classical error Back-Propagation - BP - and an adaptation of the newer Extreme Learning Machine - ELM) and the results are thoroughly explored. Then it is slightly compared with the results of a Self-Organized Map ANN [1] obtained by using the same dataset.

1. Introduction

The induction machine is consolidated as main motor force in industries. According Thomson and Fenger [2], in an industrialized nation the induction motor might consume, typically, among 40% and 50% of all capacity generated.

Despite the recognized robustness and reliability of this machine, it is subject to fault occurrence, many times due to installation environment conditions, inadequate applications and lack of preventive maintenance. The more common occurrences are bearing faults, stator or rotor isolation faults, open bars or crack of the rings and eccentricity fault [3].

Machine faults produce symptoms like unbalanced line voltage and current, increasing in torque pulsation, decreasing in the mean torque, increasing of losses, efficiency decreasing, and excessive heating [4]. Therefore several methods of detection and diagnostic has been developed past years and new solutions keep appearing with the objective to increase the accuracy but also to simplify techniques and to decrease costs [5].

In industries the cost of an unscheduled production downtime is too high; hence they invest increasingly to improve their maintenance programs. Faults like open rotor bars, eccentricity and bearing faults take time to evolve and put the motor out of operation. In this context, the constant online monitoring is important to early fault detection in a way to have time to program a maintenance order and save the machine.

The stator winding inter-turn short-circuit (SWITSC) takes a short time to evolve and to condemn the motor. Thomson and Fenger [2] tested low voltage three-phase induction machines from early SWITSC until complete failure and found that exist a time of a few minutes to occur the fault evolution. This time is probably not enough to avoid unscheduled production downtime. But the early detection makes possible to repair the machine by rewinding it or, in large machines, removing short-circuited coils and the early operation stopping avoids electrical arcs due short-circuit and then offers an additional protection to areas where there are explosion risks. Moreover, after the severe fault, the ferromagnetic core is damaged and the machine becomes probably irreparable.

It has become more and more common the use of frequency converter to drive induction motors. That gives more versatility to the drive of machines because it allows application with varying rotation speed [6]. The high current in the motor due to fault also affects the frequency converter integrity and an early detection means an additional protection. Moreover, once this electronics is already being in use, could be advantageous have detection systems previously embedded in it. Past years the developing of several computational intelligence techniques added new possibilities to fault detection and diagnosis systems, most of them potentially suitable to be embedded in electronic converters. Examples include ANN, fuzzy systems, genetic algorithms, among others.

Despite the spread of fed-converter machines, most of researches uses line-fed drive machine. Using converter-fed motor, Kowalski and Wolkiewicz [7] analyze the spectrum of instantaneous Park power and torque signals to diagnosis early SWITSC and broken rotor bars. The same authors in [8] use neural networks to diagnosis SWITSC with 80% of accuracy. Coelho and Medeiros in [1] try to map the SWITSC fault using self-organized map and classify the motor.

According Nandi et al [3], isolation fault represents from 30% to 40% of all kinds of faults reported in induction motors. This significant amount justifies the detailed investigation of the problem. In this work is investigated the motor current signature analysis (MCSA) together with the potential of a single hidden-layer feed-forward neural network (SLFN) classifier as a tool of in SWITSC detection to converter-fed three-phase induction machine. Two algorithms were used to training the neural network: the error back-propagation (BP), which is the classical one, and the ELM, which is a more recent algorithm. The datasets were obtained by an experimental test bench where different level of SWITSC can be applied.

The section 2 shows the problem of the SWITSC and how it is been treated past years. Section 3 contains the basic about MLPs and the ELM and BP algorithms. In section 4 the laboratory tests and data acquisition are explained as well as the ANN attributes selection. The classification results are in section 5 and the section 6 concludes this work.

2. Stator Winding Inter-Turn Short-Circuit Overview

Isolation systems are submitted to several kinds of efforts that might cause a failure. Due the use of inverters to drive electrical motors with a typically frequency switching of about 10 kHz, occur voltage peaks such that increases considerably the machine isolation stress. As result, the fed converter motor stress might be until ten times higher than line fed machines [9].

The failure process is usually initialized as a turn-to-turn high impedance fault (order of kΩ) in the same phase, between phases or phase-to-ground [10]. The fault current can reaches two times the rotor blocked current, which causes high localized heating and makes the fault quickly spreads. If the incipient fault was detected it is possible reutilize the machine after repairs, but if the fault evolves might possibly causes an irreparable damage to the machine core [2].

Different methods have been used in many researches to detect stator inter-turn short-circuit. Ballal et al [11] use the symmetric components theory to do the detection. This technique consists in using an expression to separate the currents in positive, negative and zero sequences. They analyze a graphic that the positive and negative sequences describe a circle with opposite spinning direction. The detection is done by a measure of the deformation caused in the graphics by the fault.

Boqiang et al [12] use as characteristic to detection the negative impedance sequence, which is defined as the negative sequence value of the voltage component divided by the negative sequence current component. In experimental tests they realized that there is an oscillation of the impedance value with time and it is necessary a low-pass filter to guarantee the technic reliability.

Considering the MCSA, Joksimovic and Penman [13] show that there are no novel components in stator motor current frequency spectrum due to the isolation fault. In fact it was observed that just occur an increase of the existents components. Stavrou et al [14] search the current frequency spectrum for the variation in frequencies as function of number of poles, slots and slip, that is, specific constructive features.

Penman et al [15] develop an equation (2.1) to calculate which harmonic components in the axial leakage flux waveform are functions of the SWITSC and propose a method to detect fault by monitoring those components.

$$f_{st} = \{k \pm n(1-s)/p\}f_1 \quad (2.1)$$

The f_{st} is inter-turn short-circuit function components, k =1, 3, 5..., means the temporal harmonics order, n = 1, 2, 3..., means the spatial harmonic order, s is the slip, p is the pair of poles, f_1 is the power supply fundamental frequency. Several kinds of faults affect the current spectrum and some harmonics are affected by more than one abnormal condition, so one must be careful to choose the correct frequencies that will be used to indicate the problem.

According Das et al [16] unbalanced supply voltage might produce current signature which look apparently identical to stator winding inter-turn fault cases. They propose a method to separate these two signatures. Their method is based in the Extend Park's Vector Approach (EPVA) and combined with signal processing tool as Fast Fourier Transform (FFT), Discrete Wavelet Transform (DWT) and Power Spectral Density (PSD) to make the discrimination.

Thomson and Fenger [2] expand the concept of the leakage flux to stator currents, once the flux inside the machine also crosses the stator windings. They do an experimental analysis in low voltage motors to verify which frequencies are function just of the short-circuit and no other conditions as unbalanced phases, misalignment of the shaft, broken rotor bars, bearing faults, etc. The components found in [2] using equation (2.1) as function only of short-circuit are f_{st1} when $k = 1$, $n = 3$ and $k = 1$, $n = 5$; to an unload motor ($s \approx 0$) with 2 pair of poles, these harmonics would be $2.5f_1$ and $3.5f_1$.

Also using MCSA, Gazzana et al [17] create a system to early detection and diagnosis rotor broken bars, air-gap eccentricities and SWITSC in induction motors. To SWITSC the equation (2.1) is used with $k = 1$, $n = 7$ and the Welch's method is used to obtain the frequency spectrum. The choice of a high order spatial component in the spectrum is because the low order eccentricity components are coincident with short-circuit components.

Based on stator currents Hyun et al [18] create neural models to simulate the state of one induction motor without any faults, one with isolation fault and other with bearing fault. The models are put in parallel with the system and the real output are constantly compared with the neural models outputs. A Bayesian network evaluates the model residues and detects the isolation or bearing fault.

Bouzid et al [19] use a neural network to locate the phase where the short-circuit is. It is chosen as fault feature the phase shift between the three phase voltages and currents. The detection is made by a MLP NN with 3 outputs, each one referent to one phase. If that neuron was active it means a fault in that phase. They validate the method using two induction motors and conclude it is an efficient method and once a NN was trained to one motor it can be used to other identical machines.

Das et al [20] process the line current signal recorded from motor terminals through a Park's transformation followed by Continuous Wavelet Transformation and uses a Support Vector Machine (SVM) to classify the extracted features. From the 18 test cases used for prediction, a total of 16 fault cases were correctly identified by the proper configured SVM.

Among all possible methods to fault detection, current signature has a great potential because it is non-invasive; does not require installation of sensor in the machine; does not require be adapted to classified areas (because it can be installed at the panel, far from potential explosive mixtures); presents high capacity of remote monitoring reducing the maintenance men exposition to risks; can be applied to any machine, with no power restriction; presents sensitivity to mechanical machine faults, stator electric faults and feed problems; among others [21]. To these advantages it can be added, to converter-fed motors, the possibility of embedded the detection system in the own converter, especially if a computational intelligence technique was used.

This work presents a MLP ANN to classification of SWITSC. The equation (2.1) developed by the Penman's theory and expanded by Thompson is initially used for feature extraction to the fault detection.

3. MLP Artificial Neural Network in a Nutshell

The ANNs appeared as mathematics tool based on the human brain biological model. Simplified models based are usually designed to specific problems solutions like classification, pattern matching, pattern completion, optimization, control, function approximation and data mining [22].

It was proved that an MLP ANN with one hidden layer can approximate any continuous function with a determined precision since it has neurons enough [23]. In classification they are recommended for applications in which there is an unknown non-linear relation between input and output dataset, even for complex non-linear multivariable problems. They are capable to learn this relationship by data presentation and then generalize the knowledge and classify new data.

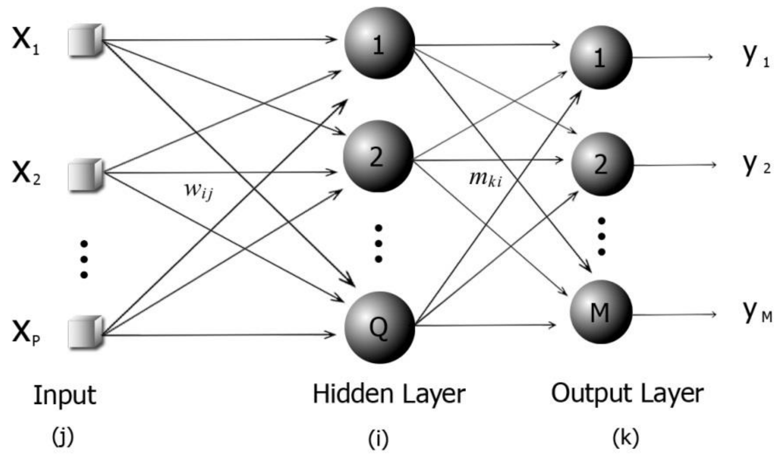

Figure 1. Generic Single-Hidden Layer Feedforward Neural Network.

In Fig. 1 is shown a generic architecture of a SLFN. First there is the input vector, that's fully connected with the hidden layer by the weights w_{ij} just like the synapses that connect biological neurons. The hidden layer uses non-linear function to make a transformation in data space and produces a linear-separable data space. The hidden-layer output is the input to the output layer, where the classification is done.

The MLP ANN trained by BP algorithm (MLP/BP) is probably the most studied and classical neural model, especially in classification applications, but even nowadays, a user soon becomes aware of the difficulties in finding an optimal architecture for real-world applications. An architecture that is too small will not be able to learn from data properly. Otherwise, an architecture having too many hidden neurons are prone to fit too much of the noise on the training data.

The many parameters that need to be adjust by heuristic or more commonly by attempt and error demands much time and effort to design a proper MLP, also the time wasted with the BP training is usually elevated. That led many researchers to look for a new algorithm that overcome the classical.

A new learning algorithm for SLFNs named ELM was presented in [24] and has become the aim of many studies. The two great advantages of the ELM are easy neural network design, which has practically no parameters to adjust and the training algorithm that computes extremely fast.

3.1 Backpropagation

This section describes briefly the most common algorithm used to training the MLP ANN, a detailed version can be find in Engelbrecht's book [22]. The learning algorithm requires two passes of computation: a forward pass and a backward pass. During the forward pass the synaptic weights remain unaltered, while the activations and outputs are computed on a neuron-by-neuron basis. At iteration t, the activation of a hidden neuron (one-hidden-layered MLP) is computed as

$$u_i^{(h)}(t) = \sum_{j=0}^{P} w_{ij}(t)x_j(t), \qquad i = 1, \dots, Q \tag{3.1}$$

where w_{ij} is the weight connecting the input j to the hidden neuron i, Q ($2 \leq Q < \infty$) is the number of hidden neurons and P is the dimension of the input vector (excluding the threshold). For the purpose of simplifying notation, it was set $x_0(t) = -1$ and $w_{i0} = \theta_i^{(h)}(t)$, where $\theta_i^{(h)}(t)$ is the threshold of the hidden neuron i. The output of neuron i is then defined by

$$y_i^{(h)}(t) = \varphi_i\left[u_i^{(h)}(t)\right] = \varphi_i\left[\sum_{j=0}^{P} w_{ij}(t)x_j(t)\right] \tag{3.2}$$

Where $\varphi_i(\cdot)$ is usually a sigmoidal function. Similarly, the output values of the output neurons are given by

$$y_k^{(o)}(t) = \varphi_k\left[u_k^{(o)}(t)\right] = \varphi_k\left[\sum_{i=0}^{Q} w_{ij}(t)x_j(t)\right] \tag{3.3}$$

where m_{ki} is the weight connecting the hidden neuron i to the output neuron k ($k = 1, \dots, M$), and $M \geq 1$ is the number of output neurons. For the same purpose, it was set $y_0(t) = -1$ and $m_{k0} = \theta_k^{(o)}(t)$, where $\theta_k^{(o)}(t)$ is the threshold of the output neuron k. The backward pass starts at the output layer by propagating the error signals from it towards the hidden layer. For that, first is computed the error value $e_k^{(o)}(t)$ generated by each output neuron at time step t

$$e_k^{(o)}(t) = d_k(t) - y_k^{(o)}(t), k = 1, \dots, M \tag{3.4}$$

where $d_k(t)$ is the target output value for the output neuron k. Due to the sigmoidal nonlinearity, the error signal $e_k(t)$ should be multiplied by the derivative $\phi_k'\left[u_k^{(o}(t)\right] = \partial\phi_k/\partial u_k^{(o)}$ before being back-propagated, thus generating the so called *local gradient* of the output neuron k

$$\delta_k^{(o)}(t) = \phi_k'\left[u_k^{(o)}(t)\right]e_k^{(o)}(t) \tag{3.5}$$

Similarly, the local gradient $\delta_i^{(h)}(t)$ of the hidden neuron i is then computed as

$$\begin{aligned} \delta_i^{(h)}(t) &= \phi_i'\left[u_i^{(h)}(t)\right]\sum_{k=1}^{M} m_{ki}(t)\delta_k^{(o)}(t) \\ &= \phi_i'\left[u_i^{(h)}(t)\right]e_i^{(h)}(t), \quad i = 0, \dots, Q \end{aligned} \tag{3.6}$$

where the term $e_i^{(h)}(t)$ plays the role of a *back-propagated* error signal for the hidden neuron i. Finally, the synaptic weights of the output neurons are updated according to the following rule

$$m_{ki}(t+1) = m_{ki}(t) + \eta\delta_k^{(o)}(t)y_i^{(h)}(t), \quad i = 0, \dots, Q, \tag{3.7}$$

where $0 < \eta \ll 1$ is the learning rate. The weights of the hidden neurons are adjusted through a similar learning rule

$$w_{ij}(t+1) = w_{ij}(t) + \eta\delta_i^{(h)}(t)x_j(t), \quad j = 0, \dots, P. \tag{3.8}$$

One complete presentation of the entire training set during the learning process is called an *epoch*. Many epochs may be required until the convergence of the BP algorithm is verified. Thus, it is good practice to randomize the order of presentation of training examples from one epoch to the next, in order to make the search in the weight space stochastic over the learning cycles.

A simple (and naive) way of evaluating convergence is through the average squared error

$$\varepsilon_{train} = \frac{1}{2N}\sum_{t=1}^{N}\sum_{k=1}^{M}\left[d_k(t) - y_k^{(o)}(t)\right]^2, \tag{3.9}$$

computed at the end of training run using the training data vectors. If it falls below a pre-specified value then convergence is achieved. The generalization performance of the MLP should be evaluated on a testing set, which contains examples not seen before by the network.

3.2 ELM

The ELM algorithm was proposed in 2004 by Guang-Bin et al [24] as an attractive option that can be used to training SLFNs instead classical gradient descent-based methods like the BP. The authors prove that the proposed algorithm can typically training any dataset thousands times faster than the error BP. It is possible because it was proved in [25] that SLFNs with arbitrarily assigned input weights and hidden layer biases and with almost any nonzero activation function can universally approximate any continuous functions on any compact input sets.

These researches results imply that in the applications of feed-forward neural networks input weights may not be necessarily adjusted at all. They just assume that the hidden-layer weights are chosen arbitrarily and can make a non-linear transformation in data space that makes the hidden-layer output as a linear system and therefore can be solved by a simple generalized inverse operation of the hidden-layer output matrices [24]. It follows a possibility to the ELM algorithm:

The equations (3.1) and (3.2) can be expressed in a matrix-vector notation respectively as (3.10) and (3.11),

$$u(t) = Wx(t) \tag{3.10}$$

$$y^{(h)}(t) = \varphi_i(u_i(t)) = \varphi_i(Wx(t)) \tag{3.11}$$

where the function $\varphi_i(\cdot)$ is applied to each one of the Q components of vector $u(t)$. The vector $y^{(h)}(t)$ is calculated to each dataset sample and organized in a matrix $Y^{(h)}$ with Q (number of hidden neurons) lines and N (number of samples) rows. This matrix is used to calculate the output weights.

To each input vector $x(t), t = 1, \ldots, N,$ there exists a target output vector $d(t)$. The N target output vectors can be organized in a matrix with M (number of output neurons) lines and N rows.

$$D = [d(1) \mid d(2) \mid \cdots \mid d(N)]_{MxN} \tag{3.12}$$

The calculation of the output weights can be considered as the calculation of a linear mapping between the output layer and the hidden layer. That means it searches the matrix M that better represents the transformation of the input vectors $x(t)$ to its correspondent target vector $d(t)$

$$d(t) = My^{(h)}(t) \tag{3.13}$$

which can be done by the least-square error method, also known as pseudo-inverse method. The expression is given by

$$M = DY^{(h)^T}(Y^{(h)}Y^T)^{-1} \tag{3.14}$$

The same way back-propagation, the average squared error can be used to evaluating convergence.

4. Experimental Data Acquisition

To collect the dataset needed to training the ANNs, an induction motor was rewound by a specialized company. The motor is a WEG with rated values: $0{,}75\ kW\ (1.0\ CV), 60\ Hz, 220/380\ V, 3.02/1.75\ A, n = 1720\ rpm, efficiency{:}\ 79.5\%, F.P. = 0.82$. Originally each phase is composed by 2 groups of 3 concentric windings, each one with 58 coils. After rewinding, coil derivations of one group of each one of the three phases were let outside the motor frame the way to allow apply SWITSC. In Figure 2 (b) it is shown the derivations details. A frequency converter WEG CFW-09 was used to drive the motor and a Foucault's brake - Figure 2 (a) - was used to apply load. The data was acquired by a data acquisition system Agilent U2352 with 16 bits of resolution, passing through a 1 kHz analog filter and a signal amplifier; that implies the band used to work is limited to 500 Hz by the Nyquist's[1].

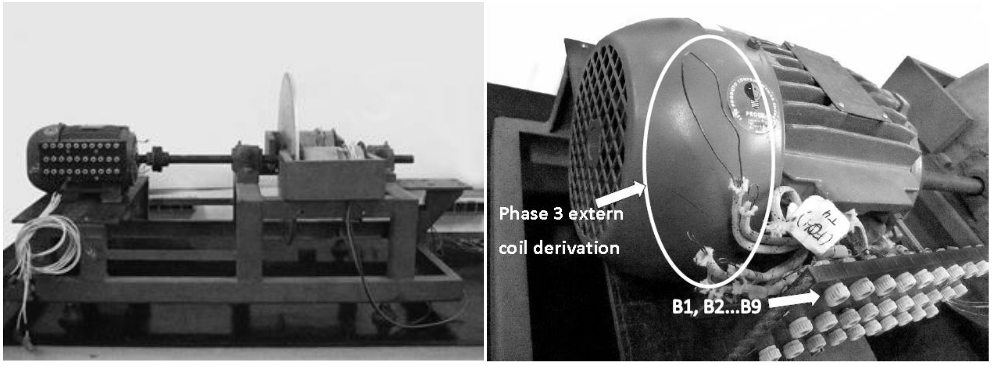

Figure 2. (a) Induction motor extern derivations details and bornes and (b) Coupling Motor-Load (Foulcault's brake).

The three phase current signals are measured by hall sensors and collected with a frequency of sample of 10 kHz during 10 seconds. That creates a dataset of 100,000 samples to each phase.

The motor is delta connected. To the acquisition the frequency converter is set to seven different values: 30 Hz, 35 Hz, …, 60 Hz. Furthermore, three load conditions are considered: unload motor, 50% rated load motor and 100% rated load motor.

To cover a considerable range of the SWITSC fault it was defined two kinds of short circuit: high impedance (HI) and low impedance (LI). The first one emulates the incipient SWITSC and the second one emulates a more severe fault. In the Figure 3 it is shown the simplified scheme of each kind of fault. In Figure 3 (a) the resistor creates a parallel way with high impedance to the current flows, similar to the first stage of short-circuit. In Figure 3 (b) the resistor limits at nominal the current that flows by electromagnetic induction in group 2, but the impedance between groups 1 and 3 is low.

One of the three phases is chosen to be short-circuited to the data acquisition tests. Three crescent levels of inter-turn short- circuits are applied both in HI and LI. Represented as the percentage of the total number of stator windings in that phase, the levels are approximately 1.41%, 4.81% and 9.26%. In the following text the HI fault might be referred as HI1, HI2 and HI3 that means HI with 1.41%, with 4.81% and with 9.26% of short circuited windings respectively. The same is valid to LI fault.

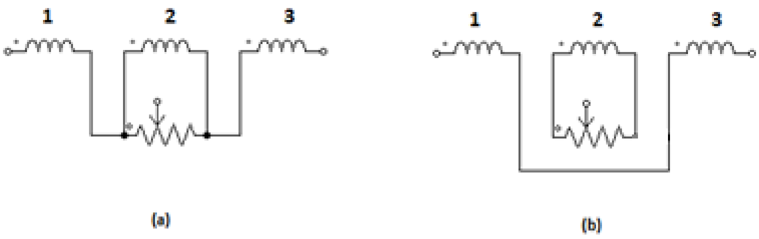

Figure 3. Emulation scheme of: a) high impedance and b) low impedance.

4.1 Datasets

Two mainly datasets created are the healthy and the fault datasets, but is important to emphasize that the fault condition can be subdivided in HI fault and LI fault. The HI and LI can once more be subdivided according the level of inter-turn short circuit (HI1, HI2, HI3, LI1, LI2, LI3).

[1] Sample Nyquist's Theorem: considering $x_c(t)$ a limited signal in band with its frequency domain version given by $X_c(j\Omega) = 0$ to $|j\Omega| \geq \Omega_N$, then $x_c(t)$ is only determined by its samples $x(n) = x_c(nT), n = 0, \pm 1, \pm 2, \ldots$ if $\Omega_s = 2\pi/T \geq 2\Omega_N$. The $\Omega_N$is usually defined as the Nyquist frequency ['OPPENHEIM et al., 1999']

The normal condition and each one of the subdivided fault (HI1, HI2, HI3, LI1, LI2, LI3) contains 100,000 time domain samples to each phase. The spectrum in frequency domain is obtained by the Fast Fourrier Transform (FFT). From the each spectrum some multiples are chosen as neural networks input attributes.

Due there is redundant information given by the two phases directly connect with the short circuit, one of them is unnecessary and can be excluded. Then the phase B current is not used in the datasets which gives a total amount of samples equal to 378 (2 classes x 2 currents x 7 frequencies x 3 loads x 2 kinds of fault x 3 levels of fault). The normal conditions dataset has 42 samples (2 currents x 7 frequencies x 3 loads), and the fault condition has 336 samples, which 168 are HI and 168 LI.

To a practical implementation of the classifier, only one sensor in anyone of the three phases would be necessary to detection. That is possible because the ANN is trained with the characteristics of the phase directly connected to the short-circuit as well as with the phase not directly connected to it.

4.2 Attributes Selection

The equation (2.1) is used to make a pre-selection of the harmonics used as ANN attributes. Considering the $s = 0$ and known that $p = 2$, the spectrums when $k = 1$ and $n = 1, 2, 3, 4, 5, \ldots$ obtained from equation (2.1) are: $0.5f_1$, $1f_1$, $1.5f_1$, $2f_1$, $2.5f_1$, $3f_1$, …. But the slip will never be zero; it depends on the load and also of the drive frequency. So an algorithm is used to get the amplitude of approximated harmonics: those harmonics are used as a central point and a search for the maximum amplitude value around each one of them is done. The range to the search is $\pm s$. Due the band limit of 500 Hz, it is done until 8^{th} harmonic, which gives 16 pre-selected parameters.

Summarizing, the pre-selected attribute vector contain 16 values that are the approximated spectrum given by equation (2.1). To reduce this number, it was done a statistic analysis (**Erro! Fonte de referência não encontrada.**) of the variance of the pre-selected attributes considering all the conditions used (load, frequencies, kind of faults, level of faults). The attributes are reduced to 0.5f; 1f; 1.5f; 2f; 3f; 5f; 7f, but it was not the final ones. It was included also 2.5f, 3.5f because these are the approximated harmonics to a 4 pole motor according [2] that gives information about short-circuit, but after testing each component relevancy of these harmonics to the ANN, the final attributes chosen were 0,5f; 1,5f; 2,5f; 3f; 5f; 7f.

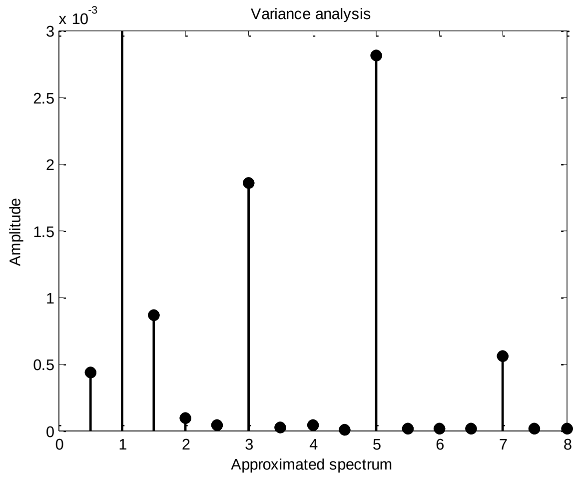

Figure 4. Variance analysis to attributes selection.

5. Results

During the training of the ANNs 90% of data samples were used. The 10% remained composed the validation dataset. However, the training dataset was equally divided to each class in a way to avoid tendentious classification. Consequently, due the healthy dataset has 42 samples and the faulty condition has 336 samples, great part of the faulty dataset are not used during the training, so these data are added to validation dataset.

There are no formulas to select the BP parameters, so all the parameters used were selected after several attempts. At the end the hidden-layer was set to 5 neurons. The learning rate used decreases exponentially with the number of epochs until a final value. Also it was used a momentum term of 0.8. It was implemented the early stop, that uses a test dataset to stop the training when the generalizing error is growing. Thus the datasets has to be divided to training, testing and validation. Respectively, they were set to 70%, 20% and 10% of the total. To the ELM, the only parameter to be adjusted is the number of hidden-layers that was set to 20 after many experiments.

In Both ANNs the activation functions are hyperbolic tangents and the datasets were normalized by two ways: i) removing the average and dividing by variance and ii) by adjusting the values between -1 and +1.

To evaluate a classifier performance it is commonly used the classification rate, that is given by the numbers of vectors correctly classified divided by the total numbers of all classes vectors. Many researchers usually evaluate the validation dataset only, i.e. the generalization capability with new data. But many samples are used during the training and then the classification rate found to training dataset is considered important.

Moreover, using simple global classification rate do not give an evaluation about individual performance of each class classification, then is common to complement the performance evaluation by the use of a confusion matrix CM. The diagonal of the CM has the classification rate to each class.

The ANNs and its algorithms are programed using the software MATLAB version 7.11. In Table 1 is shown the average results found after 50 trainings and its standard deviation. Some abbreviations are used: CR for classification rate; the subscripts TR, TS and VAL refer to training, test and validation datasets; respectively; σ for standard deviation; Nh for the number of hidden-neurons; N_W for the total number of weights.

To attest the non-linear separability of the datasets it was included a test with the simple perceptron which is a linear neural classifier. In Table 2 is shown the Confusion Matrix Average CM.

Table 1. Average results of the ANNs.

ANN	Nh	N_W	CR_{TR}	σ_{TR}	CR_{TS}	σ_{TS}	CR_{VAL}	σ_{VAL}
Perceptron	1	7	60.07%	20.56	-	-	50.46%	19.20
MLP/BP	5	41	77.95%	8.82	74.91%	11.03	64.92%	11.26
MLP/ELM	20	161	82.48 %	3.67	-	-	65.17 %	4.80

The linear classifier Perceptron hits on average about 60% of the training dataset. It means the Perceptron has no capability of mapping the dataset. It also presents poor generalization capability. Looking to MLP results with BP and ELM it is realizable that the classification to this problem is a hard task even using non-linear classifiers: on average about 65% of the new data are correctly classified both to MLP/BP as to MLP/ELM. The number of weights in MLP/ELM is almost 4 times greater than the MLP/BP, which is an important feature when one thinks in to embed the ANN in micro-processors with limited memory capacity.

Table 2. Confusion Matrices Average.

ANN	CM_{TR} (%)			CM_{TS} (%)			CM_{VAL} (%)		
		Healthy	Faulty		Healthy	Faulty		Healthy	Faulty
MLP/BP	Healthy	80.21	19.79	Healthy	77.45	22.55	Healthy	69.33	30.67
	Faulty	24.31	75.69	Faulty	27.64	72.36	Faulty	35.17	64.83
		Healthy	Faulty					Healthy	Faulty
MLP/ELM	Healthy	87.84	12.16	-			Healthy	75.60	24.40
	Faulty	23.00	77.00				Faulty	35.01	64.99

The MLP/BP present more equally classification, it is possible to see in CM_{TR} that about 75% of faulty data were correctly classified on average, and about 80% of the healthy were correctly classified. That is a discrepancy of about 5% whereas in the MLP/ELM this discrepancy is about 10%.

Table 3. Percentages of correctly classification to each level of short-circuit.

ANN - Dataset	HI1	HI2	HI3	LI1	LI2	LI3
$MLP/BP - TR$	67%	72%	74%	73%	84%	91%
$MLP/ELM - TR$	70%	75%	77%	75%	80%	92%
$MLP/BP - VAL$	59%	60%	66%	64%	70%	70%
$MLP/ELM - VAL$	60%	61%	66%	64%	67%	72%

The faulty dataset is composed by 6 sub-divisions of faults, as early mentioned, named here as HI1, HI2, HI3, LI1, LI2, LI3. Table 3 shows the average of the correctly classification to each level of fault to training and test dataset. It is possible to see that the more coils are short-circuited, the faults are more correctly classified.

Average results are used to evaluate the general behavior of the designed neural networks, but in the real implementation one ANN must be chosen. Then one ANN trained by back-propagation and other trained by ELM were chosen to be pruning and then used to show the final results. The method used is called CAPE and can be found in [26].

The choice of the specifics ANNs take in consideration the classification rate of validation and training datasets, but it was observed mainly the *CR* to each class. The priority was to choose an ANN that correctly classified all the healthy conditions in the validation datasets. That choice aims to avoid false positives in an online constant monitoring.

Table 4. Results to specifics ANNs.

MLP	N_W	CR_{TR}	CR_{TS}	CR_{VAL}	CM_{TR} (%)	CM_{TS} (%)	CM_{VAL} (%)
BP	41	89.7	81.8	68.5	H F H 94.9 5.1 F 15.3 84.7	H F H 81.8 18.2 F 18.2 81.8	H F H 100.0 0.0 F 32.1 67.9
BP/ CAPE	34	87.1	81.8	70.2	H F H 94.9 5.1 F 20.5 79.5	H F H 81.8 18.2 F 18.2 81.8	H F H 100.0 0.0 F 39.7 69.3
ELM	161	84.1	-	63.8	H F H 90.2 9.8 F 22.0 78.0	-	H F H 100.0 0.0 F 36.1 63.9
ELM/ CAPE	-	-	-	-	-	-	-

In Table 4 it is shown that the specific MLP /BP reaches better classification both to training dataset as to validation dataset. Moreover, after pruning the MLP/BP was able to improve its generalization capacity. The MLP/ELM was not able to be appropriated pruned by the CAPE method.

In [1] the same dataset used in this work was used in a Self-Organized Map ANN. There are differences in attributes used, and in datasets normalization. The final result presented by [1] gives a global *CR* of 87.5%. However, the *CR* to healthy dataset is 52%, whereas the *CR* to faulty dataset is 94.5%. That result means the most data are classified as faulty which is larger than the healthy dataset. In an online constant monitoring it also probably means that there is a high probability of false positives occurrence.

6. Conclusions

The problem of early fault detection in fed-converter induction motor is a subject that is far to be completely solved. The investigation with real datasets reveals difficulties in separating the faulty datasets from the healthy ones, which reinforces the importance of constant on-line monitoring. The use of converter adds the possibility of to embed the system directly in the equipment, which means more protection to the converter besides all the discussed benefits of early fault detection to the machine and to industries. The great advantages of this non-invasive detection system make its improvement a task with great potential; one possibility involves the choice of relevant spectrums as parameters to training the classificator which is not an ended issue and is directly related with the classifier accuracy.

The two algorithms used to training the classifier showed similar results, but the ELM computes much faster and is much easier designed, although the MLP/ELM needed four times more neurons in the hidden- layer to do so. The pruning method was capable to improve the generalization in MLP/BP through the removing of connections, but the MLP/ELM was not able to be pruning by the method used.

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Induction Motor Oversizing – Are There Any Benefits?

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Abstract

It is well known that, in general, the oversizing of three-phase squirrel-cage induction motors should be avoided. However, due to poor system design, safety factors, discontinuous availability of commercial rated power, and/or load power variation, most motors are oversized. Besides the extra capital investment, the oversizing of line-fed fixed-speed induction motors can lead to a significant efficiency and power factor reduction, leading to an increase in the consumed active and reactive energy cost. Moreover, oversized motors without speed control have lower slip, leading to an increase of the shaft output power and energy consumption. Besides that, the higher rotor inertia leads to larger starting losses and to longer stopping time. However, the rated/nominal efficiency increases with the motor rated power and the higher the latter is, the flatter the efficiency curve will be. In addition, the oversized motor will run cooler, having extended lifetime and higher tolerance to voltage unbalance and harmonic distortion. A question arises: for a given motor efficiency class and load profile, is the motor oversizing a cost-effective option for new or existing fixed-speed applications? In this paper, authors analyze these issues, on the basis of the catalogue technical data provided by one of the largest motor manufacturers for IE1-, IE2-, IE3- and IE4-class induction motors. A method to calculate the input active and reactive power for any load level, on the basis of the motor catalogue data, is proposed and applied. It can be anticipated that, if the additional reactive energy consumption due to poorer power factor and the slight speed increase are ignored, in some cases, the oversizing can be cost-effective.

I. Introduction

In the European Union, the average motor load factor in industry is around 60%. Nearly 90% of the industrial electric drive systems integrate three-phase squirrel-cage induction motors (SCIMs). In industry, SCIMs can use more than ⅔ of the electrical energy [1-3].

Due to poor system design, safety factors, discontinuous availability of commercial rated power and/or load power variation, most motors are oversized [1-6]. For example, in pumping systems, the pump and motor oversizing can be a consequence of conservative system specifications provided by the user to the supplier, including the required pressure and flow, the piping friction losses and the pressure drop in valves.

Providing the motor is well sized for maximum power required by driven equipment over the entire duty cycle, the load factor can be quite low in variable-load fixed-speed applications.

Nowadays, in developed countries, motor market is moving toward Premium/IE3 and Super-Premium/IE4 Efficiency motors. Nevertheless, Standard/IE1 and High/IE2 Efficiency motors are still widely used worldwide [7, 8].

On one hand, the commercial SCIMs rated efficiency increases with the rated power. On the other hand, the efficiency of SCIMs decreases significantly with the output power (or load) for loads lower than 60% and, typically, for the rated voltage, the peak efficiency occurs between 60% and 100% load, depending on the motor rated power, efficiency class and brand/manufacturer [4-6]. Therefore, jumping from one commercial rated power to another immediately higher, leads to a gain in the motor rated efficiency, but to a lower load level, which, in turn, can lead to a part-load efficiency lower than the nominal. Furthermore, even when an efficiency gain is obtained with motor oversizing, the part-load power factor is worse with respect to that of a well sized motor, because it decreases sharply with the motor load power. In addition, motor oversizing leads to a higher initial cost (including the additional cost associated with larger circuit-breakers, starters, variable-speed drives and/or power cables gauge) but can extend the motor lifetime (due to the longer winding insulation and bearing lifetime). The larger rotor inertia when oversizing a motor should also be taken into account in applications with frequent start/stop cycles and/or rotation direction changes, because of the consequent higher starting losses and longer stopping time. The lower slip of higher power motors also leads to an increase in the mechanical power required by the application, increasing the active energy consumption. Of course, this change of slip and motor speed can be easily compensated in motors controlled by variable-speed drives.

A question arises: for a given motor efficiency class and load profile, is the line-fed motor oversizing a cost-effective option for new or existing fixed-speed applications? In this paper, the authors perform a cost-effectiveness analysis and make an attempt to respond to this question, using motor catalogue data from one of the largest motor manufacturers, for SCIMs of IE1, IE2, IE3 and IE4 classes. A method to estimate the motor efficiency, power factor and current at any load level is proposed and applied. This method can also be used to estimate the in-field motor load level by means of methods based on line current, power factor or input active power [9], using the motor catalogue/datasheet values as reference.

II. Motor Catalogue Data and List Prices

In Fig. 1, the efficiency class limits defined in the IEC 60034-30 standard (Edition 1, in force; Edition 2, in preparation) [7, 8] and the rated efficiency of commercial SCIMs of different classes and of one Line-Start Permanent Magnet Synchronous Motor (LSPM) commercial model, all from the same manufacturer, are shown. The efficiency at 50%, 75% and 100% load levels are shown in Figs. 2-5. In Fig. 6, the efficiency gain potential when comparing the full-load efficiency for a given reference output power with the corresponding part-load efficiency for higher rated powers is evidenced. It should be noted that part-load efficiency determination is not mandatory and the values in the catalogue may not correspond to thermal equilibrium. Therefore, the steady-state part-load efficiency can be higher than those values presented in the commercial catalogues.

In Fig. 7, the rated speed for the different motor models is presented, showing that the better the efficiency class the lower the full-load slip.

The moment of inertia of the different motor models is shown in Fig. 8. Obviously, the higher the motor rated power the higher the rotor inertia.

The list prices in EUR/kW and EUR are presented in Figs. 9 and 10.

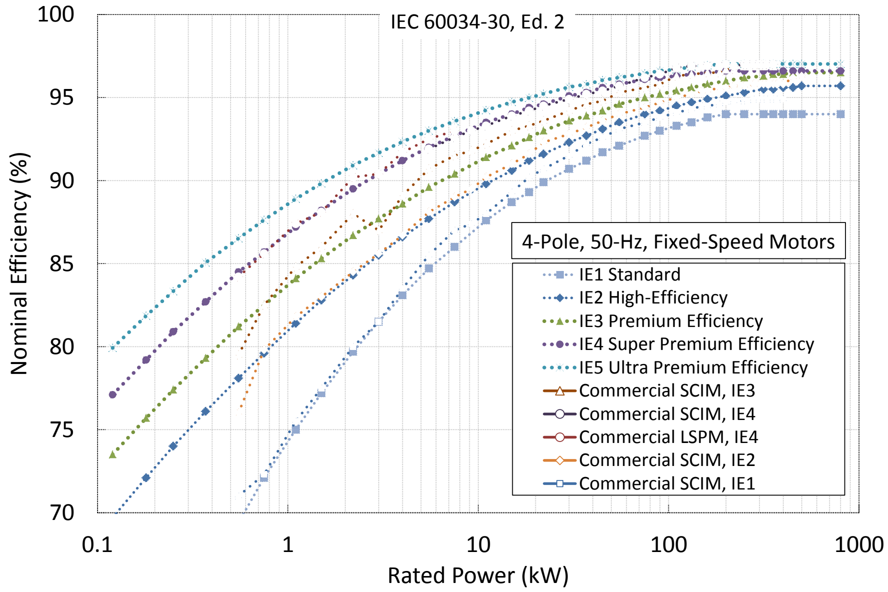


Fig. 1. IEC 60034-30 efficiency classes limits (IE1, IE2, and IE3 defined in Edition 1, in force; IE4 and IE5 defined in Edition 2, in preparation) and rated efficiency of commercial SCIM models of different efficiency classes [7, 8].

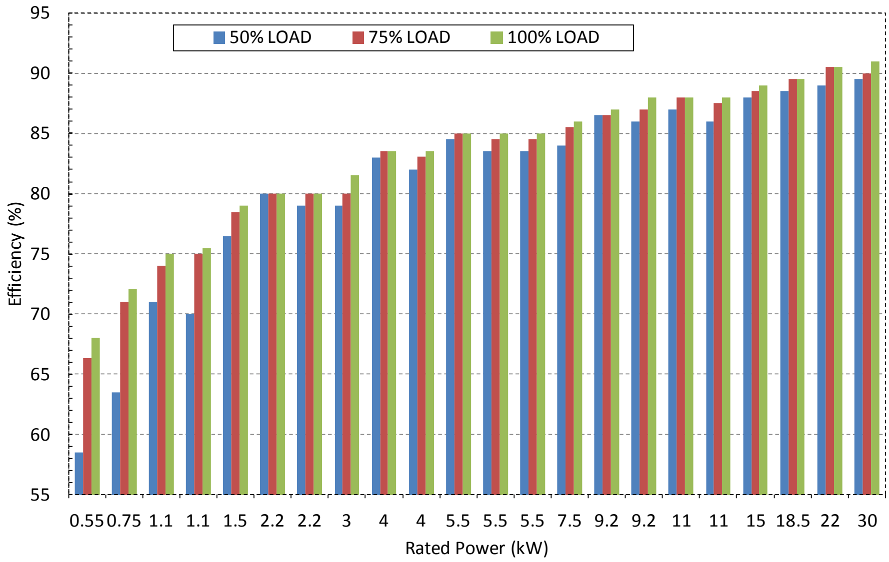


Fig. 2. Efficiency of commercial IE1-class SCIMs for 50%, 75% and 100% load levels [10].

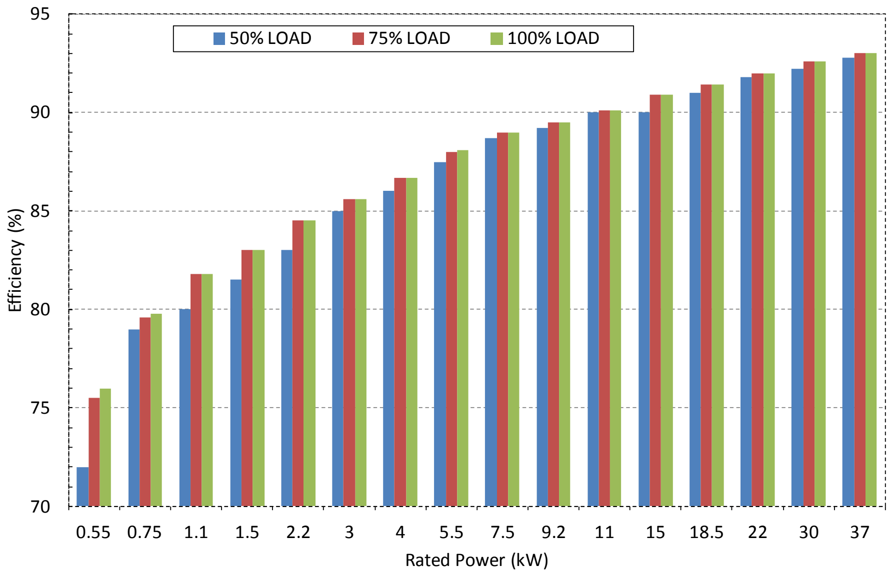


Fig. 3. Efficiency of commercial IE2-class SCIMs for 50%, 75% and 100% load levels [10].

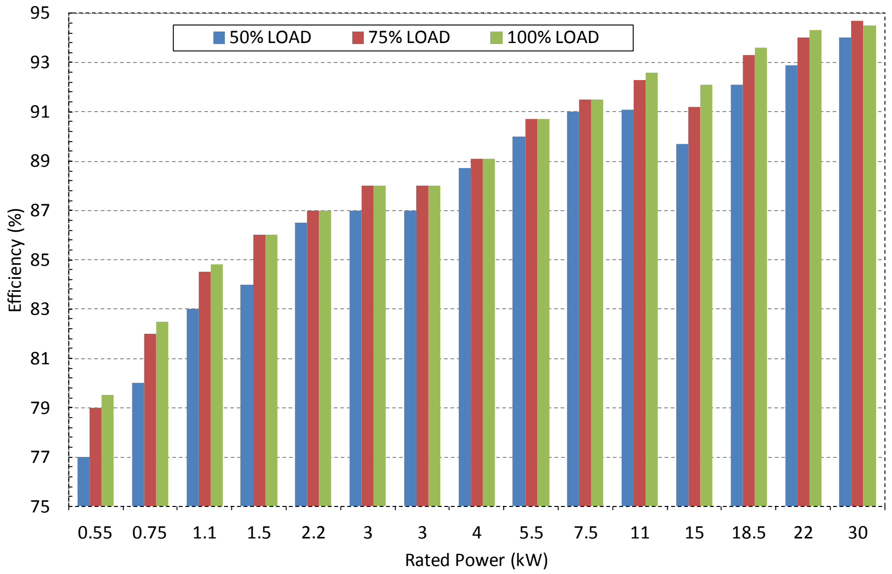


Fig. 4. Efficiency of commercial IE3-class SCIMs for 50%, 75% and 100% load levels [10].

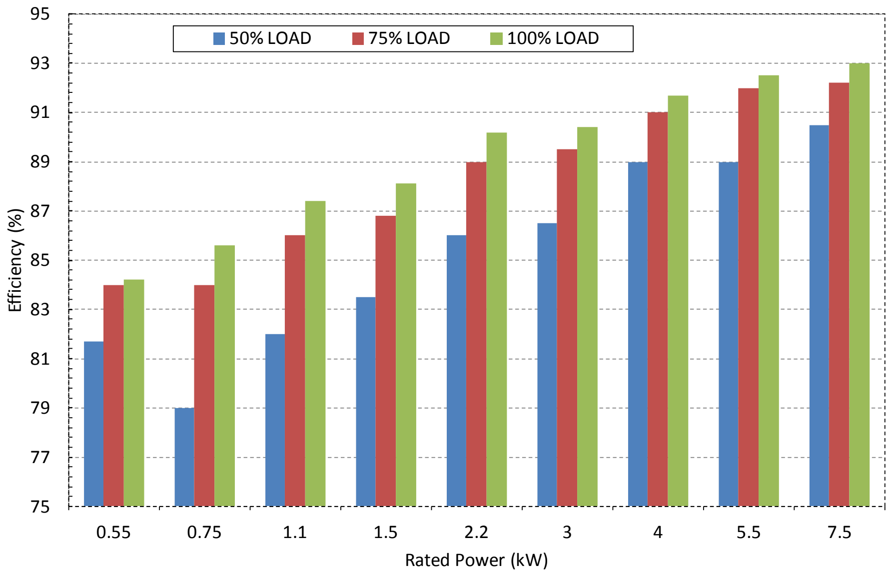


Fig. 5. Efficiency of commercial IE4-class SCIMs for 50%, 75% and 100% load levels [10].

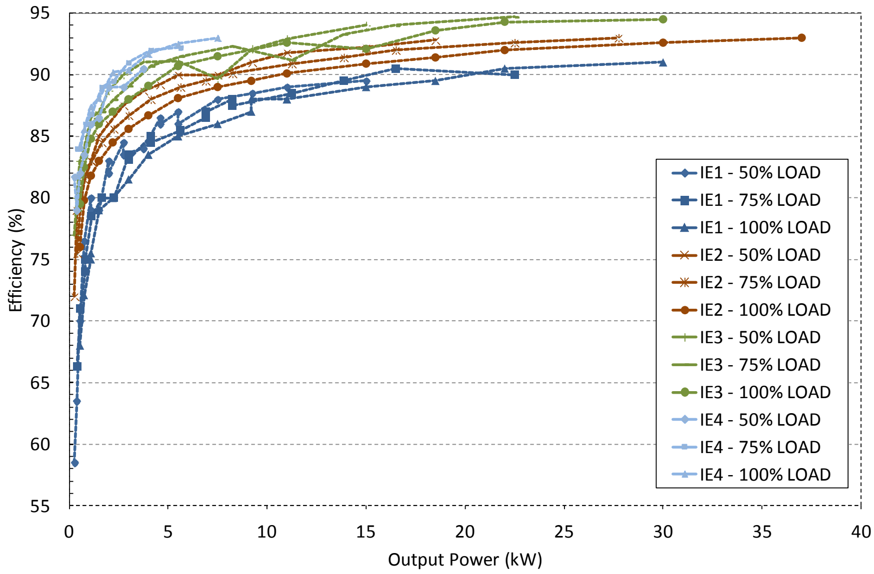


Fig. 6. Comparison of catalogue efficiency of commercial SCIMs (from the same manufacturer) as a function of the output power, for 50%, 75% and 100% load levels [10].

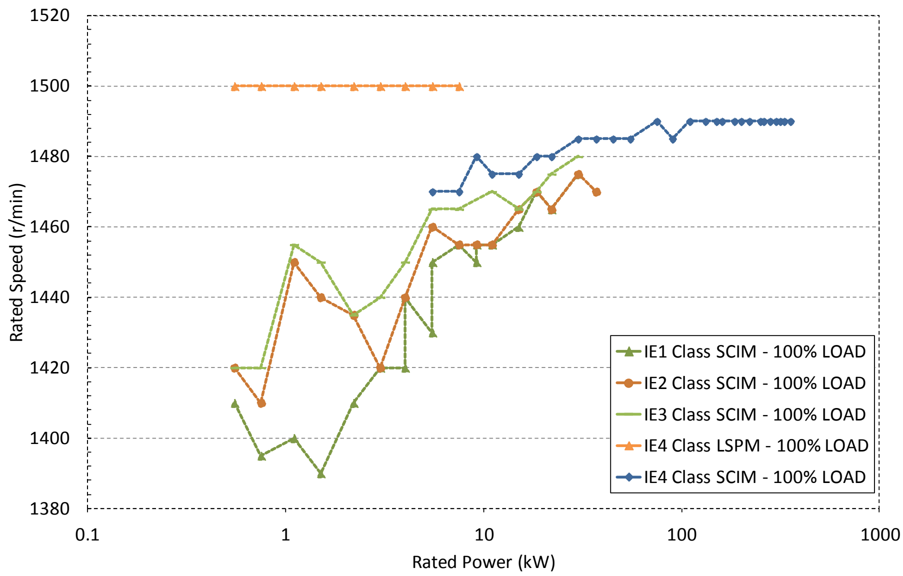


Fig. 7. Rated speed of commercial motors of different efficiency classes (from the same manufacturer) [10].

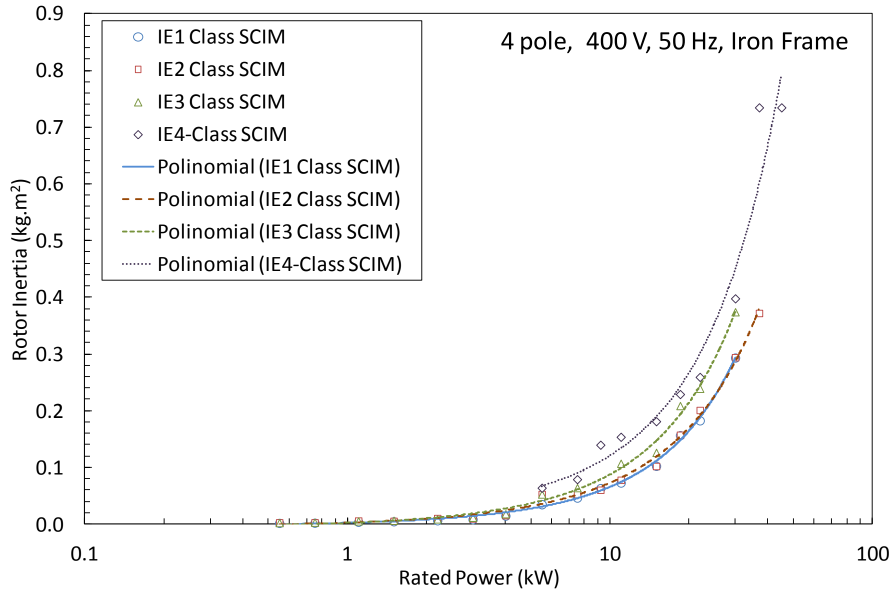


Fig. 8. Moment of inertia of commercial SCIMs of different efficiency classes (from the same manufacturer) [10].

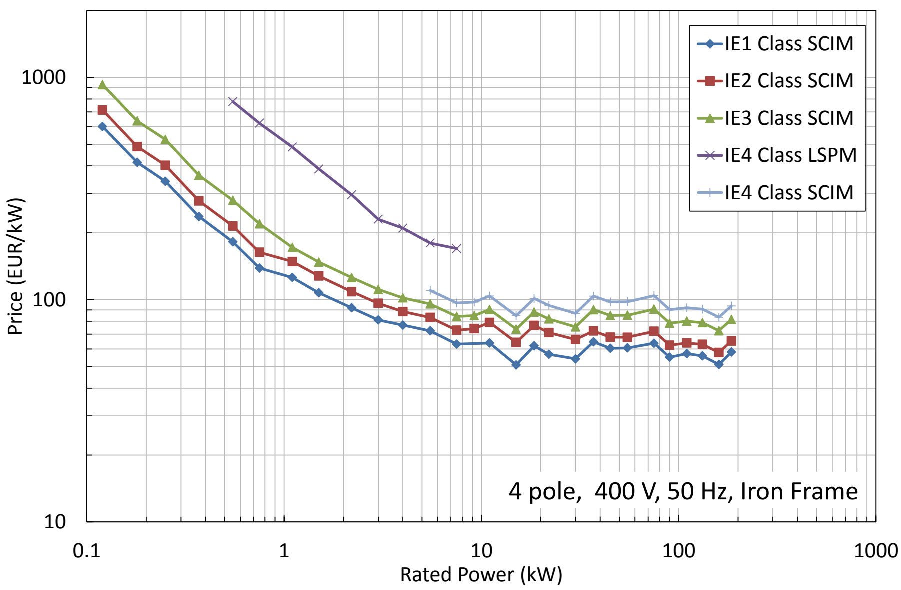


Fig. 9. List prices in EUR/kW for commercial motors of different efficiency classes (from the same manufacturer) [11].

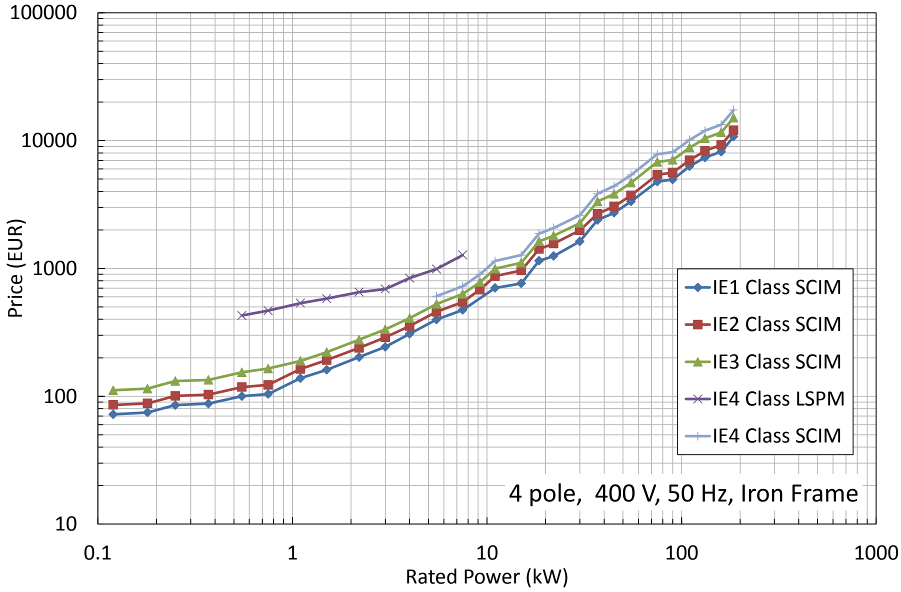


Fig. 10. List prices in EUR for commercial motors of different efficiency classes (from the same manufacturer) [11].

III. Methodology

In this study, only 400-V, 50-Hz, 4-pole SCIMs of IE1, IE2, IE3 and IE4 classes, according to IEC 60034-30, are considered. The motor technical data from the commercial catalogues of one of the world largest electric motor manufacturers has been used. The motor list prices considered were provided by that same manufacturer (Figs. 9 and 10), and a typical 40% discount has been applied in some of the considered scenarios. Average active and reactive energy prices of 0.07 €/kWh and 0.015 €/kvarh, respectively, and 8000 h/a of operation have been considered.

Typically, the motor catalogue technical data includes the efficiency and power factor at 100%, 75% and 50% load levels. The efficiency value at 100% (nominal/rated efficiency) is according to the IEC 60034-2-1, but the other two part-load values, as previously referred, in most cases, are not measured at thermal equilibrium (thermal steady state). The motor efficiency values at 75% and 50% load levels for thermal equilibrium are likely to be slightly higher, due to the expected lower internal temperature.

On the basis of the provided efficiency and power factor for three different load levels, a new method is applied to estimate the motor efficiency, power factor and line current, at any load. Actually, the estimated current can be further used to apply the in-field current-based motor load estimation method. The motor load δ is given by the quotient between the shaft output power and the rated/nominal power. The load factor is the average load in a given time period.

Firstly, the following variables and matrixes are defined for the motor:

- Rated Power, P_n;
- Rated Voltage, U_n;
- Number of Operating Hours per Year, H;
- Price of Active Energy, EP_{kWh};
- Price of Reactive Energy, EP_{kvarh};
- Reference Load Matrix, $\boldsymbol{\delta}_{ref} = [\delta_1 \quad \delta_2 \quad \delta_3]$;
- Reference Efficiency Matrix, $\boldsymbol{\eta}_{ref} = [\eta_1 \quad \eta_2 \quad \eta_3]$;
- Reference Power Factor Matrix, $\boldsymbol{\lambda}_{ref} = [\lambda_1 \quad \lambda_2 \quad \lambda_3]$;
- Load Profile Level Matrix, $\boldsymbol{D} = [D_1 \quad D_2 \quad D_3]$;
- Load Profile Time Share Matrix, $\boldsymbol{T} = [T_1 \quad T_2 \quad T_3]$.

Although only 3 different load levels are being considered, it can be used any number of load levels.
In this method, it is assumed that losses and current can be described approximately by means of a 2nd order polynomial equation, from no-load to full-load. Therefore, for that purpose, a constant matrix $\boldsymbol{C}$ is defined,

$$\boldsymbol{C} = \begin{bmatrix} 1 & 1 & 1 \\ \delta_1 & \delta_2 & \delta_3 \\ \delta_1^2 & \delta_2^2 & \delta_3^2 \end{bmatrix}.$$

Based on the previously defined constants, the reference motor loss and current matrices are given by

$$\boldsymbol{L} = P_n\begin{bmatrix} -\delta_1 + \delta_1 \cdot \eta_1^{-1} & -\delta_2 + \delta_2 \cdot \eta_2^{-1} & -\delta_3 + \delta_3 \cdot \eta_3^{-1} \end{bmatrix} \ , \tag{1}$$

$$\boldsymbol{I} = \frac{P_n}{\sqrt{3} \cdot U_n} \begin{bmatrix} \delta_1 \cdot \lambda_1^{-1} \cdot \eta_1^{-1} & \delta_2 \cdot \lambda_2^{-1} \cdot \eta_2^{-1} & \delta_3 \cdot \lambda_3^{-1} \cdot \eta_3^{-1} \end{bmatrix} \ . \tag{2}$$

After defining the values of matrices $\boldsymbol{L}$ and $\boldsymbol{I}$, the solution for the three constants of the 2nd order polynomial equations (or quadratic equation) to describe the loss and current as a function of the load obtained using (3) and (4):

$$\boldsymbol{S_L} = \boldsymbol{L} \cdot \boldsymbol{C^{-1}} \ , \tag{3}$$

$$\boldsymbol{S_I} = \boldsymbol{I} \cdot \boldsymbol{C^{-1}} \ . \tag{4}$$

Finally, the loss and current quadratic equations can be defined as a function of the motor load:

$$L = S_{L1} + S_{L2} \cdot \delta + S_{L3} \cdot \delta^2 \ , \tag{5}$$

$$I = S_{I1} + S_{I2} \cdot \delta + S_{I3} \cdot \delta^2 \ . \tag{6}$$

The efficiency and power factor at any load point are given by:

$$\eta = \frac{P_n \cdot \delta}{P_n \cdot \delta + S_{L1} + S_{L2} \cdot \delta + S_{L3} \cdot \delta^2} \ , \tag{7}$$

$$\lambda = \frac{P_n \cdot \delta}{\eta \cdot \sqrt{3} \cdot U_n \cdot (S_{I1} + S_{I2} \cdot \delta + S_{I3} \cdot \delta^2)} \ . \tag{8}$$

A MATLAB script has been written for the systematic application of the previous methodology. As an example, for the set of values presented in Table I, for 11-, 15-, and 18.5-kW, IE2-Class, 400-V, 50-Hz SCIMs, the simulated efficiency and power factor curves presented in Fig. 11 are obtained.

Table I. Set of values used to simulate the efficiency and power factor curves.

P_n = 11 kW	$\eta_{50\%}$ = 89.0	$\eta_{75\%}$ = 90.2	$\eta_{100\%}$ = 90.2	$\lambda_{50\%}$ = 0.65	$\lambda_{75\%}$ = 0.76	$\lambda_{100\%}$ = 0.83
P_n = 15 kW	$\eta_{50\%}$ = 90.6	$\eta_{75\%}$ = 91.0	$\eta_{100\%}$ = 91	$\lambda_{50\%}$ = 0.66	$\lambda_{75\%}$ = 0.76	$\lambda_{100\%}$ = 0.83
P_n = 18.5 kW	$\eta_{50\%}$ = 91.5	$\eta_{75\%}$ = 91.8	$\eta_{100\%}$ = 91.6	$\lambda_{50\%}$ = 0.68	$\lambda_{75\%}$ = 0.78	$\lambda_{100\%}$ = 0.83

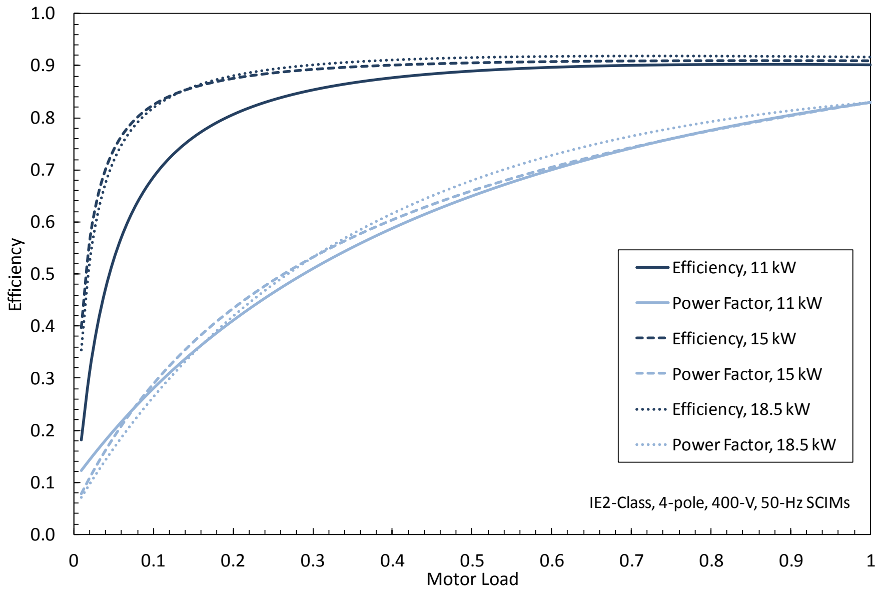


Fig. 11. Simulated efficiency and power factor curves using the proposed method.

With the proposed method, the motor efficiency and power factor can be known at any load point, and used in the economic studies for any load cycle profile.

For the load profile level matrix $\boldsymbol{D}$, the efficiency corresponding to each load level (D_1, D_2, D_3) yields

$$\boldsymbol{\eta} = \begin{bmatrix} \frac{P_n \cdot D_1}{P_n \cdot D_1 + S_{L1} + S_{L2} \cdot D_1 + S_{L3} \cdot D_1^2} & \frac{P_n \cdot D_2}{P_n \cdot D_2 + S_{L1} + S_{L2} \cdot D_2 + S_{L3} \cdot D_2^2} & \frac{P_n \cdot D_3}{P_n \cdot D_3 + S_{L1} + S_{L2} \cdot D_3 + S_{L3} \cdot D_3^2} \end{bmatrix} \quad . \tag{9}$$

The annual active energy consumption matrix $\boldsymbol{AE}$ is given by

$$\boldsymbol{AE} = \begin{bmatrix} \frac{P_n \cdot D_1 \cdot H \cdot T_1}{\eta_1} & \frac{P_n \cdot D_2 \cdot H \cdot T_2}{\eta_2} & \frac{P_n \cdot D_3 \cdot H \cdot T_3}{\eta_3} \end{bmatrix} \quad . \tag{10}$$

The total annual active energy consumption AE is

$$AE = \frac{P_n \cdot D_1 \cdot H \cdot T_1}{\eta_1} + \frac{P_n \cdot D_1 \cdot H \cdot T_1}{\eta_1} + \frac{P_n \cdot D_3 \cdot H \cdot T_3}{\eta_3} \quad . \tag{11}$$

The motor current matrix $\boldsymbol{I}$ is expressed by

$$\boldsymbol{I} = \begin{bmatrix} S_{I1} + S_{I2} \cdot D_1 + S_{I3} \cdot D_1^2 & S_{I1} + S_{I2} \cdot D_2 + S_{I3} \cdot D_2^2 & S_{I1} + S_{I2} \cdot D_3 + S_{I3} \cdot D_3^2 \end{bmatrix} \quad . \tag{12}$$

The power factor matrix $\boldsymbol{\lambda}$ is

$$\boldsymbol{\lambda} = \begin{bmatrix} \frac{P_n \cdot D_1}{\eta \cdot \sqrt{3} \cdot U_n \cdot I_1} & \frac{P_n \cdot D_2}{\eta \cdot \sqrt{3} \cdot U_n \cdot I_2} & \frac{P_n \cdot D_3}{\eta \cdot \sqrt{3} \cdot U_n \cdot I_3} \end{bmatrix} \quad . \tag{13}$$

The annual reactive energy consumption matrix $\boldsymbol{RE}$ is given by

$$\boldsymbol{RE} = \begin{bmatrix} \frac{P_n \cdot D_1 \cdot H \cdot T_1}{\eta_1} \tan\left(\operatorname{acos}\left(\frac{P_n \cdot D_1}{\eta \cdot \sqrt{3} \cdot U_n \cdot I_1}\right)\right) & \frac{P_n \cdot D_2 \cdot H \cdot T_2}{\eta_2} \tan\left(\operatorname{acos}\left(\frac{P_n \cdot D_2}{\eta \cdot \sqrt{3} \cdot U_n \cdot I_2}\right)\right) & \frac{P_n \cdot D_3 \cdot H \cdot T_3}{\eta_3} \tan\left(\operatorname{acos}\left(\frac{P_n \cdot D_3}{\eta \cdot \sqrt{3} \cdot U_n \cdot I_3}\right)\right) \end{bmatrix} \quad . \tag{14}$$

The total annual reactive energy consumption RE is

$$RE = \frac{P_n \cdot D_1 \cdot H \cdot T_1}{\eta_1} \tan\left(\operatorname{acos}\left(\frac{P_n \cdot D_1}{\eta \cdot \sqrt{3} \cdot U_n \cdot I_1}\right)\right) + \frac{P_n \cdot D_1 \cdot H \cdot T_1}{\eta_1} \tan\left(\operatorname{acos}\left(\frac{P_n \cdot D_2}{\eta \cdot \sqrt{3} \cdot U_n \cdot I_2}\right)\right) + \frac{P_n \cdot D_3 \cdot H \cdot T_3}{\eta_3} \tan\left(\operatorname{acos}\left(\frac{P_n \cdot D_3}{\eta \cdot \sqrt{3} \cdot U_n \cdot I_3}\right)\right) \quad . \tag{15}$$

When comparing two different motors, an important indicator is the average efficiency and the average power factor over the duty cycle, which are given by

$$\eta_{avg} = \frac{\eta_1 \cdot T_1 + \eta_2 \cdot T_2 + \eta_3 \cdot T_3}{T_1 + T_2 + T_3} \quad , \tag{16}$$

$$\lambda_{avg} = \frac{\lambda_1 \cdot T_1 + \lambda_2 \cdot T_2 + \lambda_3 \cdot T_3}{T_1 + T_2 + T_3} \quad . \tag{17}$$

The costs of the active and reactive energy are

$$CAE = AE \cdot EP_{kWh} \ , \tag{18}$$

$$CRE = RE \cdot EP_{kvarh} \quad . \tag{19}$$

The simple payback time is given by the quotient between the extra cost of the most expensive and/or best motor (oversized and/or with the highest rated efficiency) and the cost of the associated energy savings per year. It is considered that a solution is cost-effective if the simple payback time is less than 3 years (typical rule in industry). Neither interest rate nor inflation rate were considered in the payback time calculations.

On the basis of the previous calculations, a complete comparative economic study between two different motor solutions can be made on the basis of the typical catalogue efficiency and power factor data and on the motor list prices.

The effect of different motor torque-speed curves and the consequent operating point can be taken into account in the calculations considering torque-speed linearity between no-load and full-load, and using two points to define the line, namely: (1) rated torque and speed; (2) zero torque and synchronous speed. This approximation leads to fair results. Nevertheless, the speed change has not been taken in into account in the presented study, i.e., constant output power has been assumed when considering motors with different rated powers or efficiency classes.

In Fig. 12, the load profiles considered in this study are shown. Taking as an example the Load Profile V, the load level matrix is

$$\boldsymbol{D} = [0.3 \quad 0.6 \quad 0.9] \ ,$$

and the time share matrix is

$$\boldsymbol{T} = [0.33 \quad 0.33 \quad 0.33] \ .$$

The average load (or load factor) is 1.0, 0.9, 0.7, 0.5, 0.6, 0.7 and 0.8 for the Load Profiles I, II, III, IV, V, VI and VII, respectively.

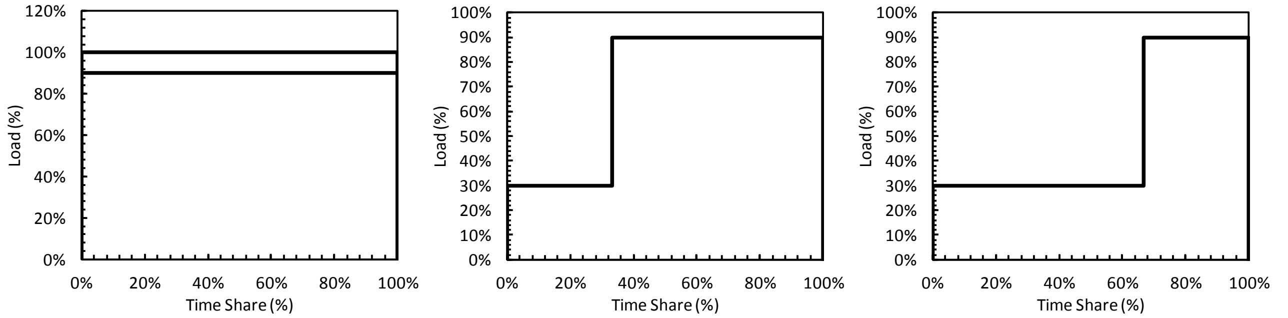
In Section III, besides the different load profiles, three different scenarios are also considered for payback calculation purposes, namely:

a) 10.0 c€/kWh, 0.0 c€/kvarh, 8000 h/a and without list price discount;
b) 10.0 c€/kWh, 0.0 c€/kvarh, 8000 h/a and 40% list price discount;
c) 10.0 c€/kWh, 1.0 c€/kvarh, 8000 h/a and 40% list price discount.

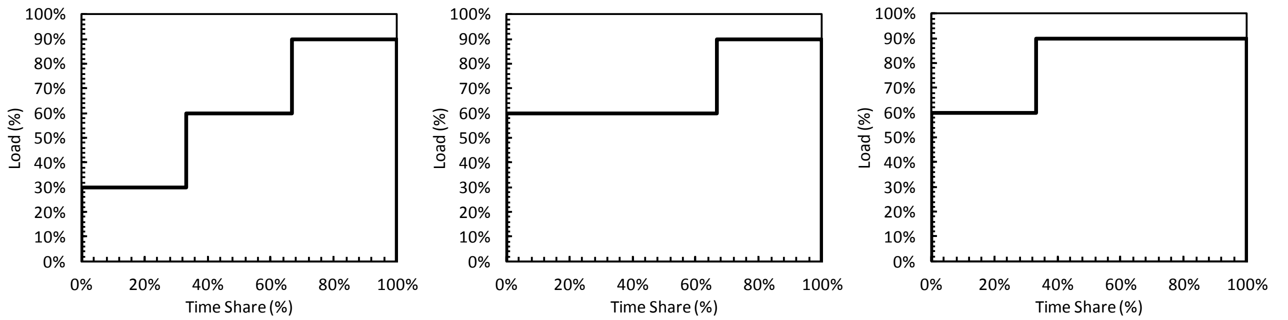
Additionally, the payback time of the extra investment in IE2-, IE3-, and IE4-Class SCIMs is also presented, for comparison purposes.

After processing all the motor efficiency and power factor data, four oversizing levels were considered to each rated power (e.g., for the 0.75 kW motor, the 1.1-, 2.2-, 3- and 4-kW motors were considered as oversized options), for each defined load profile.

In Figs. 13 and 14, the calculated efficiency and power factor at continuous full-load (Load Profile I; rated power equal to output power) of the reference motor (well sized) and of the oversized motors (oversized I – one power level above; oversized II – two power levels above) are shown. In Fig. 13, the motor efficiency gain potential associated with oversizing is clearly evidenced. In Fig. 14, the motor power factor degradation with oversizing level can be seen.



(a) Load Profile I&II (b) Load Profile III (c) Load Profile IV



(d) Load Profile V (e) Load Profile VI (f) Load Profile VII

Fig. 12. Load profiles considered in the presented study.

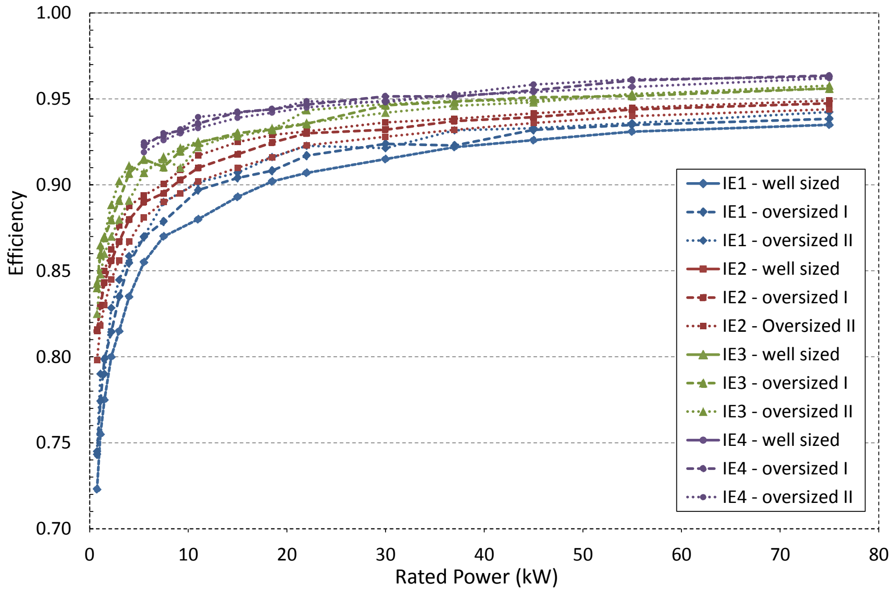


Fig. 13. Calculated average efficiency at continuous full-load (Load Profile I) for two oversizing levels.

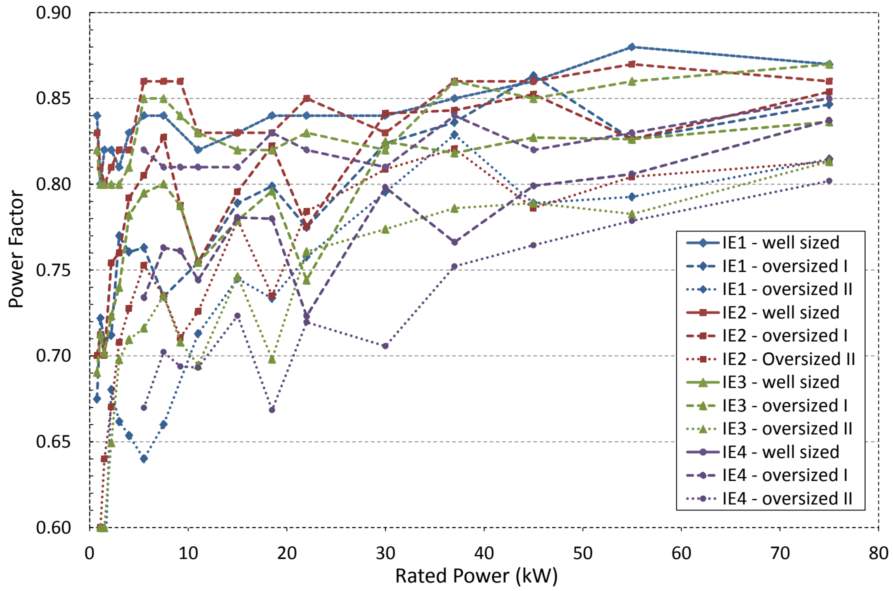


Fig. 14. Calculated average power factor at continuous full-load (Load Profile I) for two oversizing levels.

IV. Results

A. Efficiency and power factor variation with motor oversizing for fixed output power

The efficiency and power factor variation for fixed full-load output power (for the reference motor), corresponding to the Load Profile I (100% load, continuous) and three consecutive rated powers (P_{n2}, P_{n3} and P_{n4}) above the reference output rated power ($P_{n1(ref)}$) is presented in Figs. 15-18, evidencing that the better the motor efficiency class and the higher the rated power are, the lower the efficiency gain with oversizing will be.

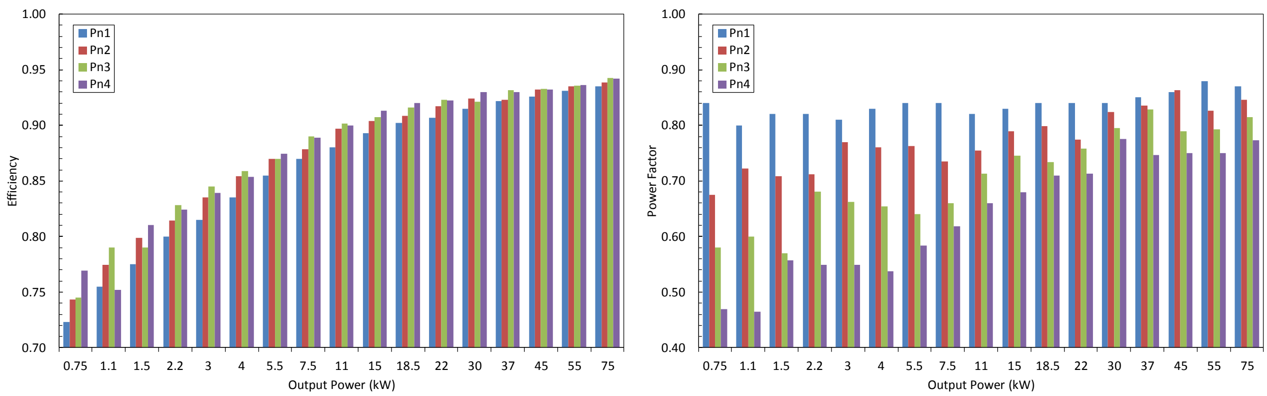


Fig. 15. Efficiency and power factor of IE1-Class SCIMs for fixed output power ($P_{n1(ref)} < P_{n2} < P_{n3} < P_{n4}$).

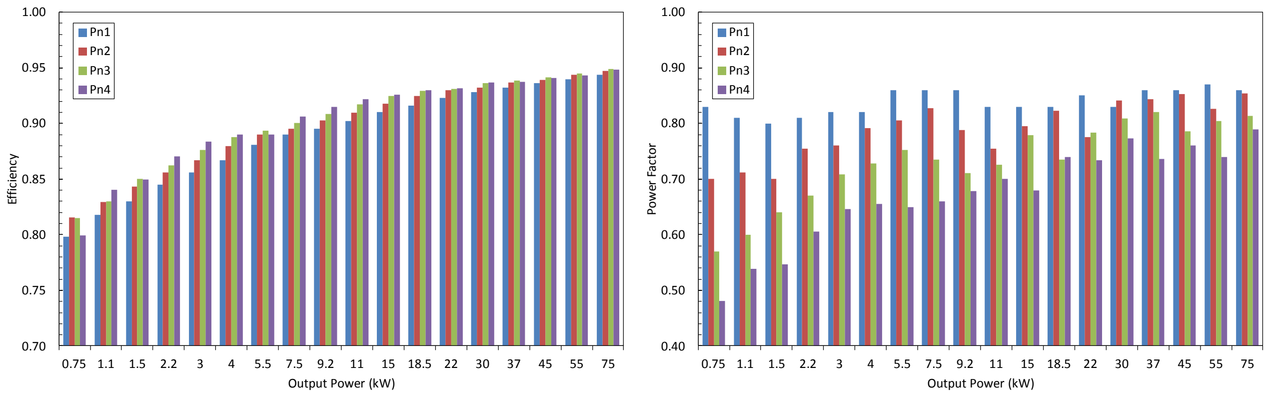


Fig. 16. Efficiency and power factor of IE2-Class SCIMs for fixed output power ($P_{n1(ref)} < P_{n2} < P_{n3} < P_{n4}$).

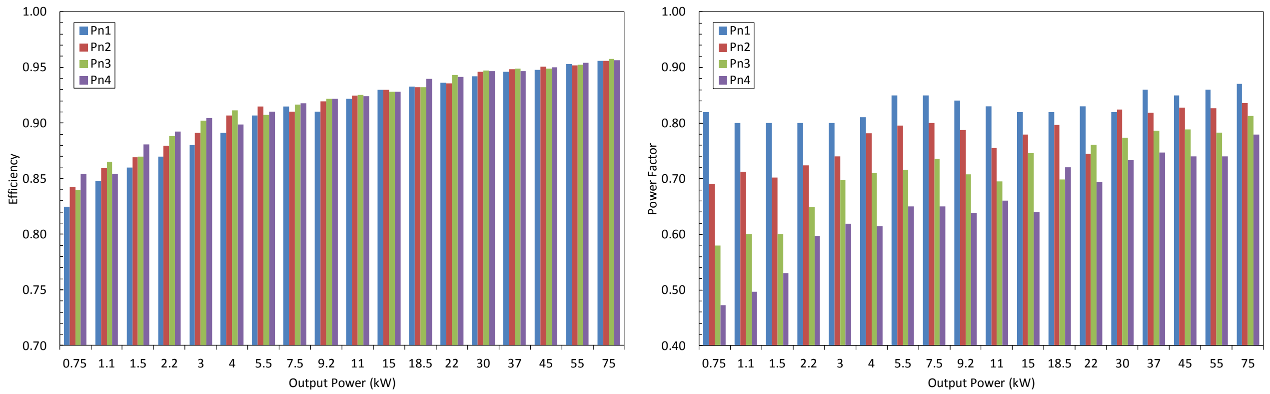


Fig. 17. Efficiency and power factor of IE3-Class SCIMs for fixed output power ($P_{n1(ref)} < P_{n2} < P_{n3} < P_{n4}$).

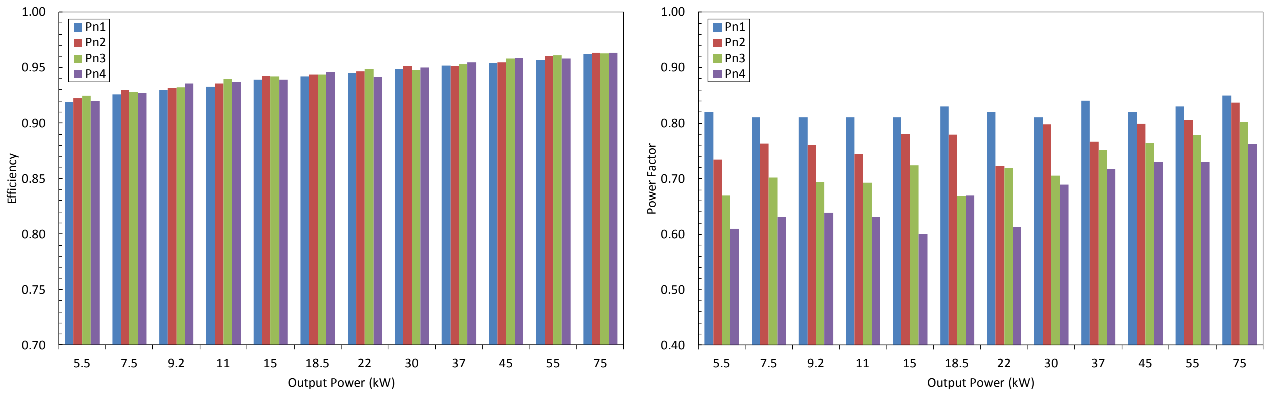


Fig. 18. Efficiency and power factor of IE4-Class SCIMs for fixed output power ($P_{n1(ref)} < P_{n2} < P_{n3} < P_{n4}$).

B. Initial plus active energy cost variation with percentage oversizing

In Figs. 19-22, the variation of the total cost (initial cost plus active energy cost) as a function of the percentage oversizing is presented for IE1-, IE2-, IE3- and IE4-Class SCIMs, considering a 12-year period, 8000 h/a, 10 c€/kWh and 40% discount on list prices. It is interesting to note that a minimum cost value can be found in each case, which varies with efficiency class and rated power.

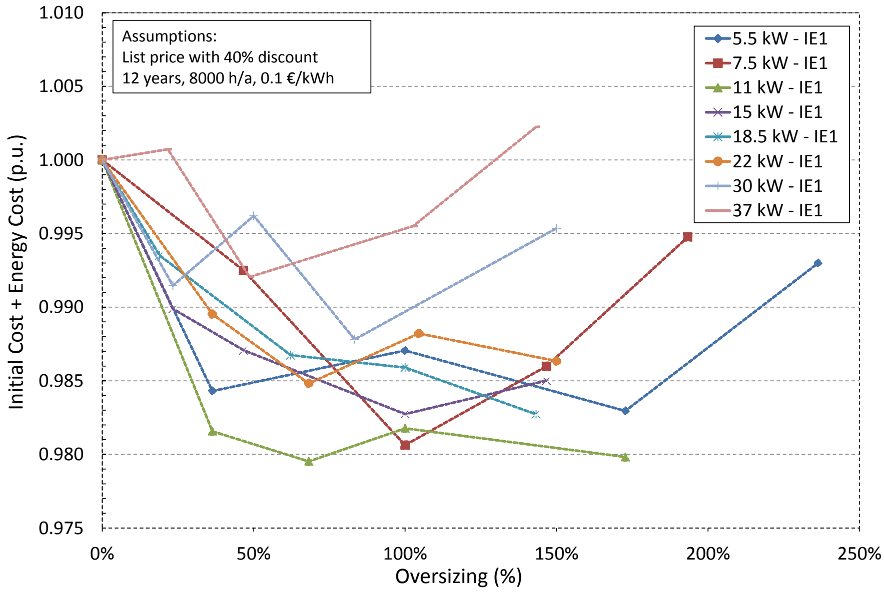


Fig. 19. Initial plus active energy cost as a function of the percentage oversizing, for IE1-Class SCIMs of different rated power (list price with 40% discount; continuous output power; 12-year period; 8000 h/a operating hours; 0.1 €/kWh energy cost).

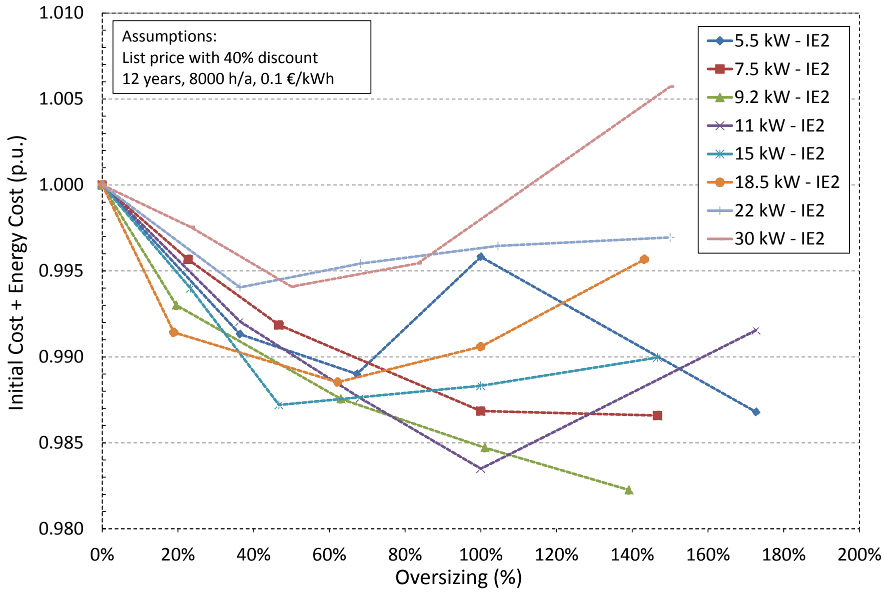


Fig. 20. Initial plus active energy cost as a function of the percentage oversizing, for IE2-Class SCIMs of different rated power (list price with 40% discount; continuous output power; 12-year period; 8000 h/a operating hours; 0.1 €/kWh energy cost).

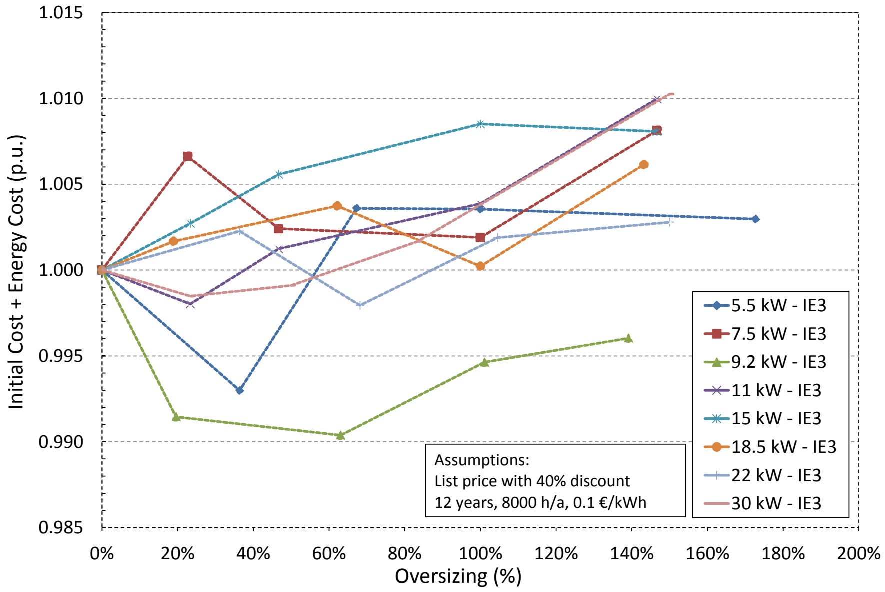


Fig. 21. Initial plus active energy cost as a function of the percentage oversizing, for IE3-Class SCIMs of different rated power (list price with 40% discount; continuous output power; 12-year period; 8000 h/a operating hours; 0.1 €/kWh energy cost).

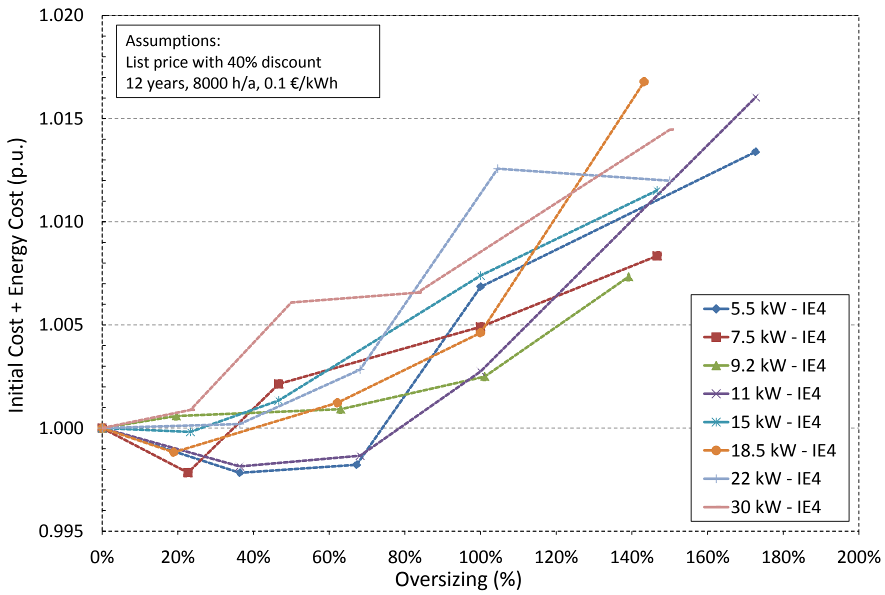


Fig. 22. Initial plus active energy cost as a function of the percentage oversizing, for IE4-Class SCIMs of different rated power (list price with 40% discount; continuous output power; 12-year period; 8000 h/a operating hours; 0.1 €/kWh energy cost).

C. Oversizing extra cost payback time for 10 c€/kWh, 8000 h/a and without list price discount

In order to compare a motor with a given rated power to those with rated powers one and two steps above (e.g., 0.75-kW motor compared with 1.1- and 1.5-kW motors), in the 0.75-75 kW power range, the method described in Section III has been applied, allowing the oversizing economic advantage/disadvantage to be properly evaluated in a wide range of rated powers.

In Figs. 23-26, the payback time for the extra cost of oversized IE1-, IE2-, IE3-, IE4-Class SCIMs is shown, considering list prices without discount, 8000 h/a, 10 c€/kWh, and ignoring the reactive energy cost. The 3-year payback line is denoted with a horizontal dashed trace. From the results presented, it comes out that once the efficiency becomes flatter for larger motors, the efficiency gain with oversizing is lower, and the oversizing payback is longer. The same applies to high-efficiency motors. For the IE1-Class SCIMs, it is evident the significant number of cases in which the motor oversizing is cost-effective (e.g., 0.75 kW → 1.1 kW, for Load Profile I; 11 kW → 15 kW, for all load profiles with exception of Load Profile IV; 75 kW → 90 kW, for load profiles I, II and VII). For the IE2- and IE3-Class SCIMs, there are fewer cases in which the oversizing is cost effective. For the IE4-Class SCIMs, the oversizing is not cost effective, regardless the rated power and load profile. This is due to both the increase in the cost and to the lower difference in the efficiency.

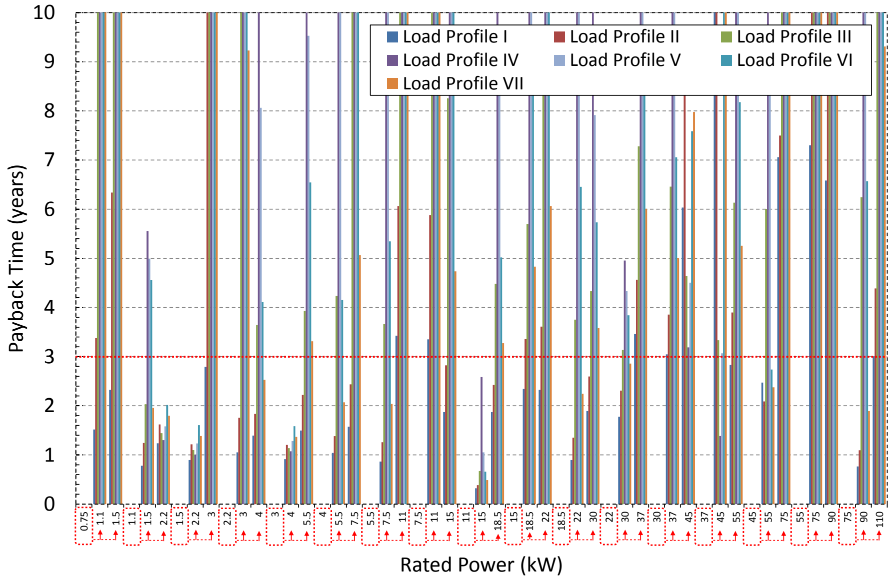


Fig. 23. Payback time for the extra cost of oversized IE1-Class SCIMs (no list price discount).

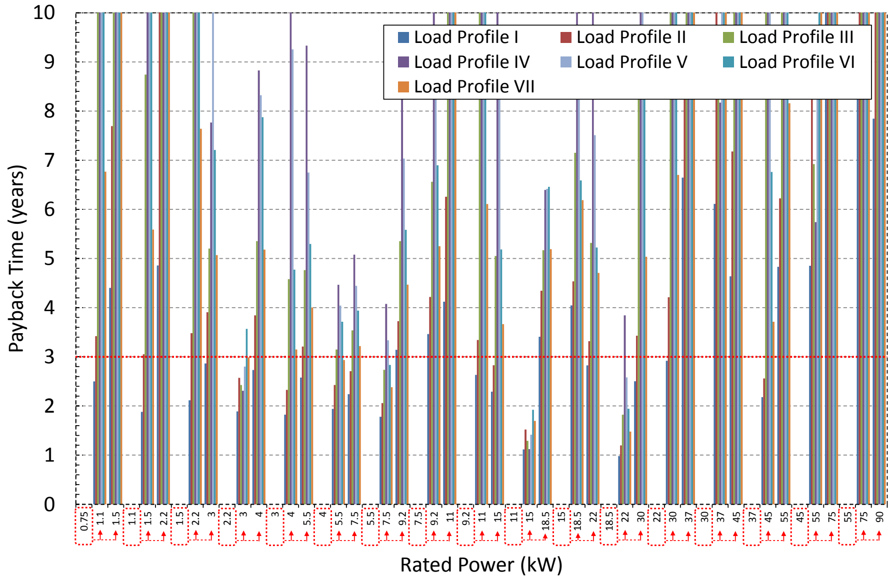


Fig. 24. Payback time for the extra cost of oversized IE2-Class SCIMs (no list price discount).

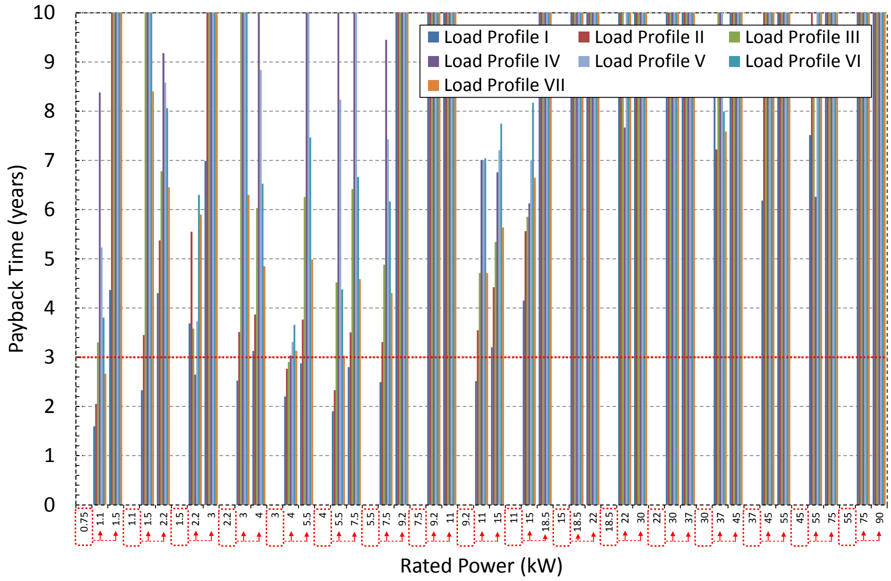


Fig. 25. Payback time for the extra cost of oversized IE3-Class SCIMs (no list price discount).

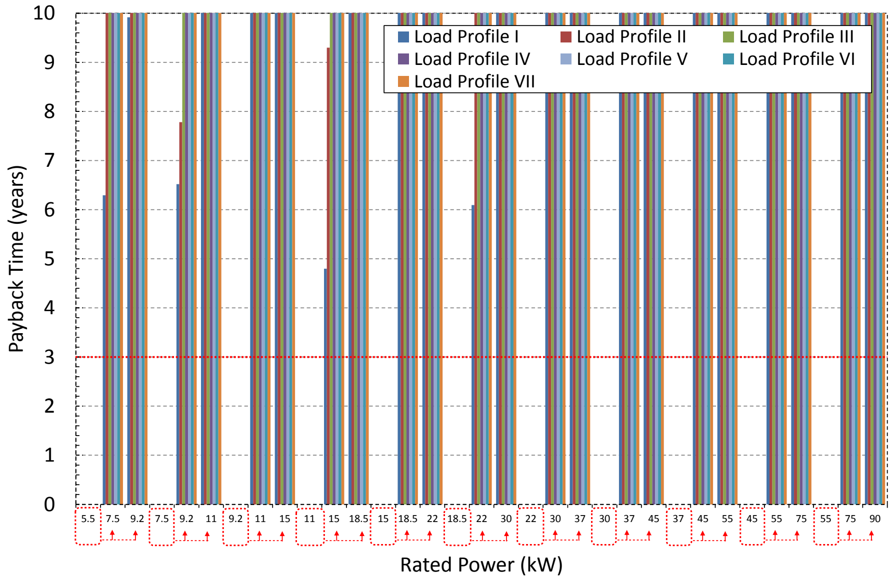


Fig. 26. Payback time for the extra cost of oversized IE4-Class SCIMs (no list price discount).

D. Oversizing extra cost payback time for 10 c€/kWh, 8000 h/a and 40% list price discount

In Figs. 27-30, the payback time for the extra cost of oversized IE1-, IE2-, IE3-, IE4-Class SCIMs is shown, considering list prices with 40% discount, 8000 h/a, 10 c€/kWh, and: (left) 0.0 c€/kvarh; (right) 1.0 c€/kvarh. For the IE1-Class SCIMs, it is evident the significant number of cases in which it is worth oversizing the motor for Load Profile I. For the Load Profile IV, very few situations present a payback time lower than 3 years. For the IE2- and IE3-Class SCIMs, there are few cases in which oversizing is cost effective, but some cases can be found in the load profiles with higher load factor. For the IE4-Class SCIMs, the oversizing is not cost effective, regardless the rated power and load profile. It is obvious that the higher the motor price discount (i.e., the lower the motor price) is, the lower the payback will be. If the reactive energy cost is taken into account (e.g., 0.01 €/kvarh), the payback will increase to more than 10 years in the majority of the cases. Therefore, if there is no power factor compensation, the oversizing is not cost effective, regardless the rated power and efficiency class, unless the active energy cost largely overrides the reactive energy cost and the motor load factor is close to 100%.

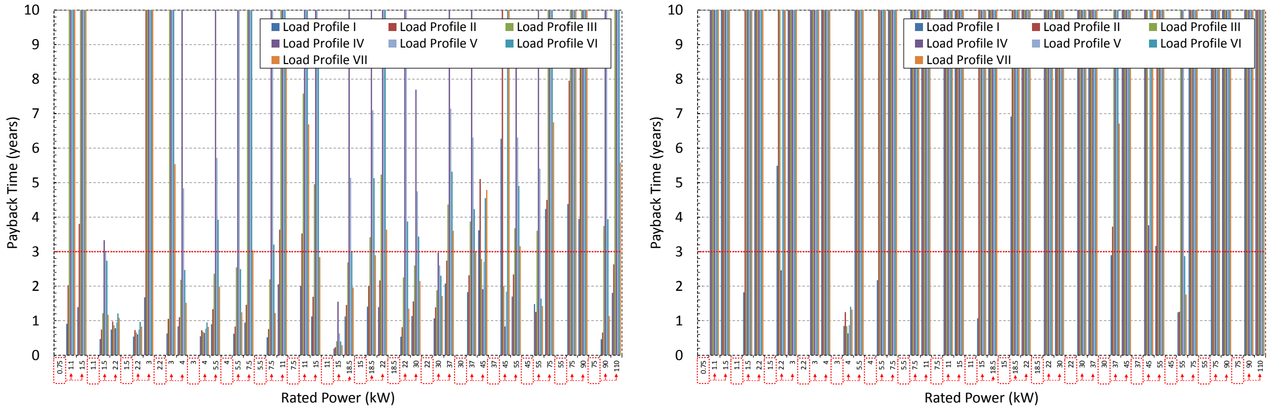


Fig. 27. Payback time for the extra cost of oversized IE1-class SCIMs (40% price discount): (left) ignoring reactive energy cost; (right) considering 1.0 c€/kvarh.

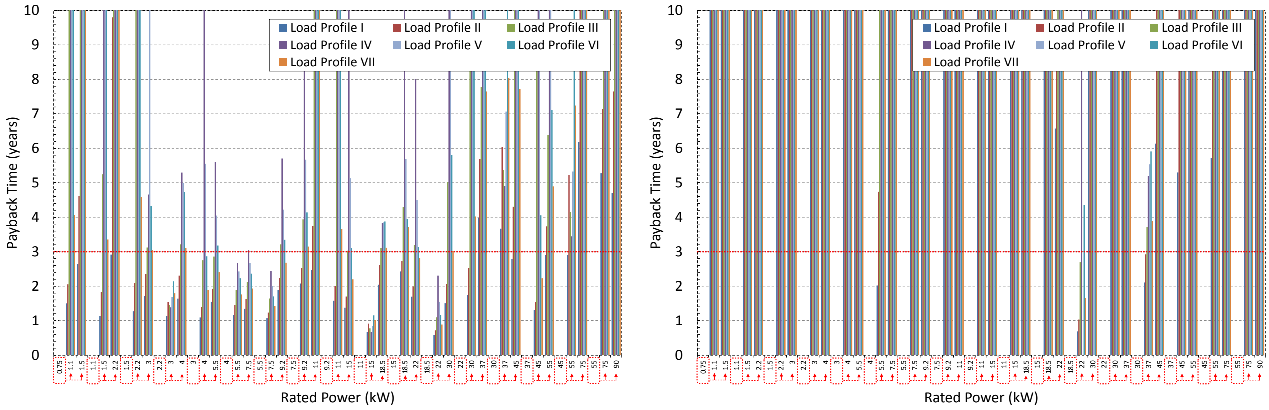


Fig. 28. Payback time for the extra cost of oversized IE2-class SCIMs (40% list price discount): (left) ignoring reactive energy cost; (right) considering 1.0 c€/kvarh.

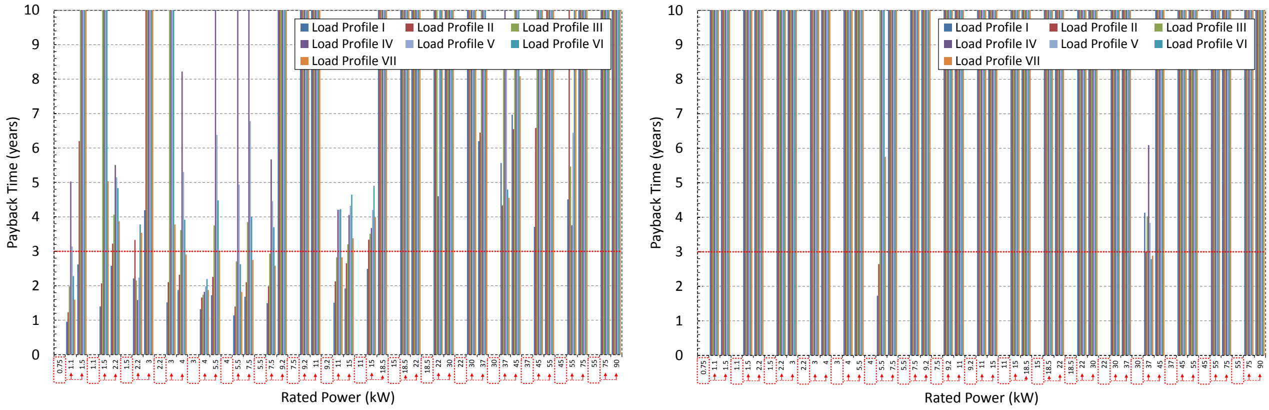


Fig. 29. Payback time for the extra cost of oversized IE3-class SCIMs (40% list price discount): (left) ignoring reactive energy cost; (right) considering 1.0 c€/kvarh.

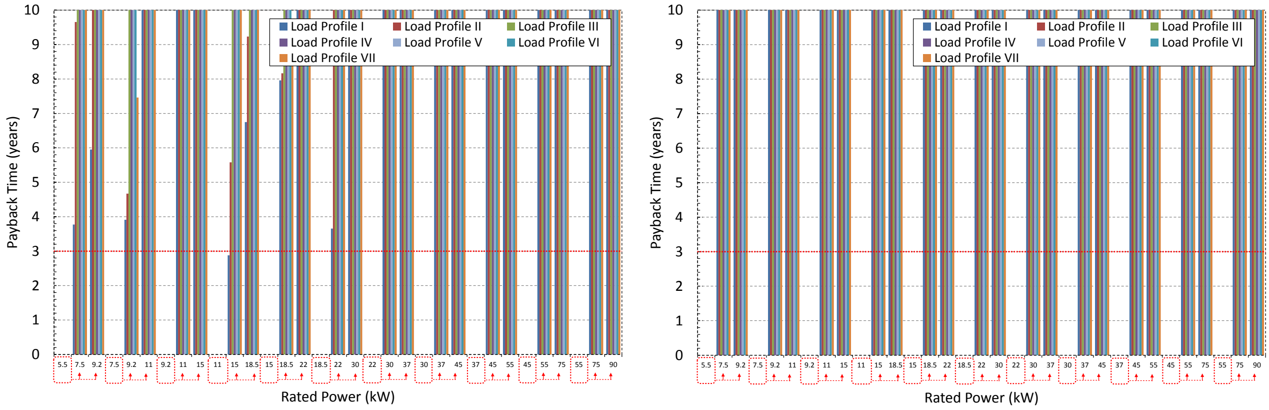


Fig. 30. Payback time for the extra cost of oversized IE4-class SCIMs (40% list price discount).

E. IE2-, IE3- and IE4-class motor extra cost payback time for 10 c€/kWh, 8000 h/a and 40% list price discount

In Figs. 31-34, the payback time for “IE2 vs. IE1”, “IE3 vs. IE2”, “IE4 vs. IE3” and “IE4 vs. IE2” motors is shown, considering list prices with 40% discount, 8000 h/a, 10 c€/kWh, and: (left) 0.0 c€/kvarh; (right) 1.0 c€/kvarh. The results show that in most cases and independently of the load profile being considered, IE2-, IE3-, and IE4-class SCIMs are cost-effective. Even so, after selecting a motor with higher rated efficiency, the user can evaluate if its oversizing is cost-effective.

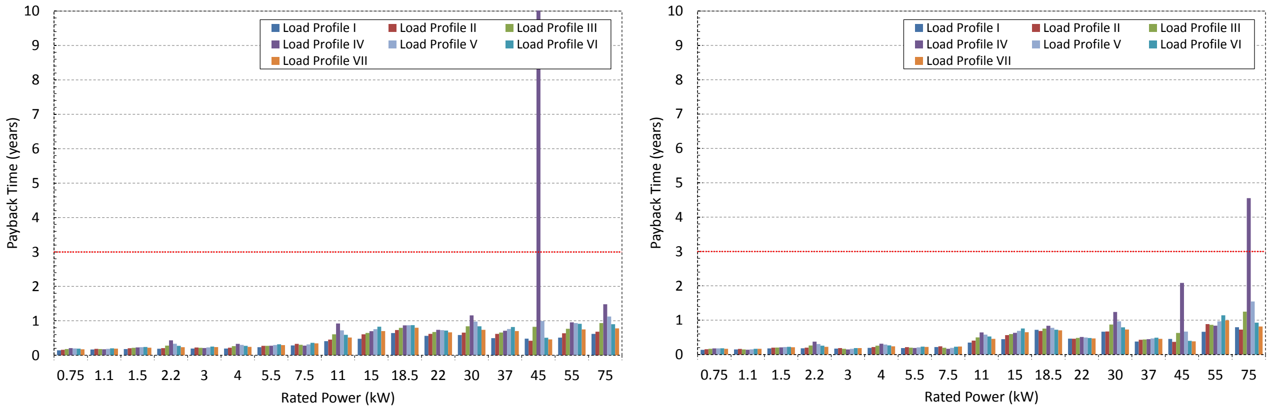


Fig. 31. Payback time for the cost difference between IE2- and IE1-class SCIMs (40% list price discount): (left) ignoring reactive energy cost; (right) considering 1.0 c€/kvarh reactive energy cost.

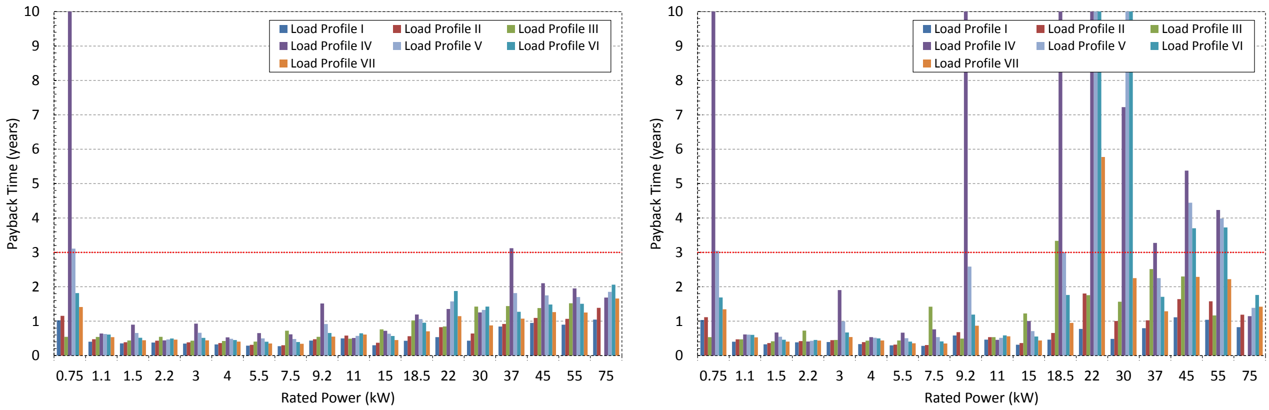


Fig. 32. Payback time for the cost difference between IE3- and IE2-class SCIMs (40% list price discount): (left) ignoring reactive energy cost; (right) considering 1.0 c€/kvarh reactive energy cost.

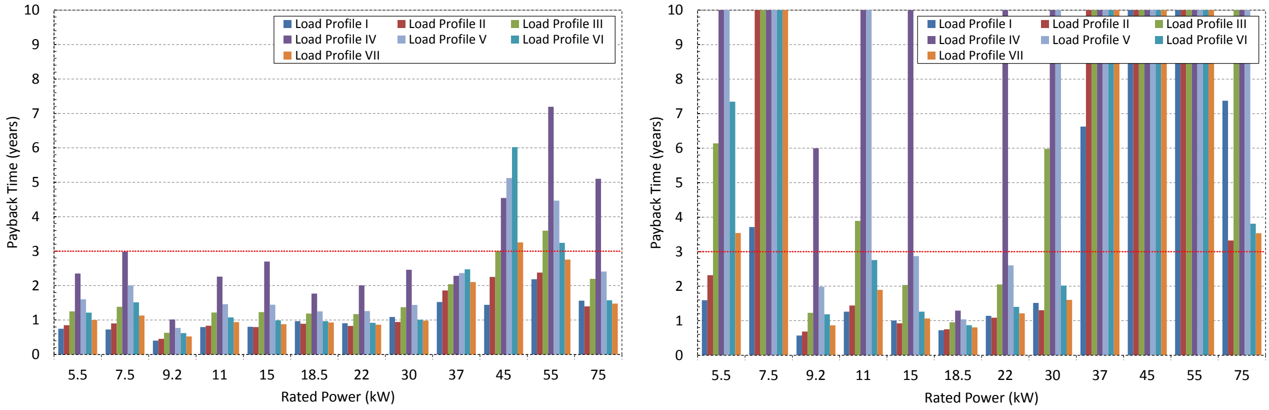


Fig. 33. Payback time for the cost difference between IE4- and IE3-class SCIMs (40% list price discount): (left) ignoring reactive energy cost; (right) considering 1.0 c€/kvarh reactive energy cost.

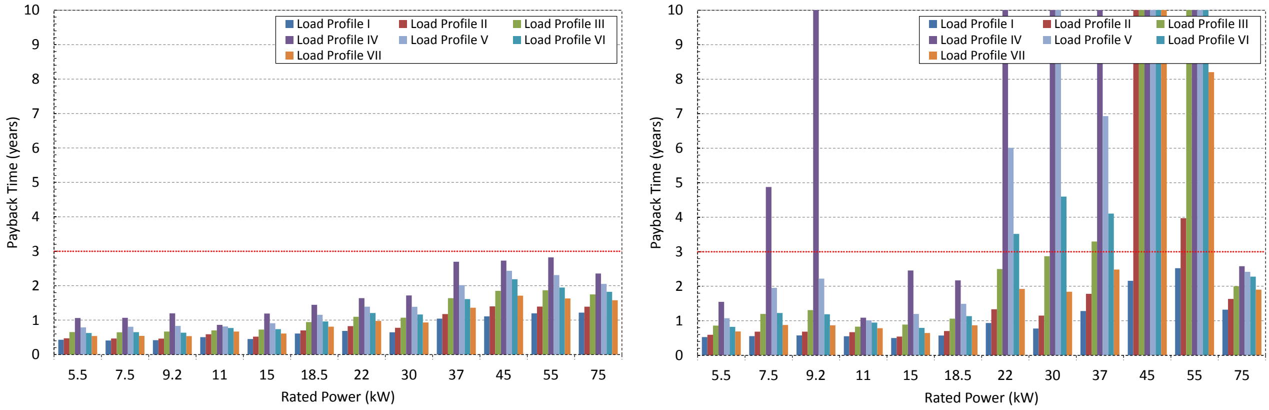


Fig. 34. Payback time for the cost difference between IE4- and IE2-class SCIMs (40% list price discount): (left) ignoring reactive energy cost; (right) considering 1.0 c€/kvarh reactive energy cost.

V. Conclusions

The general "rule of thumb" stating that the motor oversizing is a bad option has been analyzed in detail. On the basis of the presented results, it can be concluded that, in some cases, oversizing the motor in one or two rated power levels can be a cost-effective option in the IE1-, IE2- and IE3-class SCIMs operating a large number of hours per year and with a high load factor, since it can lead to considerable efficiency gains and to extended lifetime. The oversizing extra cost can be recovered in less than 3 years, provided that the power factor in the facility power network is properly compensated/corrected. The motor oversizing payback time strongly depends on the load profile (or motor load factor). Actually, as it is well known, the higher the active energy price, the load factor and the number of operating hours are, the shorter the payback time of the extra cost associated with the motor oversizing will be. In general, if the facility power factor is not compensated, motor oversizing may not be an interesting option. If the power factor is properly compensated, although motor oversizing can be cost-effective in some situations, the extra cost of the power factor compensation equipment should also be taken into account in the economic analysis. The same applies to the larger circuit-breakers, starters (contactors and/or electronic soft-starters) and/or power cables gauge that may be required for oversized motors, imposing an extra cost. These possible extra costs have not been considered in the presented study. In IE4-class SCIMs, the oversizing rarely compensates, even if the power factor reduction is ignored.

It should be highlighted that, in situations where makes sense to take the reactive energy cost into account, the simple payback time can be strongly influenced by that cost. Furthermore, if the power factor compensation is at the facility power network input (global compensation) instead of at the motor terminals (local compensation), the additional reactive component of the motor current increases the Joule losses in the conductors and transformers of the power network and may lead to the use of larger (and more expensive) conductors and transformers. These disadvantages associated with the motor poor power factor should also be considered in the economic analysis.

In addition to the increase in the reactive energy consumption, the higher motor speed and rotor inertia associated with oversizing can also be a disadvantage in some applications, and should be taken into account in a more accurate analysis, particularly in retrofitting applications.

If the motor is fed by a variable-speed drive or the applied voltage is adjusted as a function of the actual motor load by electronic/electrical voltage regulators or proper connection-mode change strategies, the issues associated with the lower power factor and the consequent increase of the reactive energy consumption can be easily overpassed. In fact, if the voltage is properly adjusted to the actual load, the efficiency gain associated with the motor oversizing can be much higher.

In general, as expected, for a given output power, the investment in a well sized motor with higher rated efficiency is a better option than in an oversized motor of the same efficiency class. Nevertheless, if the user decides to invest in high-efficiency motors, in some cases, their slight oversizing can be cost-effective. Moreover, in some cases, if the consumed reactive energy cost is considered, the payback time of the extra cost of motors with higher efficiency can increase significantly because of the lower power factor.

The expected speed increase (or slip decrease) when retrofitting an existing motor by a larger and/or more efficient motor should also be considered in further analysis. In new applications, the equipment driven by the motor can be properly adapted to the expected operating speed, and, therefore, the speed increase should not be an issue.

Since the data used in the presented study comes from one single large motor manufacturer, further studies should be carried out using other data sources (e.g., EURODEEM and/or MOTOR MASTER).

Finally, since the motor market is moving toward Premium/IE3 and Super-Premium/IE4 efficiency classes, this study also highlights the importance of properly determine the actual load of motors or the actual power required by the application for proper motor sizing/selection. When the user plan to replace existing standard motors, it is very important to monitor the actual motor load over the operating cycle in order to identify the maximum mechanical shaft power (within significant periods, longer than motor time constant), to properly select the new motor rated power.

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Power De-Rating Scheme for Power Factor Corrected Variable Speed Pool Pump Drive

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Abstract

Internal operating temperature of an electric drive can be influenced by the ambient temperature, the input voltage, and the load. In other words, each motor drive product has a maximum operating ambient temperature, minimum operating voltage, and maximum operating load. Operation beyond its intended maximum operating limits is usually not allowed because it will shorten the life cycle of the product and cause premature failures. However, in pool pump applications, operation of the pump drive is most needed when the ambient temperature is high. It is not uncommon for operating ambient temperature to be above the maximum ambient temperature. Therefore, a power de-rating method will largely benefit the pool pump drives. The power de-rating method is activated beyond its operating limits to provide undisrupted service and extend the life of the product. The power de-rating scheme allows the motor drive to operate by gradually reducing its power output, not allowing components to exceed their rated temperature. This paper discusses a power de-rating scheme applied to a product in production for this application.

Introduction

In recent years, pool market has seen the introduction of many variable speed pump drives, mainly driven by energy savings and efficiency. Because the peak usage of pools is in hot summer days, and that is when the sanitation of the pool can be affected with the interruption of service in shorter amount of time, operation beyond maximum operating limits is desirable. A drive normally shuts down once the temperature of components reach to a maximum limit. By doing so will extend the life of the product and prevent premature failure. In order to extend the operation beyond its operating limits as the maximum ambient temperature and the rated voltage, the power de-rating or power limiting scheme is used. This scheme reduces the output power by slowly reacting to the slowly changing variables such as temperature inside the electronic enclosure, and the long period of drop in the input voltage, which in turn limits the temperature of the components. By activating the de-rating scheme, the maximum temperature is limited. As it will be clear in later sections, the way the power de-rating is accomplished is that the output power is reduced by lowering the current limit of the drive. As a result, the motor speed drops and reduces the water flow in the pool system. Since the pump power is proportional to the cube of the pump speed, the reduction in speed translates into power reduction. This paper discusses a power de-rating scheme applied to a product in production for the pool pump application. In the following discussions, controller or control refers to the inverter and the power factor correction combination.

Drive Description

The motor is a surface mounted permanent magnet synchronous motor type. It operates with a sensorless vector control algorithm. Startup of the motor is open loop. The vector control switch over occurs at 500 RPM. The pump motor operates from 600 RPM to 3450 RPM. The controller is made up of an inverter and a power factor correction boards. A microcontroller is located on the inverter board and controls the inverter. Power factor correction circuit is self regulating by its controller IC depending on the enable/disable signal received from the microcontroller. Inverter switching frequency is 16kHz and the PFC switching frequency is 50kHz. The input (mains) voltage and current is not sensed by the microcontroller. The DC bus voltages before and after the PFC circuit are measured in addition to the motor currents. As shown in Figure 1, a thermistor (NTC) has been place on the inverter board to measure the temperature of the enclosure. The drive is rated at 2.7HP output power at 230VAC and is able to operate in the range from 208 to 250VAC.

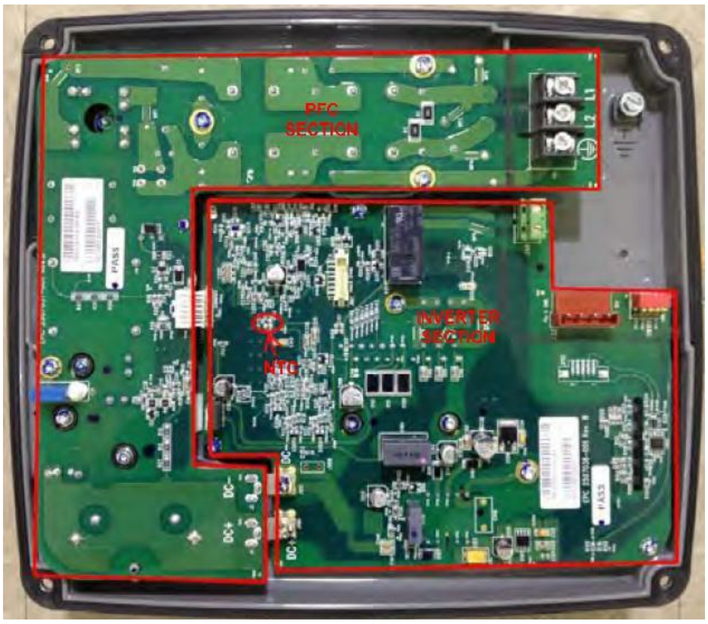

Figure 1 Controller sections and location of thermistor

The temperatures of the components are influenced by the air flow, the ambient temperature, the mains voltage and the load. As shown in Figure 2, a fan is attached to the exterior end of the shaft, which sucks air from the end and redirects it to the top surface of the motor and under the controller heat sinking fins. Since the fan is attached to the pump motor shaft, the air flow will vary depending on the motor speed. The power factor correction board constitutes the hottest part of the enclosure. Specifically, the coil of the PFC inductor is the hottest component, in other words, it is the critical component. If the temperature of the PFC inductor coil is limited, all the other components in the enclosure stay within their temperature limits. The insulation class of the inductor coil is Class B, which allows temperature to go up to 130°C. Since UL does not allow the temperature to exceed 110°C, that is our maximum temperature limit. The drive is normally rated to operate up to 50°C ambient at the full power. Operating temperature range with the de-rating is defined up to 60°C ambient. Above 50°C ambient temperature, the drive starts to de-rate.

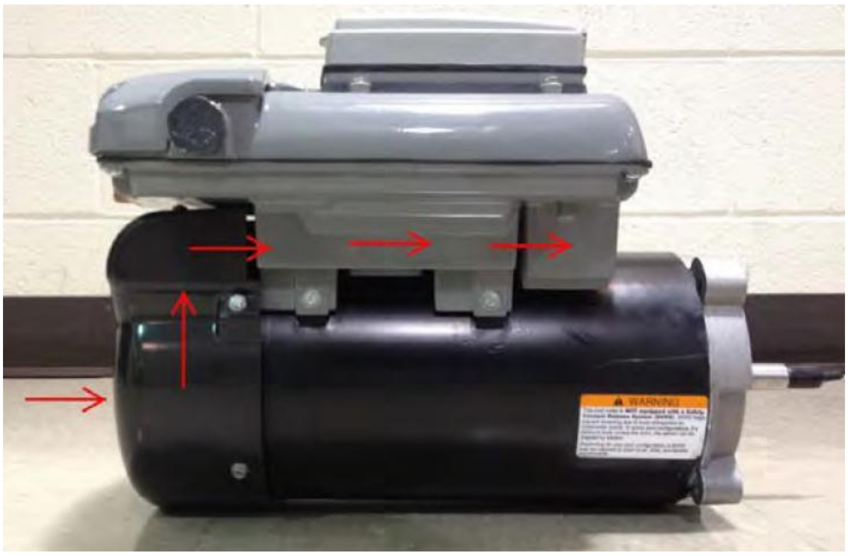

Figure 2 Air flow of the drive

Calculation of Mains Voltage

The topology of the PFC section has been demonstrated in Figure 3. Major power dissipation takes place in two different areas in the controller: IGBT module section (module and current sense resistors) and the PFC section (inductor, IGBT, diode, and current sense resistor). Since the PFC section is noisy and is connected to the inverter board with a connector, a thermistor (NTC) has been placed on the inverter board. When operating at a particular load point, if the mains voltage drops, the input current increases to maintain the same power. Power dissipation on the inverter board does not change as long as the load point stays the same. The reason the inverter power dissipation does not change is because the PFC boosts and regulates the voltage to a constant value. As a result, voltage fluctuations will create power dissipation change and temperature change. There is a delay for the temperature change to be detected by the thermistor on the inverter board. At the same time, the temperature of the critical component we are trying to regulate is on the PFC board away from the thermistor, in a potting material. Ideally, we would like to measure the input voltage or the input current to be able to determine when to start the de-rating in case the voltage goes down. However, those measurements increase the number of components, circuit complexity, and electrical noise. Therefore, the following input voltage estimation method has been developed. As it will be clear later sections, the de-rating due to the power dissipation change in the PFC section alone is solely based on the input voltage.

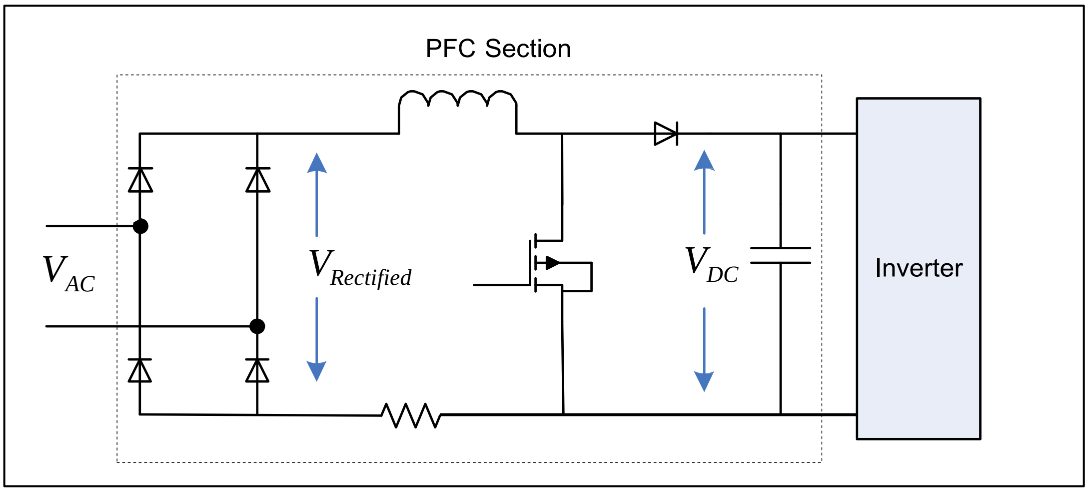

Figure 3 Power factor correction (PFC) circuit topology

As indicated, two DC voltages are measured by the microcontroller. One is immediately after the rectification and the other is after the PFC section at the main DC bus before the inverter. See Figure 3. Figure 4 presents the block diagram of the input voltage estimation algorithm. The basis in determining the AC input voltage is the rectified voltage. Since the rectified voltage has ripple, it is filtered by a low pass filter. Two diode drops are added to the filtered value and the result is multiplied by the rectification coefficient K_R.

Calculated motor power is filtered by a low pass filter. The filtered motor power is multiplied by the inverse of the controller (inverter+PFC) efficiency to estimate the power drawn by the controller. The estimated power is divided by the estimated input voltage from the previous cycle to find an estimated input current. Then, the estimated current is multiplied by the input resistance to calculate the voltage drop.

The value that has been multiplied by the rectification coefficient, K_R, is added to the $I_{AC}R$ drop. The total value is added to an offset value to find the final estimated input voltage. The accuracy in the input voltage estimation is only needed in the high power region, which is the speed range from mid to high speed. The algorithm described below is only active during that range. Because there is high frequency filtering immediately after rectifier and the rectification factor relies on the ideal rectification, the estimated input voltage is not very accurate in the very low power/speed region.

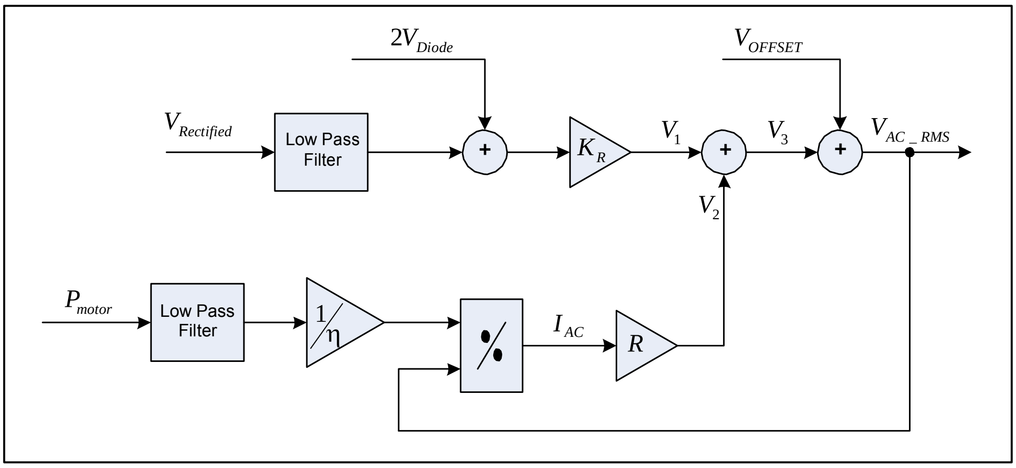

Figure 4 Mains voltage calculation

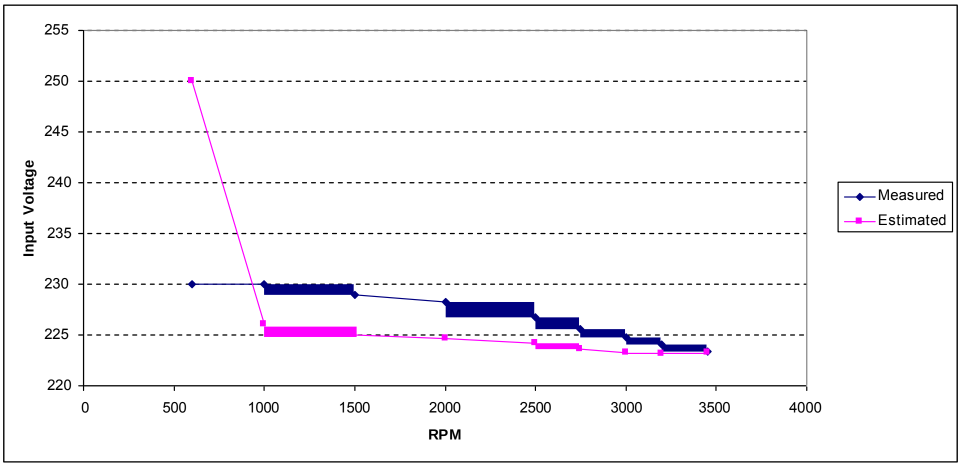

Figure 5 Measured and estimated voltage comparison

Control Architecture

The following diagram describes the simplified control architecture. The control is a sensorless vector control. The motor is surface mounted Permanent Magnet Synchronous Motor (PMSM). Because it is a surface mounted PMSM and there is no constant power region, the d-axis current is controlled to be zero. Hence, there is only q-axis component of the current that determines the motor total current and the output power at a given speed. As a result, limiting the q-axis current will limit the power. Because of this reason, once the q-axis current is determined by the speed PI controller, i is limited by the limiting block. This is going to be the point where the de-rating algorithm feeds in as will be seen later.

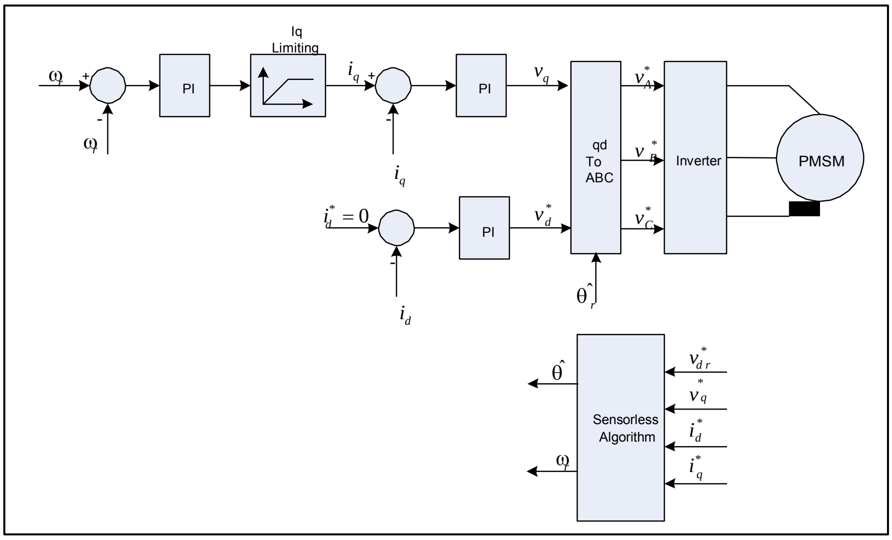

Figure 6 Simplified control diagram

De-Rating on Speed

Because the cooling fan is attached to the motor shaft, the cooling of the controller depends on the motor speed. Therefore, at the maximum ambient temperature, the maximum current can only be applied with the full air flow at the rated speed. In pool pump applications, it is not uncommon to have a range of impellers that can be installed in the same pump housing resulting in different power draw and water flow. In order to prevent higher power draw from the pump without having sufficient air flow, a maximum power profile has been defined. Since the power delivered by the motor is proportional to the cube of the speed, there is no need to make the full current available to the whole operating speed range. A current limit profile with respect to speed has been defined based on the characteristic of the expected 2.7HP impeller. To be able to accelerate and allow room for tolerance, the current limit profile is slightly more than the expected maximum current pump drive profile. Due to the characteristic of the pump, just the current limit profile with respect to speed is sufficient to limit the temperature in low to middle speed range for the worst operating case: low mains voltage and high ambient temperature.

In openloop, higher current limit is available in order to achieve stable start up. Once the switch over to sensorless vector control mode takes place, there is a delay period due to switch over transient in which the maximum current as in the rated load is available before the current limit profile becomes active. If a higher load applied due to the installation of a higher flow impeller, the de-rating on speed will result in the motor not being able to accelerate to the commanded speed and settling to a lower speed and not delivering the flow and the power desired.

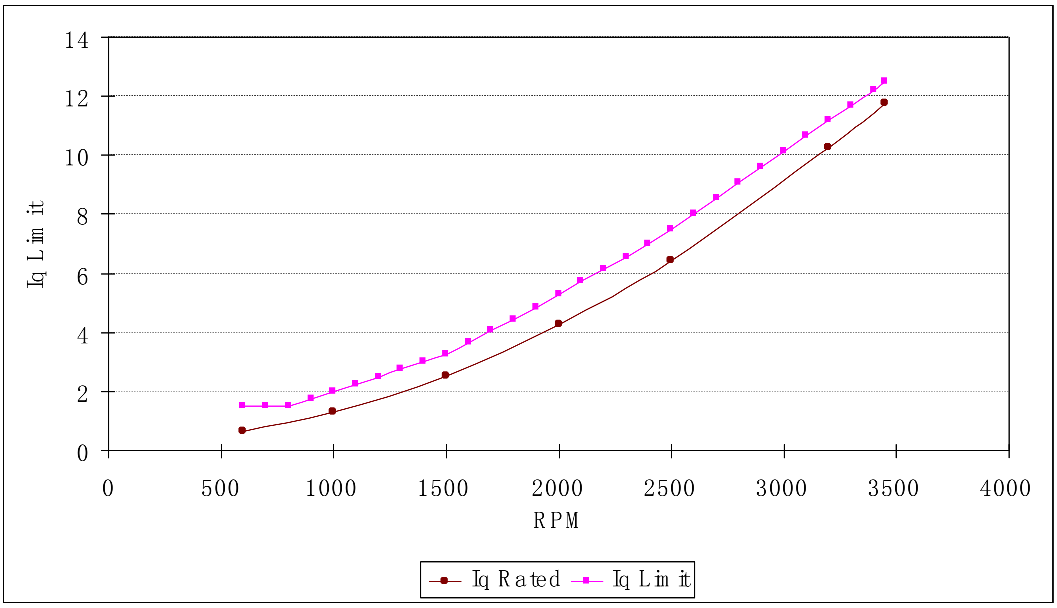

Figure 7 Current versus speed profile

There is another benefit to have a de-rating scheme defined based on speed versus current profile limit and that is the feedback effect. In high temperature, the torque generated per ampere drops due to two reasons: the magnet flux reduction, which requires higher current/voltage to generate the same torque, and the motor parameter change, which requires higher voltage to push the same amount of current. As a result, the voltage saturates at some temperature and the motor speed starts to drop. As the motor speed drops, the current limit drops due to the speed versus current profile. At some point an equilibrium point is reached with a current limit which produces a particular torque and speed where the temperature rise stops. As the ambient temperature increases, this process will continue to stabilize the temperature rise.

De-Rating on Voltage and Temperature

Due to the large amount of power draw in middle to high speed range (2500RPM to 3450RPM), the drop in the mains voltage and the increase in the ambient temperature have significant effect on the temperature rise in the electronic components. In middle to high speed range, applying current limit profile limiting (depending on the speed) is not sufficient to keep the temperature within specified limits. Therefore, a new current limit is calculated based on the mains voltage and/or the ambient temperature above 2500RPM. There are two conditions and a different formula is used for each condition to calculate the de-rated current limit.

Condition 1: Voltage and Temperature

This condition presents the de-rating formula, which calculates the current limit, based on voltage and temperature at the same time. If the PCB temperature is above the maximum ambient temperature, and the mains voltage is below the rated voltage, Equation (1) is used to calculate the de-rated current limit.

$$i_{q\_limit} = I_{q\_MAX} - \left[\underbrace{(V_{AC\_Rated} - V_{AC}) \times K_V}_{\text{voltage de-rating}} + \underbrace{(T_{PCB} - T_{OFFSET}) \times K_T}_{\text{temperature de-rating}} \right] \qquad \text{Equation (1)}$$

Where,

i_{q_limit} : De-rated current limit

I_{q_MAX} : Maximum current limit without de-rating

V_{AC} : Estimated input RMS voltage

V_{AC_Rated} : Rated RMS input voltage

T_{OFFSET} : Offset PCB temperature obtained from characterization

T_{MAX} : Max allowed temperature at the rated condition

K_V : Mains voltage compensation coefficient obtained from characterization

K_T : PCB temperature compensation coefficient obtained from characterization

The intent with the characterization is to maintain maximum power possible and operate as long as possible without exceeding the critical component maximum temperature. There are two factors in Equation (1) that are subtracted from the rated maximum current limit. One of them is the voltage de-rating factor and the other is the temperature de-rating factor. The purpose of the voltage de-rating factor is to account for the increase in input current and power dissipation in the power factor correction section. The time that is going to occur is when the input voltage drops. Therefore, we desire the voltage de-rating to be active below the rated value. As a result, K_V has to be a positive number.

The purpose of the temperature de-rating factor is to introduce a de-rating factor based on the temperature. T_{OFFSET} and K_T are values determined from testing. K_T is a positive number. T_{OFFSET} is selected such that when the enclosure temperature exceeds T_{OFFSET} temperature, the correction factor becomes positive and subtracted by the maximum current limit. Ideally speaking, T_{OFFSET} will be the PCB temperature at the maximum ambient temperature. It is possible that T_{OFFSET} is selected such that even though the temperature is above the maximum temperature, the temperature de-rating factor becomes a negative number. However, the total de-rating factor is a positive number due to the voltage de-rating factor. Since there is a feedback effect of speed limiting with the temperature, the total de-rating factor might be a negative number, which will not be used due to minimum selected current limit as explained below.

Condition 2: Temperature

When the mains voltage is above the rated voltage and the PCB temperature is above the maximum ambient temperature, the PCB temperature alone is used in the current limit calculation. The following formula has been developed to calculate the de-rated current limit.

$$i_{q\_limit} = I_{q\_MAX} - (T_{PCB} - T_{OFFSET}) \times K_T \quad \text{Equation (2)}$$

When the de-rating method is characterized, Condition 1 and Condition 2 are characterized together. Hence, T_{OFFSET} and K_T values are the same for both conditions. The purpose with the de-rating equation is that above the rated voltage, the power dissipation in the power factor section does not increase. Hence, there is no need for the voltage de-rating factor. The voltage de-rating factor is eliminated and we end up with the simpler equation, Equation (2). All the points explained above in Condition 1 about temperature de-rating factor apply to this condition and Equation (2) as well.

Integration of De-Rating Algorithm

Operation of the overall de-rating algorithm has been presented below in the block diagram and the flowchart formats below. There is a maximum current limit, which is never exceeded. Normally, without any temperature and voltage de-rating, it will be the limit that is present at the rated speed. In the above equations it has been designated as I_{q_MAX} .

Let us now explain how the three pieces of the de-rating algorithm is integrated. First of all, Iq limit is calculated based on the speed and the current profile of the pump drive. In low speed range, less than 2500 RPM, that is the only de-rating since there is not sufficient power draw to overheat the components in high ambient and low input voltage cases.

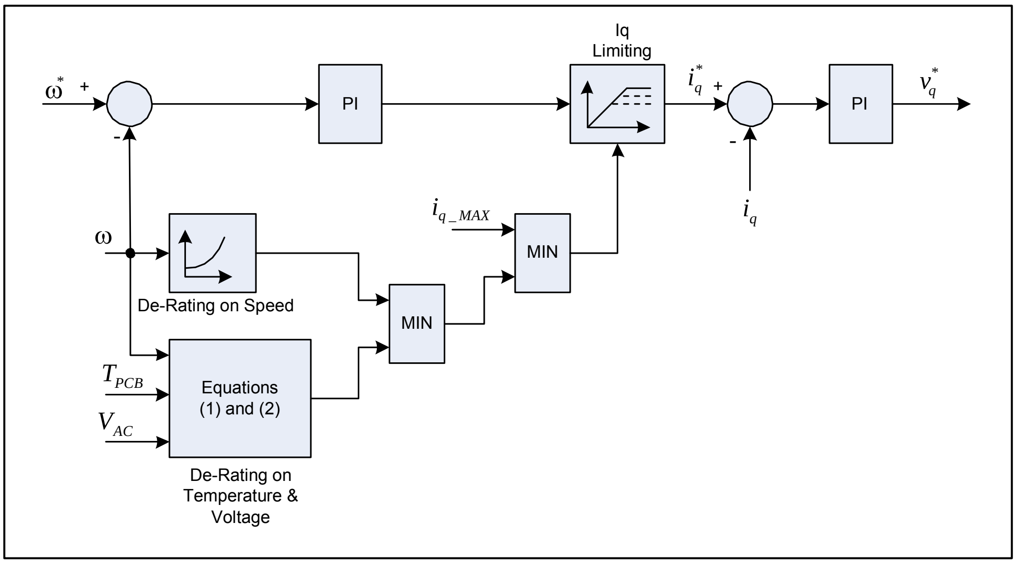

Figure 8 De-rating algorithm overview

Above 2500 RPM limit, PCB temperature is compared with the maximum temperature. If the temperature is less than the T_{MAX} , no second current limit is calculated and the first calculated current limit from the speed de-rating is compared with the maximum current limit and the minimum value is used to set the allowed maximum current limit out of the speed controller. If the temperature is more than the T_{MAX} temperature, the input voltage is compared to the rated voltage and if the estimated input voltage is less than the rated voltage, Equation (1) is used to calculate the second current limit. Equation (1) will take into account the temperature as well as the voltage de-rating. If the estimated input voltage is more than the rated voltage, Equation (2) is used to calculate the second current limit. Equation (2) will only take into account the temperature de-rating. The smaller of the two calculated current limits is selected as the current limit. Next, the calculated current limit is compared with the maximum current limit. The smaller of the current limit becomes the limiting current value out of the speed controller.

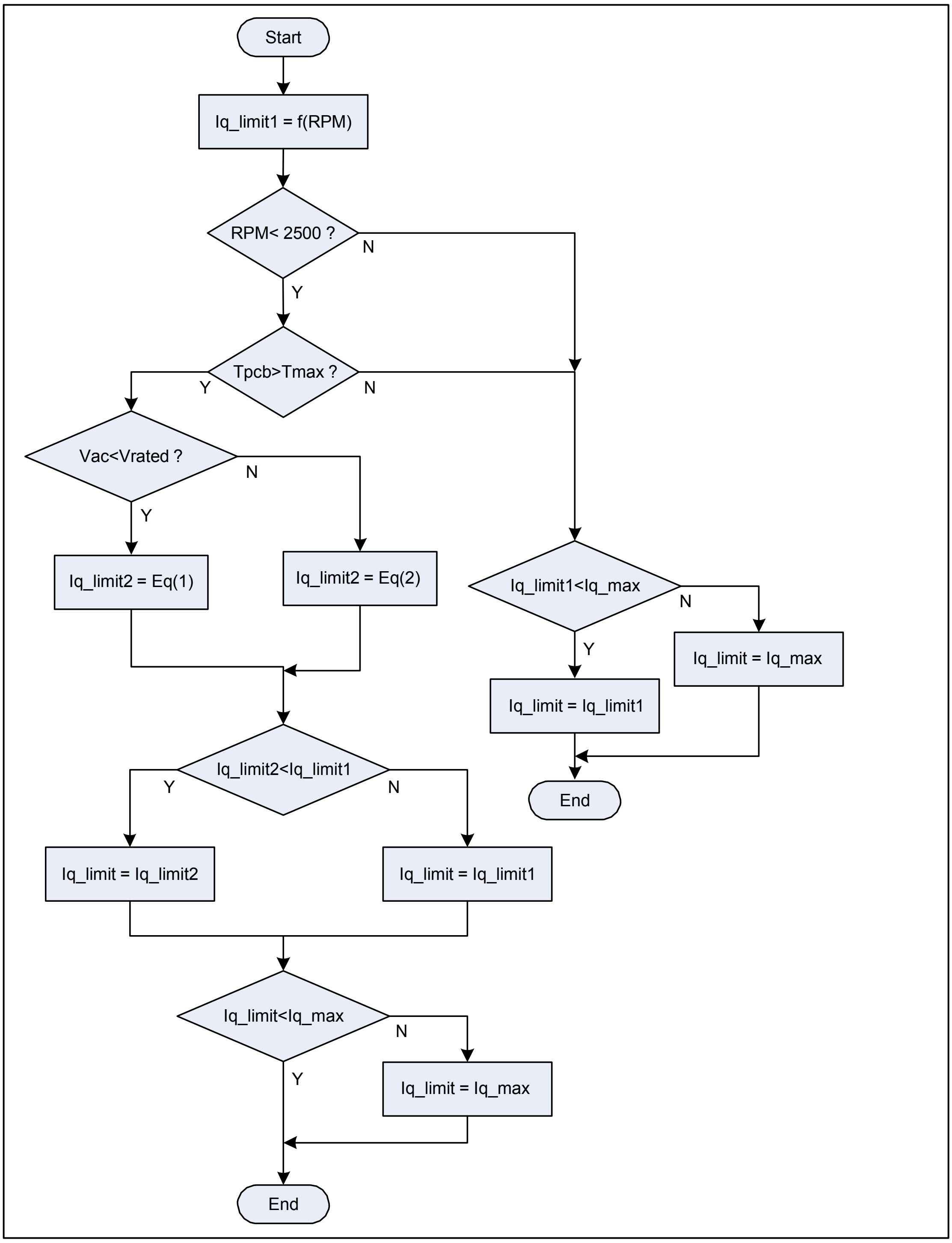

Figure 9 De-rating algorithm flowchart

Test Results

In order to demonstrate the operation of the algorithm, the pool pump drive is placed in a chamber that is temperature controlled. Thermocouple has been attached to the PFC inductor coil and another thermocouple placed to the inlet of the motor fan to measure the ambient temperature. Each data point has been obtained after temperature has stabilized. The following is the list of the test parameters.

$I_{q\_MAX} = 12.5$ A, $V_{rated} = 230$ V, $T_{OFFSET} = 73.5$ C, $K_V = 0.13$, $K_T = 0.29$

Figure 10, 11, and 12 show the operation of the de-rating algorithm.

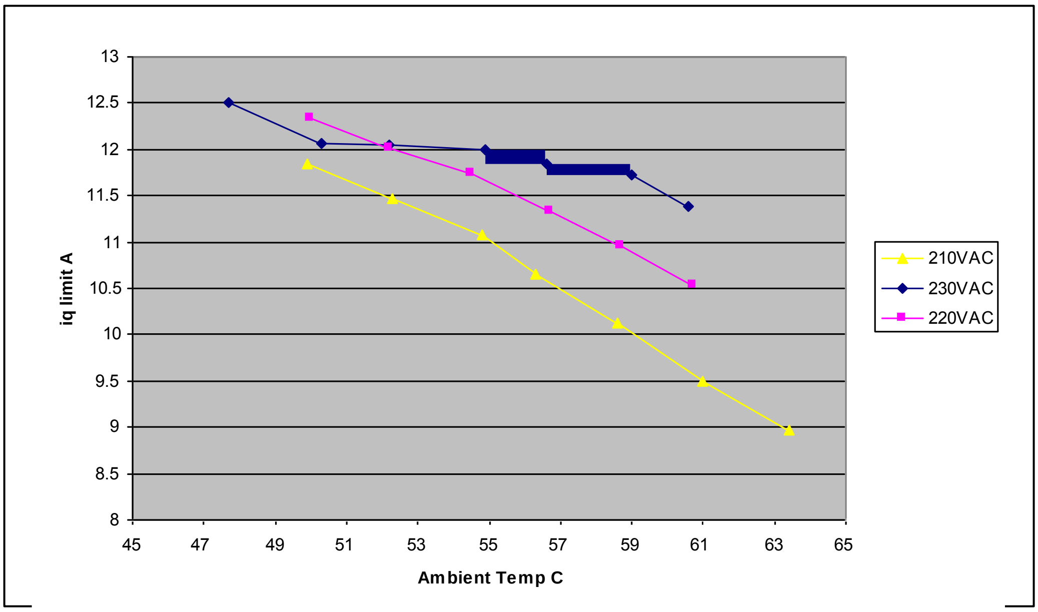

Figure 10 Current de-rating

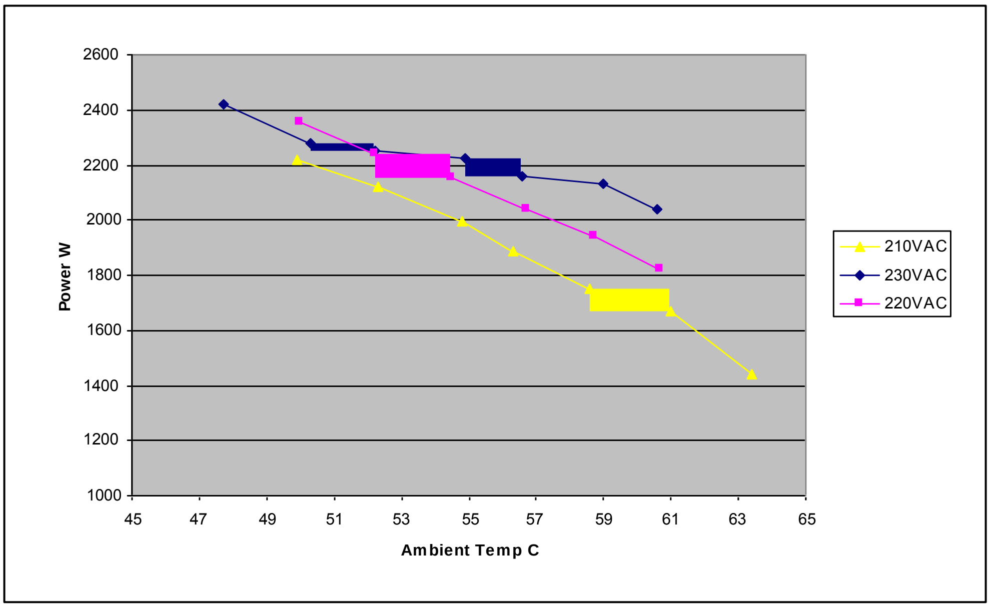

Figure 11 Power de-rating

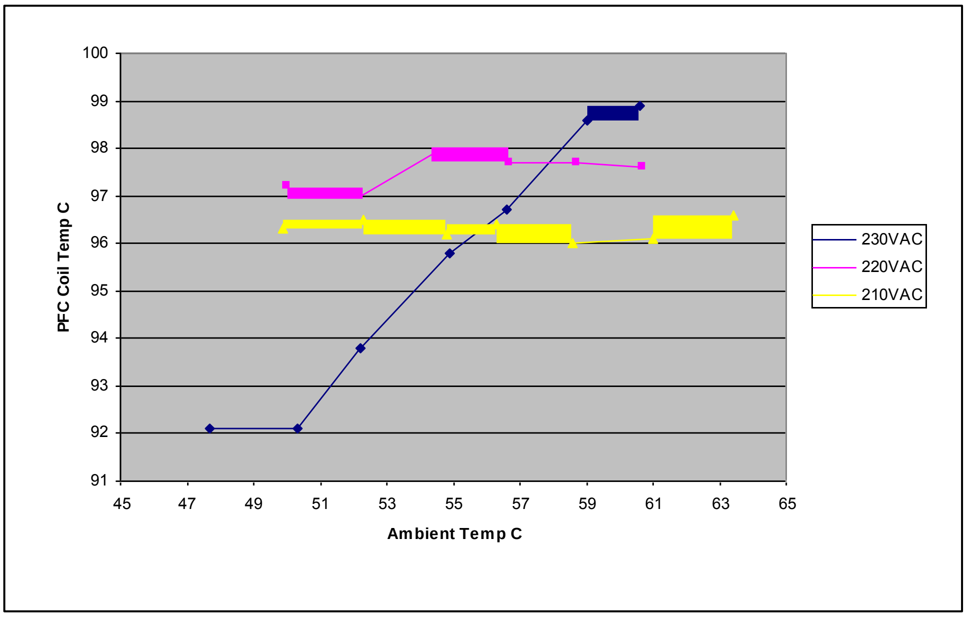

Figure 12 Critical component (PFC inductor coil) temperature during de-rating

Figure 13, 14, and 15 demonstrates the currents calculated by each piece of the algorithm. These figures show when which algorithm is effective. Iq limit is the final value that is used by the software to control the motor. Temp/Volt line in the figures is the value that is calculated based on the temperature and/or temperature/voltage equations that were described previously. Speed line in the figures shows the value that is calculated based on the speed versus current profile.

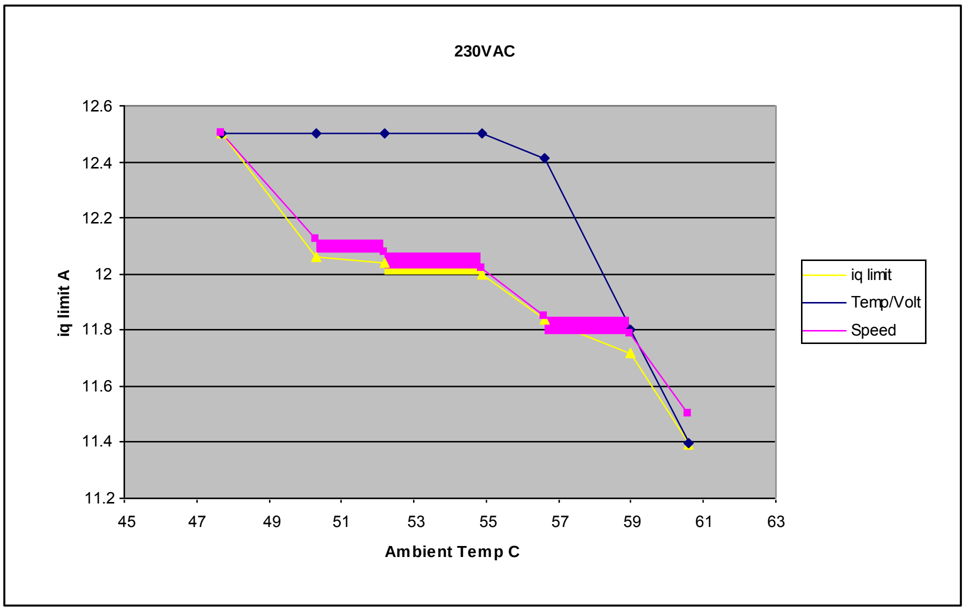

Figure 13 Calculated currents during de-rating at 230VAC

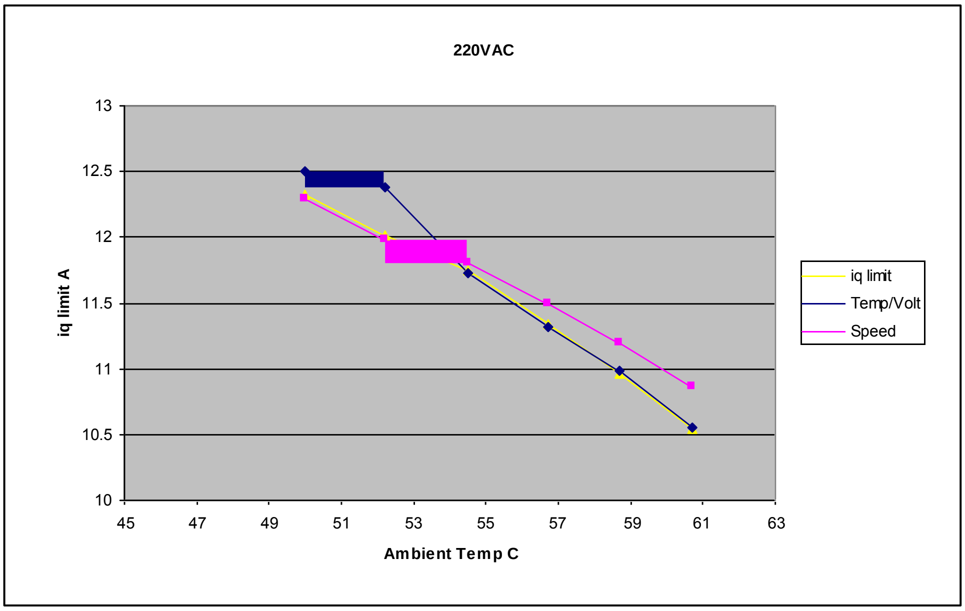

Figure 14 Calculated currents during de-rating at 220VAC

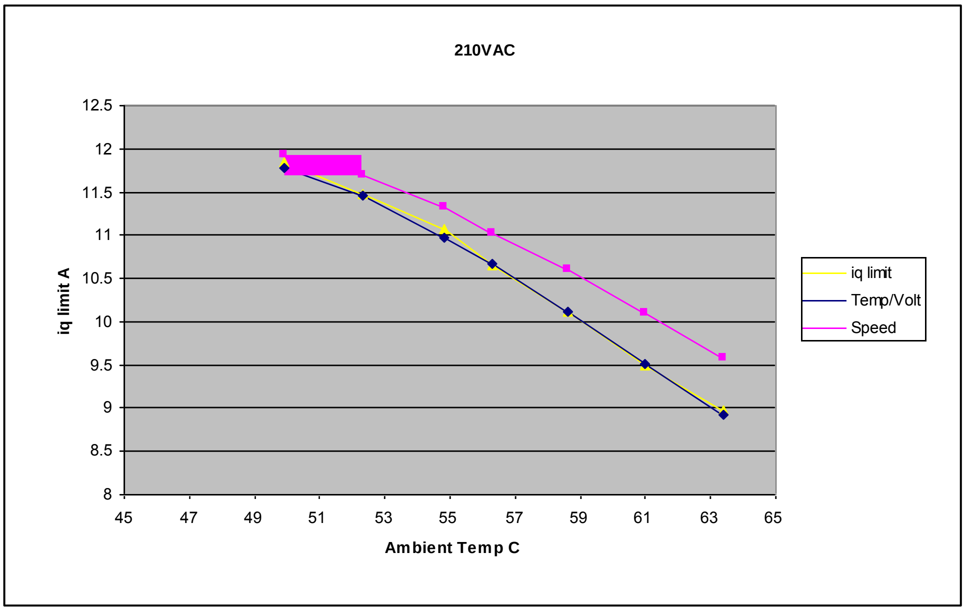

Figure 15 Calculated currents during de-rating at 210VAC

Conclusion

In pool pump drive application, operation beyond the specified operating limits is an important requirement. The maximum ambient temperature and the minimum input voltage are the two important limits of the pool pump drive. In order to allow operation beyond the maximum ambient temperature and the rated input voltage without exceeding the critical component temperature limit, output power of the drive is sacrificed. In other words, reducing or de-rating the output power of the drive allows operation of the drive beyond its rated operating parameters. A power de-rating scheme for a power factor corrected pool pump drive is particularly challenging due to the reasons explained in this paper. A de-rating method based on the pump characteristic, in other words, speed versus current profile has been introduced. In addition, a two part method based on both temperature and voltage, and only temperature has been introduced. Since there is no input voltage sensing, a voltage estimation method developed to accurately track the input voltage that is used in the de-rating method. At any given time, by limiting the current to the minimum of the calculated limits, the output power is de-rated.

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Short Primary Linear Drive with Induction or Synchronous Operation applied in Automated Material Handling Applications

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Abstract

An industrial manufacturing system, which uses a short primary linear drive, where several vehicles can travel with high speed, high degree of independency and high precision is proposed in this paper. Solutions with short primary and long primary are compared. Short primary linear drives on passive track are advantageous in material handling applications, where moderate dynamic, very long track and closed paths are required. The short primary type uses a passive track and an active vehicle which is supplied by a contactless power transmission system. In order to reduce the costs, a combined operation of permanent magnet linear synchronous motor (PMLSM) and linear induction motor (LIM) is applied to operate the primary as vehicle, avoiding adjustment or releasing of the material during the drive cycle. A theoretical and experimental study was conducted to assess the feasibility of employing the short primary linear motor for a flexible manufacturing system, in which a contactless power transmission provides the basic power and an ultracapacitor storage system provides the peak power. An experimental setup composed by software and hardware, was implemented to perform a smooth transition between the different sections of the track (processing section and transporting section).

1. Introduction

Nowadays, the control of electrical machines has an increasing progress, due to the evolution of the power electronics components and the information processing devices, improving the efficiency and safety of industrial systems through the adjustment of the speed, thrust and braking control. The linear electric motors have found their niche and they are now becoming widely used in industrial applications. The linear motors perform better than rotary motor system when the linear motion is required. So far rotary electrical motors with a complex mechanical system of gears, belts, and pulley and screw systems are often used to convert the rotary motion into linear motion. However, this increases the size of the system and reduces the overall system efficiency. Thereby, the use of a linear motor allows to improve the characteristics of an industrial system involving a linear movement of the load, like e.g. low operational and maintenance costs, high efficiency, no backlash, high production throughput and no extra mechanical coupling elements [1][2][3]. Therefore, for each type of rotary electrical machine such as: synchronous, induction, reluctance and direct current (DC), there is a linear equivalent.

The high demands on automated handling applications, which require flexible machines, short machine cycle times, high dynamic and linear movement are increasing steadily. In face of that, the linear motors are a suitable solution to these demands, since the linear motion and thrust force generation is direct, not requiring any mechanical transmission component subject to elasticity and wear. Thereby, they are found nowadays in many material handling markets, such as sealed environments for production of solar cells, LCD glass transportation, wood processing, loading gantry systems, packaging systems, machine tools, container transport, pharmaceutical production and food and beverage processing/filling.

This paper deals with the short primary linear drive designed for synchronous and induction operation in different sections applied in automated material handling applications. This opens new ideas to investigate the current systems, simplifying the mechanical complexity and increasing the scalability and independency of the vehicles.

2. Automated Handling Applications

In applications like automated material handling systems, there are typically two different sections: 1.) sections where the work piece should only be transported and 2.) sections where the work piece is sequentially processed with high accuracy. Conventionally, the work piece is fastened within the processing station and released after the processing. As a result, the manufacturing time is significantly increased.

Figure 1 shows a simple example of combined transportation and processing of work pieces with a linear drive system. There, two sections can be distinguished. The first section is the processing station (P1…P4), where high thrust force and high precision are demanded, and the second section is the transporting zone where the vehicle moves forward with lower acceleration. In such flexible chain process with linear drives, the work piece is adjusted at the beginning of the process and released only at the end; that means there is no fastening or releasing of the work piece from the vehicle. Many benefits are achieved by having linear drives, such as: reduced manufacturing time, high dynamic, high precision (few µm), high productivity and reduced maintenance cost [3].

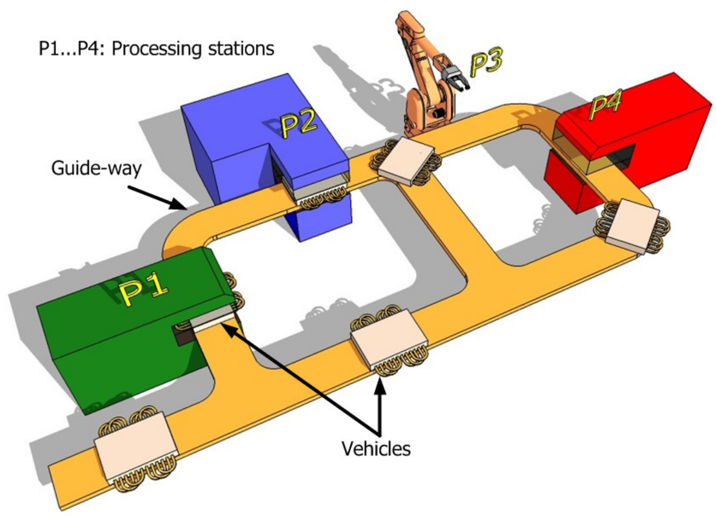

Figure 1. Combined material transfer and processing line system with a short primary linear drive.

Combined transportation and processing of work pieces using linear drive systems, as depicted in Figure 1, requires the following properties:

- On the guide-way (track) several vehicles must travel with a high degree of independency (all the vehicles can start and brake without dynamic restriction).
- Each vehicle has to be controlled very precisely by using a position sensor, when the vehicle operates within the processing section. Unlike the processing section, the sensorless motion control or one sensor with less accuracy may be used within the transporting section, in order to reduce the costs.
- The guide-way must allow for horizontal and vertical curves and for closed paths.

Regarding to the features of the automated material handling application, like: number of vehicles, track length, maximum speed and acceleration, sealed environment (vacuum), scalability and cost, the suitable linear drive topology (e.g. short or long primary) may be discussed. Therefore, the long and short primary topologies used to fulfill the system depicted in Figure 1 are presented and discussed in the following subsection.

2.1 Long Primary topology

For the long primary configuration, the primary remains static as a track and the secondary is the work piece carrier. Hence, we have an active track (primary) with passive and lightweight vehicles (secondary), avoiding brushes and cables to transfer energy and information to the moving part and with the possibility to reach a high dynamic. In applications with very long active tracks, the primaries are arranged in several electrical independent segments, in order to reduce the reactive power of the dedicated inverter and save energy (only the segments where the vehicle is located are switched on, all the other are turned off) [3]. Furthermore, in short active track applications with multiples carries, the active track is also divided in many segments, since the desired number of vehicles depends on the size of the long primary (for individual vehicle motion control). The lowest possible number of segments per vehicle are two, considering that two segments are activated during the transition [4].

The position measurement is made by installing a scale at the passive vehicle and a stationary position sensor only within the processing station, so that, depending on the length to be acquired, the control system to be implemented is very complex (segmented position sensors) [5]. Under the application condition, that the vehicle must have a high dynamic inside the processing station, the flat single-sided PMLSM provides a good and feasible solution. Therefore, the moving secondary is a plate with a permanent magnet array. In single-sided PMLSM, the attractive force between the primary and secondary is very high, being necessary a robust mechanical structure. However, the double-sided topology can be used to fulfill the high acceleration requirement, without the strengthening of the mechanical structure.

For automated material handling application with long primary topology, there are two alternatives to supply each primary segment. The first option is multiplexing of inverters, which feed the primaries, by mechanical or electronic switches [3]. Such concept can reduce the number of inverters (two inverters per vehicle), but it seems not to be a good option, since the complexity and cost rise together with the track size [3][4]. The second alternative is to feed each primary segment with a dedicated inverter, so that a large number of primary segments imply a large number of inverters. The physical distribution of the components for the second alternative produces another two possibilities. They are listed below:

- Long primary topology with centralized controllers: The inverters and controllers are accommodated together in a cabinet with all auxiliary components, and each inverter feeds one primary segment. Furthermore, each vehicle has its own vehicle controller. Then, all segments are connected by shielded motor cables [5].
- Long primary topology with distributed controllers: the inverters and controllers can be placed near each segment along the track with a common DC-link, reducing the cable installation costs [6]. Moreover, each primary segment has one vehicle controller.

2.1.1 Long primary topology with centralized controllers

According to the previous subsection, the long primary topology with centralized controllers has one vehicle controller (VC) assigned to each vehicle, as depicted in Figure 2. The VC receives feedback data (current, speed and position) from the active inverter which feeds the respective segment. Then, the received data are processed by the VC control algorithm, and the switching time information is transmitted back to the inverter through an inverter-bus. The inverter-bus provides communication between each VC and each inverter inside one control cycle [4]. All inverters are connected at the same DC-link, and they are installed with the VCs within a cabinet, as illustrated in Figure 2. The motion controller (MC) is composed by industrial PC or PLCs which control the actual position of the vehicle.

For such topology, one control cycle should be splitted in some intervals, which are equivalent to each controlled vehicle [4]. In one vehicle interval, two primary segments can be activated and controlled simultaneously. Since a good dynamic is demanded for such application, the number of travelling vehicles is limited, due to the reduction of these time intervals, which requires an increasing of the bandwidth. [3][4]. Such inverter-bus bandwidth limitation is the bottleneck point to increase the scale of the system. Figure 2 shows that the motor cable connection (cabinet ⇔ motor) could increase the overall costs for large applications with several segments. Altogether, the given topology is recommended for automated material handling system with low traffic density (low number of vehicle per track length).

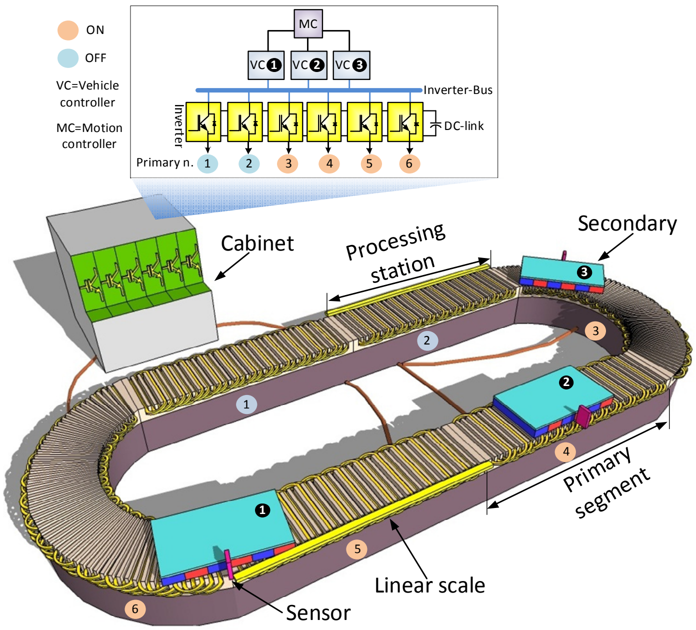

Figure 2. Long primary topology with centralized controllers.

2.1.2. Long primary topology with distributed controllers

For industrial automated material handling application which requires a high traffic density, the long primary topology with distributed controllers is a suitable solution. The inverter-bus bandwidth limitation for centralized controllers is settled by placing the VC and inverter inside a module. Therefore, the module is responsible to supply the primary segment. Figure 3 shows a system with three passive vehicles, six segments and six modules. The travelling vehicle is commanded directly by the module, since one VC is attributed to one inverter, as shown in Figure 3. In case of the vehicle be moving between two segments, the data (speed, position and current) are transmitted synchronously to the adjacent VC (inside the next module) using a high speed point-to-point communication [6].

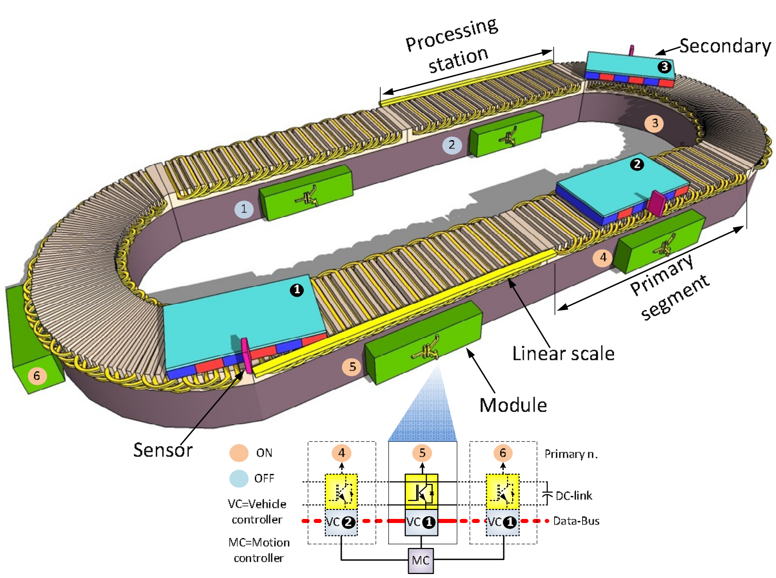

Figure 3. Long primary topology with distributed controllers.

Moreover, the motion controller is connected to each module by a physical industrial field bus interface [6]. The MC generates the reference position and receives the actual position from all vehicles. Such a topology has a high degree of scalability, and future expansions can be easily implemented increasing the number of modules and primary segments. On the other hand, the implementation costs rise with the number of the segments and modules for a very large system.

2.2 Short Primary topology

The short primary topology uses the three-phase winding mounted on the moving part (active vehicle) to produce the travelling magnetic field, and the secondary is the passive part, which is utilized as guide-way. The energy has to be transmitted to the vehicle, since the primary part must be supplied. Exact commutation of motor current, speed control and positioning require a linear measuring sensor which is typically attached to the active vehicle. Generally, in industrial application with very short track (e.g. machine tools), the power supply and the actual position are transferred and acquired from the moving primary by using a drag-chain or sliding contacts. The same drag-chain is also used to place the cables, which are used to read the actual position information. The inverter and controllers are located in a stationary cabinet near to the vehicle. The utilization of a drag-chain is improper for the system presented in Figure 1, where the vehicles should move along a track with closed paths and sharp curves. Considering an automated material handling application with linear drives that is characterized by a very long track, low density of vehicles and moderate dynamic, the short primary topology affords a very simple track construction, allowing also sharp horizontal and vertical curves and causing lower implementation cost for the track than the long primary topology presented in the previous subsections. The limitations of the short primary topology are given mainly by the power supply system (energy must be transferred to the moving windings) and the significantly reduced dynamic (acceleration), due to a heavier vehicle than with the long primary topology. On the other hand, the system is more flexible in case of vehicle failure, since it can be easily removed, and the system can continue the work normally.

To fulfill the application requirement of transfer energy without contact, the vehicle should be supplied by using a contactless energy transmission, thereby the VC and all necessary converters are installed on-board the vehicle [7], as shown in Figure 4.

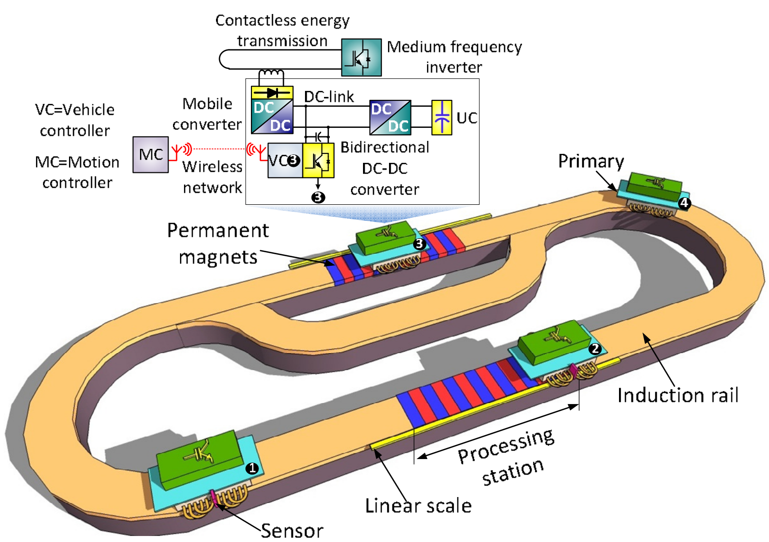

Figure 4. Short primary topology with contactless power transmission.

In order to improve the dynamic, to allow individual motion control for several vehicles (in case of all vehicles accelerate at the same time) and to absorb the generated braking energy, each vehicle is fed by an on-board ultracapacitor energy storage system. Together, both energy sources will increase the overall efficiency of the system. Moreover, it can reduce the size and cost of the contactless system, but weight, volume and complexity increases as well. In summary, the ultracapacitor storage system is used to increase the available peak power, and to absorb the generated braking energy. At last, just one contactless energy system is responsible to supply energy to all vehicles, as depicted in Figure 4.

This short primary topology has some advantages in comparison with the long primary topology, such as:

- The number of inverters and VS units is equal to the number of vehicles plus a stationary medium frequency inverter. Therefore, the number of vehicles is not limited as with the long primary topology (two primary segments for one vehicle).
- Reduced reactive power in the on-board inverter.
- The short primary has a better efficiency.
- The position sensor is attached to the active vehicle, thus one sensor per vehicle is necessary, and the acquired actual position is processed on-board of the active vehicle, making it simpler than the long primary topology.

The central MC produces the reference position to coordinate all active vehicles, and get the actual position data transmitted by the VC. To fulfill this communication demand, a wireless network should be utilized, since no contact is demanded. Figure 4 outlines two sections. The first section is a station where the work pieces are processed. While processing, high thrust force and precision are necessary. The second section is outside the processing station. There, a lower thrust force is sufficient to keep the active vehicle moving with a low acceleration towards the next processing station. As a result, the passive track will consist of two different section types: high thrust force sections using stationary permanent magnets and low thrust force sections using an induction rail. The induction rail is composed of two layers: copper and back iron. Surely, the cost of the track can be reduced by saving the stationary permanent magnets outside the processing station.

3. Experimental setup and results

3.1 Construction and Specification of the Experimental Setup

The laboratory prototype of a short primary linear drive with an on-board energy storage device was constructed for experiments, based on the proposed system. The system employs one track divided in two sections and one active vehicle, which represents the material transfer and processing line. The control unit and the ultracapacitor energy storage system are on-board of the vehicle. The experimental setup is an integration of commercial equipments and boards developed at the laboratory. The chosen linear motor is a convection-cooled synchronous motor. The primary core was mounted under the active vehicle as illustrated in Fig. 5.

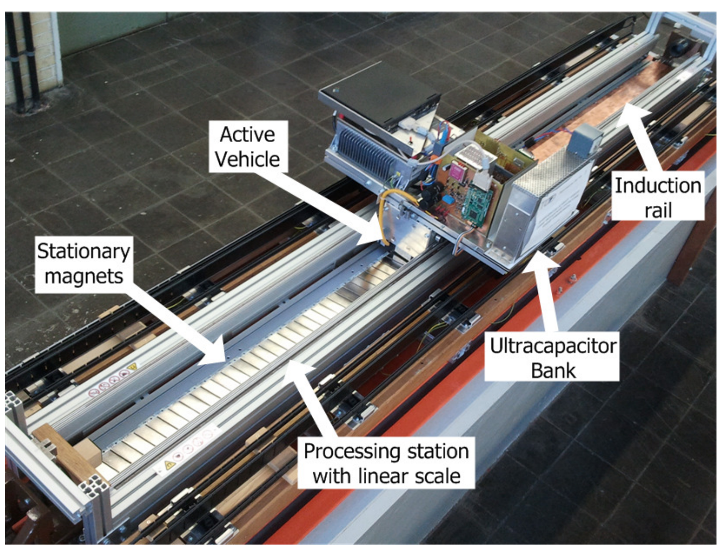

Figure 5. Structure of the experimental setup.

The primary comprises of a laminated iron stack and a distributed three-phase winding. The primary is also fully laminated with carbon fiber allowing the motor to reach high stiffness and good heat dissipation. Table I shows the construction dimensions and information of the primary core.

Table I: Motor parameters for different sections

Synchronous Operation				**Induction Operation**			
Nominal current	3.0 A	Force constant	83.05 N/A	Nominal current	4.18 A	Force constant	44.2 N/A
Primary Resistance	3.9 Ω	Air gap	2 mm	Secondary Resistance	16.94 Ω	Air gap	1 mm
Nominal thrust force	250 N	Peak thrust force	664 N	Primary inductance	101 mH	Magnetizing self-inductance	67 mH
Phase inductance	32 mH	Secondary length	159 cm	Secondary inductance	81 mH	Secondary length	159 cm

The secondary part within the processing section employs skewed permanent magnet segments. The segment has a galvanized back iron with 8mm thickness, and the array of four magnets pieces with 4mm thickness bonded on the surface of the back iron. Hence, the long passive track was arranged using eleven segments one next to another. For the transporting section, the secondary part is an induction rail. The induction rail has two layers: one copper layer and one back iron layer, and it was constructed screwing both sheets together in the edge. Finally, both secondaries were installed between the guidance profiles. Considering that we have different sections, the linear motor can operate as synchronous or as induction machine. Therefore, the linear motor parameters are splitted for induction operation and for synchronous operation as shown in Table I. Fig. 5 shows the structure of the experimental setup.

The mechanical structure was built using a commercial aluminum profile system. According to the proposed system of a material handling system, the track was divided in two sections. The track has 3.3 meters, and each secondary section has the length shown in Table II. The active vehicle moves along a linear guide rail, thus the air-gap is kept constant between the vehicle and the track. The vehicle has a four wheels system, which allows it to move only in the horizontal axis.

Table II: Mechanical structure parameters

Track length	3300mm	Vehicle length	353mm
Track width	730mm	Vehicle width	712mm
Active vehicle weight (vehicle + on-board devices)	53.7kg	Vehicle weight (mechanical structure)	9.8kg

At the station where the materials are processed a high accuracy (few µm) is demanded. It was used a linear measuring system composed by a linear magnetic scale with fixed pole pitch (1mm) and an anisotropic magneto-resistive incremental encoder. The incremental encoder was attached at the active vehicle, to inform the actual position for orientation of rotating AB- reference frame and to calculate the real speed value. It has a resolution of 200 increments per mm (5µm). The linear magnetic scale with 3m long was installed along the whole guidance profile.

The rotating reference frame is oriented towards (or aligned with) the secondary flux vector, which is called field orientation. In other words, the secondary flux has a component only in the A-axis, but there is no component in the B-axis. While the secondary flux linkage for the induction motor operation is produced by induced currents on the secondary, the secondary flux for synchronous motor operation is generated by stationary magnets. There, the secondary flux is electrically fixed to the secondary and rotates with the electrical secondary speed [8].

The source to feed the vehicle is composed by a 4 kW contact less power transmission system, a 4 kW DC-DC bidirectional converter and an 4 kW inverter with a rated DC-link voltage of 500V. The developed control is realized by a DSP of type TMS320F2812. The Digital Signal Processors (DSP) was utilized to control the position and speed, to calculate the required current for the moving primary and for the energy management of the ultracapacitor bank.

3.2 Experimental Results

The incremental encoder measures the position. The speed is obtained by numerical derivation and filtering. This filter may hide transients in real speed and of course in acceleration (force). Additionally, the very high mass (53.7 kg) of the vehicle prevents that transients in force can be easily concluded from the recorded speed. In order to test the position performance of the proposed control strategy, a position command (x*=2.8m) was sent to the vehicle. The vehicle starts from the initial position (x=0m) on the processing station at time t_0, and reaches the transition area at the time t_1. Afterwards, the optimum position γ is achieved at time t_2, and at time t_3 the vehicle covers only the induction rail.

The optimum position γ was determined experimentally such that a sufficient thrust force with acceptable disturbance is reached. In other words, if the operation mode is changed too late from PMLSM Field Oriented Control (FOC) to LIM-FOC, the thrust force required to guarantee a constant speed will not be achieved in the transition area.

For the synchronous operation, it is utilized only the B-axis current component i_{1B}, whereas in induction operation mode, both current components (i_{1A} and i_{1B}) are injected. During the transition moment, the majority of the thrust force should be generated with the primary working in synchronous operation mode due to the fact that the induction operation requires more power and causes more power losses to keep the thrust force at the same level. Definitely, the LIM-FOC operation should be activated as late as possible. In face of that, the position value γ was fixed taking such that the speed variation of the active vehicle was small. Based on the criteria above, several experimental tests were carried out, and it was determined that the operation mode should be changed when the vehicle has 64% of its length above the induction rail, then the optimum position value is γ=209mm.

At time t_4, the vehicle receives the new reference position (x*=0m) and finally returns to the original position, as illustrated in Figure 6.

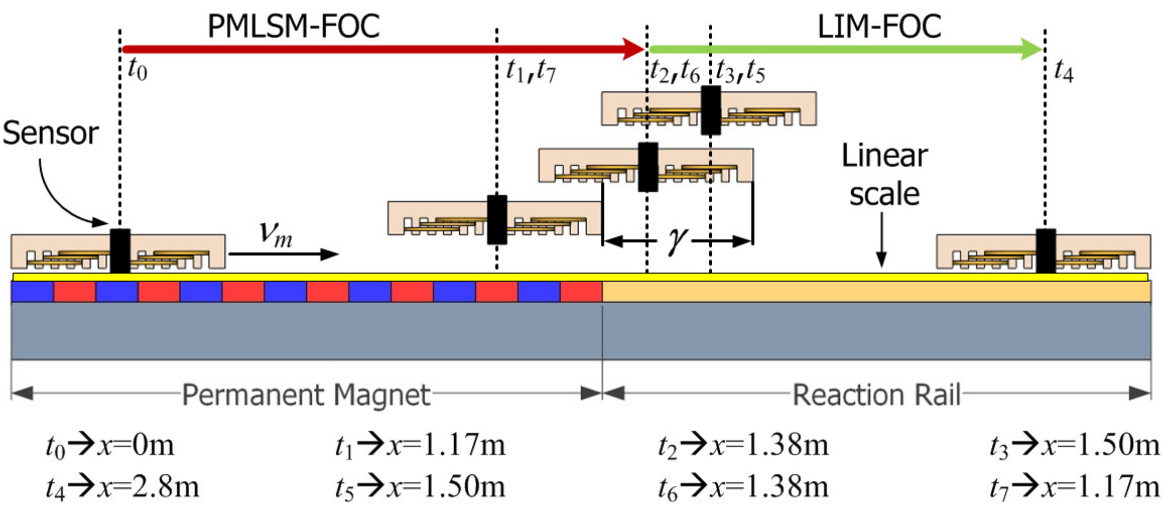

Figure 6. Sketch of the active vehicle position during the experimental drive cycle.

For this experimental test, the speed was limited to 1m/s, the current i_{1B} was limited to 8A and the magnetizing current was set to i_{1A}=3.6A. During the drive, the active vehicle crosses both secondaries and returns to the original position.

The experimental test was carried out in order to simulate a supposed situation where the vehicle leaves a processing station, but it needs to wait for the next processing station to be released. Then, it should stop for few seconds and move again toward the next processing station. At the border between both secondaries, there are some disturbances in the vehicle's speed that must be compensated by the current controller. The speed, position and current responses for the executed experimental test are shown in Figure 7. Also, Figure 7 shows that LIM FOC starts with the magnetizing current i_{1A} being injected by the current controller (Δt=t_6-t_2).

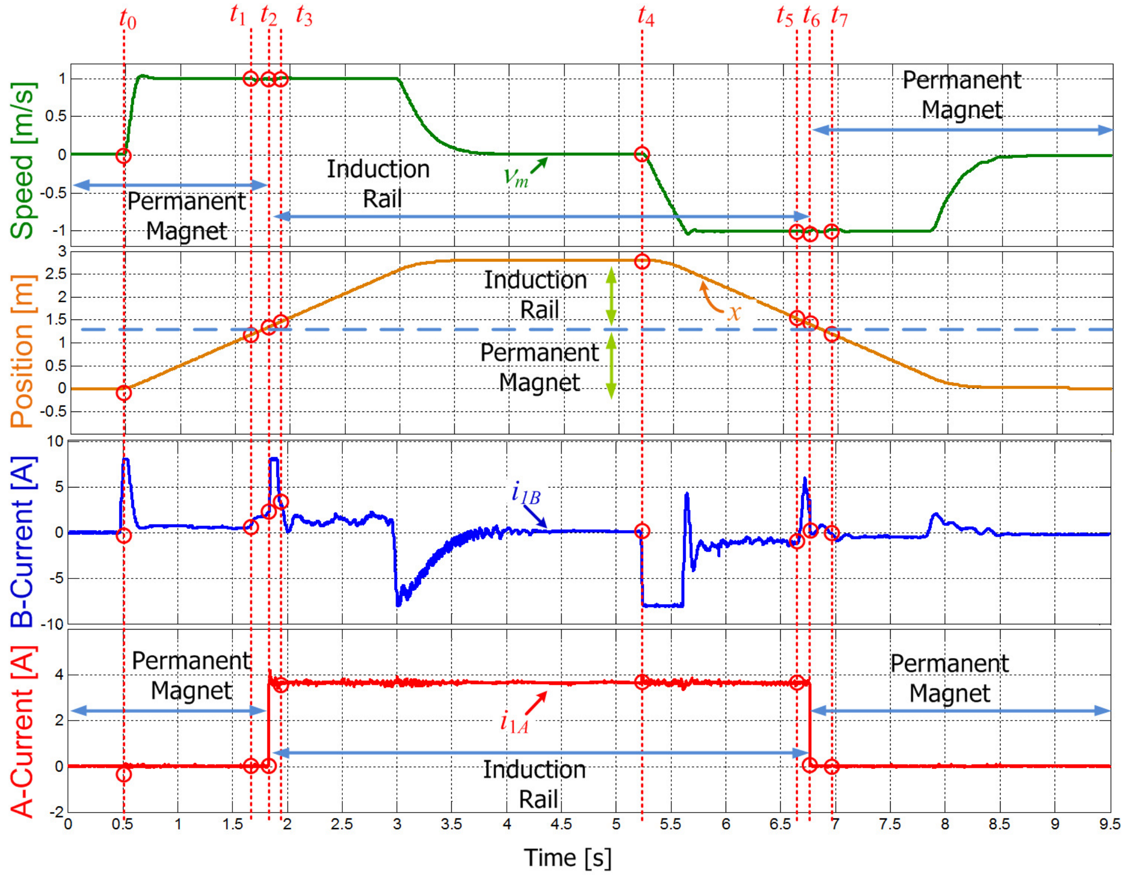

Figure 7. Measured position, speed and current for the drive cycle.

4. Conclusions

Considering automated material handling applications, the use of short primary linear drives are proposed. Solutions with short primary and long primary were compared. For the long primary linear drive, different topologies concerning power- and information- processing were compared. Concerning costs reduction, sections where the work pieces are transported, the final cost of the application is reduced by saving magnets. The short primary linear drive was implemented, which allows that horizontal and vertical curves be easily built due to the simple secondary part (reaction rail or stationary magnets). The track was equipped with a linear magnetic scale inside and outside the processing station, for high accuracy of positioning. As the linear scale was installed in the whole track, all the traveling vehicles can be stopped inside the transporting section and wait the next processing station be released. Therefore, in automated material handling applications with very long track, low density of vehicles and moderate acceleration, short primary linear machines are a good solution. The developed transition control strategy was implemented to control the active vehicle for a lower speed drop, a sufficient thrust force, optimal dynamic performance and low power consumption, when it moves between the permanent magnets and the reaction rail sections.

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Energy Regeneration in a Magnetically Levitated Vehicle for Urban Transportation

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Abstract

The fully electric levitation train Maglev-Cobra for urban transportation presents unique features of energy consumption, construction costs and efficiency, addressing sustainability issues and creating innovation in science and technology. The added ability to regenerate energy contributes to improve the efficiency.

The superconducting magnetic levitation method (SML), based on the diamagnetic property of superconductors in the presence of permanent magnets, dispenses feedback control loops and electrical energy supply, which makes the technique more advantageous when compared to electromagnetic levitation (EML) or electro dynamic levitation (EDL) methods.

A Single Sided Linear Induction Motor (SLIM), with a differentiated geometry patented by UFRJ, increases the carrying capacity of the vehicle using the force of attraction between primary and secondary, an intrinsic feature of induction machines, besides giving the traction. The self-cooled SLIM machine has the following nominal values: 420Vac, 53A, 25Hz, 6 poles, developing a speed of up to 8m/ s.

A regenerative braking system uses a back-to-back converter, which allows bidirectional power flow. It operates with a supply voltage of 380Vac, 500Vdc on the intermediate loop and two SLIM's. The electricity generated by the deceleration of linear motors can be used by the auxiliary systems of the vehicle or returned to the grid, eliminating the use of resistive load to dissipate energy.

The efficiency of the linear induction motor is the object of analysis of this paper. The longitudinal force and the force of attraction between primary and secondary, depending on the air gap, are investigated. The energy generated during braking and the uphill-downhill operation will be presented.

Introduction

New transportation systems must be proposed to interconnect people in highly populated cities [1]. Subway construction costs reached unsustainable values, mainly to developing countries with many infrastructure and environmental problems. The superconducting magnetic levitation train named Maglev-Cobra proposes a vehicle with low noise emission, non-polluting and energy-efficient. The implantation cost compared with those of subways can reach one third.

This paper presents the linear induction motor used in the vehicle traction.

A brief description of the linear induction motor model and the equivalent circuit are shown. The characteristics and behavior of the engine during operation are analyzed. Results of the traction force, the ability to overcome steep paths, the attraction force and regeneration are presented.

Linear induction motor

The linear induction motor (LIM) allows the displacement of a load in a longitudinal direction without gears, pulleys, or other mechanical mean. The main parts of a LIM are defined as:

• Primary: it contains the phase windings and receives the energy supply.

• Secondary: made by laminated iron and short-circuited conducting bars, similar to a squirrel cage rotor.

The Maglev-Cobra uses a LIM of short primary and long secondary. The low manufacturing cost of this choice makes it financially viable. The project generated a patent (PI 1105529-4) by presenting a different LIM geometry, as shown in Figure 1. A With this new format, the attraction force that exists between primary and secondary will contribute to the levitation force.
There are different methods to supply current to the primary, for instance collecting brushes, energy transfer by induction or ultra-capacitors. The first method is applied in the present study. [2-4].

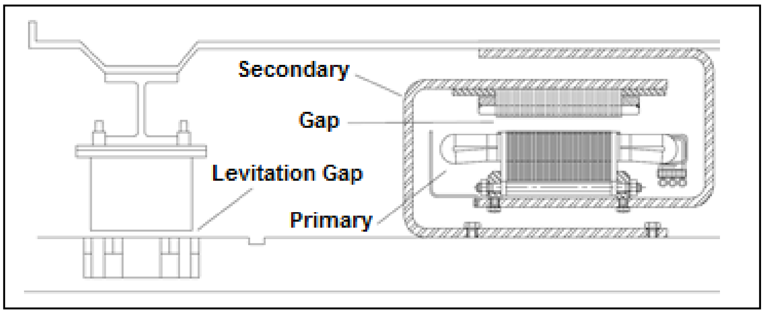


Figure 1 – Linear Induction Motor and Levitating Cryostat

Equivalent Circuit

The equivalent circuit of the LIM is shown in Figure 2. The dimensionless quantity Q depends mainly on the edge effects. The constants are defined as follows [3]:

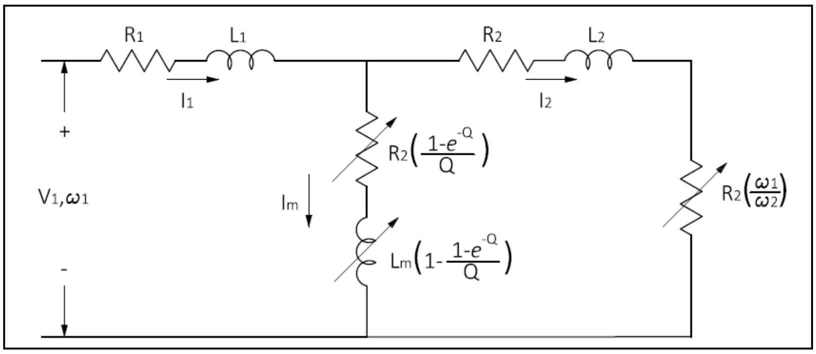


Figure 2 – Equivalent Circuit LIM

$$T_2 = \frac{L_m + L_2}{R_2}$$

$$T_v = \frac{D}{v}$$

$$Q = \frac{T_v}{T_2} = \frac{DR_2}{v(L_m + L_2)}$$

$D =$	primary length
$v =$	motor speed
$R_2 =$	secondary resistance
$L_2 =$	magnetizing inductance
$L_m =$	secondary magnetizing

Traction Force

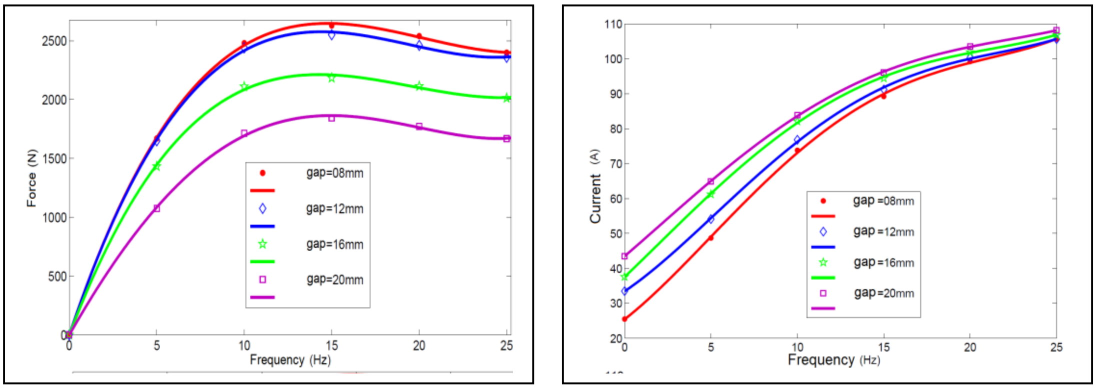
The LIM develops a force in the longitudinal direction (F_x), responsible for the movement, and a force (F_n) in the normal direction [7]. The traction force F_x is generated by the interaction between the induced current in the secondary with the travelling field in the air gap $\bar{J} \times \bar{B}$. The electromagnetic traction power developed by the motor is given by the equivalent circuit and Equation (1).

$$P_m = \frac{3I_2^2 R_2 \omega_1}{\omega_2} \tag{1}$$

The measurement system shown in Figure 3 was used to obtain experimental data and validate the model. The tests were performed with the primary blocked for different air gaps and keeping the ratio V/f constant, as shown in Table 1. The results for air gaps between 08 mm and 12 mm are shown in Figure 4 (a,b). In rotary motors, the air gap varies between 0.2 and 0.3 mm, but for the LIM used in the Maglev-Cobra it varies between 08 and 24 mm. Unfortunately, in general, linear motors need large air gaps to operate.

The magnetic flux in the LIM is longitudinal, that is, the magnetic flux lines are parallel to the direction of the travelling magnetic field. Motors with transverse magnetic flux have lower longitudinal forces [10].

Figura 3 – Traction Force measurement



a b

Figura 4 – Curves f x F and f x I in the LIMS

Table 1 – V/f constant

V	f	V/f
085	05	17.0
165	10	16.5
245	15	16.3
320	20	16.0
390	25	15.7

Attraction Force

The normal force F_n existing in the LIM is the result of the magnetic flux crossing the air gap and has two components. The first component F_{na} is an attractive force between the primary and the secondary iron core and the second component is the force of repulsion F_{nr} between the primary and secondary *FMM* [7]. Figure 7 shows the measured attraction force for a range of currents $(40 < i < 50)$.

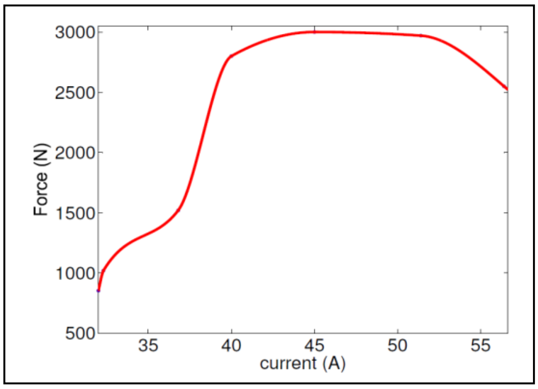


Figure 7 – Attraction Force; air gap = 8mm; M=450 kg

Operating Conditions

Each LIM is responsible for a maximum load of 30000N which corresponds to 15000N per module. The total route is composed of acceleration ramp, rated speed and deceleration ramp. Winning uphill slopes belong to the machine operating conditions [6].

Uphill and downhill operation

Experimental tests attempt to measure the ability of uphill and downhill traction, varying the mass and acceleration. A tilted platform, shown in Figure 8, was used. The platform has a length of 06m with three possible inclinations: 10%, 12.5% and 15%. These tests allow the determination of the regenerative capacity of the system.

Figure 8 –Platform used for uphill and downhill operation.

Figure 9 shows a free body diagram of the system in the inclined plane and the traction force exerted by the motor to raise the load. The accelerating and braking forces can be described as shown in Equations 5 and 6. The tests were done varying the mass (M = 450 and 1000kg) and slope (h = 10 and 15%). Figures 10 and 11 show the results. The acceleration and deceleration imposed in each test is present in Table 2.

$$F_{xa} = \frac{1}{\eta}\{[\mu m\cos(\alpha) + m\sin(\alpha)]g + ma\} \quad (5)$$

$$F_{xd} = \frac{1}{\eta}\{[\mu m\cos(\alpha) + m\sin(\alpha)]g - ma\} \quad (6)$$

Table 2 – Acceleration and deceleration values

	M=450; h=10%	M=1000; h=10%	M=1000; h=15%
a (m/s²)	0.40 – 1.400	0.27 – 1.260	0.400 – 0.500
d (m/s²)	1.72 – 13.86	7.31 – 30.90	26.56 – 22.47

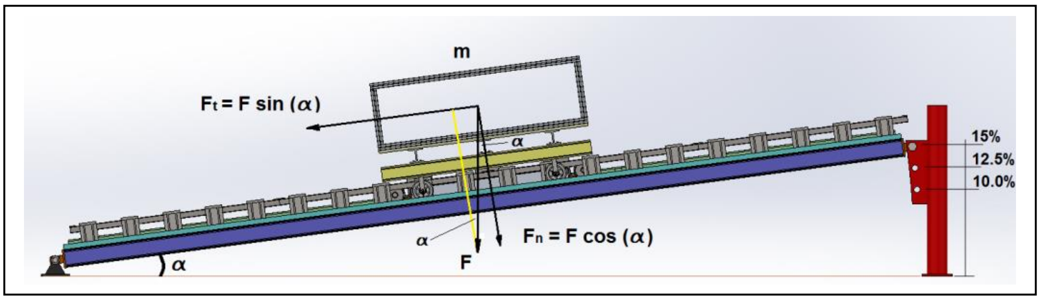


Figure 9 – Free body diagram of the inclined plane.

The traction and braking conditions used in these tests do not correspond to conventional operating conditions, being useful only for measuring the responsiveness of the system. The motor current and voltage to pull the load are shown in Figure 12.

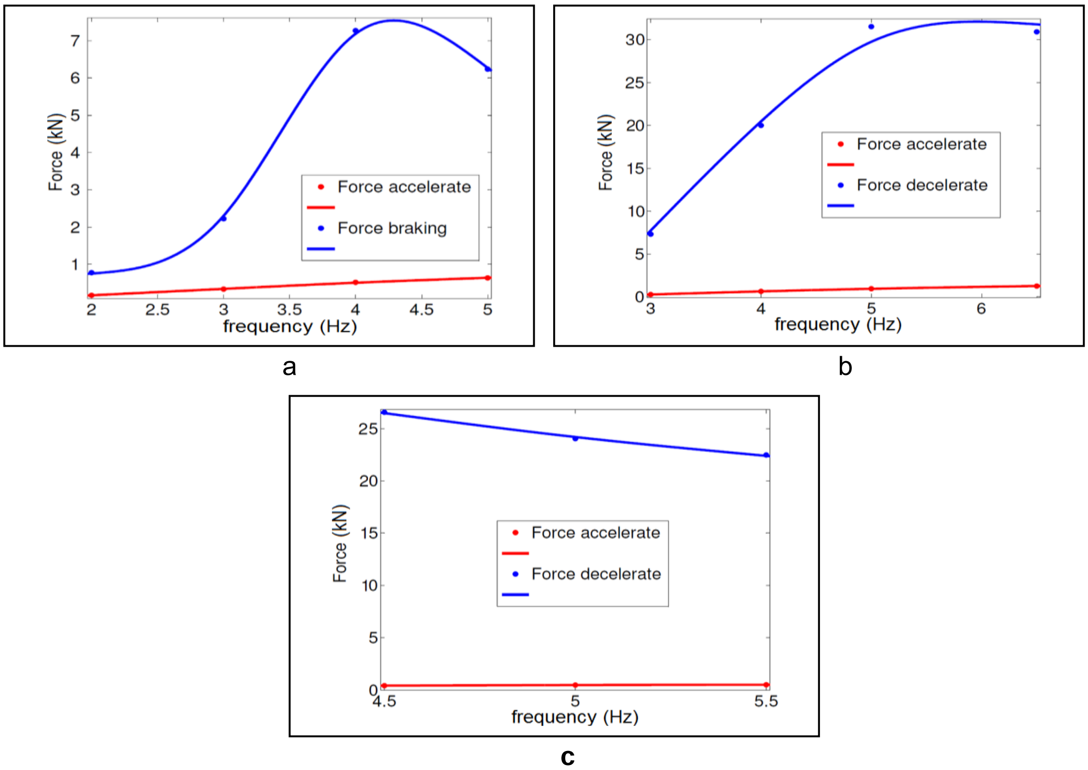
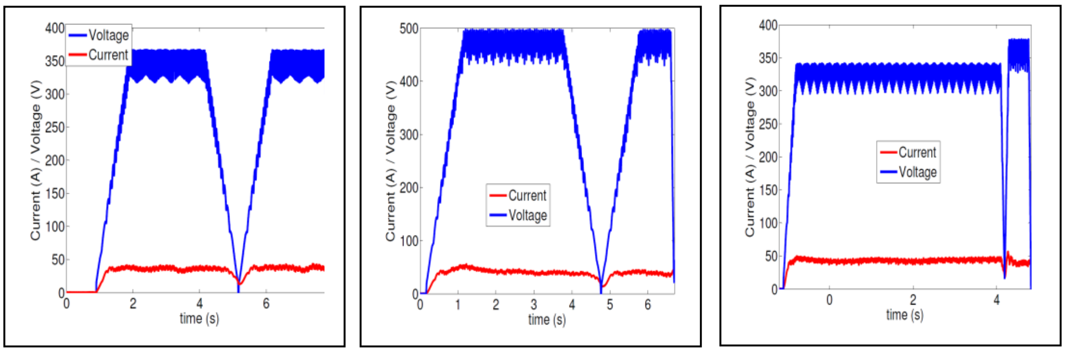


Figure 10 – (a) M=450kg; h=10% , (b) M=1000kg; h=10% and (c) M=1000kg; h=15%

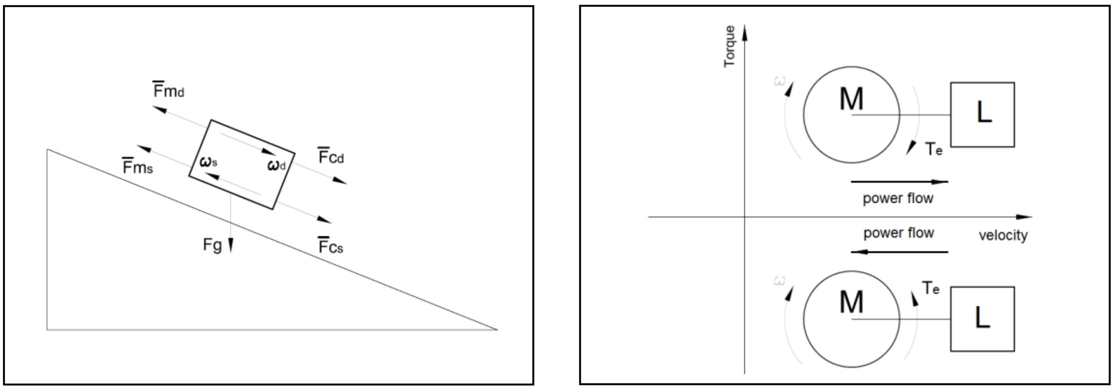


a b c

Figure 12 – Voltage and Current in the motor for traction: (a) M=450kg with h=10% (b) M=1000kg with h=10% (c) M=1000 with h=15%

Regenerative Braking

Regenerative braking occurs when the load torque has reversed its direction but the operation direction remains the same. When the load drives the motor, synchronous speed can be exceeded and mechanical power converted into electrical allowing regeneration. Figure 15(a) illustrates a ramp considering that the load torque and motor torque always have opposite directions. Power flow is also shown in Figure 15(b).



a b

Figure 15 – Conditions of regenerative braking

The tests were performed with the motor pulling a mass of 1000kg with 10% inclination. Table 3 shows the operating conditions [8].

The energy generated during the braking equals the amount of current injected into the link DC, during the period in which the current remained negative, multiplied by the DC link voltage. As the capacitance of the DC link is known and the braking time is 0.7s, the total energy regenerated during braking, for the conditions described in Table 3, was 298.66 J.

Results of regenerative braking obtained by simulation are shown in Figure 18. The simulation shows a significant region of negative current and does not consider the effects of line inductance. The energy generated in braking was 1808.41 J considered a descent speed $v = 6.05 m/s$ and mass $m = 2500 kg$. The power and energy during this time interval can be seen in Fig. 19 and Fig. 20, respectively.

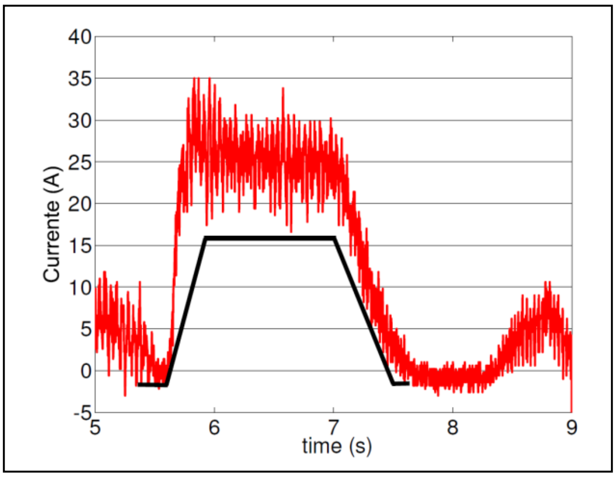


Figure 17 – Measured: Current in the DC link

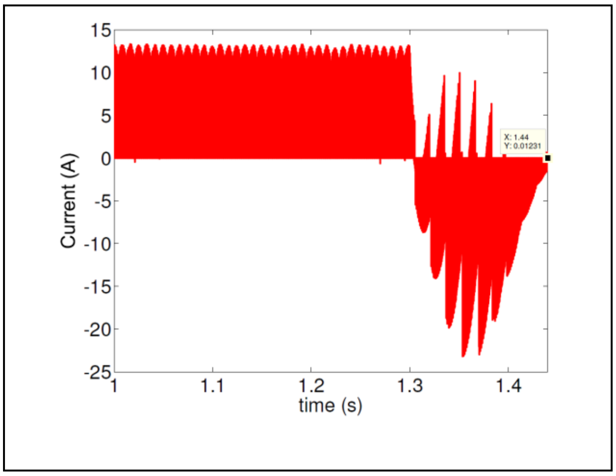


Figure 18 – Simulation: Current in DC link

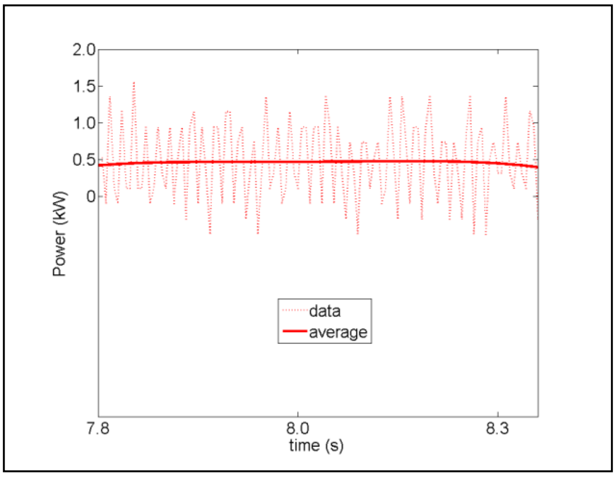


Figure 19 – Power supplied to the source

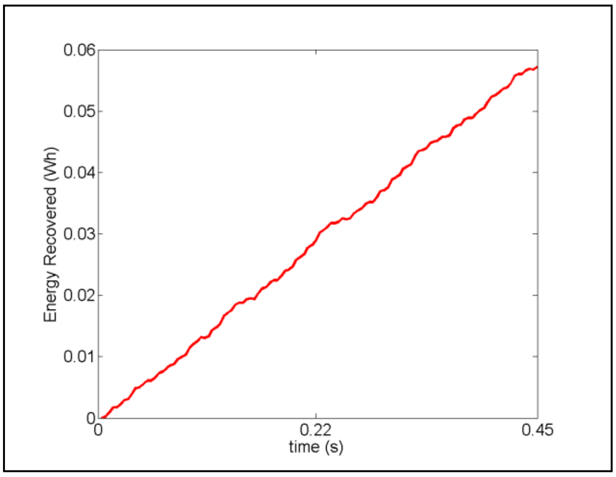


Figure 20 – Energy Recovered

Table 3 – Operating conditions regenerative braking test

	amplitudes
travelling field	2.28 m/s
slip	-0.27
time downhill	1.54 s
velocity downhill	2.92 m/s
acceleration downhill	8.59 m/s^2
time acceleration downhill	0.34 s
force deceleration downhill	16233.8 N
power deceleration downhill	64.53 CV

Conclusions

The Maglev-Cobra proved to be a promising vehicle due to its low power consumption. The LIM offers the necessary forces to attend the load demand. The V/f scalar control scheme allows the adequate motor control for low speed variation and enables the regenerative braking. It was not possible to quantify the power returned into the grid. The short 6m test track does not allow a complete quantitative analysis of the regenerated energy. In future studies, with the conclusion of a 200 meters long test track, being presently constructed in UFRJ campus, total energy generated and returned to the grid by the linear induction motor will be measured.

Acknowledgment

To BNDES, FAPERJ, WEG and CNPq for the financial support.

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Harmonic effects on Induction and Line Start Permanent Magnet Machines

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Abstract

Power Electronics (PE) are implemented in a wide variety of appliances, either to increase its controllability or energy efficiency, or simply because a DC supply is needed. The massive integration of rectifiers has resulted in a decrease of the supply voltage quality. Although PE have enabled the end user to control electrical machines, the resulting distortion inversely affects Direct On-Line (DOL) machines. In this paper a review is presented of the influence of these supply anomalies on Induction Motors (IM). The suggested problems have already been subject of much study. However, as new DOL technologies are emerging, for example Line Start Permanent Magnet Machines or Induction Generator systems, the influence of supply distortion on these systems should also be considered. This paper will present a comprehensive overview of the loss mechanisms, the magnitude of the losses and the impact of these losses on operation of IM, LSPMM and IG.

1. Introduction

Both due to economic and ecological incentives, energy has become a scarce product. The electric consumption is a significant part of the total energy consumption and consequently the complete chain of generation, transportation and usage of electricity should be optimized. The usage of electrical energy is often optimized by controlling the output of electrical equipment towards the desired value. Advances in Power Electronic (PE) energy conversion have led to an optimization of electrical equipment. Practical examples of PE controlled energy conversion are dimmable halogen lighting, low and high pressurized discharge lights, variable speed drives (VSD) for Induction Machines (IM) etc. Additional to the advantages of PE in terms of energy optimization, a lot of PE is also used for DC supply in for example IT equipment, DC arcing or electrolysis.

AC/DC converters, cited as rectifiers, are generally build with passive components. Inherent to the operation of diodes, does the discretization of current imply a non-sinusoidal current demand. In combination with the present grid impedance this current distortion results into a distortion of the supply voltage. In Section 2 the nature and limits of the supply voltage at end user are presented.

If the electrical power consumption at industrial plants is regarded, more than 65% of all generated power is consumed for electromechanical conversion. IM have several advantages in respect to other electric motors and as a result a lot of effort has been done to increase the efficiency of these machines (Section 3). IM have one disadvantage, the fact that the mechanical speed of the machine is directly coupled to the frequency of the supply voltage, which limits its flexibility when supplied directly from the grid. Although the usage of VSD can adjust the supply frequency, only 25% of the newly installed machines are supplied from a VSD.

A lot of efforts are done to increase the efficiency of IM, however, distortion of the supply voltage does inversely affect the efficiency of IM. Although this effect is well known, it is often neglected or marginalized. If the actual limits of the supply distortion are taken into account, a reduction of efficiency of more than 1% is not uncommon. This one number also indicates that the influence of supply voltage distortion can undo a lot of efforts of motor efficiency enhancement. In Section 4 the influence of supply voltage distortion on IM is summarized and confirmed by measurements.

The efficiency of the standard IM is practically limited to IE3. This is due to the fact that the magnetizing power for the rotor has to be delivered through the stator. The integration of Permanent Magnets (PM) is one way to tackle the problem and still maintaining the DOL operation. If the motor would consist of only PM, the motor would be unable to start up at line frequency. The combination of PM with a standard IM rotor cage results in a machine which is able to start up as a standard IM and once near synchronism, the PM can synchronize with the magnetic field in the stator. This machine is commonly referred to as a LSPMM.

However, if the LSPMM is to become the next evolutionary step of IM the influence of supply voltage distortion on LSPMM should be addressed. Although attractive, in Section 5 it will be elucidated that straight forward comparison of the loss mechanisms for an LSPMM and a standard IM can result in serious miscalculations and/or estimations.

Electrical machines are responsible for 50% of the total electric consumption worldwide. For the industry the electrical machines consume up to 65% of the total electrical energy. Almost 90% of the installed power of machines that convert electrical energy to mechanical energy are IM. This essentially led to the machines being optimized for motor operation. Secondly, nearly all of the studies which examine the influence of distorted voltages are focused towards motor operation.

Both consumption as electrical generation should also be performed with the highest possible efficiency and overall yield. The rise of decentralized production such as small wind, hydro, Combined Heat Power (CHP) or Organic Rankine Cycle (ORC) power, resulted in an increased interest towards Induction Generators (IG). However, anomalies in the supply voltage also affect the operation and efficiency of IG systems. Although IM and IG are the same machine, in Section 6 it will be illustrated that the use of IM loss models, derating methods etc, are insufficient to estimate the effect of harmonic distortion on the energy efficiency of IG.

2. End user voltage distortion

Estimation of end user voltage quality has proven to be difficult, as it is function of many parameters such as the loads connected to the grid, the grid impedance and the background distortion. In order to give some reference to the voltage quality, studies generally refer to the normative reference EN50160, which defines the voltage quality at Point of Common Coupling (PCC). This approach however does not include the distortion generated at the internal low voltage grid. Consequently, the voltage quality is overestimated, as is the overall energy efficiency of electrical appliances. This chapter results in concrete values and estimation guidelines of the amount of distortion of the voltage supplied at loads, taking into account both background distortion and internally generated distortion. These results will be implemented to give more accurate estimations concerning energy efficiency of electrical loads such as DOL IM.

Most of the current distortion, and therefore the resulting voltage distortion, is generated by PE converters. The combination of the grid impedance and the nature of the current distortion, namely single or three phase loads, will determine the resulting voltage distortion. The background distortion is limited by standards such as the EN50160 to 8%. In order to have an idea of the actual background distortion, 42 measurements according to the EN50160 are presented for both large power industrial sites (35) and sites situated in urban areas (7) Fig. 1. If the generated distortion is superimposed on the already present background distortion, the resulting voltage distortion at end user can be simulated and the results are presented in Fig. 2. [3]

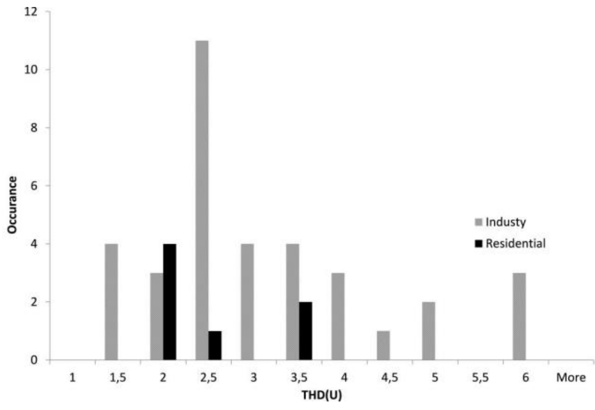

Fig. 1: 95% occurrence THD(U) values obtained by EN50160 analysis for 42 sites

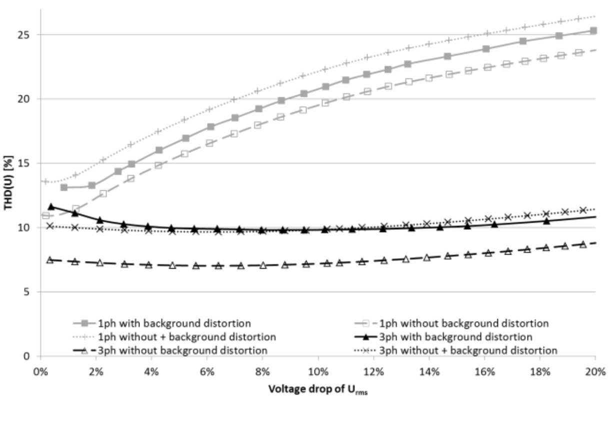

Fig. 2: Variation of THD(U) with shifting grid impedance for single and three phase rectifiers including background distortion

From Fig. 2 it is clearly illustrated that the limits of voltage distortion can well exceed the limits stated by the EN50160. A limit of 12% distortion can be calculated, while still complying to all the standards and design procedures. Harmonic mitigation equipment, such as active filters, can significantly reduce the current distortion ratio, consequently, this also suggests that active filters can have a positive effect on the resulting voltage distortion. The effect of harmonic filtering to both the resulting current and voltage distortion has been monitored for 2 separate industrial installations and the results are listed in Table 1.

Table 1: Measurements of 2 industrial sites of the reduction of THD (I) and THD (U) by active filtering

	THDU			THDI		
	L1	L2	L3	L1	L2	L3
Filter inactive (Company 1)	5.67	5.93	6.22	18.99	18.84	19.14
Filter active (Company 1)	1.99	2.00	2.06	2.42	2.91	2.34
	L1,L2,L3 (AVG Value)			L1,L2,L3 (AVG Value)		
Filter inactive (Company 2)	6.39			16.20		
Filter active (Company 2)	3.72			3.67		

The values of Table 1 are measured values, however, it is delicate to generalize or even predict the effect of filtering harmonic currents in relation to the present distortion. The influence of the filtering to the present voltage distortion is function of the filter settings, the physical location on site and the power relation between the installed filter and injected current distortion. Table 1 does indicate the positive effect of reducing current harmonics and the relation to the present voltage distortion.

3. Increasing the energy efficiency of IM

Currently, almost 70% of the world's electrical energy is consumed for electro-mechanical energy conversion and 90% of this power is converted by standard Squirrel Cage Induction Machines (SCIM). If the efficiency of IM's is to be increased this can be achieved at every design parameter of the machine. Fig. 3.

In order to uniform the efficiency of IM, the IEC has introduced a classification system (IEC 60034-30) which states the efficiency, from IE1 up to IE4 as listed in Table 2.

Table 2: Rated efficiency levels for commercial 50-Hz, 4-pole LSPMSMs up to 7,5 kW and IE2-, IE3- and IE4-class limits defined in IEC60034-30/31 [9].

	Frame	80	80	L90S	90L	100L	100L	112M	132S	132M
	Rated output (kW)	0,55	0,75	1,1	1,5	2,2	3,0	4,0	5,5	7,5
Efficiency	LSPMSM	84,2	87,5	87,6	88,3	90,2	90,4	91,7	92,4	92,8
	IEC IE4		85,6	87,4	88,1	89,7	90,3	90,9	92,1	92,6
	IEC IE3		82,5	84,1	85,3	86,7	87,7	88,6	89,6	90,4
	IEC IE2		79,6	81,4	82,8	84,3	85,5	86,6	87,7	88,7

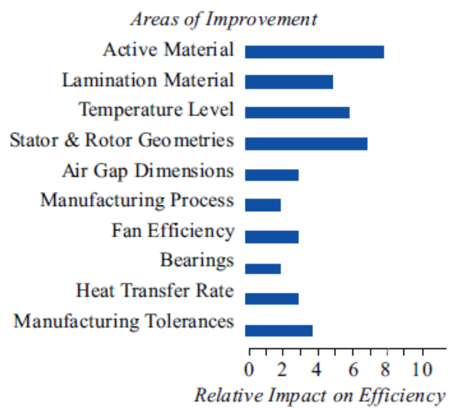

Fig. 3: Impact of the possible areas for improving the motor performance

A lot of research is performed in introducing better active materials, such as in Diecast Copper Rotors (DCR) or increasing the performance of the lamination steel. Because an energy efficient machine dissipates less power, this not only results in a reduced power consumption or operating cost, additionally this implies a direct decrease of the operating temperature in the different motor components [7].

From Table 2 it is observed that nearly every step of efficiency increase is varying approximately 3% points. However, these efficiency levels are valid for sine wave voltages. In the latter it will be pointed out that the efficiency reduction caused by voltage anomalies can significantly reduce the overall efficiency of an IM. If this reduction is within the same order of magnitude as the efficiency enhancement from for example IE3 to IE4 , this effect should be taken into account.

4. The effect of harmonic Voltage Distortion on IM

The effects distorted supply voltage are numerous as it affects almost every single operational parameter of the machine, such as output torque, torque ripple, motor temperature, vibrations, bearing stress etc. However, as this paper focuses on the additional losses due to harmonic voltages, some key effects are listed.

1. The higher frequencies force the current to flow on the outer rims of the conductor. This effect is known as the “skin effect”. However, for IM this effect is predominantly present in the rotor bars and is accordingly addressed to as the “deep bar effect”. This effect is far less pronounced in the stator, due to both the reduced section of the stator coil windings and the relatively low frequencies considered (<40 order of harmonic).

2. The deep bar effect results in a reduced active surface area, which results in an increased current density towards the outer radius. This results in an increase of the rotor bar resistance. Subsequently, the top of the rotor lamination begins to saturate, and results in a decrease of rotor reactance. In terms of total harmonic current, the RMS value of the current is dominated by the RMS harmonic voltage and the total reactance at harmonic frequency, the losses can be calculated by Joule’s law taken into account the skin effect.

3. The total averaged voltage is influenced by the phase of the harmonics, accordingly this influences the magnetizing current. However, this effect is only measureable for low power ratings of machines and at partial loading [10]. As the loading increased, the increased stator voltage drop results in a slight demagnetization of the machine. Accordingly a linear induction is assumed and the effect on the magnetizing current is often neglected [1][8].

4. Harmonics also result in electro-magnetic power and consequently mechanical torque. In motor operation, voltage harmonics of $h_{k>1}$=1-6k result in breaking torques. Because the magnitude of voltage distortion decreases with increasing order, and the damping of harmonics is increased with increasing harmonic order, all harmonic power is assumed to be additional loss.

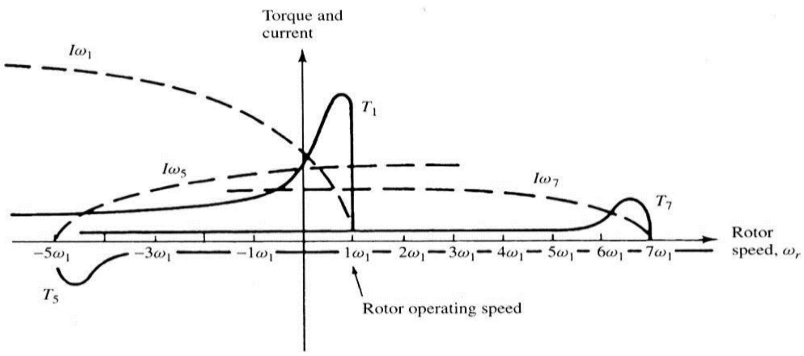

Fig. 4: Harmonic torques caused by supply voltage distortion

In order for an IM to cope with additional harmonic losses, the IM nominal power is reduced in case of severe distortion. Different derating methods for IMs when supplied with a distorted voltage have been suggested. If the derating is necessary from a technical perspective, generally excessive stator heating, Thermal Based Derating has been suggested. If the actual losses are of interest, Loss Based Derating (LBD) is more convenient. Due to both the increase in distortion of the supply voltage, and the increase of IM supplied from VSD’s, there was a demand for a relatively easy method of derating. Consequently, normative derating, such as the NEMA MG1 have been suggested which directly calculate the reduction of efficiency.

The goal within this paper is not to fully present the scientific details concerning the efficiency reduction caused by supply voltage distortion, but rather to present a comprehensive overview. As the influence of harmonic voltage distortion to the overall energy efficiency is inversely proportional to the harmonic order, it makes more sense to introduce a weighted voltage distortion ratio, rather than using the linear parameter Total Harmonic Distortion THD(U) [10].

Both the NEMA Standard MG1 as the IEC 60034-17 specify the "Harmonic Voltage Factor" HVF as:

$$HVF = \sqrt{\sum \frac{(V_n)^2}{n}} \tag{1}$$

With n, the odd harmonics, excluding triple n harmonics and V_n the p.u. value of the n^{th} harmonic. From the HVF, and using Fig. 5 the Derating Factor (DF) can be obtained, accordingly the resulting efficiency can be calculated according to Eq.(2).

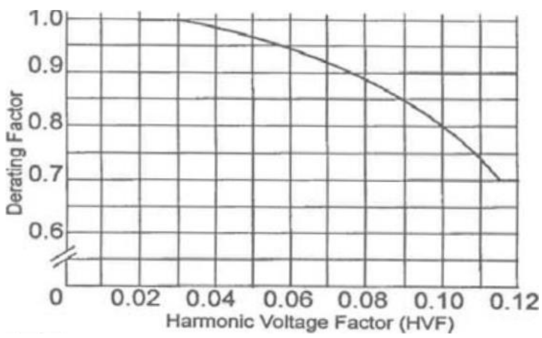

Fig. 5: DF as function of the HVF

With DF: the derating factor obtained from Fig. 5, η : de motor efficiency at sinewave condition and η_C the corrected motor efficiency in case of a distorted voltage.

$$\eta_c = \frac{DF^2}{\frac{1}{\eta} + DF^2 - 1} \tag{2}$$

Studies have indicated that the normative derating methods present fairly good estimations concerning the reduction of motor efficiency. Subsequently, the absolute losses can be calculated, and combined with the correct knowledge of the thermal parameters of the motor, this can result in estimations concerning the temperature increase of the different motor parts. In Fig. 6 the temperature increase of different motor parts is presented for a 4kW IM IE2 at full load and supplied with a distorted voltage.

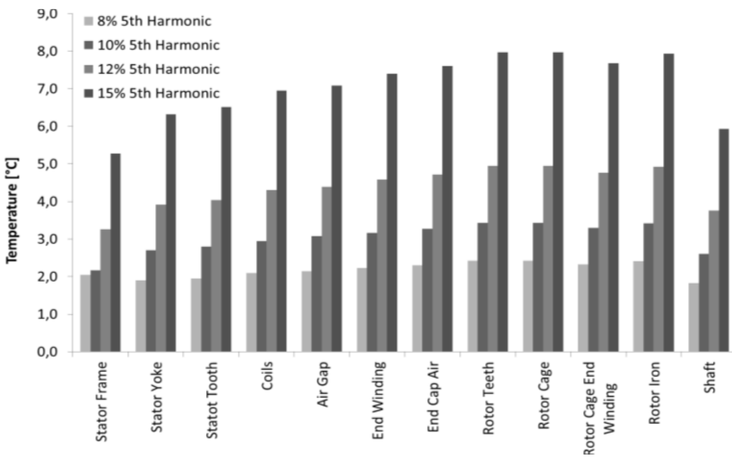

Fig. 6 Estimated temperature rise for a 4 pole 4kW IE 2 IM caused by harmonic distortion @ full load. Temperatures obtained by lumped thermal modeling

Based on Eq.(2) and Fig. 6 some important conclusions can be made. First of all, from Eq.(2) it can be deduced that for increased efficiency of the IM, the susceptibility of the IM towards supply voltage harmonics reduces. Consequently, the same amount of voltage distortion will result in a reduced loss in both actual power [W] as in pu, if an IE3 is compared to a IE2 of the same rated power. This also indicates that with increasing motor size, the harmonic losses in pu will reduce Fig. 7. However, in terms of actual active power [W], there is an increased loss for higher power ratings.

Secondly, harmonic modeling of IM assumes that the harmonic losses are nearly independent of the loading ratio. Measurements have indicated that the losses caused by harmonic voltage distortion slightly shift as function of the applied load. But harmonic losses are indeed present even at no load. This can have a significant cost if the motor is constantly unloaded. Fig. 7. The additional loss results in additional operating costs, but additional losses can also be evaluated from a technical perspective.

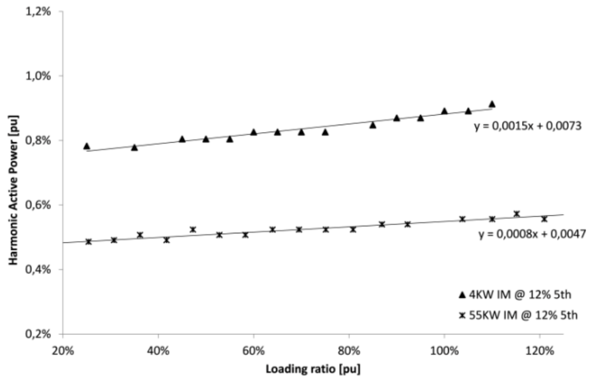

Fig. 7: harmonic loss [pu] for a 4pole 4kW IM and a 55kW IM for different loading ratio's and 12% 5th distortion

Additional losses imply additional heating and thus harmonic voltage distortion could result in premature failure, generally accelerated stator winding insulation breakdown. However, IM are usually over dimensioned as the general load ratio is only 60% [10]. Although according to Fig. 6 the additional losses increase, the operating temperature this effect is only to be taken into account at full load. At partial load stator winding temperature is significantly under the nominal temperature, even when supplied with a considerable distortion.

To conclude it can be stated that harmonic voltage results in additional losses and additional heating. Although the additional heating can cause problems, this effect is only important for small machines (which have an inherent large thermal resistance from stator coils to ambient) and at full load [1]. If the cost of harmonics is evaluated this is not negligible. It has to be stipulated that, according to Fig. 5 the losses are not linear to the applied distortion. This inversely implies that even a slight reduction of the distortion can result in significant energy savings.

5. The effect of harmonic Voltage Distortion on LSPMM [11]

The integration of Permanent Magnets (PM) in the rotor reduces both rotor and stator losses as the magnetizing power for the rotor is no longer supplied by the grid. If the rotor consists of both PM and rotor bars, the motor can start as a IM and once near synchronism the MagnetoMotive Force (MMF) of the PM can synchronize with the MMF induced in the stator. Consequently, these high efficient Line Start Permanent Magnet Machines (LSPMM) have been developed from the mid-eighties and recently became an off-the-shelf product. LSPMM are often suggested as one of the possibilities to achieve IE4 or even IE5.

Fig. 8: Rotor inserted PM, Courtesy of WEG ®

A state-of-the-art review of both practical advantages and limitations of these LSPMM's has been presented in [9]. If LSPMM are to become an actual substitute for standard IM, the influence of voltage distortion on its overall energy efficiency should be evaluated. Literature concerning the influence of harmonic distortion on the efficiency and operation of LSPMM is scarce. However, due to the similar configuration and operation to standard IM, it is tempting to straightforward adapt the loss mechanisms and models of IM.

A more profound analysis indicates that, in case of IM, the effect of slip combined with the additional voltage drop over the stator impedance allows superposition of losses obtained by harmonic modeling. Contradictory, for a LSPMM the use of superposition is prohibited, due to both the presence of PM and the synchronous operation. The supply voltage rarely holds one single harmonic imposed on the fundamental. If multiple harmonic distortions are superimposed on the supply voltage, certain harmonics will interact due to synchronous operation. Harmonic rotor currents, induced by stator harmonics of orders $h_{-\infty<k<+\infty}=1+6k$, and with equal value of |k| interact with one other resulting in either an amplification or reduction of the resulting rotor harmonic current.

If the phase angle of the different harmonics is shifted in reference to each other, the corresponding losses shift with a factor 4. A 4kW LSPMM machine has been subjected to both 10% fifth and seventh harmonic content. The losses were monitored as the phase angle from the seventh and the fifth shifted in reference to each other. The total power loss was averaged, and the variation of the losses is plotted in Fig. 9.

Fig. 9 does illustrate the interaction of individual harmonics and consequently discard superposition.

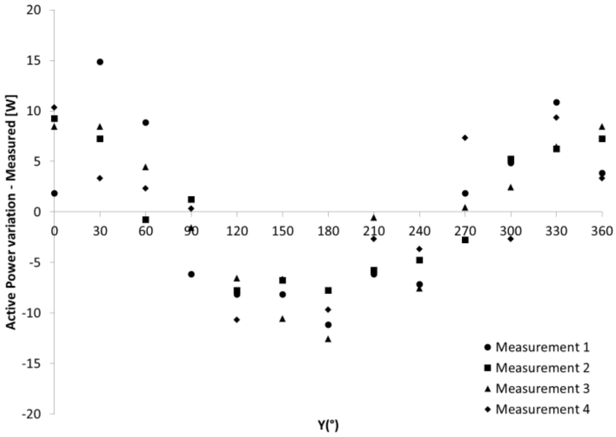

Fig. 9: Shifting the relative phase shift between Harmonic Five and Seven (Y) and its influence on the overall losses

The absence of rotor joule loss additionally reduces the stator joule loss. As the magnetizing losses become more dominant, the phase angle of the voltage distortion has significant influence on the overall efficiency of these machines Table 3.

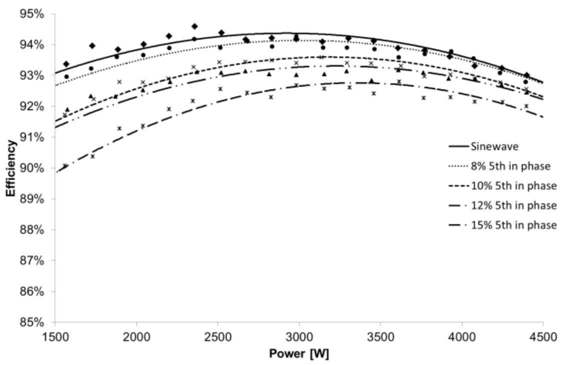

Fig. 10: Efficiency of LSPMM when supplied with a distorted voltage

Table 3: absolute values of the efficiency at nominal loading for LSPMM

Phase angle	0	180		0	180
$8\%5^{th}$	93.78%	93.32%	$8\%7^{th}$	93.72%	93.86%
$10\%5^{th}$	93.03%	93.18%	$10\%7^{th}$	93.80%	93.74%
$12\%5^{th}$	92.90%	92.97%	$12\%7^{th}$	93.18%	93.37%
$15\%5^{th}$	92.29%	92.68%	$15\%7^{th}$	92.57%	93.02%

A 15% fifth distortion ratio leads to a reduction of efficiency of 1.2% for IM and a maximum reduction of 1.5% for LSPMM. The previous evaluation indicates that LSPMM are more sensitive to harmonic voltages in reference to IM. However, if the absolute efficiency is evaluated, the LSPMM is still more efficient referred to IM.

6. The effect of harmonic Voltage Distortion on IG

Due to the high power to weight ratio, its robust construction and line start capabilities is the Induction Generator (IG) still the preferred choice of energy converter for certain types of CHP's, backup power or low cost Wind turbines. As the integration of IG continues to rise, the effect of supply voltage distortion on IG should be considered. The same effects occur in generator mode as in motor mode, however, similar to LSPMM, the use of harmonic motor models is prohibited. Additionally, there are several practical considerations which have to be taken into account in order to practically test an IG under distorted supply conditions.

First of all, when harmonic models of induction motors are build, a linear flux linkage is assumed. This is generally valid for motor operation, as the additional stator impedance voltage drop results in a decrease of the flux linkage. In case of IG the assumption of linear induction is no longer generally valid. If high efficient motors or specifically designed IG are used, these are specifically build with low stator resistance and a high amount of lamination steel in the stator to maintain an unsaturated operation. In these cases linear induction in generator mode can be justified, however, if standard motors are used as IG, the higher stator resistance combined with the reduced amount of lamination steel can result in saturated operation, and thus prohibiting linearization. (Fig. 11)

Furthermore, as the mechanical speed is above the synchronous speed for IG, the frequency of the injected harmonic rotor currents also varies. The frequency of the current harmonics of order $h_{k>1}$=1+6k will reduce in frequency in reference to motor operation. Contrary, in IG operation the frequency induced by harmonic orders of $h_{k>1}$=1-6k will increase. Skin effects are often derived by measurement in motor operation, however, the previous directly implies that neither skin coefficient for neither resistance and impedance are still valid in generator operation. In addition harmonics of $h_{k>1}$=1-6k do result in breaking torques in case of motor operation, however in generator operation this is a positive torque.

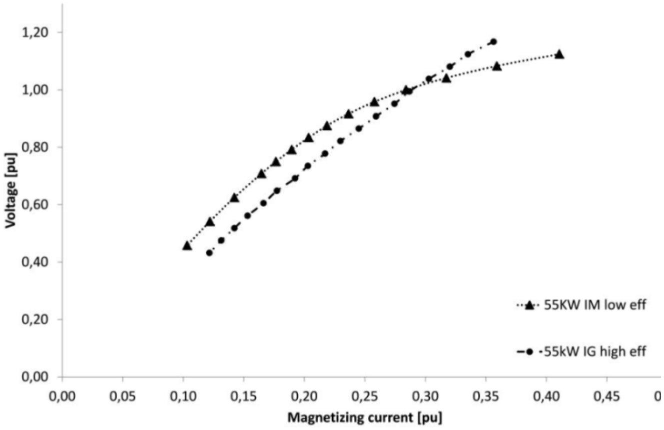

Fig. 11: magnetization curves for an IM used as a IG and a machine specifically designed for IG operation

From the previous it can be concluded that straightforward adaption of harmonic loss mechanisms for IM to IG can result in severe errors. Similar to the pitfalls of harmonic modeling, straight forward comparison between efficiency in motor and generator operation is equally delicate.

In Eq.(3) and Eq. (4) the definitions of the efficiency are given for motor and generator mode. When evaluating the efficiency of IM in case of voltage distortion, identical output power can be easily achieved by loading the test machine with a machine controlled towards constant output torque or constant output power. The increase in electrical input power is a measure for the additional losses in case of voltage distortion.

$$\eta_{motor} = \frac{P_{mech}}{P_{elk}} = \frac{P_{elk} - P_{loss}}{P_{elk}} \tag{3}$$

$$\eta_{generator} = \frac{P_{elk}}{P_{mech}} = \frac{P_{elk}}{P_{elk} + P_{loss}} \tag{4}$$

When motor and generator operation are compared, the following question arises. If a machine is designed particularly for motor operation, but used as a generator, what is the nominal IG operating condition and to which reference should efficiencies be compared? Both from a theoretical point of view, as from an design point of view, the general conclusion should be that machines are designed towards certain thermal limits. As the stator and rotor joule losses account for the majority of the total losses, it is logic to relate to maximum allowed current and therefore the nominal electric input power is often used as reference. If harmonics are imposed on the voltage, the mechanical power should be increased to obtain identical electrical power in reference to pure sine regime.

$$\eta_{generator} = \frac{P_{elk}}{P_{mech}} = \frac{P_{elk}}{P_{elk} + P_{loss} + P_{h\_mech}} = \frac{P_{elk} - P_{h\_elk}}{P_{elk} + P_{loss}} \tag{5}$$

$$P_{h\_mech} \neq P_{h\_elk} \tag{6}$$

The increase in mechanical input power P_{h_mech} is a measure for the additional losses and not the reduction of electrical output power P_{h_elk}. Note that this effect is more dominant as the efficiency reduces, especially for low efficient or low power ratings of machines. The previous also imposes practical difficulties, because the measurement accuracy is now function of both electrical and mechanical sensors, as are the practical tests more time consuming.

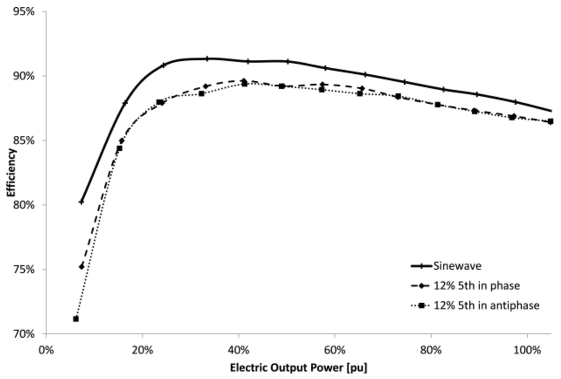

Fig. 12: a 4KW IM used as a IG, supplied with a distorted voltage and controlled to constant P_{mech}[WRONG]

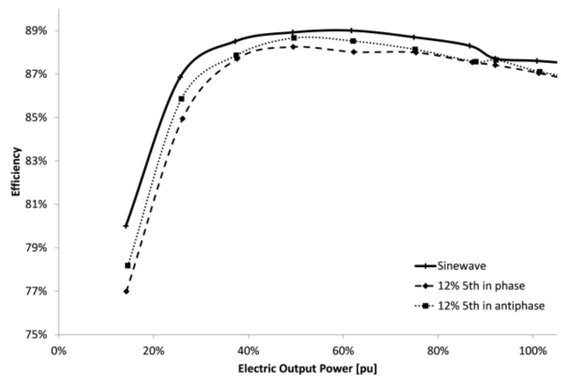

Fig. 13: a 4KW IM used as a IG, supplied with a distorted voltage and controlled to constant P_{elk}[Correct]

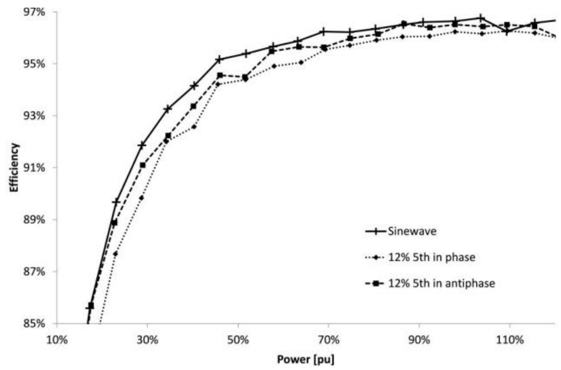

Fig. 14: influence of 12% fifth harmonic for a 55kW IG [6]

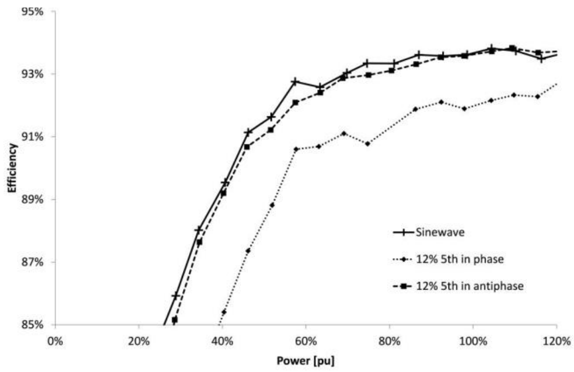

Fig. 15: influence of 12% fifth harmonic for a 55kW IM used as IG [6]

7. Conclusions

In this paper it is suggested that voltage distortion can have a significant influence on the overall energy efficiency of Induction Machines. In case of motor operation, this effect is well known, however in terms of energy efficiency the effect is often marginalized or even neglected.

This paper starts by proposing limits to end user voltage quality, and it indicates that the supply voltage distortion can reach up to 12% while still complying to all the design guidelines and normative references.

A supply voltage distortion of 12% fifth harmonic results in approximately a reduction of 1% efficiency. However, because the induction machine is a nonlinear system, even a small reduction of the supply voltage distortion can result in a significant energy reduction. Harmonic mitigation tools, such as filters or tuned capacitor banks could be mutually beneficial in both a reduction of the supply distortion and simultaneously the increase of energy efficiency of machines.

As energy efficient electromechanical energy conversion is of key importance, new types of high efficient machines are suggested, such as LSPMM. If LSPMM are to become an actual substitute for standard IM, the influence of voltage distortion on its overall energy efficiency should be evaluated. Within the presented research initial steps are made, additionally, it has been stressed that harmonic modeling of IM is not applicable for LSPMM. New models should be suggested and validated.

Induction machines can also be used as generator systems. As the integration of IG continues to rise, the effect of supply voltage distortion on IG should be considered. Literature concerning this subject is thin and obtaining measurement results has proven to be difficult. Similar to LSPMM is the use of harmonic models of IM prohibited for IG and more detailed loss modeling is needed.

To conclude, the LSPMM could also be used as an generator system. Due to its self-excitation, the high energy efficiency and its line start capability, LSPMM could be promising for “low cost” and “low maintenance” generator systems. Within this research no measurements are presented concerning the influence of supply voltage distortion on LSPMG, although this is subject for further research.

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Line-Start Permanent-Magnet Motors And Their Use In Typical Industrial Applications

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Abstract

The first known proposal of line-start permanent-magnet motors (LSPM) is dated more than 50 years ago [3]. Soon after, the German company Siemens introduced their SIMOSYN products in 1966. These motors were mainly designed for multi-motor drives in the textile and beverage industry. Meanwhile, LSPM motors are produced by many companies and are used in white goods like refrigerators or washing machines, as drives for heating pumps and small compressors. Due to the upcoming energy efficiency regulations in many countries, in particular regarding the efficiency class IE4 (super-premium efficiency), LSPM motors have recently been considered as a replacement for induction motors in standard industrial applications [1], [2], [17]. They are capable of direct-on line starting and yet provide a high-energy efficiency due to their synchronous operation. But the use of LSPMs in industrial automation applications needs careful consideration of the somewhat critical start-up characteristics.

General Operation and Performance

Line-start permanent-magnet motors are basically salient pole synchronous machines with a damper squirrel-cage for direct on-line starting. Machines for industrial application usually have a squirrel-cage design that is very close to that of industrial induction motors, see figure 1.

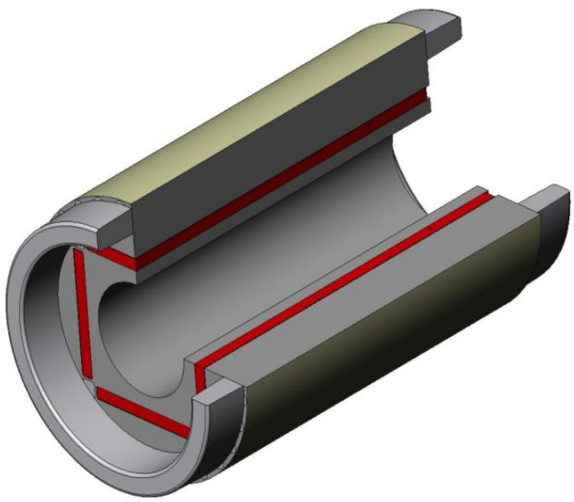

Figure 1: Rotor design of a LSPM-Motor for industrial applications

In order to improve starting capabilities, the squirrel-cage has a large slot area. In smaller induction motors the cage is made of casted aluminum or casted copper. The rotor slot geometry of LSPM is usually identical to that of induction machines, including a high bar design for greater rotor resistance and start-up torque at low speeds.

Due to the large slot area there is relatively little space available for the permanent magnets. Furthermore, they are relatively far from the air gap resulting in increased leakage flux.

A vast number of rotor designs have been proposed and patented over the years. Figure 2 gives an impression of some of the many possibilities. Each of them has specific advantages and disadvantages. The top-left design is often used in rare earth permanent magnet LSPM-machines for industrial applications.

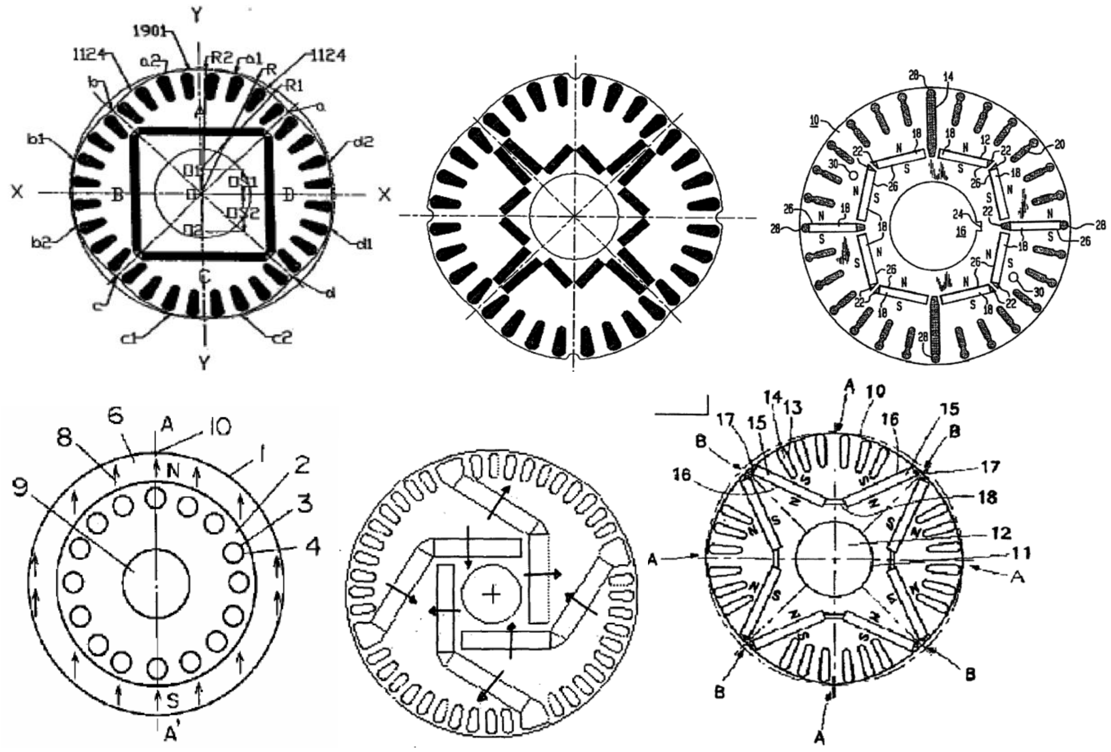

Figure 2: Examples of slot and permanent magnet geometry of LSPM motor designs

The general operation can be understood as follows: Induced voltages in the rotor cage cause currents and a rotor field. The rotor field is attracted by the rotating stator field and spins the rotor. Once the machine has accelerated to slip frequency, the synchronous torque of the permanent magnets takes over and pulls the machine into synchronism. At that point no more voltages are being induced in the rotor squirrel-cage and no asynchronous torque is generated. The cage continues to act as a dampening cage in case of sudden load changes and reduces load angle oscillations.

The obvious problem of the start-up process is the torques generated by the permanent magnets, which add on top of the torques from the squirrel-cage [18]. The start-up torque is basically a steady average torque (comprised of the cage torque and a magnet torque) with an overlaid pulsating torque. The pulsating torque produces noise and vibration during the run-up phase. It has components of single- and double-slip-frequency. The magnet torque is a braking torque that reduces the cage torque, see figure 3. A thorough calculation of the start-up process requires the calculation of the steady state as well as the pulsating torques in combination with the solution of the mechanical differential equation that describes the mechanical oscillations ([18]).

Since the current is also pulsating along with the torque, demagnetization of the permanent magnets can occur unless the machine is properly designed.

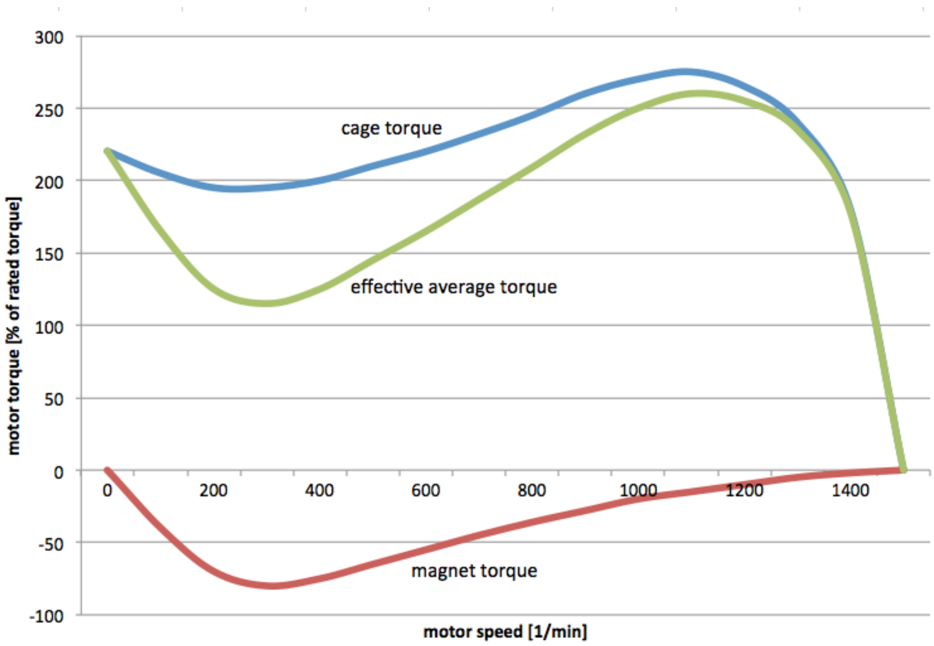

Figure 3: Average torques of an LSPM-motor

LSPM can also be operated at variable voltage and frequency. Groups of LSPM automatically run at synchronized speed without the need of speed sensors and complicated control software.

Energy efficiency benefits

Rotor losses of small induction machines are in the magnitude of about 20% of the total losses. By using a synchronous rotor, these losses can be eliminated. Therefore, total losses are reduced by about 20%. Since the step from one efficiency class to the next is about 15 to 20% of total losses, the introduction of an LSPM-rotor will improve motor efficiency by more than one efficiency class in general.

Frame Size	European Standard	IE2	IE3	IE4
	ASM	*LSPM*		
71	0,37 kW	0,75 kW	0,55 kW	0,37 kW
80	0,75 KW	1,5 kW	1,1 kW	0,75 kW
90	1,5 kW	3 kW	2,2 kW	1,5 kW
100	3 kW	4 kW	3 kW	2,2 kW
112	4 kW	7,5 kW	5,5 kW	4 kW

Figure 4: 50 Hz, 4-pole output power for each frame size for standard aluminum induction motors (column European Standard) and LSPM motors (column IE2, IE3, IE4).

Figure 4 gives an overview of the rated output power of available LSPM-type energy efficiency motors [1] and [2]. They are all in the output power range up to 7,5 kW.

A more detail look [4] reveals certain difficulties for larger LSPM motors. In particular, starting torque and counter-inertia are becoming more and more difficult to master, especially at under-voltage. There are limitations for the starting currents of large motor by the power networks as well. Therefore LSPM are particularly suited in the power range of up to some 10 kW. Current offerings on the market [1], [2] confirm this assumption.

The design of a 4-pole 75 kW LSPM motor for a submersible pump is demonstrated in [13]. Efficiency was increased to 94,5% and starting-capability was maintained up to 15% voltage drop. On the downside, this motor was not designed to start-up against significant counter torques and the achieved efficiency is just equivalent to IE2.

For super-premium IE4 motor designs of larger output power some companies are using synchronous reluctance motors ([19]) or conventional induction machines with an optimized motor design (special electric sheet material with reduced losses, copper rotor, reduced magnetic flux etc.).

Start-Up Performance

Figures 5, 6 and 7 show the torque (red) and speed (blue) of a 4-pole IEC frame size 71M LSPM motor without load-torque (figure 5) and with load-torque (figures 6 and 7) at reduced voltage (-5%, figures 5, 6) and over-voltage (+5%, figure 7) during start-up.

The motor is rated 0,55 kW, which is one step higher than the 0,37 kW that are standardized in EN 50347 for this frame size. Yet the motor's measured efficiency (79,7%) is well above IE2 level (77,1%) and almost reaches IE3 (80,8%) according to the new edition of IEC 60034-30-1.

The load-torque during the test (4,5 Nm, figures 6 and 7) was app. 28% higher than nominal torque (3,5 Nm), i.e. the motor was severely overloaded. At the same time the motor was running against a high external inertia (20 kgcm^2) of app. three times the rotor's self-inertia.

Vibrations and oscillating speeds of rotation can be seen in every measurement. Due to the high counter-torque and inertia, the motor was not able to achieve synchronism at under-voltage (see figure 6). Such an operation must be avoided, as it is associated with loud noise, vibration and high currents. By increasing terminal voltage, it was possible to achieve synchronism (figure 7) even in the case of severe overloading.

At nominal voltage (400 V) and nominal torque (3,5 Nm) the motor had no problems to synchronize.

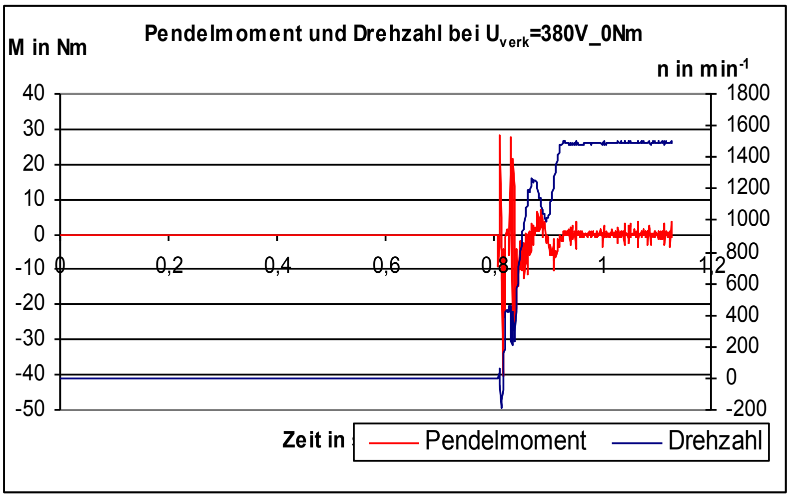

Figure 5: Start-up of an LSPM motor without counter-torque at nominal voltage (IEC frame size 71M motor, 0.55 kW, 79,7% eff at full load, $J_{external}$ = 20 kgcm^2, $T_{external}$ = 0 Nm, U = 380 V)

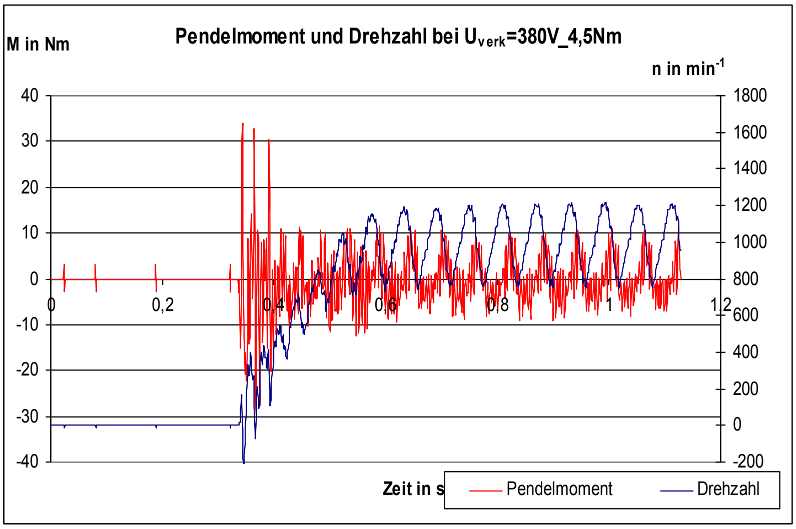

Figure 6: Start-up of an LSPM motor with counter torque at nominal voltage (IEC frame size 71M motor, 0.55 kW, 79,7% eff at full load, $J_{external}$ = 20 kgcm^2, $T_{external}$ = 4.5 Nm, U = 380 V)

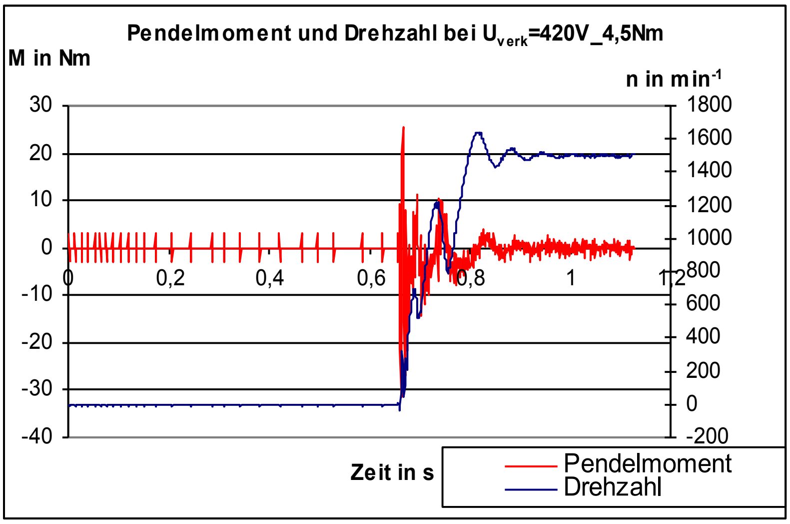

Figure 7: Start-up of an LSPM motor with counter torque and over-voltage (IEC frame size 71M motor, 0.55 kW, 79,7% eff at full load, $J_{external}$ = 20 kgcm^2, $T_{external}$ = 4.5 Nm, U = 420 V)

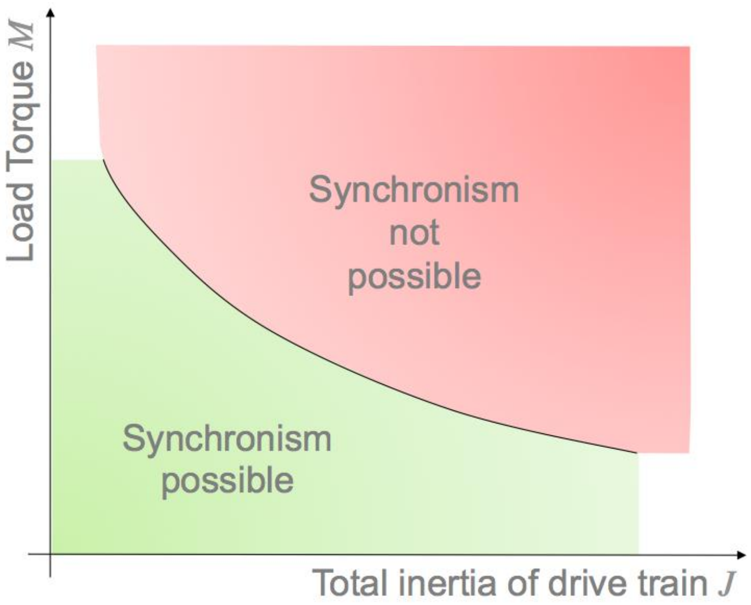

Figure 8: Areas of operation (green) and forbidden areas (red)

Generally speaking, high counter torque and high load inertia cannot be present at the same time, see figure 8.

The rotor design has an important influence on the start-up performance of the motor. Design parameters are in particular slot design, shape and placement of the permanent magnets, leakage flux etc. Figure 9 and 10 show the start-up performance of the same motor with two different rotors.

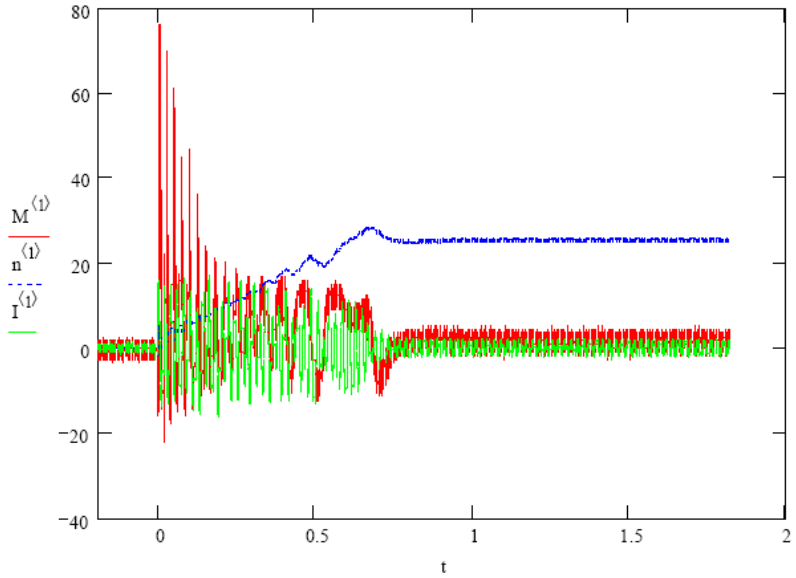

Figure 9: Start-up performance of LSPM rotor design A at app. 40% load torque (red: torque, green: current, blue: speed).

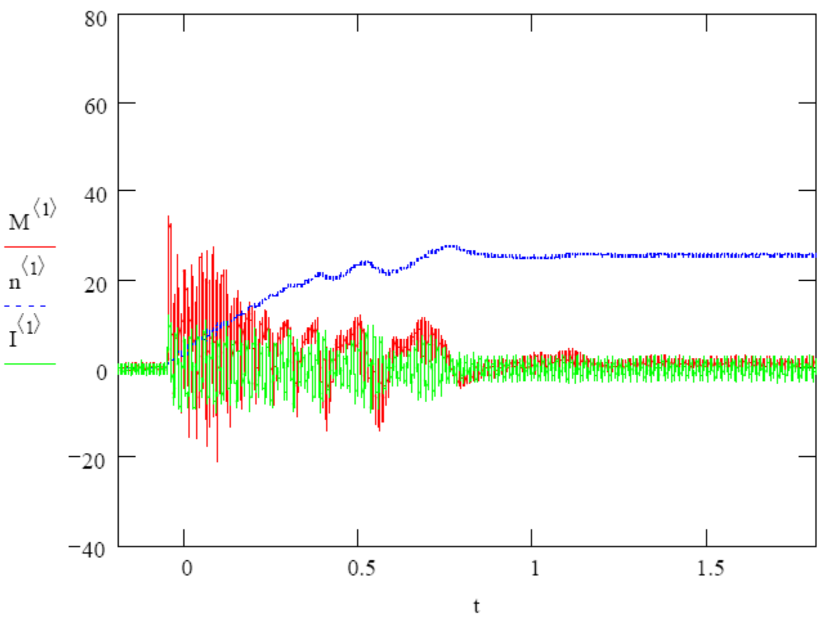

Figure 10: Start-up performance of LSPM rotor design B at app. 40% load torque (red: torque, green: current, blue: speed).

By redesigning the rotor it was possible to reduce the torque peaks from 80 Nm (app. 17-times the nominal load) to 35 Nm (app. 7-times the nominal load). The start-up time has been increased slightly from 0,75 s to 0,8 s. Torque peaks are responsible for noise, vibration and can be particularly dangerous to the gear wheels of gear boxes, when not carefully considered and limited by the manufacturer of the motor.

Summary

The dominant advantage of LSPM motors is the removal of rotor losses during normal operation, which leads to a high energy efficiency. At the same time, the motor is of very compact size. IE4 super-premium efficiency motors can be designed having the same frame sizes as conventional IE1 and IE2 industrial induction motors. Yet, such motors can be started direct on line or by a frequency converter. Groups of LSPM motors can be operated in synchronous speed without rotary encoders and complicated software control. Due to the robust mechanical construction, high speeds are possible. When desired, the use of the field weakening range (i.e. operation above the rated speed) is also possible as the motor has a pronounced reluctance torque. When turning the rotor by an external drive, the induced terminal voltage is not rising too high and generally does not endanger frequency converters and their electronic circuits.

On the downside, the start-up process of LSPM motors is critical. A high counter-torque and a high inertia cannot be started at the same time. During start-up, strong oscillating torques create noise and vibration. Therefore, such motors are especially suitable for pumps, fans, compressors and similar applications, i.e. whenever the torque is a function of the square of the speed. They can also be used for conveyor belts due to the low inertia of such applications, provided the starting torque is sufficient. LSPM motors are less suited for hoist drives, lifts and other applications, where overloads can occur and lead to critical situations. In particular, under-voltage is critical and can lead to a loss or failure of synchronization.

Very small motors (below frame size 80) are difficult to design due to space restrictions (magnets and cage must find their place in the rotor) and motors larger than some 10 kW are also difficult to design due to the start-up behavior.

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Super Premium Synchronous Reluctance Motor Evaluation

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Abstract

Electric motors are used worldwide in a great variety of applications, consuming a considerable part of the world generated electric energy. However, due to the arising concerns about global warming, sustainability and energy resource constraints, government agencies and organizations are imposing more stringent regulations and promoting energy efficiency. Accordingly, this paper presents a performance evaluation of a synchronous reluctance motor (SynRM) drive. Electric motors based on this technology were recently introduced in the market, being capable to achieve the IEC 60034-30 Super-Premium Efficiency level class (IE4). A detailed efficiency analysis is presented through the format of efficiency maps, which allow to fully characterize the motor operating range. Furthermore, this new SynRM is directly compared with an equivalent permanent magnet synchronous motor (PMSM), also having an IE4 efficiency level. Several key parameters are considered such as motor efficiency, power factor, input current and operating temperature.

1. Introduction

Electric motors perform an important role in a great number of industries, being used in various industrial applications. As far as energy consumption is concerned, electric motors are responsible for approximately 40% of the electrical energy generated worldwide [1]. In the European Union, electric motors use approximately 70% of the consumed electricity in industry, being therefore the most important load type in this sector.

Due to the wide use of electric motors, the improvement of their energy efficiency has become a major research focus. Both energy consumption as well as the environment impact can be significantly reduced by adopting electric motors with high efficiency levels.

Considering the various electric motor types available in the market, the three-phase induction motor is by far the most used machine. During the last decade, there has been a great effort in global harmonization of motor standards in order to promote energy efficiency in electric motors. As a result, the International Electrotechnical Commission (IEC) has introduced new standards dealing with motor testing procedures and efficiency classifications [2]. As an example, the IEC 60034-30 standard proposes four different efficiency classes, namely Standard Efficiency (IE1), High-Efficiency (IE2), Premium Efficiency (IE3), and Super-Premium Efficiency (IE4).

With the aim to improve efficiency of induction motors, more copper and lamination materials can be used. Further efficiency gains can be achieved by casting copper cages in squirrel-cage induction motors. As main disadvantages, the motor frame size is typically increased as well as the manufacturing costs. Moreover, there are the problems associated to the cast copper cage. Due to the copper high melting point, the die casting process is more demanding and complex. On the other side, the too high die casting temperature will lower the life expectancy of moulds, increasing even more the cost of producing cast copper rotors [3].

In the last years, line-start PMSMs were introduced in the market, allowing to achieve the Super-Premium Efficiency class (IE4). Comparing with induction machines, these motors can also be directly connected to the grid and present other advantages such as synchronous speed operation, higher efficiency (mainly due to the enormous decrease of the rotor losses), higher power density and higher power factor. However, this technology is not very mature yet since this motor type still presents some limitations. Due to the starting torque characteristics, these motors present some restrictions when the load presents high inertia and requires high starting torque. On the other hand, the generated cogging torque may cause relatively high levels of noise and vibration during the motor starting [4]-[5]. Line-start PMSMs can also be used with a converter for variable speed operation, eliminating these problems. Probably the biggest drawback of PMSMs is their price since the rare earth materials used in the magnets are still relatively expensive.

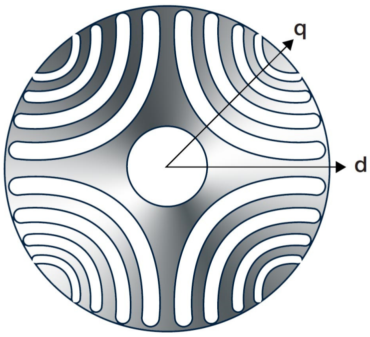
More recently, a different AC drive was release in the market based on synchronous reluctance motors (SynRM). Comparing with induction motors and PMSMs, the major difference is the rotor structure that is built taking into account the magnetic reluctance principle. Despite this concept dates back to 1923, only with the more recent improvements of the rotor design and the advance of power converters, this drive technology become suitable for industrial use.

The rotor design of synchronous reluctance motors present a magnetically anisotropic structure and it is only built using punched electric steel plates stacked together to form the rotor package. Therefore, no cage or magnets are used, making this motor cheaper to produce, more robust and avoiding the negative impact of rare-earth materials mining, used in the magnets production.

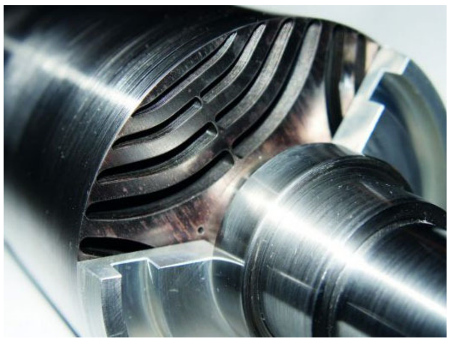
Accordingly, this paper presents a performance evaluation of an IE4 efficiency class SynRM. A detailed efficiency analysis is presented through the format of efficiency maps, which allow to fully characterize the motor operating range. Moreover, the SynRM performance is directly compared with an equivalent PMSM, also having an IE4 efficiency level. Several key parameters are considered such as motor efficiency, power factor, input current and operating temperature.

2. Synchronous Reluctance Motors

Comparing with the standard AC machines such as induction motors and PMSMs (sinusoidal back-EMF), the stator construction of SynRMs is also very similar. However, the rotor design of these machines is unique, as depicted in Figure 1.



(a)



(b)

Figure 1 – SynRM rotor: (a) cross-section schematic representation; (b) detail of a built rotor [6].

The rotor is built in such a way in order to take advantage of the magnetic reluctance principle. Considering a four pole rotor as shown in Figure 1a, it presents four high- and four low-reluctance axes. In practical terms, reluctance is equivalent to the magnetic resistance. The axes with low reluctance can be referred to as the direct or d-axis, while the axes with high reluctance can be referred to as the quadrature or q-axis.

When the motor is supplied by applying exciting currents to the stator windings, a rotating magnetic field is produced in the air gap. Then, the rotor attempts to align its most magnetically conductive axis, the d-axis, with the applied field, in order to minimize the reluctance in the magnetic circuit. As result, torque is produced in the air gap between the stator and rotor whenever the air gap rotating field and the d-axis of the rotor are not aligned. The generated torque amplitude is directly proportional to the difference between the inductances on the d- and q-axes. Consequently, the greater this difference, the greater is the torque production.

In order to properly control the motor, a frequency converter must be used since the performance is dependent on the information about the position of the rotor (easily obtained using sensorless control due to the high saliency ratio). Therefore, it will not operate correctly connected to the grid. With the converter, SynRMs can run smoothly due to the sinusoidal air gap field distribution and operate with sinusoidal current.

All this makes the rotor construction of SynRMs less complex than for induction motors or PMSMs. Without a cage or magnets, the rotor has a plain structure since it only consists of punched laminated electrical steel sheets to form flux barriers that are fitted in the shaft. The synchronous reluctance motor is therefore designed with magnetically conductive material, iron, in the d-axis and magnetically insulating material, air, in the q-axis.

Hence, the rotor construction is more robust than either induction motors or PMSMs. On the other side, the synchronous operation means that SynRMs operate at lower temperatures than induction motors (no rotor currents), increasing their life-time since the cool running of the rotor also means lower bearing temperatures, which in turn increase the reliability of the bearing system.

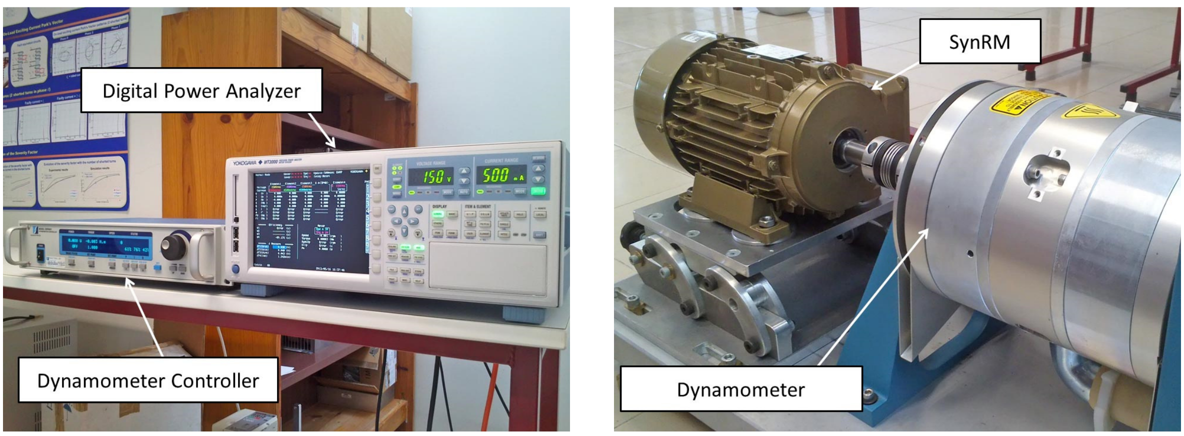
Comparing with PMSMs, no magnets are used, resulting in lower production costs (due to the expensive rare earth materials), avoiding simultaneously the problem of demagnetization due to possible overheating problems. Moreover, since no back-EMF voltage is induced, SynRMs are inherently safe and eliminate the need for converter over-voltage protection. The maintenance is also much easier since if a bearing eventually needs to be replaced, having no magnetic forces, unlike a PMSM, the bearing change of a SynRM is as easy as for an induction motor.

Due to the lack of a cage and magnets, the rotor inertia is also smaller. This feature becomes very advantageous in high dynamic applications where low inertia enables faster operating cycles and brings further benefits in energy efficiency.

As main disadvantage, it can be pointed out the low motor power factor due to the need of rotor magnetization. This means that, comparing with induction motors, the power converter must be designed to a higher current rating. However, since there is always the converter between the motor and the grid, the lower SynRM power factor is not visible on the grid side and consequently does not have an impact on the grid supply dimensioning.

3. Electric Motor Test Bench

With the aim to perform a detailed evaluation of the SynRM drive, a dedicated electric motor test bench was built. Basically, the experimental setup comprises a converter that supplies the SynRM, a hysteresis dynamometer and its corresponding controller, and a digital power analyzer (Figure 2).



(a) (b)

Figure 2 – Electric motor test bench details: (a) power analyzer and dynamometer controller; (b) SynRM and hysteresis dynamometer.

The SynRM load torque is imposed by a Magtrol HD-815 hysteresis dynamometer (measurement accuracy of 0.25%) and it is precisely adjusted using a Magtrol DSP6001high speed programmable controller. This device also provides the speed and torque signals to the power analyzer, which allows to calculate the motor mechanical power (Figure 3).

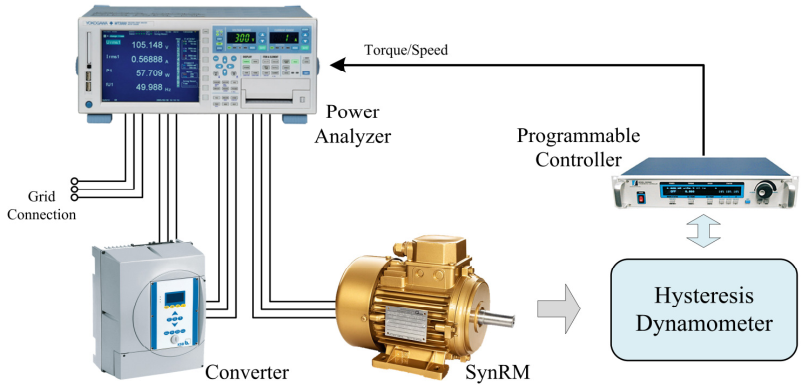


Figure 3 – Schematic representation of the experimental setup.

The used digital power analyzer is a state-of-the-art Yokogawa WT3000 (measurement accuracy of 0.01%), which provides all the required measurements with the highest accuracy available. This device is connected in series with the power circuit in order to measure all the converter input and output quantities. As a result, the converter and SynRM efficiency values are calculated by the direct measurement of the converter input power (P_{in}), the converter output power, corresponding to the motor input power (P_{motor}), and the mechanical power available at the motor shaft (P_{mec}). Accordingly, the efficiency values are given by:

$$\eta_{conv} = \frac{P_{motor}}{P_{in}} \times 100\% \quad (1)$$

$$\eta_{motor} = \frac{P_{mec}}{P_{motor}} \times 100\% \quad (2)$$

Other important quantities such as voltages, currents and power factor, are also directly calculated and obtained by the power analyzer. The ones directly related to the SynRM are also considered for a detailed evaluation of the machine.

The tested SynRM is a 2.2 kW 1500 rpm 50 Hz machine. The complete dataplate parameters can be found in the Appendix.

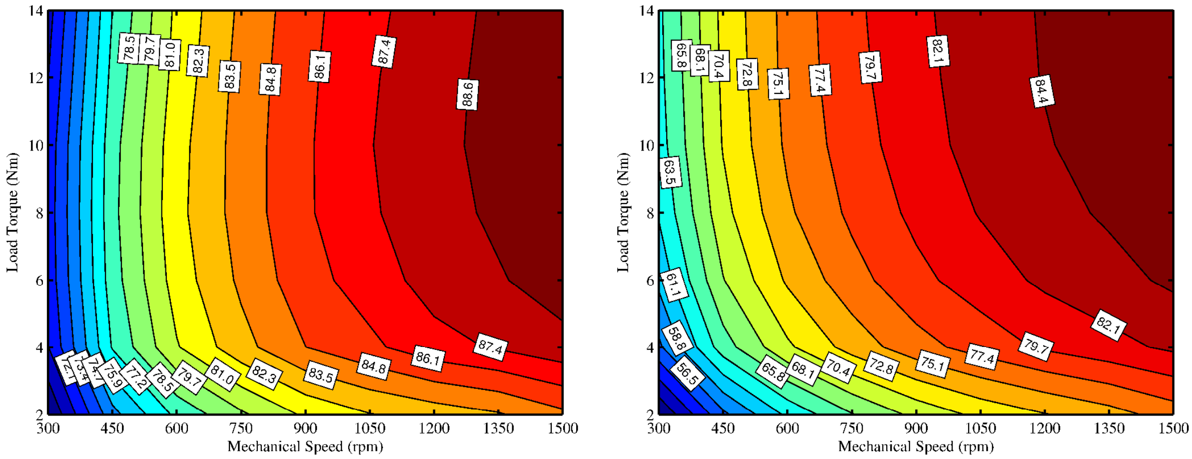
4. Experimental Results

SynRM Performance Evaluation

With the aim to perform a detailed analysis of the SynRM drive, a great number of data points were acquired. Then, using an interpolation algorithm, all results are presented through the format of contour maps, allowing to fully characterize the motor operating range.

Regarding the efficiency results, Figure 4 presents the SynRM and global drive efficiency results.

From the SynRM efficiency map, it can be observed that for a given operating speed, and excluding the motor operation at very low torque values, the motor can maintain a relatively high efficiency for an extended load level operation. Moreover, it can also be verified that the motor efficiency is strongly dependent on its operating speed. Finally, considering the drive operation at rated conditions, a value of approximately 89.8% is obtained for the SynRM efficiency.

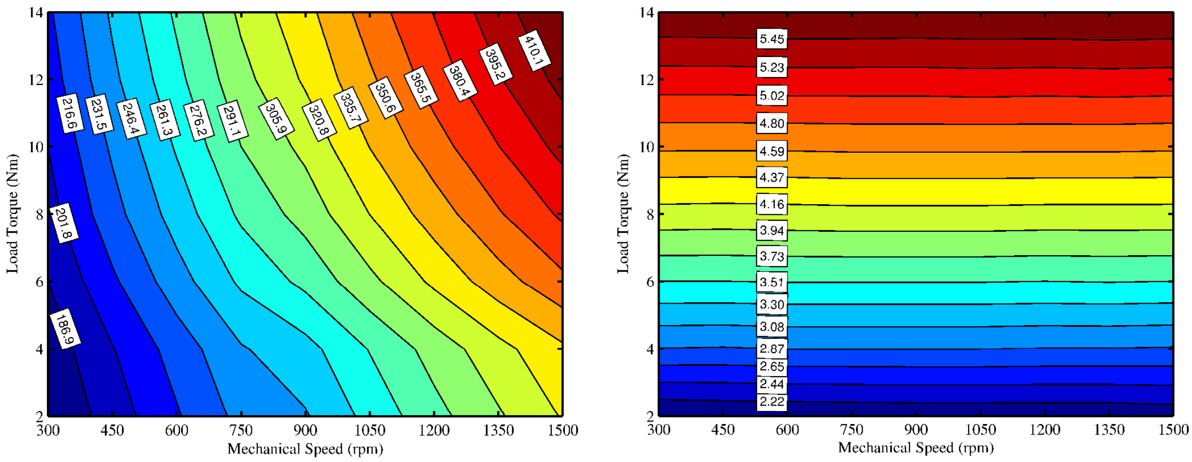


(a) (b)

Figure 4 – Efficiency maps obtained for (a) the SynRM and (b) for the entire drive.

As far as the global drive efficiency is concerned (SynRM+converter efficiency), the results shown in Figure 4b allow to conclude that the drive global energy conversion process efficiency is directly proportional to the motor operating speed and load torque. From this point of view, a value of 86.7% is obtained for the drive rated operating conditions.

Figure 5 presents the experimental results obtained for the SynRM supplying voltage and current values.



(a) (b)

Figure 5 – Experimental results of the SynRM supplying (a) voltage and (b) current values.

Analyzing the results depicted in Figure 5a, it can be observed that the motor supplying rms voltage values are also directly proportional to its operating speed and load level. On the contrary, the results obtained for the motor supplying rms current values show that, as expected, the motor current values only depend on the load torque level.

Finally, the experimental results obtained for the SynRM power factor are illustrated in Figure 6.

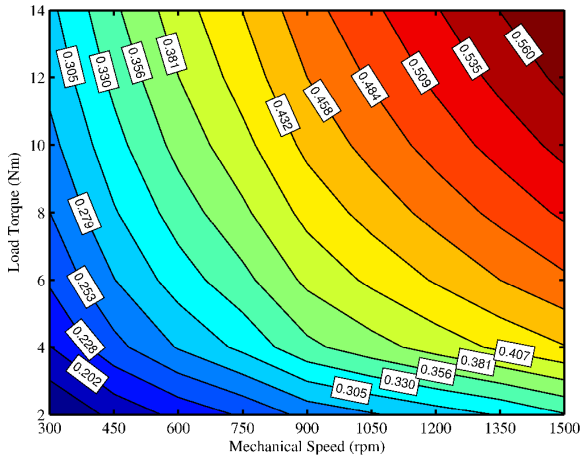


Figure 6 – Experimental results of the SynRM power factor.

As expected, these results show that the SynRM power factor values are also directly proportional to the operating mechanical speed the load torque values. In this case, a power factor value of approximately 0.59 is obtained for motor rated operating conditions.

SynRM Comparative Analysis

In order to better evaluate the performance of this recently introduced variable speed drive system, a comparative analysis is presented. As a result, an equivalent PMSM drive was also tested, having the used PMSM also a Super-Premium efficiency classification (IE4). Its parameters can be found in Table I of the Appendix.

In order to perform a direct comparison between the two motor drive systems, a quadratic load profile was used to obtain the majority of the experimental results. This particular load profile typically characterizes fan and pump applications, very common both in industrial and services sector, being therefore responsible for an important part of the electricity consumption of electric drives.

Taking this into account, the used load profile is given by:

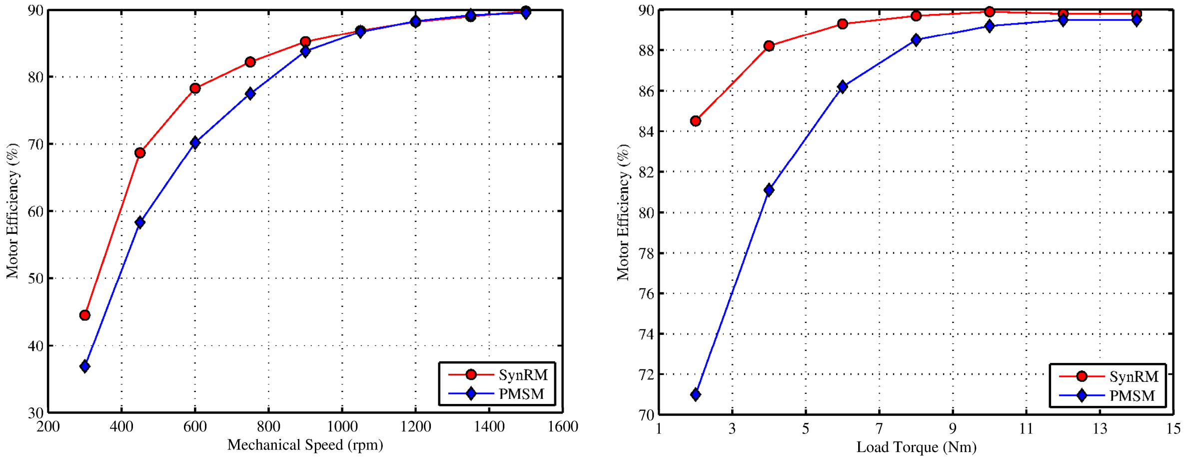
$$T_L = \left(\frac{56}{9}\times 10^{-6}\right)\omega_m^2 \tag{3}$$

where T_L is the load torque and ω_m is the mechanical speed in revolutions per minute (rpm).

Figure 7 presents the motor efficiency results obtained for both SynRM and PMSM drives, considering a quadratic load profile and for rated speed operation.

Analyzing first the results obtained for a quadratic load profile, it can be verified that for operating speeds near the rated speed, both electric motors achieve the same efficiency values. Nevertheless, for mechanical speeds less than 1000 rpm, the SynRM performs better than the PMSM, achieving higher efficiency values.

Regarding the results shown in Figure 7b for rated speed operation, it can be observed that for a load level near the rated torque, both SynRM and PMSM present similar efficiency values. However, for lower load torques, it can be seen that the efficiency performance of the SynRM is clearly superior to the PMSM. This characteristic was already seen in the SynRM efficiency map (Figure 4a), where for a given speed, a relatively high efficiency value is maintained along the load torque variation.



(a) (b)

Figure 7 – Efficiency results of the SynRM and PMSM considering (a) a quadratic load profile and (b) rated speed operation.

From these results, it can be concluded that despite both electric motors have an equivalent efficiency level at rated operating conditions, the SynRM presents a superior performance for partial load operation.

With respect to the motors supply current analysis, Figure 8 presents the measured rms current values for the considered quadratic load profile.

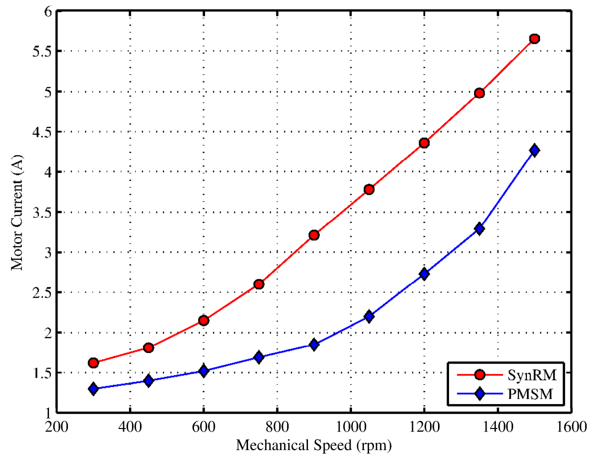


Figure 8 – Experimental results of the SynRM and PMSM supplying current considering a quadratic load profile.

It becomes clear that comparing both electric motors, the SynRM input current is higher than for the PMSM for all operating range. This is justified by the distinct rotor construction of the two machines. Since the SynRM rotor is only made of laminated electrical steel sheets (it does not have any magnets), it can be only magnetized through the stator. Consequently, the machine must be supplied with larger current values, comparing with PMSMs.

Figure 9 presents the motor power factor results obtained for both SynRM and PMSM drives, considering a quadratic load profile.

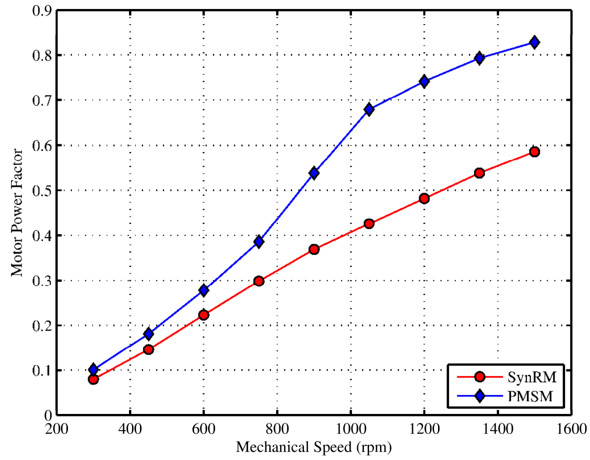


Figure 9 – Experimental results of the SynRM and PMSM power factor considering a quadratic load profile.

Regarding the power factor analysis, it can be verified that the SynRM presents the lowest values comparing with the PMSM. As seen before, this is justified by the larger motor supplying current, required for the rotor magnetization, which lead to the increase of the SynRM apparent power and the decreasing of its power factor.

Finally, regarding the temperature results, Figure 10 presents the temperature results obtained for both SynRM and PMSM under rated load operating conditions.

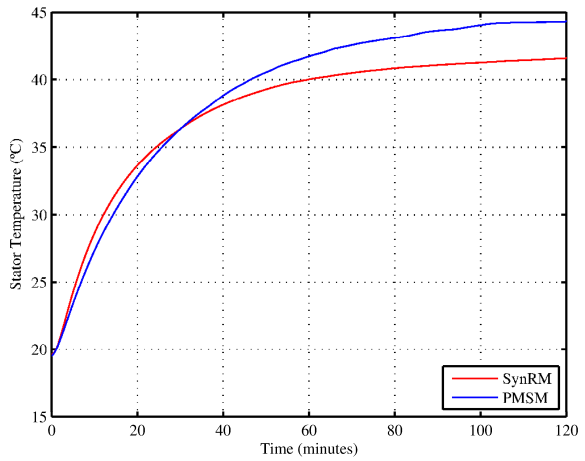


Figure 10 – Stator temperature results obtained for both SynRM and PMSM under rated load operating conditions.

The temperature was measured using a pt100 resistance thermometer probe, inserted in the motor frame through a hole. The temperature data points were acquired using a National Instruments data acquisition board NI cDAQ-9174 together with a NI 9217 module. A dedicated program was designed using the software LabView, allowing to view and save the data points to a file.

The temperature measurements were performed by operating the machine at full load conditions and starting with the motor cold. The data acquisition is stopped once the thermal stability is reached. This condition is defined by the standard IEC 60034-1:2004 [7] which states that the thermal equilibrium is reached when corresponding points of successive duty cycles on a temperature plot have a gradient of less than 2 Kelvin per hour. The environment temperature was also measured since its average value during the tests is used to adjust the offset of the stator temperature curves.

Analyzing the results in Figure 10, it can be seen that during the first 30 minutes of operation, the SynRM temperature is higher than the PMSM one. However, at the end of the tests, the PMSM temperature reaches a value of 44.3 ºC while the SynRM stabilizes in a lower temperature of about 41.6 ºC.

Despite the SynRM larger supplying current, it achieves a lower operating temperature comparing with the PMSM. This can be justified by the combination of several important aspects. In first place, the SynRM stator frame is made of aluminum, whereas the PMSM is made of cast iron. Therefore, and taking into account that aluminium has a higher thermal conductivity, the SynRM has a better heat transfer from the stator to the outside. Further than this, the motor fan/frame design also has an impact on the motor cooling. Finally, the electrical and mechanical losses distribution in both motors can also influence the operating temperature.

5. Conclusions

Despite the magnetic reluctance principle applied in electric motors is not a new concept, only until very recently this technology became sufficiently mature, allowing a few manufacturers to release into the market this new type of motor drive.

This paper has presented an evaluation of a Super-Premium Efficiency (IE4) synchronous reluctance motor. With the aim to perform a detailed analysis, a great number of data points were acquired, allowing to generate contour maps that fully characterize the SynRM operating range. In this context, several key parameters were evaluated such as motor efficiency, global drive efficiency, motor supplying voltage, current and power factor.

The obtained results allow to conclude that the SynRM presents a very good efficiency level, achieving a value of 89.8% at full load operation. From the global drive point of view, an efficiency value of approximately 86.7% was obtained for rated operating conditions.

A comparative analysis was also performed by comparing the used SynRM with an equivalent PMSM, also in compliance with the IE4 efficiency class. Regarding the efficiency results, a direct comparison was done by analyzing both motors for a quadratic load profile (very common in industrial applications) and for rated speed operation. The obtained results permit to conclude that for operating conditions near full load, both electric motors have similar efficiency values. However, for partial load operation, the SynRM performs better than the PMSM, maintaining a higher efficiency for low speed/torque values.

Regarding the motors supplying current and power factor, the PMSM presents a better performance since it has lower current and higher power factor values. This is justified by the SynRM operating principle since higher current is required in order to magnetize the rotor. However, from the grid side, the power factor is imposed by the converter, which is similar for both cases.

The thermal tests allow to concluded that, comparing with the PMSM, the tested SynRM presents a lower operating temperature at full load. In this case, the SynRM aluminum frame has an advantage over the PMSM cast iron frame.

Considering all this, it is clearly that these new SynRM drives present performance levels similar to the PMSM ones. Furthermore, and comparing to PMSMs, this motor type does not have magnets in the rotor, making it cheaper, more robust, capable of handling higher operating temperatures and requiring less maintenance. Therefore, it is expected that SynRM drives become a serious competitor against induction motors drives, achieving simultaneously high efficiency levels.

Acknowledgement

The authors gratefully acknowledge Reel/KSB company for their collaboration and for providing the SynRM drive used in this paper. The authors also acknowledge the financial support from the Portuguese Foundation for Science and Technology (FCT) under project nº SFRH/BPD/87135/2012.

Appendix

Table I – Main parameters for the SynRM and PMSM

	SynRM	**PMSM**
Power (kW)	2.2	2.2
Speed (rpm)	1500	1500
Torque (Nm)	14	14
Voltage (V)	366	400
Current (A)	5.7	4.1
Power Factor	0.64	0.87
Frame Size	100L	100L
Frame Material	Aluminum	Cast Iron
Weight (Kg)	25	33
Insulation Class	F	F

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ABB Synchronous reluctance motors for industrial variable speed applications with measured motor-drive package efficiency

Ari Tammi, ABB IEC low voltage motors

Abstract

Magnet-free synchronous reluctance technology can deliver similar benefits compared to more commonly known permanent magnet technology. Additionally synchronous reluctance motor is as easy to service and cost-efficient as an induction motor making it an excellent new technology motor alternative. This paper focuses on synchronous reluctance motors, which are designed exclusively for variable speed applications. In addition to having good efficiency at nominal load the partial load efficiency is better compared to traditional induction motors. This is particularly important in variable speed applications where the whole idea is to save energy by speed control when full output of a device is not needed.

In the market there are synchronous reluctance motors with various characteristics. This paper presents two different synchronous reluctance motor ranges commercialized by ABB. One of the ranges emphasizes compactness and another one IE4 efficiency and replaceability with traditional induction motors. Similar motor characteristics can be found in other synchronous reluctance motors in the market today. Characteristics are compared mainly against traditional induction motors but also against typical permanent magnet motors.

These synchronous reluctance motors feature a new kind of rotor combined with a conventional induction motor's stator. The rotor has no windings unlike traditional motors, which means that rotor power losses are virtually nonexistent. This not only increases efficiency but also ensures that the rotor runs cool, which keeps the bearing temperature low and improve bearing reliability.

When comparing efficiency performance of different solutions it's important to understand what values are compared against each other. Presently only motor efficiency with sinusoidal supply at nominal speed and power and associated IE classes are standardized. In variable speed applications however the efficiency of the whole motor-drive package is more important. This paper offers practical advice what to consider when comparing efficiency performance of different solutions for variable speed applications.

Technology vs. motor characteristic

The most common mistake concerning new motor technologies is to assume that all motors utilizing the same technology have identical characteristics. Currently the only standardized motor type for general purpose industrial applications is the induction motor harmonized by Cenelec- or NEMA rules with specific mounting dimensions and output steps. But when it comes to permanent magnet motors or synchronous reluctance motors there is no such thing as a standard motor. For this reason it's more important to focus on product characteristics rather than technology. In a typical example a motor user may request a permanent magnet motor when in fact they may be after compactness of efficiency.

Another important point in doing comparisons is to understand whether a comparison is between the potential of different technologies or between products which are available in the market today. This paper focuses on comparing products available in the market today.

Target market

Before evaluating the suitability of a product or technology the intended target market or application should be defined. For example it's not fair to assume that a motor designed for stable duty industrial applications would perform great on a motion control application. For some reason any product with new technology is often automatically assumed to offer a solution for any application where traditional technologies have not performed well enough. Again – motors may have the same technology but actual product characteristics may be very different.

Bench mark for motor characteristics

When it comes to “stable load” industrial variable speed applications the only standardized motor is an IP55 (totally enclosed) induction motor. It is clearly the most commonly used motor type in these applications today. Other technologies have only fractional market share compared to induction motors. That’s why an induction motor is a good bench mark for new technology motors.

Figure 1, Typical IP55 (totally enclosed) industrial induction motor

Motor characteristics

Academic society usually focuses on measurable characteristics such as efficiency, volts, amps, watts etc. However for motor users there are also other important characteristics such as ease of service. Both types of characteristics should be compared when evaluating the full potential of a motor type. In the following table there is a comparison of different motor types against induction motor with IE2 efficiency level. The “typical PM motor” is not any particular PM motor from a certain manufacturer but these are characteristics typically found in PM motors available in the market today. Again it should be noted that actual available motors may have different characteristics and accurate comparisons can be made only between particular motor ranges, not in general level based on technology.

	ABB HO SynRM	ABB IE4 SynRM	ABB IE4 IM	Typical PM
Motor size	Smaller	Same	Bigger	Smaller
Mechanical replaceability	Not always	Yes	Not always	Not always
Efficiency	Same or higher	Higher	Higher	Higher
Ease of service	Same	Same	Same	More difficult
Price	Same	1-2 year payback	1-2 year payback	Higher (?)
Reliability	Same or higher	Same or higher	Same or higher	Magnets ?
Availability	1,1-315kW now	11-315kW now	Above 75kW now	?
Motor-drive package efficiency data	Yes	Yes	No	?
Mix & match motors and drives	No	No	Yes	No
All applications available	No	No	Yes	No
Pre-selected motor-drive packages	Yes	Yes	No	?

Table 1, Comparison of different motor types against IE2 induction motor

Main characteristics of ABB Synchronous reluctance motor-drive packages

IE4 synchronous reluctance motor-drive package

In addition to excellent efficiency performance the motor size and output combinations are chosen so that they can typically replace existing induction motors without mechanical modifications. It should be noted though that Cenelec size-output harmonization practically applies only to IE2 or lower efficiency class motors and with sinusoidal supply. Variation to this harmonization can be caused by special motor selection for variable speed applications, use of higher efficiency class induction motors or use of high output induction motors. Replaceability should always be checked case-by-case.

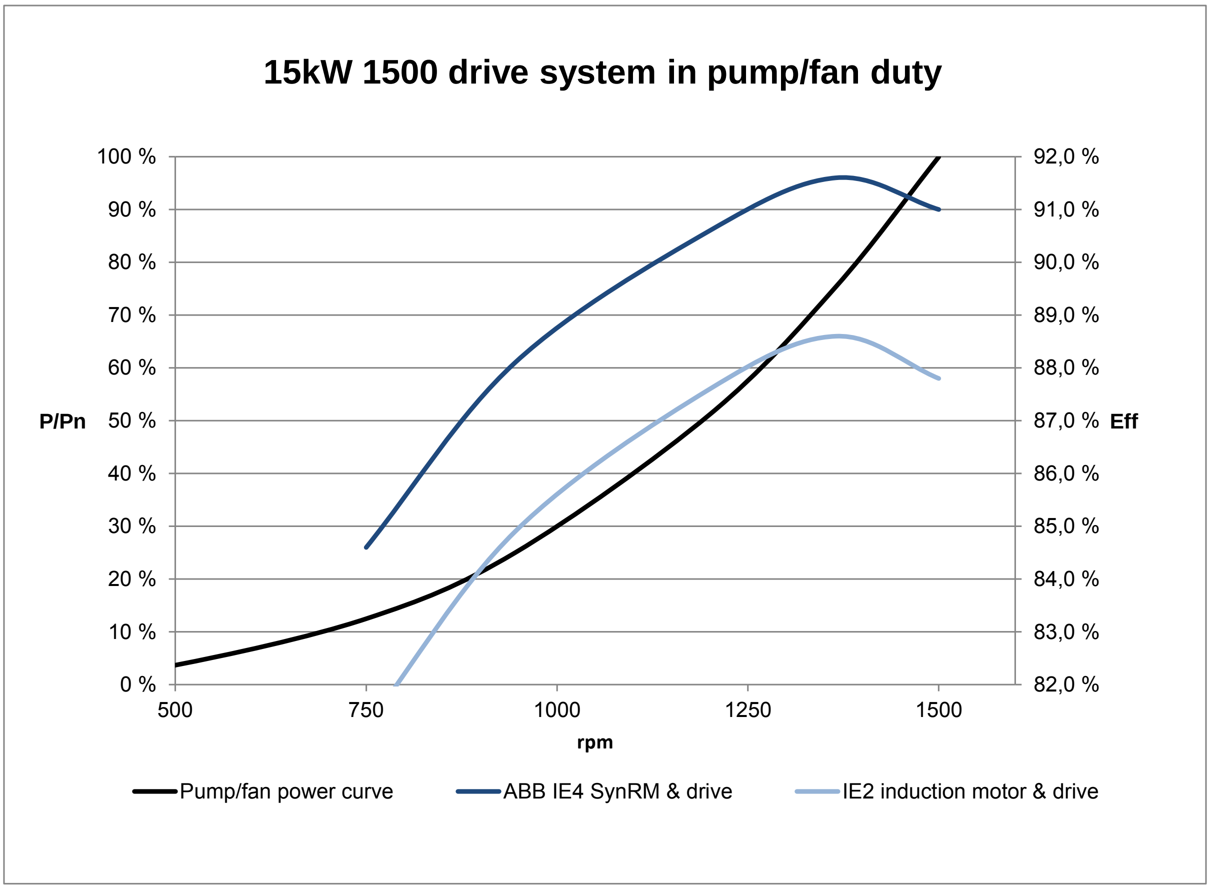


Figure 2, Motor-drive package efficiency comparison between ABB IE4 SynRM-drive package and typical IE2 induction motor-drive package [1]

High output synchronous reluctance motor-drive package

Compactness is the most obvious advantage of this motor type. Compared to induction motors the advantage is higher at 3000rpm than at 1500rpm level. This behavior is similar to permanent magnet motors. ABB High output SynRM motors are also designed to offer commercially competitive alternative against IE2 induction motors.

Efficiency performance of the high output package is typically the same as IE2 induction motor-drive package or better.

Figure 3, 11kW 3000rpm motors. IE2 induction motor frame size 160 (left), High output SynRM frame size 132 (right).

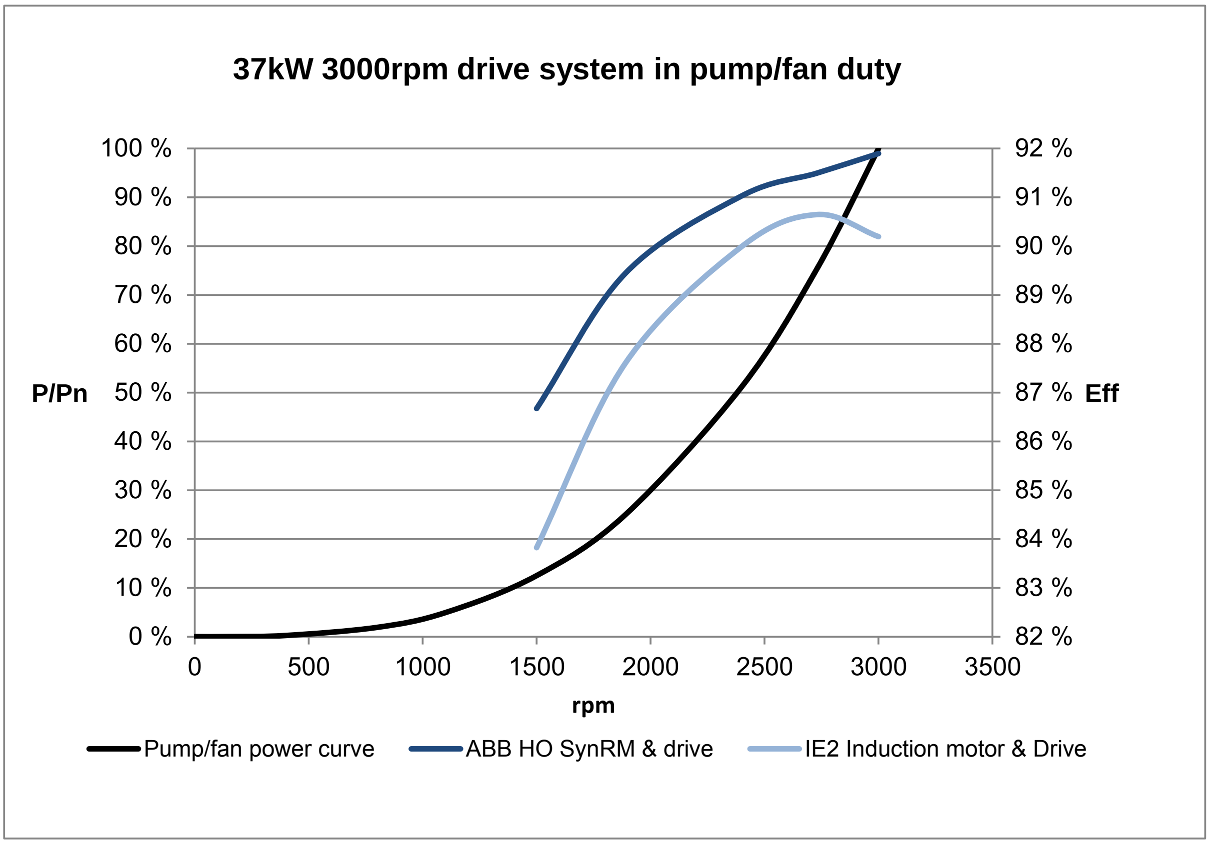


Figure 4, Motor-drive package efficiency comparison between ABB HO SynRM-drive package and typical IE2 induction motor-drive package [2]

Efficiency “categories” and new motor technologies

For decades the standardized induction motor has dominated the industrial motor market. Due to this it’s natural that efficiency classification and measurement methods are focused to the induction motor technology with direct-on-line sinusoidal supply. Standardization enables fair product comparisons between different manufacturers but also make it possible to set minimum levels for motor efficiency such as the IE classes. Unfortunately efficiency potential of new technology solutions for variable speed applications doesn’t become visible when efficiency measurements are done with sinusoidal supply. Standardization committees are working on this issue but in the meanwhile awareness among users should be increased by other means such as this paper.

Motor efficiency with sinusoidal supply and with frequency converter supply

New motor technologies are often optimized for variable speed applications also when it comes to efficiency. According to IEC TS 60034-31 [3] motor losses increase 15% to 20% when an induction motor is supplied with a frequency converter compared to sinusoidal supply directly from network (these additional losses are however practically always more than compensated by energy saving provided by speed control). In order to put these additional losses in perspective it’s good to understand that the loss difference between different IE classes is about 20%.

One of the key elements with new technology motors such as permanent magnet motors and synchronous reluctance motors is that these non-sinusoidal supply related losses are lower compared to induction motors. In laboratory conditions it’s possible to measure also new technology motor efficiency with sinusoidal supply. However even if this information would be available for traditional and new motor technologies it would still be impossible to evaluate which motor would be better with frequency converter supply. When comparing solutions users should at least understand if motor efficiency is given with sinusoidal supply or with frequency converter supply. Many times motor efficiency for new technology solutions is given with frequency converter supply whereas induction motor efficiency is given with sinusoidal supply which means that figures are not directly comparable. Unfortunately manufacturers rarely have induction motor efficiency values available with frequency converter supply in order to make a fair comparison. This is somewhat understandable because standards for measurements are not yet available. Motor users should however be encouraged to request this information with variable speed applications. This information is usually available for new technology motors.

Motor-drive package efficiency

Motor efficiency with frequency converter supply is a good start when comparing different motor technologies for variable speed applications. However even that doesn’t guarantee that the whole motor-drive package operates with good efficiency. Another component for a variable speed solution is naturally a frequency converter which has losses as well. There are no efficiency classes for frequency converters yet but it’s good to understand that frequency converter losses and additional motor losses related to frequency converter supply are related to each other. Unfortunately the relationship is such that motor losses are increased when converter losses are decreased and wise versa. Converter losses can be decreased by lowering the switching frequency but this leads to higher additional losses in the motor. On the other hand motor losses can be decreased by increasing the switching frequency [3] but then converter losses are increased. This sets yet another challenge for efficiency performance comparisons. Even if efficiency values for each component is known it doesn’t necessarily mean that the multiplication of component efficiency values is the real motor-drive package efficiency value. There are no standards for motor-drive package efficiency measurements but it doesn’t mean that reliable package efficiency values could not be measured with today’s state of the art equipment.

Figure 5 illustrates typical efficiency performance of different motor – drive packages in a quadratic torque (typical pump or fan) application. The minimum efficiency levels of IE2, IE3 and IE4 motors with sinusoidal supply are also listed in order to show typical efficiency difference of motor-only with sinusoidal supply and motor – drive package when the same motor is used in both cases. The curves are based on ABB measurements of SynRM package and one ABB IE3 induction motor-drive package where the induction motor efficiency with sinusoidal supply has been 92,5%. The IE2 to IE4 induction motor-drive package efficiency curves have been calculated based on this measurement. The package efficiency measurements have been carried out with the same test system and the same ABB ACS850 frequency converter in order to minimize other than motor related differences. It should be understood that different motors even within the same IE class can have different efficiency curve. Converter model and control algorithm also impact on the results. Since there are so many variables it's advisable to request data for the particular package in question when reliable information concerning efficiency performance is needed.

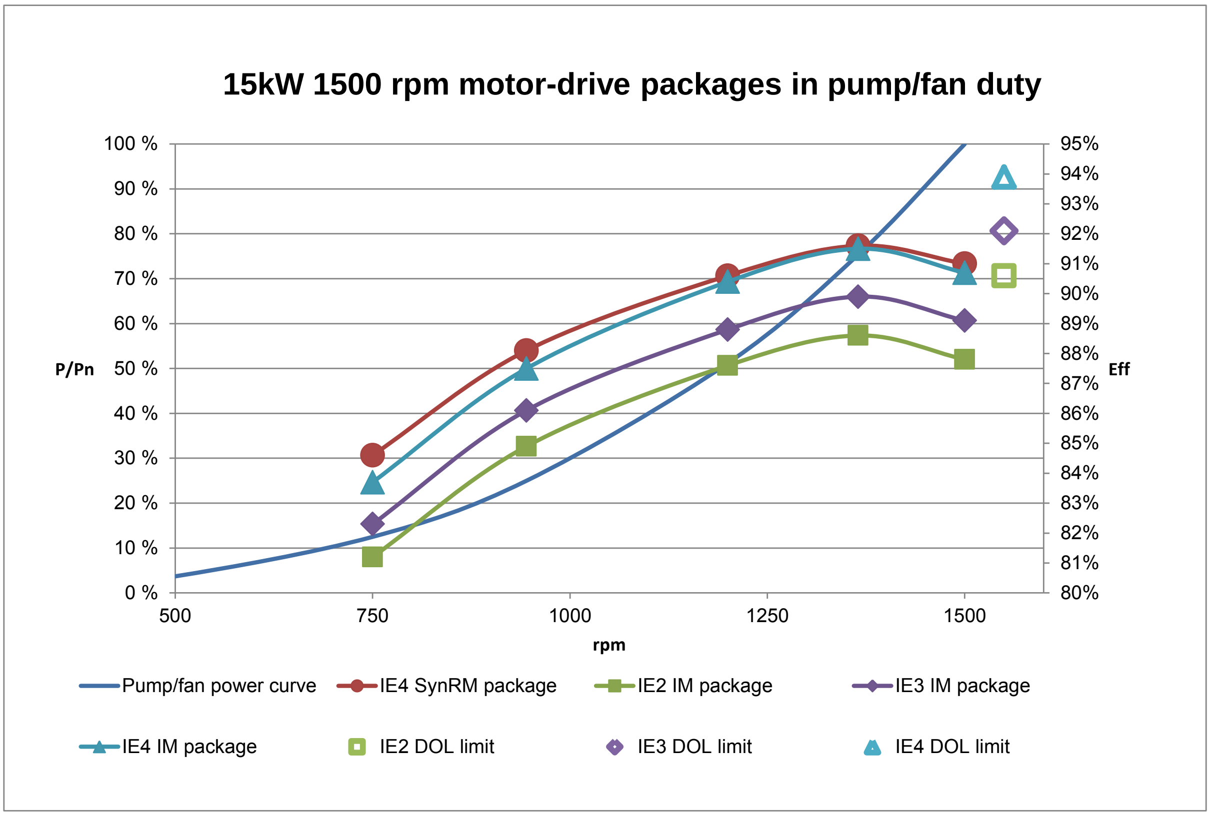


Figure 5, Typical motor – drive package efficiency of different packages and IE class limit values for line rated motors

For a motor-drive package user the question setting is actually very simple. For a given shaft output power, how much electrical power is needed from the network. For a true motor-drive package this information should be available.

Conclusion for efficiency performance comparisons

In the best case for a true motor-drive package the package efficiency is available. However in many cases today a motor-drive package is assembled by separate components. When doing efficiency performance comparisons it's again very important to understand what type of values are compared against each other. There can be:
1) motor-only efficiency with sinusoidal supply,
2) motor-only efficiency with frequency converter supply (usually with specific converter type)
3) motor-drive package efficiency, Figures 6 and 7.
Ironically the actual efficiency value gets lower in the same order whereas the real package efficiency may very well get better. That's because in a true package solution the additional motor losses due to converter supply are minimized and total minimum between motor and drive losses can be found.

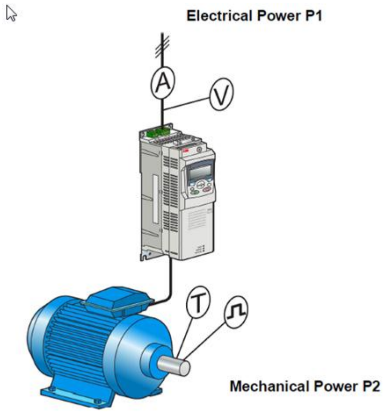


Figure 6, Measurement points for motor-drive package efficiency. Package efficiency = P2/P1

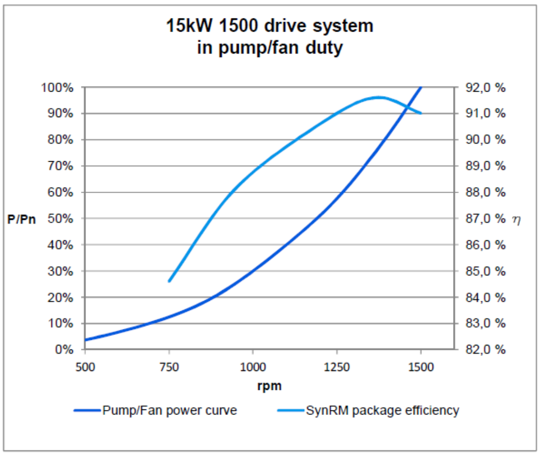
Document no: SEVEN201211160001

Manufacturer's statement

ACS850-04 and IE4 SynRM motor package efficiency

Drive: ACS850-04-035A-5

Motor: M3BL 160MLB, 3GBL162105-ASC, P_n 15kW, 1500rpm



Speed rpm	Speed %	P/P_n	Package efficiency
750	50	12 %	84,6 %
945	63	25 %	88,1 %
1200	80	51 %	90,6 %
1365	91	75 %	91,6 %
1500	100	100 %	91,0 %

Figure 7, Example of motor – drive package efficiency report. Manufacturer's package efficiency statement for ABB synchronous reluctance motor-drive package

Synchronous reluctance motor technology [4]

Introduction

The synchronous reluctance motor is a three-phase electric motor with a magnetically anisotropic rotor structure. In the four-pole version, the rotor has four high- and four lowpermeance axes. High permeance means high magnetic conductivity and higher inductance, while low permeance means lower inductance. Reluctance is the inverse of permeance and is, in practical terms, magnetic resistance; high reluctance results in low inductance. The axes with high permeance can be referred to as the direct or d-axis, while the axes with high reluctance can be referred to as the quadrature or q-axis.

The figures below show cross-sectionals of a synchronous reluctance motor. The different axes in the rotor are identified in the figure on the right.

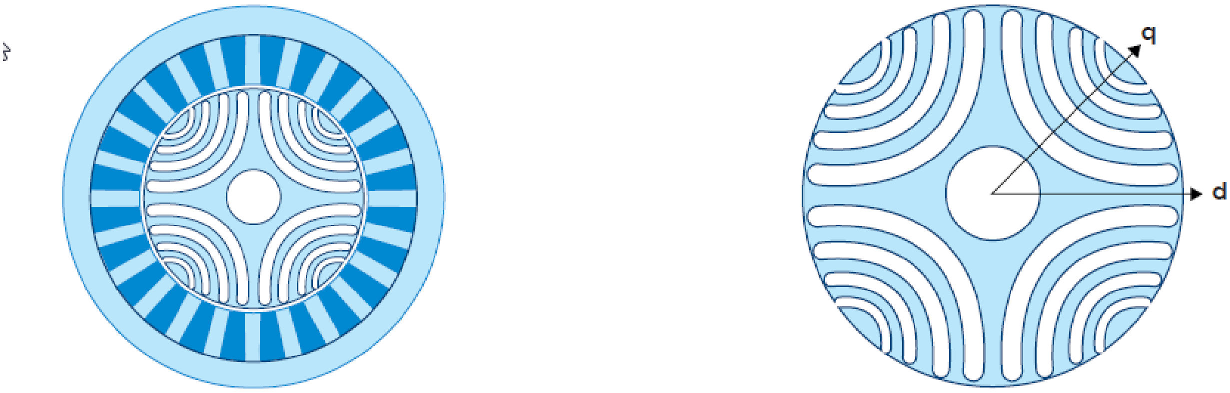


Figure 8, Cross-sectional illustration of a four-pole synchronous reluctance motor (left), and the definition of the magnetic d- and q-axes of its rotor (right).

Functional principle

When a magnetic field is produced in the air gap by applying exciting currents to the stator windings, the rotor will strive to align its most magnetically conductive axis, the d-axis, with the applied field, in order to minimize the reluctance in the magnetic circuit. In other words, torque is produced in the air gap between the stator and rotor whenever the applied field vector and the d-axis of the rotor are not aligned.

The magnitude of the vector field and the speed of its rotation can be controlled by a frequency converter. The high saliency of the rotor means that its angular position can be simply detected by a sensorless control. Expensive absolute encoders, resolvers and other rotational sensors are therefore not required.

The sensorless control system keeps track of the rotor's angular position in relation to the stator and creates a vector field with accurate magnitude and rotational speed in accordance with the control reference signals dictated by the load.

Since performance is dependent on information about the position of the rotor, the motor always needs a frequency converter – it will not operate properly direct-on-line. The rotor runs in synchronism with the applied vector field, striving to minimize reluctance in the magnetic circuit that is present, and this functional principle has given its name to the technology – synchronous reluctance.

Synchronous reluctance motors run smoothly due to the sinusoidal air gap field distribution and operation with sinusoidal current.

Rotor design

The rotor of a synchronous reluctance motor comprises electric steel plates stacked together to form a rotor package. Holes punched in the electric steel plates form flux barriers, as illustrated in figure 8.

The torque produced by the motor is proportional to the difference between the inductances on the d- and q-axes: the greater this difference, the greater the torque production. The synchronous reluctance motor is therefore designed with magnetically conductive material, iron, in the d-axis and magnetically insulating material, air, in the q-axis.

As the rotor has no windings and consequently no joule losses, it runs considerably cooler and with better efficiency than the rotor in an induction motor. The cool running of the rotor also means lower bearing temperatures, which in turn increase the reliability of the bearing system.

Other considerations

Eliminating rotor joule losses in the synchronous reluctance motor has led to compact construction, good efficiency levels and cooler bearing temperatures. The main disadvantage of this technology is that the motor's power factor is generally not as good as with induction motors.

Since there is always a frequency converter between the motor and the grid, the lower power factor is not apparent on the grid side and consequently does not have an impact on the grid supply dimensioning. However, the lower power factor may sometimes mean that a frequency converter with a higher current rating is needed.

The stator and frame design are based on proven induction motor technology, and the rotor consists of only iron and air. The lack of windings and permanent magnets in the rotor eliminates the potential faults associated with these components, resulting in robust motor technology optimized for industrial variable speed applications.

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PM Motors for High Efficiency Applications

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Sebastião Lauro Nau

WEG Equipamentos Elétricos S.A.

Abstract

PM motors are suitable for nearly all applications, like pumps, elevators, compressors, blowers, extruders, generators, electric vehicles, servodrives, cooling towers, household appliances, etc. This paper will present some applications where the use of PM motors allowed for enhancements in energy efficiency and process quality.

Introduction

According to recent studies [1], electric motor-driven systems (EMDS) account for between 43% and 46% of all global electricity consumption. Induction motors have been the most used drives in industry, due to its robustness, reliability and simple operation (direct connection to the mains, without electronic control). However, in many applications variable-speed drives offer significant energy saving potential [2]. In this scenario, permanent magnet motors are competing technologies for the induction motors, because they present higher efficiency and do not need forced ventilation neither over sizing.

Permanent Magnet Motors

PM motors offer the highest efficiency of all motors, due to the absence of joule losses in the rotor, and high power factor due to the excitation flux of the permanent magnets (resulting in smaller currents). Since PM motors have no Joule losses in the rotor, bearing temperature is lower, and lifetime is increased.

They have a significant higher efficiency at low speeds than the induction motors and do not need forced ventilation, neither over sizing for constant torque operation (rated torque in all speeds). Figure 1 shows a comparison among an IPM motor (IE4 +) and two induction motors (IE2 and IE3), all rated 30 kW at 1800 rpm, operating over a 4:1 speed range with constant rated torque.

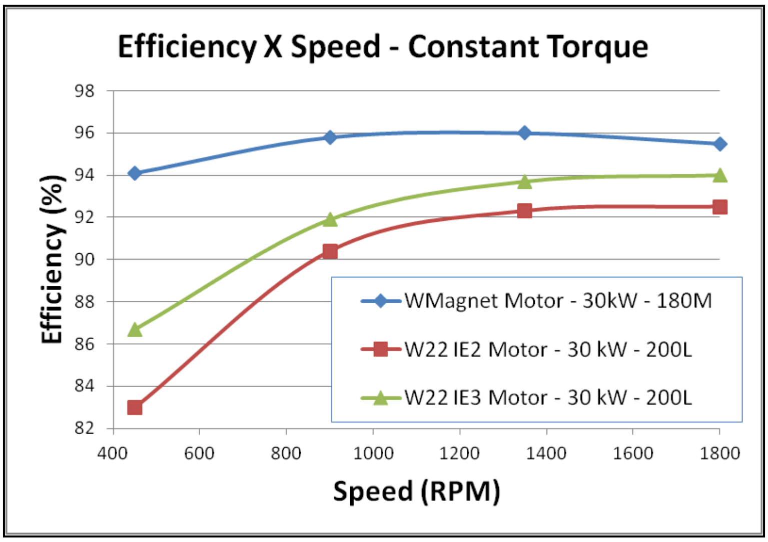


Figure 1. Efficiency over a 4:1 speed range with constant torque for three motors: a PM synchronous motor (Wmagnet), and two induction motors (W22 IE2 and W22 IE3), all rated 30 kW at 1800 rpm.

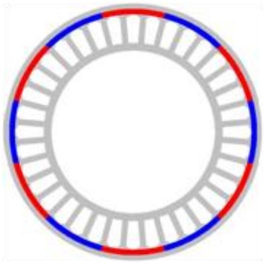
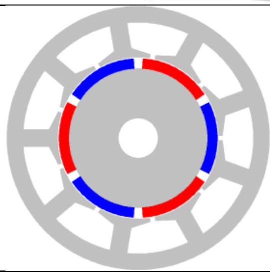
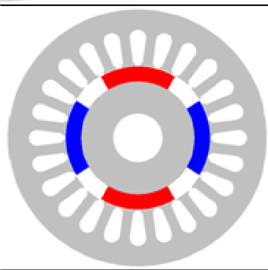
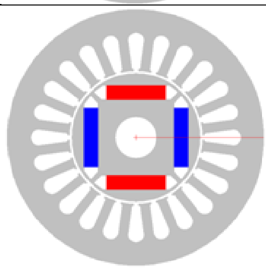
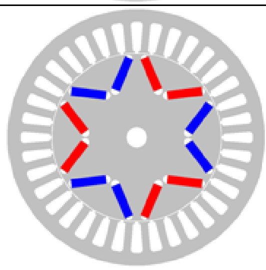
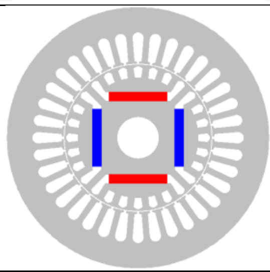
Construction Characteristics

PM motors can have different construction characteristics. The permanent magnets can be placed on the surface or inside the rotor (IPM – Interior Permanent Magnet), the rotor can be external or internal, the windings can be distributed (as for conventional induction motors) or tooth-wound (as in universal motors). They can use low-cost, low-energy ferrite magnets (usually for low-power, low-cost applications) or high-cost, high-energy rare-earth magnets (usually for high performance motors in industrial applications), resulting in more compact designs with high torque/volume ratios.

Furthermore, they can be classified as BLAC (Brushless Alternating Current) or BLDC (Brushless Direct Current) motors. The first use a sine wave current drive (their back-EMF is sinusoidal) and the latter use a square wave current drive (their back-EMF is trapezoidal). Typically, BLDC motors have tooth-wound windings, and BLAC motors have distributed windings. But BLAC motor can have tooth-wound windings as well, mainly for low-power applications.

There are several topologies, and the applicability of each one depends on the application requirements, as shown in the table below.

Characteristics of different topologies

Topology	Characteristics	Example
External rotor	high-torque, low-speed applications (i.e. washing machine, elevators), ventilation, wheel motors for traction applications.	
Surface magnets	low-speed applications (i.e. ventilation, exhaustion, residential pumps, elevators).	 
Interior magnets	low and high-speed applications (i.e. blowers, compressors, pumps, elevators, electric vehicles).	 
Line-start	low-speed, low-inertia applications, direct-on-line connection (i.e. small fans, pumps)	

Applications for PM Motors

Industrial PM motors

IPM Motor

IPM synchronous motors have similar stator windings as induction motors, but have high-energy rare-earth magnets inside the rotor.

Figure 2 shows a detail of a one-pole finite element simulation of a 6-pole IPM motor on load. The rotor has a special designed lamination to minimize flux leakage while keeping the necessary mechanical strength at the higher speed allowed.

These motors can be one frame size smaller than induction motors (up to 43% reduction in volume and 35% in weight), while offering super premium efficiencies (Figure 3) [3].

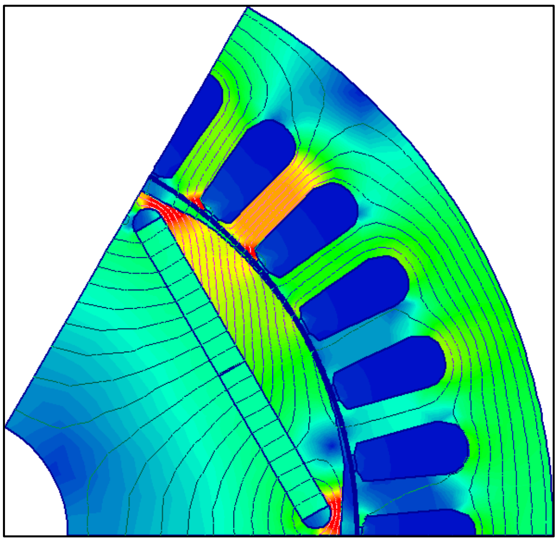


Figure 2. Detail of one pole flux pattern and flux density of a 6-pole IPM motor.

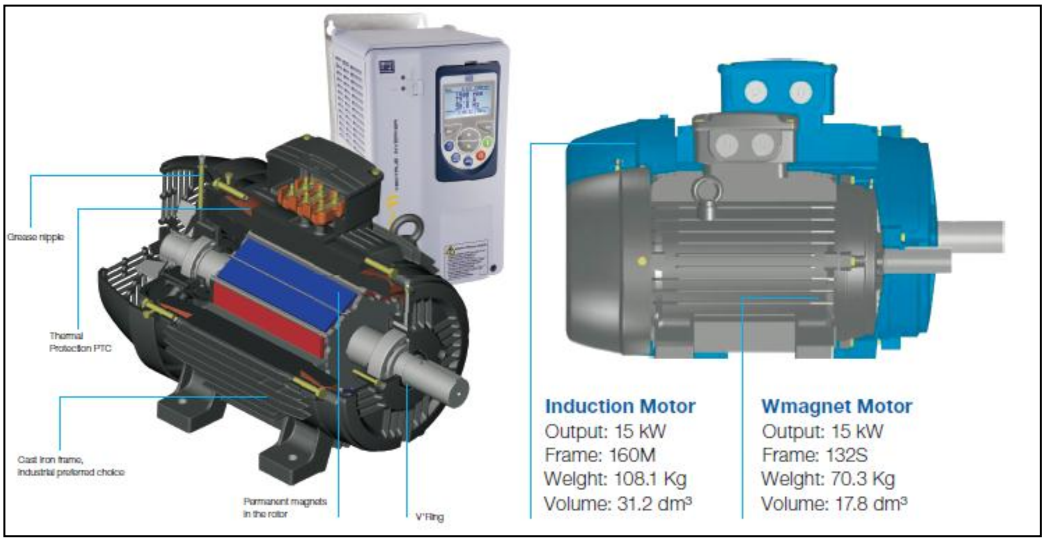


Figure 3. Interior permanent magnet motor with rare-earth magnets and reduced frame size.

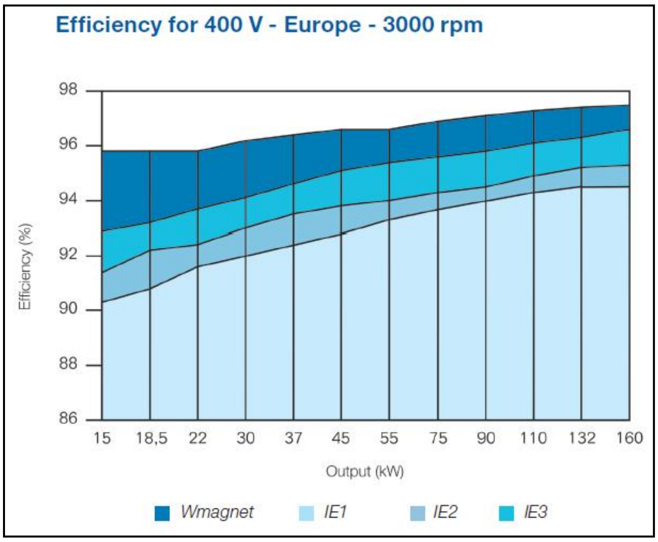


Figure 3. Efficiency comparison between IPM synchronous motors and IEC efficiency levels.

Since they are in a reduced size frame, they have lower noise levels than induction motor of the same output power.

The main applications are pumps, ventilation systems, compressors, wire drawing machines, extruders and conveyor belts.

Line-start PM Motor

These motors are hybrid motors because they have rare-earth magnets below the squirrel-cage [4]. They have similar windings as induction motors and have the ability to start direct on line, without the need for electronic controller. They start and accelerate like an induction motor, until synchronism is achieved, keeping constant speed with varying load, with super premium efficiency.

Figure 4 shows an example of a 6-pole line-stating motor lamination. The stator has the same lamination as the induction motor counterpart. The rotor lamination has especially designed aluminum bars and slots for permanent magnets to allow good starting capabilities (starting torque and synchronization) and good synchronous operation (high pull-out torque and high efficiency).

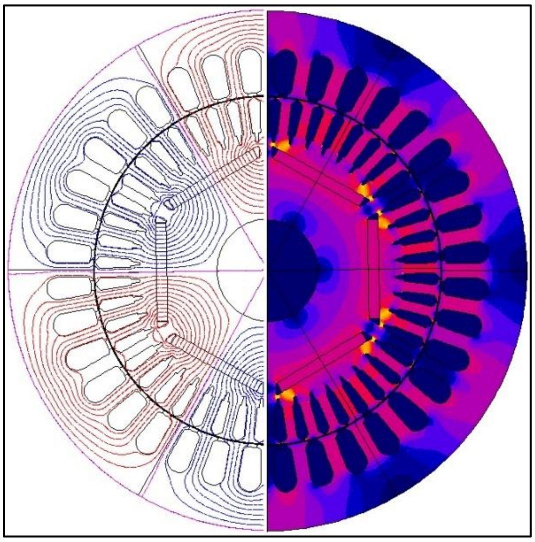


Figure 4. Example of a 6-pole line-start motor showing flux pattern and flux density.

If variable speed is needed, they can be driven by a conventional frequency inverter, in scalar mode. This allows several motors to be driven by the same inverter, running at the same speed.

Figure 5 shows the efficiency levels compared to IEC levels.

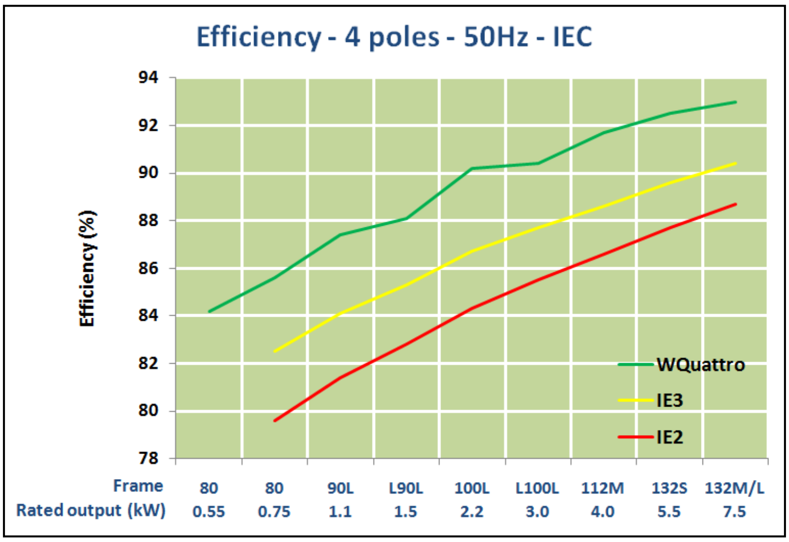


Figure 5. Efficiency comparison between Line-start PM motors and IEC efficiency levels.

The main applications are low-inertia loads (up to 30 times de rotor inertia), and multi-motor variable-speed with one single inverter. The inertia of the load is an important issue, because if it is greater than the limit value, the motor shall fail to synchronize, and will operate at a speed below synchronous speed, having high currents, noise and vibration, and the motor must not operate in this condition.

Multi-motor variable-speed applications with on inverter can be an economic solution for those applications that need that several motors work in the very same speed.

Application in compressor

A PM motor was used in substitution of an induction motor in a 200 HP screw compressor (Figure 6). Figure 7 shows the efficiency comparison of the compressor over its speed range when using an induction motor and when using a PM motor.

Figure 6. Compressor with PM motor

The induction motor was rated 150kW, 2 poles, IEC frame 280 S/M. The PM motor was rated 150kW, 3600 rpm, IEC frame 250 S/M PM motor. There has been a significant increase in efficiency by the use of the PM motor. Also, the PM motor is one frame size smaller, with 52% of the weight of the induction motor.

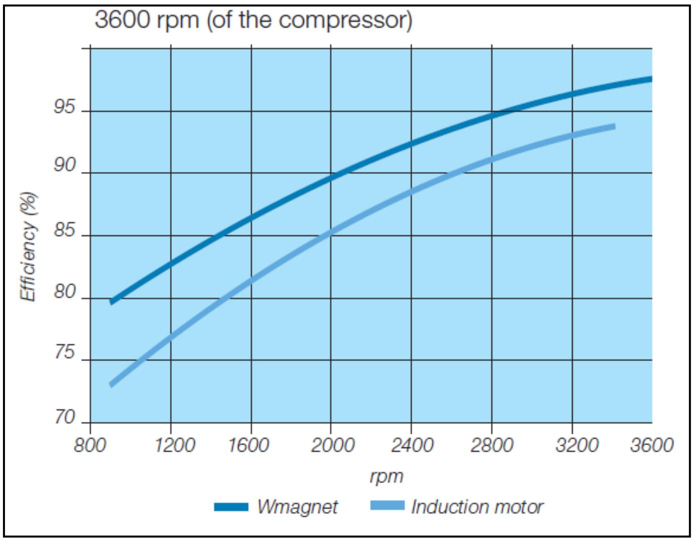


Figure 7. Efficiency of the compressor with IPM motor and induction motor

Application in wire drawing machine

A 100HP, 4 poles, IEC frame 250 S/M Induction motor was substituted by a 100HP, 1500 rpm, IEC frame 225 S/M PM motor in a wire drawing machine (Figure 8). This change allowed average energy savings of 3.9% in the operation cycle of the machine, corresponding to a monthly saving of 720kWh considering continuous operation; an increase in the wire production range (lower speed with increased load torque), because the PM motor works cooler than the original induction motor; and the temperature of the bearings was greatly reduced, allowing a longer useful life of the bearings, longer lubrication intervals, and less maintenance.

Figure 8. Wire drawing machine with PM motor

Application in textile industry

The original motor of the yarn starching machine (Figure 9) was a ring induction motor, which had brushes that needed to be replaced regularly and demanded constant maintenance. When this motor burnt and needed to be repaired, the decision to seek a more efficient alternative led to the choice of a PM motor. The cost to fix the old motor would be 115% of the amount to acquire a new and more efficient motor. So, the new motor chosen was a 15 kW PM motor. The replacement reduced the maintenance costs (practically zero) and shutdown hours of the machine, and enhanced the process with speed variation with constant torque (which means saving energy) and more power in the operation. It also brought more versatility to speed control which is essential for the quality of the starching, a process prior to the production of fabric. The PM motor is 50% smaller than the original motor. This calls for less space and makes eventual maintenance easier.

Figure 9. Textile machine

Application in cooling tower

PM motors for cooling towers use rare-earth magnets and have a high number of poles, producing high torque at low speeds, for direct-drive coupling (Figure 10). This eliminates gear-boxes, leading to less maintenance and less mechanical losses, that together with the lower electrical losses of the PM motor, increases the overall efficiency of the system.

Figure 10. Cooling tower with PM motor

Application in extrusion machine

The volume of plastic material that is extruded depends on the rotational speed of the helical thread. Extrusion machines demand constant speed of the helical thread to assure the quality of the process. Also, different materials require different speeds. DC and induction motors with magnetic clutch are commonly used in these machines, but the maintenance of these motors is costly and frequent. Also induction motors with frequency inverters are used.

A PM motor was applied in an extrusion machine (Figure 11), which used a DC motor. Annual energy savings of 21% were obtained. Besides the higher efficiency, the PM motor offers other advantages like low maintenance (less shutdown time machine), no necessity for forced ventilation and constant torque at low speeds.

Figure 11. Extrusion machine with PM motor

Conclusions

PM motors can have different construction characteristics, to meet different application requirements. Due to their higher efficiency compared to induction motors, PM motors present a significant reduction in energy consumption in all the applications shown in this paper.

Moreover, in variable speed applications, PM motors are even more advantageous, because they do not need forced ventilation nor over sizing for constant torque operation, and as the speed decreases, the efficiency decreases less than it does for induction motors.

It should also be emphasized that for industrial applications rare-earth PM motors are usually one frame size smaller than the induction motor counterparts. This leads to a reduced volume and weight, and lower noise and vibration level. Since the motor operates cooler because there are no Joule losses in the rotor, bearing temperature is lower, and life time is increased.

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EXPERIMENTAL ANALYSIS OF ELECTRICAL ENERGY EFFICIENCY FOR SPEED CONTROL OF A THREE-PHASES INDUCTION MOTOR

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Abstract

The inductive motors represent an important load in different industrial sectors but these motors have been not changed by recent high efficient models. Therefore, the energy efficiency is a critical issue to be improved implementing suitable control systems. This paper performs an experimental analysis to analyze the relationship between an index of energy topic and the speed control applied to inductive motors. The speed control is modeled using standard configurations such as a proportional-integrative (PI) control and an electronic oscillator. For this study, we use squirrel cage motor equipped with 4 poles, 175W of nominal power, 220V, and 1.2A. This system is acoppled with a thyristor module, the electrical losses of this module are estimated on 5W.

Computational simulations were performed to propose a general model to evaluate the electrical losses related to the motor speed control. Some test performed under controlled environments allows us to check the relationship between motor speed control and this index. The results allow to conclude that the energy efficiency is directly related with the control systems used to vary the motor speed.

Background

The analysis of energy savings conservations assume that the motor is operating at the efficicient of this plate characteristics. The indirect test uses the measured electrical input power and a determination procedure for the losses to calculate efficiency [1]. This condition is a reasonable estimation if the motor is operating above 50% of the load point because the efficient curve has a maximun around 3/4 of load. Others motors operates in a flat efficient curve above 25% of full-load [2]. Its hard to determine the efficiency of a motor operating for a long time by various reasons. For example, the plate characteristics have been erased, spool activities, etc.

The efficiency of a motor-driven process depends upon several factors which the motor efficiency, motor speed controls, proper sizing, power supply quality (harmonics and others), distribution losses, maintenance. AC induction and synchronous motors are essentially constant-speed motors. Most motor applications would benefit if the speed could be adjusted to the process requirements. This is especially true for new applications where the processes can be designed to take advantage of the variable speed. Motor system operation can be improved through the use of several speed-control technologies, such as Mechanical and Eddy-Current Drives, Multi-Speed Motors and Electronic Adjustable-Speed Drives. [3].

PI speed control for a induction motor

Fig. 1 shows a block diagram including all control signals. The feedback signal for the PI control us the speed sensor in the rotor [4].

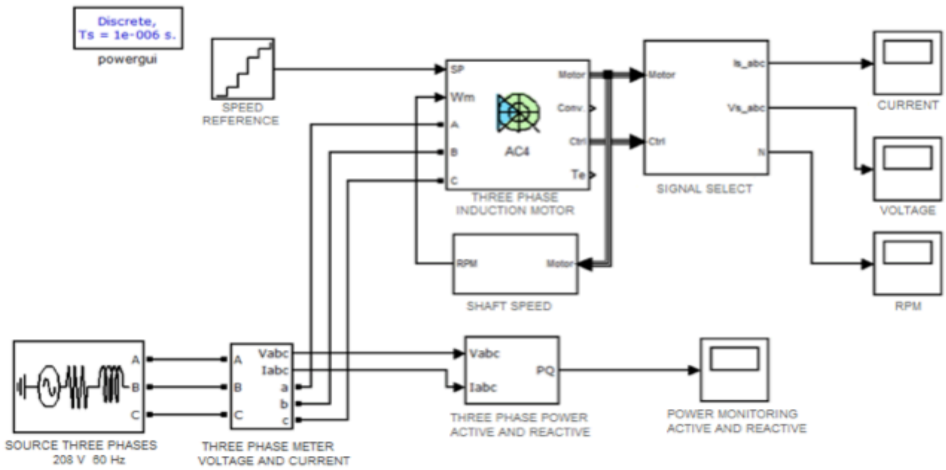


Figure 1. Speed control simulation for a inductive motor.

Fig. 2 show a detailed configuration for the PI control used for speed control in a inductive motor [5].

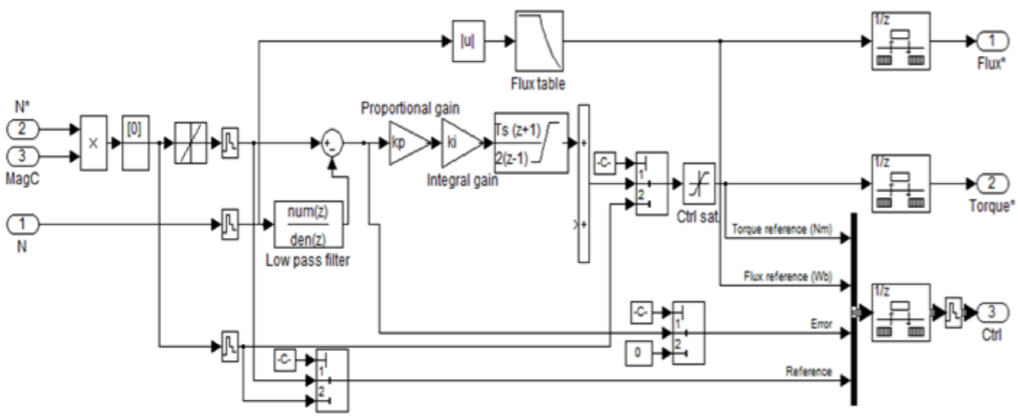
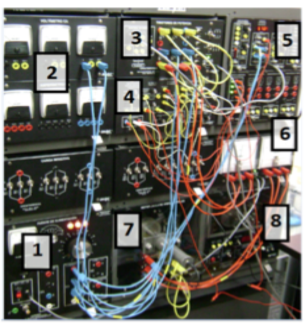


Figure 2. Speed control for a inductive motor.

The test is showed in the Fig. 5. The load used are 0,3 Nm, 0,6 Nm y 0,8 Nm



1. Power Source 208/120 Vac
2. Current Meter
3. Thyristor Module
4. Controller P.I.D.
5. Thyristor Fire Module
6. Power Meter
7. Induction Motor
8. Dynamometer

Figure 3. Test of PI Control

The PI control present minor losses in spite of that the motor does not reach his nominal power. This indicates that the method is not effective to reduce losses. For the load at 0,3Nm, the PI control shows a stable signal with high losses.

During the test of 0,6Nm, the PI control has a major stability and it can reduce the mechanic losses. Other methods are unstables and it presents high peaks of losses. This allows to conclude that the PI control is more appropiate when this load is connected to the motor. With a load of 0,8Nm the PI control is more stable but the mechanics losses are high.

Speed control by relaxation oscillator

The relaxation oscillator is a electronic circuit that it is constituted by a unijunction transistor (UJT - 2N2646), three resistances, one capacitor, and a DC source. This DC sources generates a control signal which is applied in the power stage to speed control [6]. The oscillator and the control pulses show in figures 4 and 5 respectively.

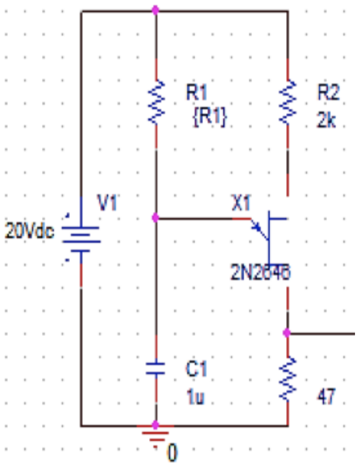


Figure 4. Relaxation oscillator.

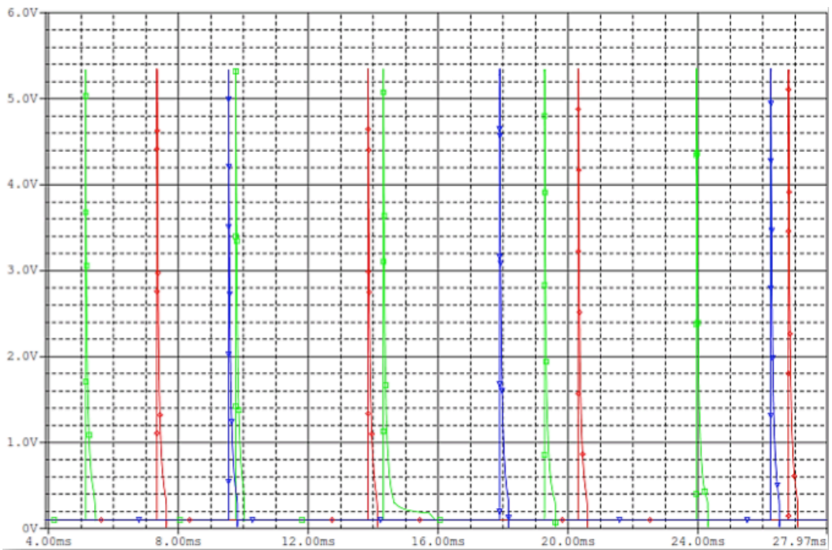


Figure 5. Control pulses.

The control scheme is showed in the Fig. 6. The relaxation oscillator is connected through photo-accoplators with triacs. These triacs modifies the power signal applied to the motor for speed control.

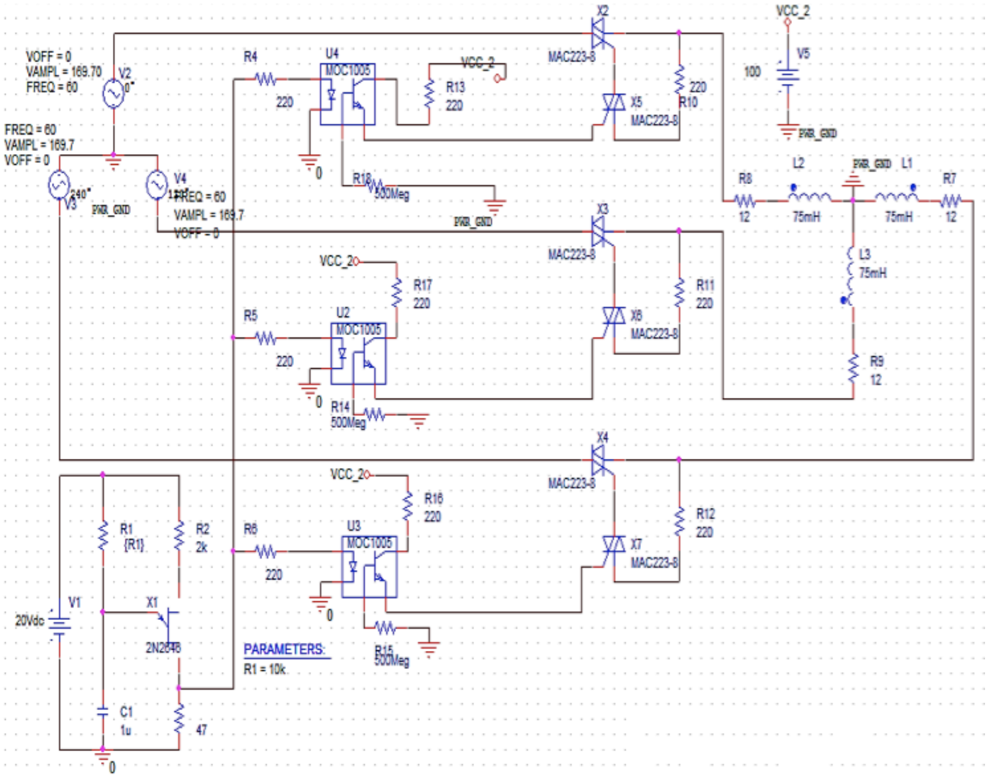


Figure 6. ORCAD simulation.

RESULTS

According to the results we can conclude that the motor performance under empty conditions are base on the stator performance. Taking into account that the rotor performance is cero because the active power in the axis does not use. The electric power is delivered in mechanical losses and electric losses. According to the Table 1, the efficiency during no load conditions get a 1,5% using a PI control. On the other hands, the efficiency diminish to 0,2% with a relaxation oscillator.

Test	Without Control	With P.I Control	With Oscillator
1	83,3	97,2	83,3
2	95,8	97,8	96,1
3	98,6	98,3	97,8
4	99,4	98,9	98,3
5	99,4	99,4	99
6	99,7	99,7	99,6
Average	96	98,5	95,7

Table 1. Performance of motor without Load

The reference efficiency is when the motor is staring directly because we do not have data about efficiency. For a motor with a load of 0,3 Nm can observe that the efficiency is equal to 4,5% using a PI control and it diminish to 7,8% with the relaxation oscillator.

Test	Without Control	With P.I Control	With Oscillator
1	66	56,7	60
2	66,4	54,5	56,8
3	64,2	56,6	57,7
4	58,6	58,3	52,2
5	55,5	57,3	52,8
6	52,6	55,4	49,4
Average	60,5	56,5	54,8

Table 2. Performance of motor with load of 0,3 Nm

For a load of 0,6Nm the efficiency get an average value of 5,3% using a PI control and a 4,3% of efficiency with a relaxation oscillator. Table 3.

Test	Without Control	With P.I Control	With Oscillator
1	61,5	15,8	59,3
2	68,2	15,7	64,7
3	72,5	16,5	67,5
4	71,4	16,6	65,7
5	70,9	17,2	66,6
6	70	17,9	64,9
Average	69,1	16,6	64,8

Table 3. Performance of motor with load of 0,6 Nm

When the motor is operating with a load of 0,8Nm, the efficiency diminish to 4,6% using a PI control and the efficiency get an average value of 3,7% of efficiency using a relaxation oscillator. Table 4.

Test	Without Control	With P.I Control	With Oscillator
1	69,5	32,9	65,3
2	67,6	38	61,4
3	70,8	41,1	67,2
4	72,2	42,6	68,2
5	72,4	42,9	70,3
6	71,3	43	68,6
Average	70,6	40,1	66,8

Table 4. Performance of motor with load of 0,8 Nm

CONCLUSIONS

The implementation of simulations in the software tools for a speed control of a inductive motor base don a PI control and a relaxation oscillator allow us to evaluate the efficiency and perfomance. The simulation allow us to see what is happening with the voltage, current, and electric power. The only limitation was on the applied load because we do not know information about it. With the charts, we can determine qualitatively a speed control method with differents conditions of load.

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Construction of an energy efficiency measuring test bench for belt drives

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Abstract

A test bench for the evaluation of the energy efficiency of belt drives is presented. The construction and measurement procedure is discussed with respect to measurement accuracy and reproducibility. Also the impact of additional parameters such as belt tension and misalignment can be analyzed. First measurement results comparing a V-belt drive and a synchronous belt drive are discussed. The efficiency of the drives is measured in the entire operation range and represented by means of iso efficiency maps.

Introduction

Belt drives are still frequently used in industry for the power transmission between electric motor and mechanical load. The power transmission efficiency of such belt drives, according to most references, varies between 90 and 98 percent [1]. These efficiency values are typically related to nominal operation conditions of the belt. Experimental data on belt drive efficiency at reduced speeds and torques are only occasionally reported in literature and recent references are missing.

Belt manufacturers have been very active in research. This has resulted in improved belts with respect to wear, noise and according to the manufactures also efficiency. Unfortunately, efficiency values mentioned by manufacturers are hard to compare. There are no standardized measurement procedures prescribed and catalogs do not mention whether and how the efficiency values have been determined.

Commissioning a belt drive requires manual operations in order to obtain a good and reliable power transmission. Mounting of the pulleys and belts(s) and adjusting the belt tension needs to be performed with care. This is important not only for a reliable operation of the belt drive but also has an impact on the power transmission efficiency. It is well known that belt tension might vary over time resulting in a lower belt tension with respect to the commissioning value. Experimental results to identify the impact of belt tension on efficiency are rare and further research is required to determine if maintenance actions with respect to the belt tension could be justified or required.

This paper contributes to a better understanding of belt drive efficiency. A test bench is discussed which allows to measure power transmission efficiency with adequate precision in the entire operating range of speed and torque. Additional belt drive parameters such as belt tension, misalignment and pulley size can be evaluated as well. Measurement results are represented by means of iso-efficiency contour maps for V-belts drives and synchronous belt drives.

This work is part of a public research project (IWT – Tetra Project) on the efficiency of transmissions (gearboxes and belt drives). This project was preceded by a project on motor and drive efficiency. The next step is to optimize the complete drive train with the gathered knowledge.

Test bench setup

The challenges that come with the construction of a test bench for belt drives are numerous. An overview of the test bench is given in **Figure 1**. One pulley is driven by a 15kW, 4 pole induction machine with a variable speed drive. The second pulley is loaded by means of a second 15kW, 4 pole induction machine in generator mode, also controlled by a variable speed drive. This machine is torque controlled to impress a specific load profile to the belt drive. The DC busses of both variable speed drives are connected in order to limit the energy consumption of the test bench. A schematic overview is given in **Figure 2**.

First, the efficiency must be determined with high accuracy because of low losses in a belt drive. This requires high end measurement devices with high accuracy class. Most test benches for belts use a direct measurement principle. Torque and speed are measured at input and output pulley. Because belt drives use tensioning of the belts, special torque sensors should be used which are not influenced by the radial forces due to belt tensioning. Here, dedicated torque sensors are used for each pulley to overcome this problem (Lorenz Messtechnik MR 12) with a 0.1% full scale accuracy and 200 Nm range. The torque sensors are mounted at the free end of the pulley, avoiding an impact from the radial tensioning force. First measurements revealed the sensitivity of these sensors with respect to the ambient temperature in the test room. The torque sensors were calibrated at 23°C. To correct for different ambient temperatures and different housing temperatures of the torque sensors, thermocouples are used. Furthermore, the test room is equipped with an air-conditioning unit to limit the ambient temperature variation. The setpoint for the ambient temperature is 23°C. Correction of the torque readings with respect to temperature is performed in the data acquisition system of the test bench. The correction table was obtained by performing a static torque measurement for temperatures ranging from 23°C up to 35°C. Pulley speeds are measured by incremental encoders (1024 pulses) mounted on the driving and loading electric motors.

The data acquisition and control of the driving machine and loading machine is performed by means of a dSpace 1103 controller board and a Simulink/ControlDesk interface. For protection reasons, the sensor signals are electrically isolated from the controller board by means of high precision and high bandwidth isolation amplifiers. A calibration of the isolation amplifiers and AD convertors in the controller board has been performed to achieve high accuracy. Calculation of the overall accuracy of the efficiency measurement indicate that the accuracy is less than ±1% for measurements from 200 Nm to about 25 Nm. Durings tests load torques beneath 25Nm are used to acquire complete iso-efficiency contours, but one should take into account an inaccurary of >1% in these lower torque ranges.

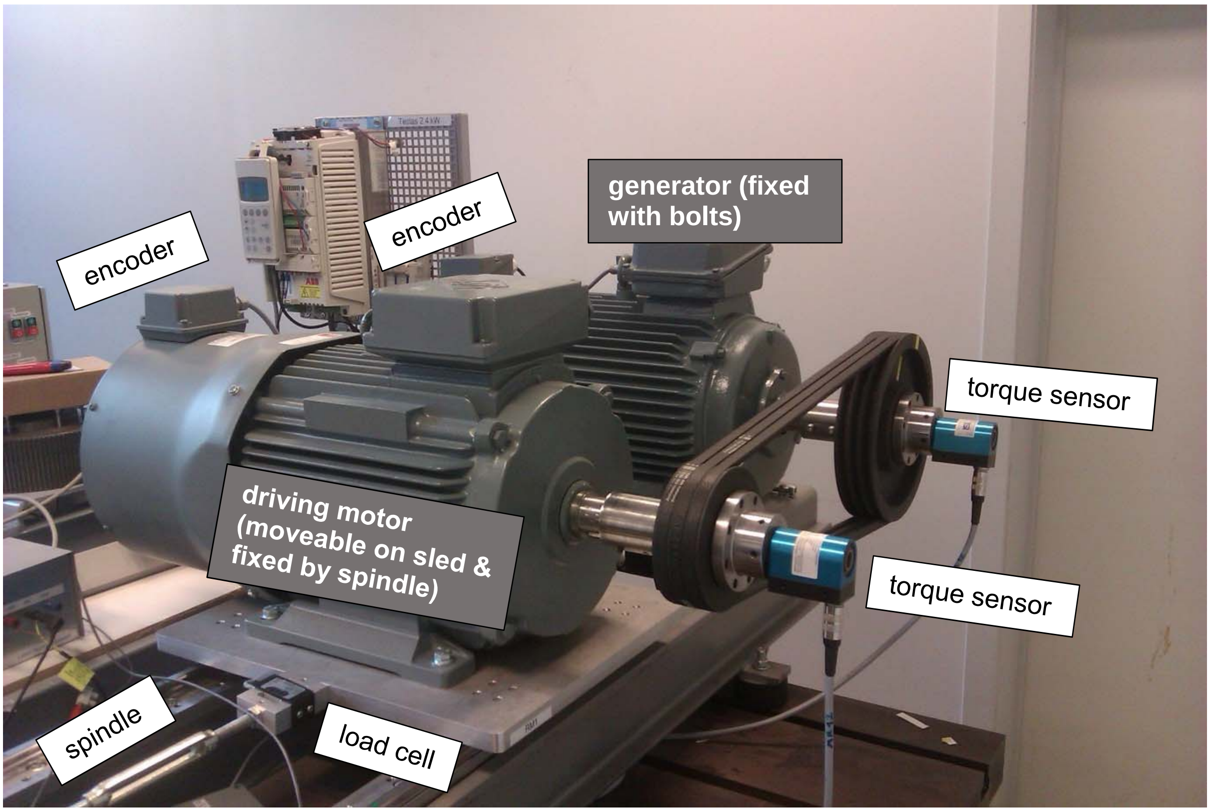

Figure 1: overview of belt test bench

The repeatability of the measurement results is also a major concern. Comparing different belt technologies requires mounting and demounting of belts and pulleys. This mechanical work needs to be performed with great care in order to introduce no additional errors or losses other than the actual belt drive losses. Measurement tools to analyze the misalignment of the pulleys and to check the belt tension are used whenever mechanical changes are required.

To apply a certain belt tension, one of the electric machines can be moved along the belt direction on a sled by means of a spindle (see **Figure 1**). Between the spindle and the electric machine, a load cell is mounted (Sensy 2712, 500 daN). This allows testers to modify the belt tension in a direct way. The load cell is fixed against a 20 mm thick aluminium plate and elongates only 0,35 mm when 500 daN is applied. The spindle is attached to an eye bolt. So theoretically the spindle – and thus the driving motor – could move back and forth because of the eye bolt. But due the tensioning of the belt, the spindle and eye bolt are not moving one to another. Therefor both the load cell and the spindle can be regarded as rigid mechanical components. Other test setups mentioned in literature to adjust belt tension do not show this mechanically rigid construction [2]. In that case, depending on the forces related to the power to transmit, the motor can slightly move. Especially when the belt drive is tested in other than nominal conditions (part load and speed variation) the moving of the machine can result in erroneous results because of a change in belt tension. This is overcome in the test setup described in this paper. If required, the belt tension can also be adjusted when the system is running. In this condition, the belt tension can be recorded by the load cell.

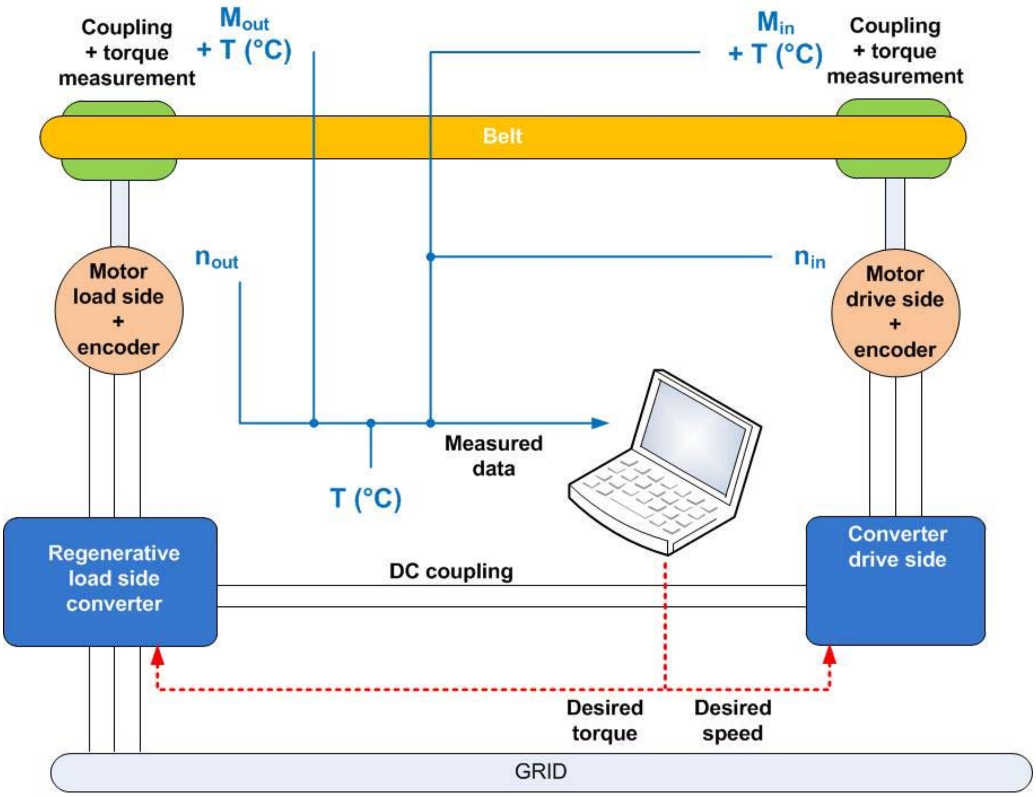

Figure 2: measurement principle belt drive efficiency test bench

Measurement procedure

To guarantee reproducible results, the tests are carried out using a predefined measurement procedure. The procedure starts with a running in of new belts according to the manufacturer's guidelines. Due to possible stretching of a new belt, the belt tension is adjusted typically after one hour of operation. The applied speed and load during running depends on the belt type and the number of belts. If possible, rated torque and speed is applied. Due to torque limitations caused by the motors, some belts cannot be tested in their entire working area.

The first running in test is completed when all system parameters have stabilized (torque signals, temperature readings, etc.). After the first running in test, the setup is shut down and cooled down to ambient temperature again. Then the procedure is repeated at least twice to ensure reproducibility. When the stabilized system parameters of each test are similar, the running in phase is considered done.

In the second step of the measurement procedure, an iso efficiency map is measured starting from a stabilized system. The torque speed region is divided over 16 different speeds and 17 different torque values [3],[4]. This results in 272 operating points to be measured. The measurements start at the highest load and speed allowed by either the belt or test bench. The load is decreased gradually at constant speed until zero. Then speed is lowered, the load is increased to its maximum and decreases again. Before recording the measurements in an operating point, the system is given time to stabilize. When stabilized, 50 measurements are performed in a period of 5 seconds. These results are averaged and result in the efficiency value for the operating point considered.

Performing all measurements to obtain such a detailed iso efficiency map requires about 4 hours. At the moment work is being done to automate these tests. The iso efficiency map itself is created using Matlab.

Another procedure is created to analyze the impact of belt tension on efficiency. First, the belt drive is tensioned correctly, according to the specs, and runs at a fixed speed and load. After one hour the tension is lowered by approximately 25% of its required value expressed in Newton, by looking at the load cell. This cannot be done by measuring the belt frequency because the test bench keeps running to avoid errors. The tension drop is possible due to the drive motor which is on a sled. Again, the efficiency is recorded during an hour and then the test bench is stopped. At that moment the effective frequency is measured with the frequency meter.

Finally, the load side motor can also be moved in order to misalign the pulleys. On a center distance of 60 cm a parallel mistake of 1 cm can be achieved which is an extreme situation. The efficiency measured here is compared to a previous one with correct alignment at the same speed and load. But comparing does imply a risk of enlarging errors as one cannot be sure that all external parameters were the same. This is why the other tests are always done without stopping the test bench. An alternative for testing misalignment is by using double groove pulleys. In the first test the belt is put in a normal position on drive and load side pulley. In the second test, the belt stays on the drive side pulley but is moved to the second groove on the load side. This method limits the risk of inducing mechanical errors. Later in the project, the effect of a belt tensioner will be investigated.

Measurement results

Three parallel matched V-belts type SPA with length of 1682 mm are compared to a 50 mm width timing belt 8M 1800 (synchronous belt). The pulley at the drive side was respectively 140 mm, 56 teeth. At the load side it was 250 mm, 102 teeth. Identical loading for both belt drives is assumed during the test. The choice for this configuration was industry driven.

Figure 3 clearly shows the relation between the efficiency and the applied torque. The impact of speed on the efficiency is shown to be very small. The efficiency at the highest load is 97% which is in accordance to the manufacturer’s documentation.

Figure 4 shows the iso efficiency map for the synchronous belt. The same conclusions on the relation between efficiency and torque can be made. Speed has more impact on the efficiency values compared to the V-belt system. The maximum efficiency here reaches 98%.

To compare the V-belt drive with the synchronous drive in the entire operating range, an efficiency improvement contour can be constructed by subtracting the contour information of the V-belts from the synchronous belt data. The result is shown in Figure 5. For high loads, the synchronous belt is approximately 2% more efficient compared to the V-belt system. If the system is running at low load, the synchronous belt system outperforms the V-belt with approximately 6%. Again, speed seems to have little impact on the efficiency values.

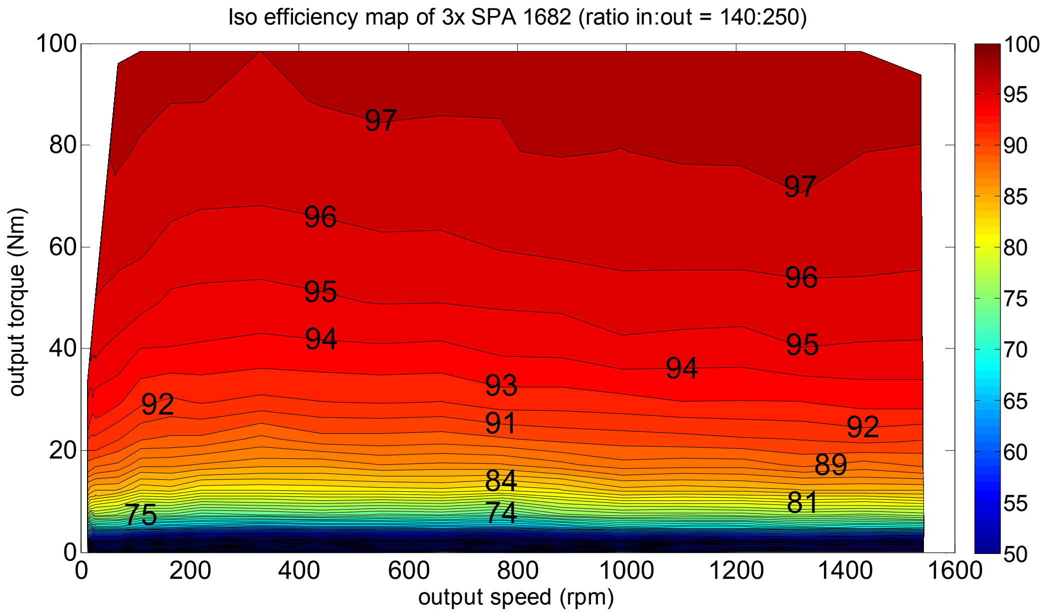

Figure 3: iso efficiency map of 3x SPA 1682

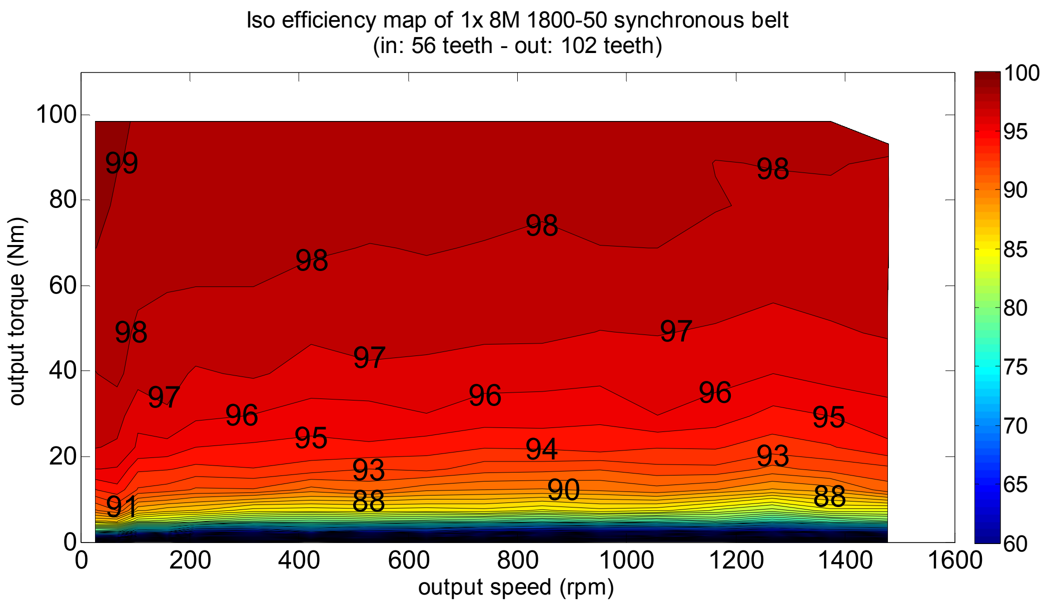

Figure 4: iso efficiency map of 1x 8M 1800-50

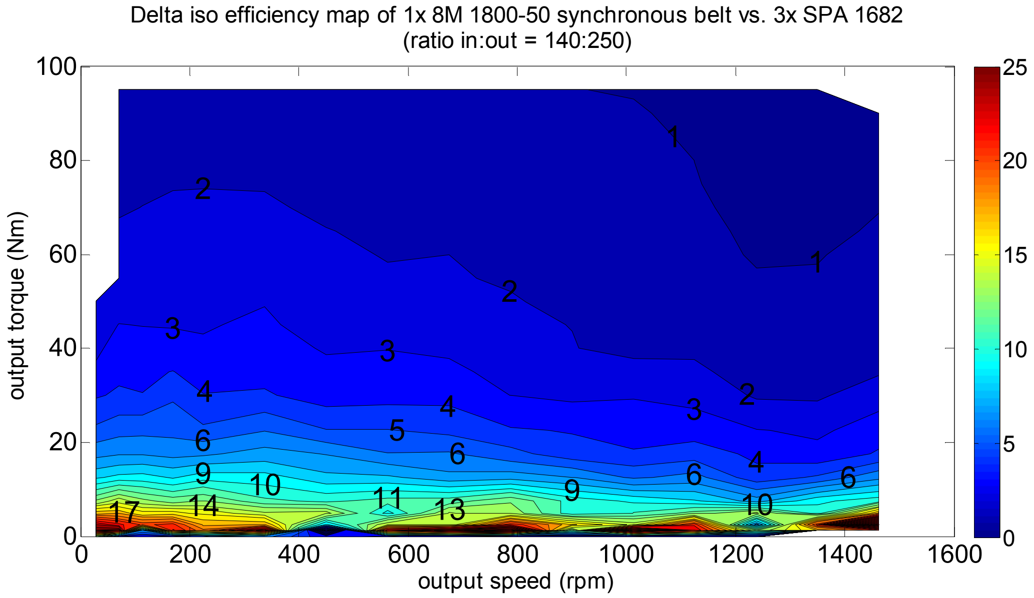

Figure 5: efficiency improvement contour of 1x 8M 1800-50 vs. 3x SPA 1682

Finally in Figure 6 the impact of belt tension at one operating point is shown. Belt tension is in red and the efficiency is in blue. The ripple of about 0,8% on the efficiency is due to the constitution of the belt, which influences the transmitted torque that is used to calculate the efficiency.

Initially, the belt was correctly tensioned with a belt frequency of 33 Hz. After 15 hours of operation the tension was reduced by 33% (in Newton) without stopping the test bench. At hour 21 the test was interrupted as all values were stable. The belt frequency was only 18 Hz, almost 50% lower than recommended. The drop in tension resulted in an efficiency reduction of 1,5%. The test was started up again, without changing the tension. The belt tension was further decreased until the belt slipped audible. The efficiency dropped further as expected. For the lowest belt tension, the efficiency is 2% lower compared to the value with correct belt tension.

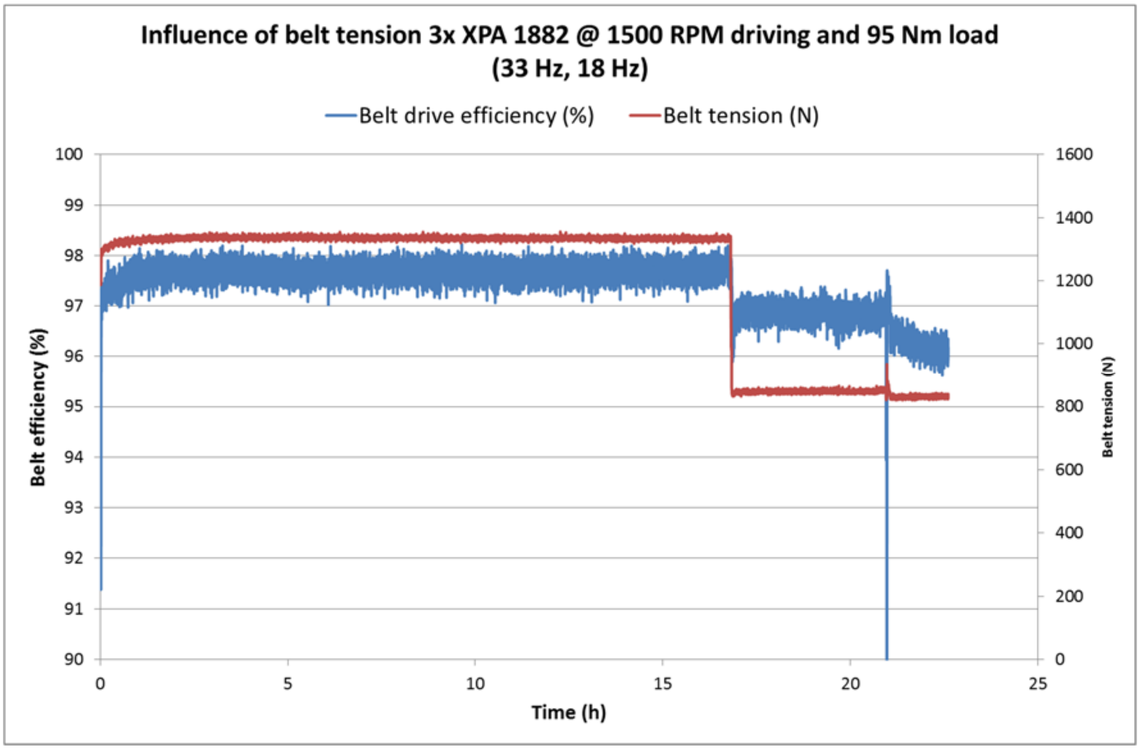

Figure 6: impact of belt tension on efficiency

Conclusion

This paper discusses the construction of a test bench for efficiency evaluation of belt drives up to 15 kW. The required steps to obtain accurate and reproducible efficiency values in the entire operation range are discussed in detail. Also the impact of belt tensioning and possible misalignment of the pulleys can be verified by means of the test bench. Iso efficiency maps are used to analyze the efficiency. First measurement results show that for both V-belts and synchronous belts, the impact of the load torque has a significant impact on efficiency. Speed has a rather limited impact. The measurements also show that the synchronous belt drive is always more efficient compared to the V-belt drive. The lower the loading, the better the synchronous drive performs compared to the V-belt drive. The impact of belt tensioning on efficiency is also measured. Reduced tension results in lower efficiency but the efficiency reduction is lower than is often claimed by producers. Further measurements have to be performed to make conclusions. The test bench has shown to produce reproducible measurement results. Further research will focus on testing a larger number of belts. Finally, to the opinion of the authors, a discussion to define a general measurement procedure related to belt drives could enhance the understanding and the exchange of efficiency data between manufacturers of belt drives and industrial customers.

Usage of a more efficient belt and pulley requires less power from the electric motor to produce the same output torque. Downsizing the motor rating can add to system efficiency and cost.

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USING ODS VIBRATION TECHNIQUES TO SOLVE PROBLEMS IN MOTOR BEARINGS TO MAXIMIZE COMPRESSOR SERVICE TIME

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Abstract

This paper presents a case study, in which motor bearing damage problems were solved with the aid of ODS (Operating Deflection Shapes) vibration analysis technique. In the application in question, an electric motor was directly coupled to an improved newly designed screw compressor. Operational pre-tests were carried out in five different compressors prototypes and three of them presented severe premature damages in the motor's rolling bearings. The first step towards the problem solution was trying to identify the failure mode of the damaged bearings. A detailed visual inspection of the bearings raceways led to the hypothesis of a critical misalignment between the motor and the screw compressor. A new motor was then more carefully coupled to a compressor for tests. An ODS analysis performed in this assembly confirmed the misalignment hypothesis. These results fostered the manufacturing of a new coupling flange for the compressor aiming at a finer alignment between motor and compressor. A new ODS measurement confirmed the success of the proposed solution, once that considerably lower vibration levels were achieved with the new coupling flange, thereby preventing the premature failure of the bearings and maximizing the compressor service time.

Introduction

As it is widely known, impact and vibration often accelerate the failure mechanisms of industrial machinery and equipments [1]. It is therefore necessary to minimize or control these effects in order to avoid premature failures. This statement can be verified in the industry through increasingly demanding client specifications, which sometimes adopt severer vibration level criteria than those predicted by international standards such as ISO 10816.

As stated in NEMA MG-1 part 7, for example, machines as installed (in situ) may exhibit higher vibration levels than those specified for machines operating at no load and uncoupled. In the case of motors, these higher vibration levels are generally caused by misalignments or the influence of the driven equipment, including coupling, or, sometimes, by mechanical resonances within the whole system and the resilience of the base on which it is mounted.

This paper is focused on a misalignment problem between an electric motor and a newly designed screw compressor, which was causing severe premature damages in the motor bearings.

The problem

Five electric motors rated 200 hp, 2 poles, 60 Hz, each of them coupled to an improved newly designed screw compressor (Figure 1), presented in 2008 severe bearing damages after only 3,5 months of operation (around 2560 service hours). In all the five motors the drive end rolling bearings were the main parts that have actually failed. In consequence, three of these motors had both the stator and the rotor severely damaged too, resulting in the total loss of these full motors (Figure 2). The damaged motors were replaced and some investigations were done as listed below:

1. Preliminary vibration measurements.
2. Damaged rolling bearings visual inspections.
3. ODS measurements.

The study methodology followed towards the solution of this case and the results achieved are presented in the next section.

Figure 1 – Picture of the coupling of one of the studied machines.

a) Front bearing of a damaged machine.

b) Stator and rotor of a damaged machine.

Figure 2 – Damages caused by the bearing failure.

Investigation Methodology and Results

Preliminary vibration measurements

Firstly the conventional vibration spectra were measured on both motor bearings (drive end and non drive end) in the three cartesian directions, as per ISO 10816 Part 1 (Figure 3). When operating at full load, the motor presented overall high axial vibration levels at the drive end side, as expected, reaching up to 10 mm/s rms, with dominant peak frequency around 240 Hz (Figure 4). Since the compressor has a four lobule male screw (Figure 5) directly coupled to the rotating motor at approximated 3600 rpm (or 60 Hz), the fundamental screw frequency (or pulsation frequency) was expected to be near 240 Hz, [4] and [5]. According to [4] a high axial vibration with multiples of this pulsation component indicates a system with excessive load or overstressing assembled elements, probably caused by a severe misalignment between the coupled components.

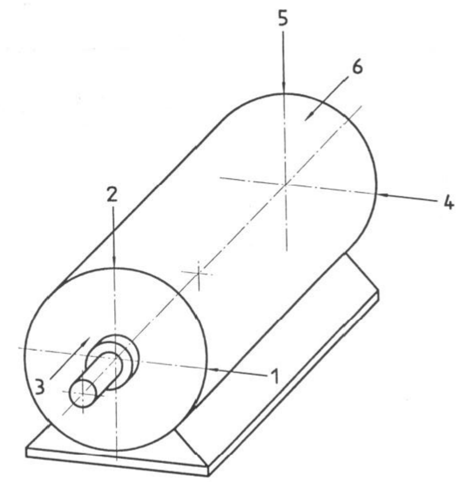


Figure 3 – Vibration measurement points according to ISO 10816 part 1

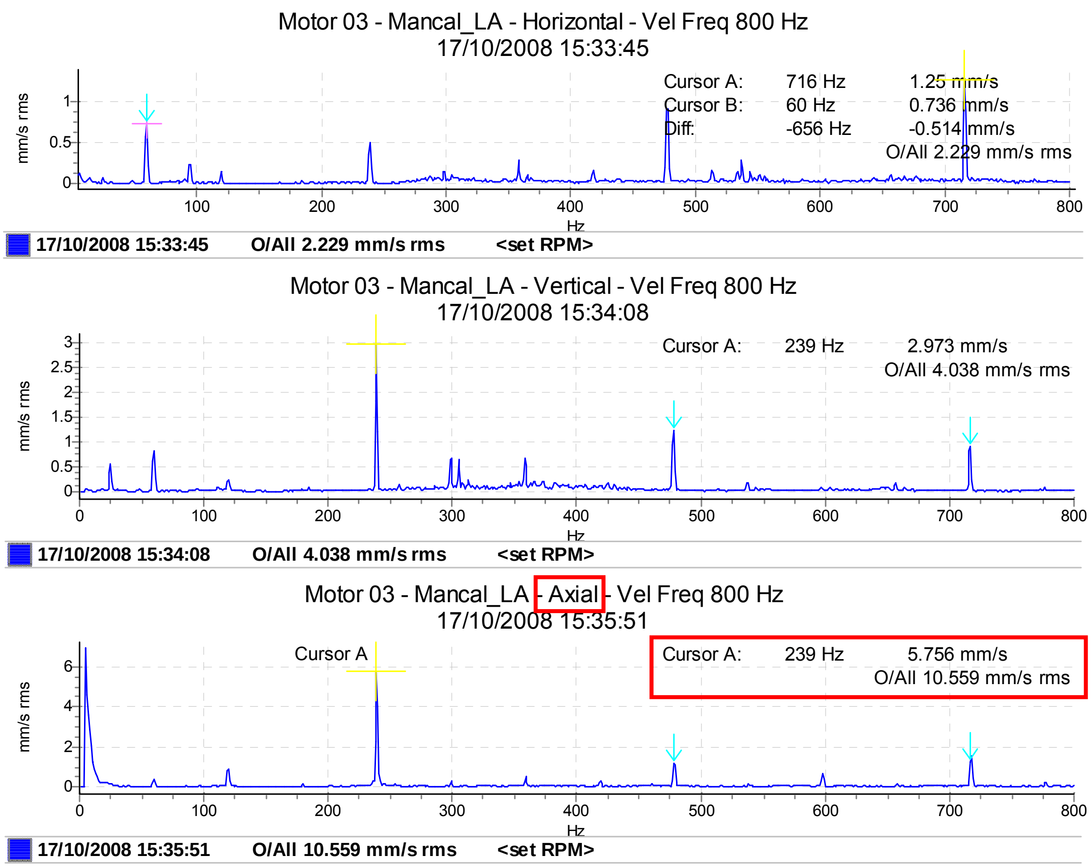
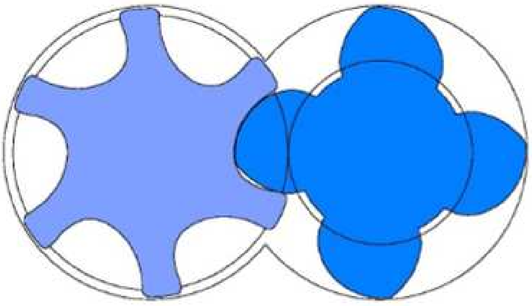


Figure 4 – Front bearing vibration spectrum.

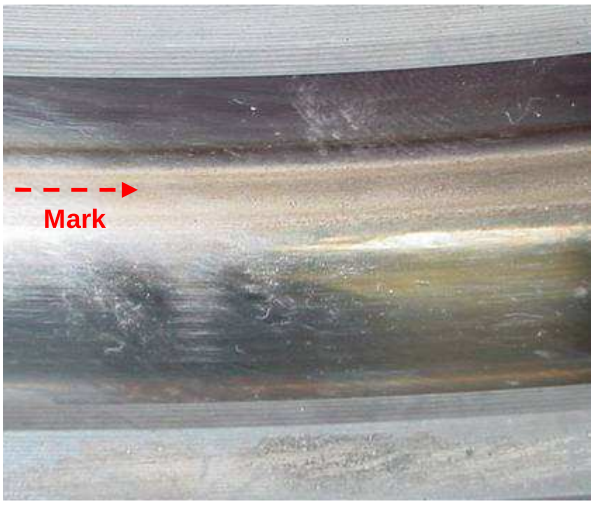


Female **Male**

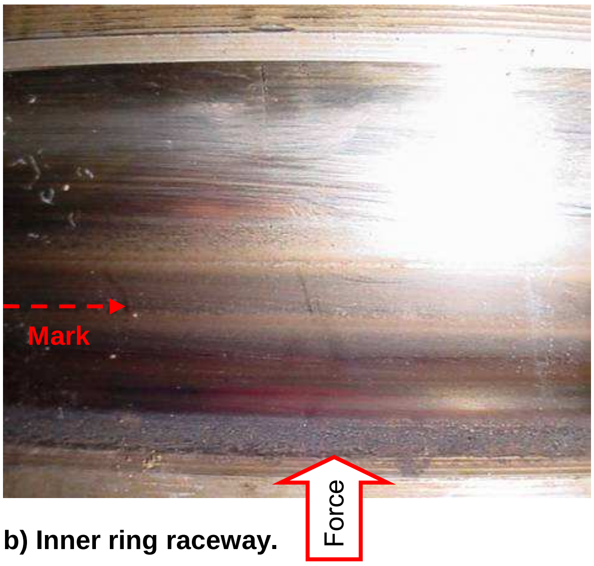
Figure 5 – Screw compressor rotor design.

Damaged elements of the rolling bearings

The visual inspection of the damaged bearings (Figure 6) confirms that a severe misalignment between motor and compressor generated an axial force component that caused the rolling bearing rings to show mark patterns identical to those found in [6] (Figure 7).



a) Outer ring raceway.



b) Inner ring raceway.

Figure 6 – Motor drive end rolling bearing visual inspection.

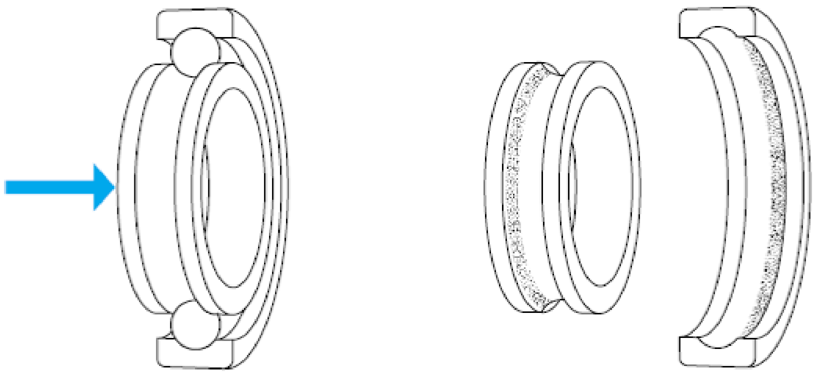


Figure 7 – Typical pattern of rolling bearing raceways subjected to high axial force.

ODS measurements

Measurements were made for an ODS analysis to provide more information about the operational deformation of the compressor plus motor at 240 Hz. This information was important for the compressor's manufacturer engineers to understand the vibration behavior of the complete system, thus allowing a design starting point to solve the problem.

For the vibration measurements a Bruel & Kjaer Pulse 3560C was used. This equipment includes four channels plus two ENDVECO accelerometers 752A12 and works with an associated lap-top using the ME'scope ODS software. The ODS analysis consists of mapping the structures under consideration by performing simultaneous measurements of vibration at two points, one of which is fixed. The vibration measurement will report, at each frequency, the vibration magnitude at the considered point and its relative phase difference to the reference point. By plotting all measured points of the spatial geometry together, taking into account the magnitude and phase difference of each of them relative to the reference point, the structure deformation shape when it vibrates at a specific frequency is revealed. A harmonic animation of this shape allows a visualization of the dynamic behavior of this vibration. Figure 8 presents the ODS project for the machine in question. The red vectors indicate the direction and position of the accelerometers.

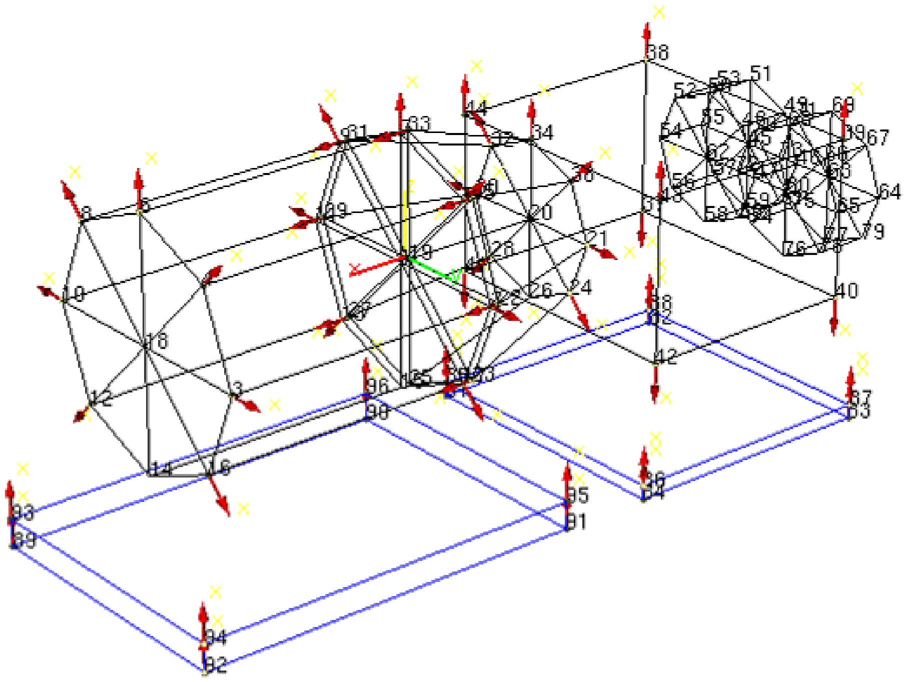


Figure 8 – ODS project – motor (left) and compressor (right).

Figure 9 shows three moments of the resulting vibration shape animation at 240 Hz, with the motor at left and the compressor at right. One can notice that the motor and the compressor vibration movements are 180° out of phase, what indicates tha t the machines are operating misaligned.

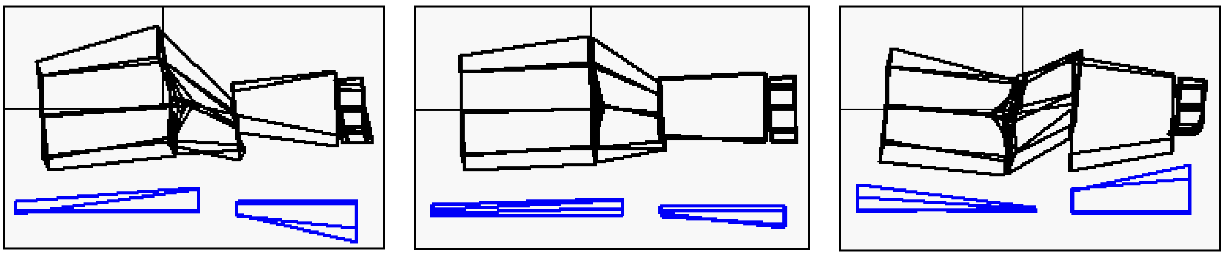


Figure 9 – ODS result of the motor compressor assembly at 240 Hz.

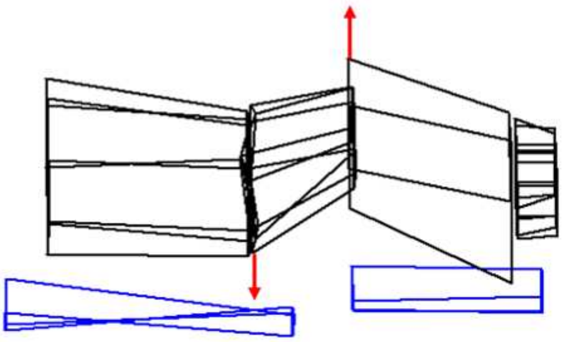
Solution

As the coupling flanges of the compressor and the motor are the only means to guarantee the alignment between both machines, these results led to the design and manufacturing of a new coupling compressor flange aiming at an improved dynamic behavior and a finer alignment between motor and compressor (Figure 10). A new ODS measurement performed with the new compressor coupling flange confirmed the success of the proposed solution (Figure 11), once that considerable lower vibration levels were thereby achieved. The maximum global vibration measured with the new coupling flange design was around 2 mm/s rms at the same point and axial direction as before, corresponding to a decrease close to 80% in the axial vibration.

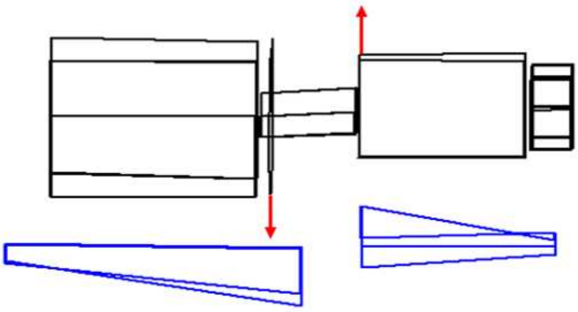
a) Old coupling flange.

b) New coupling flange.

Figure 10 – Pictures of the old and the new coupling flanges.



a) Before the new coupling flange.



b) After the new coupling flange.

Figure 11 – ODS result at 240 Hz before and after the installation of the new coupling flange.

As expected from these results, similar problems have no longer been registered since the flange design modification, and the compressor service lifetime increased considerably in the last four years.

Conclusion

With a substantial decrease in the axial vibration it was possible to considerably increase the service lifetime of a screw compressor. This indicates the relevance of considering the vibration issue as an important parameter of the machine design. Controlling and minimizing the vibration levels should always be one of the main concerns of the machine designers.

The ODS vibration technique proved to be a powerful tool in helping understand and solve vibration problems by providing the engineering team with important dynamic information on the application.

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IS 60 HZ ELECTRIC MOTOR-DRIVEN SYSTEM EFFICIENCY REALLY ALWAYS BETTER THAN 50 HZ?

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Abstract: It is highlighted that 60 Hz electric-motor driven systems' efficiency in comparison with those of 50 Hz cannot be made just by means of today's eyes. Typically, motors are rated for operation on both 60 Hz and 50 Hz, and as well documented in the new IEC 60034-30 standard, the different efficiency classes IE1, IE2, and IE3 are mostly higher for 60 Hz. Nevertheless, one must take into consideration that an efficiency change as a function of feeding voltage is an intrinsic characteristic of induction motors.
Based on experimental results, it was verified that in the case of rated voltage, the efficiency falls with the frequency decrease. However, it was also established that when the grid feeding voltage is decreased from 230 V to 200 V, 50 Hz motor driven system shows relatively lower under-load, but higher full-load and overload efficiency.

On the obtained results basis, the new IEC 60034-30 standard can be enhanced by taking into account the feeding voltage drop.

I. Introduction

Nowadays, travelers from North America to *four and a half* continents of the Earth globe don't have to bring with them personal appliances that require voltage increase from 110 V to the 220 V, and frequency adaptation from 60 Hz to 50 Hz. Even so, 60 Hz versus 50 Hz selection as standard power frequency continues to intrigue.

Of course, it's not suited to compare 60 Hz electric-motor driven systems efficiency with those of 50 Hz with only by means of today's eyes. The fact is that in the long race towards a standard frequency during the last decade of the 19th century and the beginning of the 20th, one has to take into account those time constructional constraints, as well as advantages and impediments of every frequency, such as then understood.

At the present time, Motors rated for operation at frequencies 60 Hz and 50 Hz are classified in efficiency classes according to the new IEC standard 60034-30. As illustrated in IEC tables, the difference in efficiency between 60 Hz and 50 Hz varies with the size of the motor and the number of poles. As general rule, the 60 Hz efficiency of three-phase, international efficiency (IE) cage-induction motors in the output power range from 1 to 500 Hp (0,75 kW to 370 kW) is greater when compared to the 50 Hz efficiency.

What is imperfect and unexplored in this wide-ranging conclusion is that the statement is limited to rated feeding voltage, as it's well acknowledged that a change in efficiency as a function of voltage is an intrinsic characteristic of induction motors.

The purpose of the present work is to compare experimentally 60 Hz versus 50 Hz electric motor-driven system efficiency, taking into account the feeding voltage drop.

II. Back to 60 Hz History

The so-called Light Period and prolific development of the alternating current applications peaked years 1884-1890 with:

- The large-scale introduction of the street and private lighting,
- The development of the transformer and the electricity transport,
- The invention and the application of the three-phase,
- The induction motor invention…

It's important to remember that during all these years in North America, the predominant applications were in dc (direct current). But, the new immigrant N. Tesla greatly helped to transform this continent in cradle alternating current applications development.

At those times, there was no standard frequency: Westinghouse used the most wide-spread 133 1/3 Hz frequency, while the wild competitor Thomson-Houston Company (one of General Electric GE ancestor) preferred 125 Hz. The two frequencies, 133 (Westinghouse) and 125 Hz (Thompson-Houston Company), were very close, and fixed to a large extent by constructional constraints. They were also perfect for the purpose of those time single-phase lighting and transformer applications....

For the time being, in Europe, the trend was rather to use much lower frequencies, typically ranging from 30 to 40 Hz, before AEG adopts 50 Hz, since 1891. Ten years later, this 50 Hz became the most common frequency.

Around 1890, North American scientists realized that to allow a reduced functioning speed with an appropriate number of poles, it was necessary to prominently lower the until then common 125-133 Hz frequencies. Moreover, around this date direct coupled (without belt drive) alternators were being introduced, while Westinghouse recognized that the use of high frequency was impeding development of their new three-phase induction motor. As illustration, an alternator directly driven by a 75 rpm engine would require 200 poles to deliver 125 Hz frequency, and such construction was considered not only unaffordable, but unreasonable. In addition it is indeed at the instigation of N. Tesla and his works on the electric machines that Westinghouse began since 1890 to lower its frequency of 133 1/3 Hz towards 25-60 Hz.

As can be subtracted in formula (1), to reduce magnetic poles number requires a significant frequency reduction:

$$f = \frac{n\,p}{120} \quad (1)$$

Where p is a number of poles and n the speed of rotation.
For the time being, as the design of the two-phase and three-phase induction motor was in constant progress, the larger speed range provided by 60 Hz for the induction motor undeniably boosted this frequency implementation, and the beginning of 4-pole machine construction. Today, a century and a quarter later, 4 poles induction motors represents around ¾ of the total park of this motor type!

It became more and more obvious that for power applications (electrical machinery and transport systems) a smaller frequency is required, whereas for lighting and transformer cores sizing reduction, a higher frequency was more appropriate. That is why a focus was not to find one optimal all purposes frequency, but to select two representative frequencies, each of them being the best in specific field application. That is why two frequencies were intensively used in North America as compromise: 25 Hz for the transport systems and heavy dc-based industry that needed dc or reduced speed machinery, and 60 Hz for lighting and general use applications. In the meantime, General Electric Company (after the fusion with Thomson-Houston Company) attempted to take advantage of the breach, and vainly tried to introduce 40 Hz as fine compromise frequency between 25 Hz and 60 Hz. Nevertheless, this attempt was unsuccessful because it did not benefit from required support.

The era of 25 Hz found its peak with the tremendous hydroelectric development of the Niagara Falls, where one major objective was the transmission of dc power to Pittsburg Reduction Company, the ancestor of Alcoa (Aluminum Company of America). One of the main reasons for the 25 Hz selection was linked to the perfect adaptation of the rotary converters with this reduced frequency. Moreover, the dc power was needed during this era due to extensive Buffalo dc distribution network for light and power. After wide discussions and investigations, Westinghouse gained the market of the century by proposing the design of 12-pole machine operating at 250 rpm, and generating 25 Hz.

At the beginning of the new 20th century, it looked like there would still be two frequencies, but the development of high-speed turbines and the progress in rotary converters that worked well at 60 Hz made possible to switch to 60 Hz frequency. So, by the next years of the 1st World War, transport systems restrictions had been overcome so that there was no longer any advantage of using 25 Hz. But, some parts of the distribution system continued to use 25 Hz in Canada (particularly in Quebec and Ontario), even after a new 60 Hz frequency was chosen. By the next years of the 2nd World War, many 25 Hz systems were converted and standardized, but 25 Hz as industrial frequency definitely stopped in Niagara only on October 12th, 2006, after 111 years of loyal services.

III. Motors rated for 60 Hz and 50 Hz

Motors rated for operation at frequencies 60 Hz and 50 Hz are classified in efficiency classes according to IEC 60034-30. This new standard defines efficiency classes IE1, IE, IE3 and IE4 for three-phase cage motors. IE stands for international efficiency and ensures a common international basis. The proposed energy efficiency classes are worthwhile, as the 60 Hz efficiency values for IE3 (Premium efficiency) and IE2 (high efficiency) are, respectively, taken from existing north American NEMA Premium and EPAct tables, while the 50 Hz efficiency values for IE1 (standard efficiency) and IE2 (high efficiency) are close to the existing European Union EFF2 and EFF1 tables, with some adjustments to take into consideration the new test procedure standard 60034-2-1 (Standard methods for determining losses and efficiency from tests). The 60 Hz efficiency values for IE1 (standard efficiency) are issued from PreEPAct tables, while the 50 Hz efficiency values for IE3 (Premium efficiency) are newly designed. It's important to notice that the professed IE4 Super Premium Efficiency motors are not commercially available yet, and it is awaited that in average, their losses reduction should be 15 % compared to IE3. Moreover, IE4 future motors are not limited to three-phase cage induction type, but extended to other types, like permanent-magnet synchronous motors…

The graphs of the figure 1 give the 4-pole motors IE1, IE2 and IE3 efficiency curves, drawn on the basis of IEC 50 Hz tables. One can observe a continuous and substantial improvement in motors efficiency.

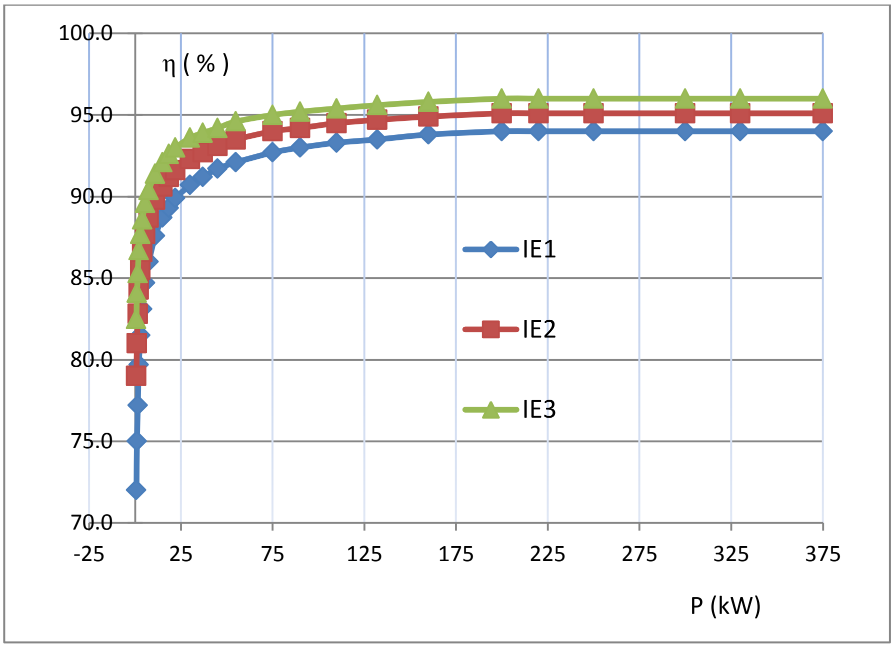

Fig. 1 Typical efficiencies for IE3 4-pole mootors

As illustrated in IEC tables, the difference in efficiency between 60 Hz and 50 Hz varies with the size of the motor and the number of poles. According to these tables, the 60 Hz efficiency of three-phase, 4 poles, IE3 cage-induction motors in the output power range from 1 to 500 Hp (0,75 kW to 370 kW) is about 3,0 to 0,2 points greater when compared to the 50 Hz efficiency. This so-called *bonus efficiency* permitted by 60 Hz compared 50 Hz one is illustrated in figure 2.

In the IE1 motor cases, the efficiency bonus is likely higher, with 5.9 to 0.5 points efficiency extra. On the contrary, as a consequence of their higher mechanical losses, 2-pole motors more 20 Hp may have a slightly lower efficiency at 60 Hz compared to 50 Hz.

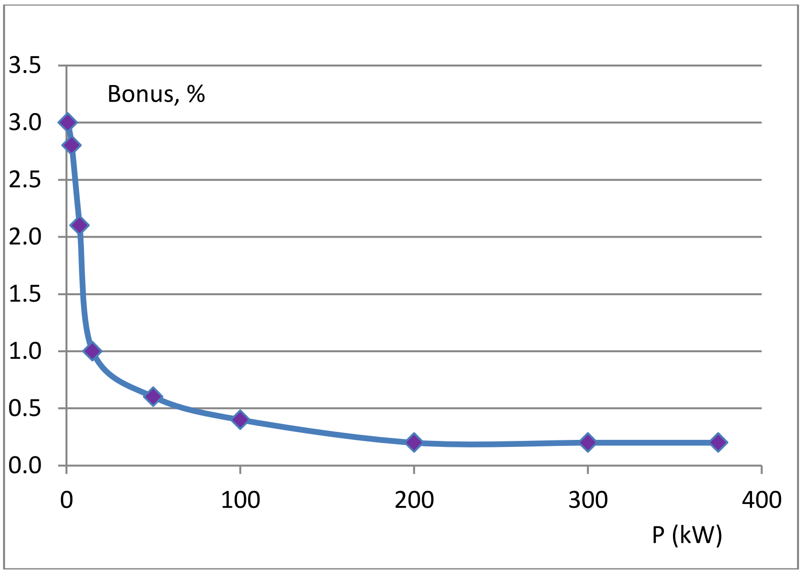

Fig. 2 Typical 60 Hz efficiency Bonus

Better efficiency 60 Hz motors compared to 50 Hz can be explained by the fact that the theoretical output power increases linearly with speed, i.e. by 20% from 50 Hz to 60 Hz, according to relationship

$$P = C\,\omega \quad (2)$$

Where C is the torque and ω the mechanical speed.

Usually, the motors are rated for operation on both 60 Hz and 50 Hz with nearly the same magnetic flux and the same output power, and as well recognized nowadays; the different efficiency classes (IE1, IE2, and IE3) are generally higher for 60 Hz motors than for 50 Hz motors.

What is imperfect and unexplored in this wide-ranging conclusion is that it's in reality limited to rated feeding voltage, as it's well established that a change in efficiency as a function of voltage is an intrinsic characteristic of induction motors.

IV. Experimental results

Nowadays, the typical drive system is a squirrel-cage induction motor fed from a Variable Frequency Drive, or VFD. The realized experimental laboratory set-up is depicted in [17, 18]. Several 3 hp NEMA Premium efficiency induction motors issued from different major manufacturers and directly on line DOL connected or fed by a DTC (direct torque control) drive ACS-800 were tested.

The main research objective was to determine motor efficiencies under variable loads and variable speeds, induced by a VFD controller, and variable feeding voltage. So, when computing efficiency, it is matter-of-fact to provide separate efficiency curves for each component in the system.

First of all, it's remarkable to notice that to date, there is no commonly accepted test protocol and no agreement that allows the determination of motor & drive efficiency at any given operating load and operating frequency. So, when computing efficiency in the feeding voltage rated conditions, it is matter-of-fact to provide separate efficiency curves for each component in the system, i.e.

- motor efficiency, feed direct on line DOL
- motor efficiency, feed by a VFD,
- motor & drive (system) efficiency,
- VFD efficiency,
-

Figure 3 presents the results obtained for two 4-pole 3 Hp motors, issued from two different manufacturers, B and C. The curves show the efficiencies of the motor, the VFD efficiency and the whole system efficiency for different loads and speeds. This figure 3 gives the drive efficiency for the most common industrial converter type, uncontrolled three-phase diode rectifiers and IGBT PWM (pulse width modulation) inverter, and VFD drives generally have a high level of energy-efficiency

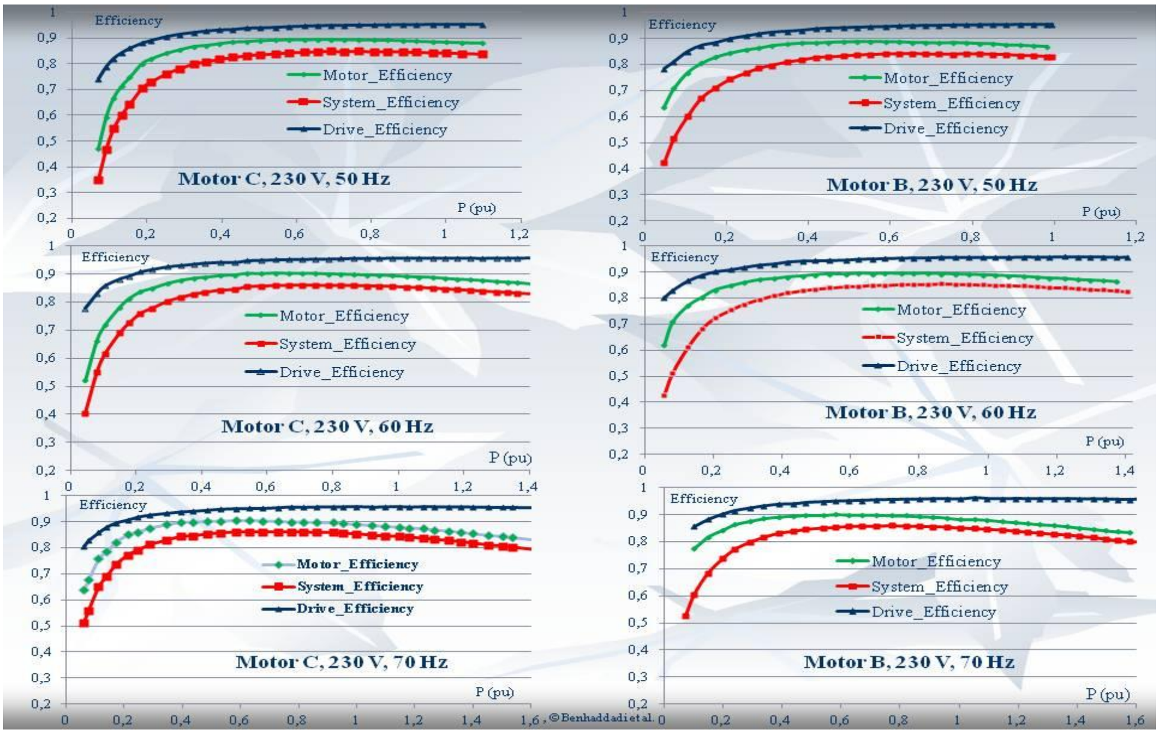

Fig. 3 Experimental results

As can be seen, one can observe that as with motors, drives efficiencies increase with power consumption, and drop substantially at very low partial load. An exhaustive analysis of obtained results is provided in [16].

Figure 4 presents the results for different frequencies of motor B, feed across 230 V line. One can observe a harmonious efficiency reduction with frequency diminution. The 60 Hz efficiency of the motor is about 2 % greater when compared to the 50 Hz efficiency [17], what is in accordance with the new 60034-30 standard table.

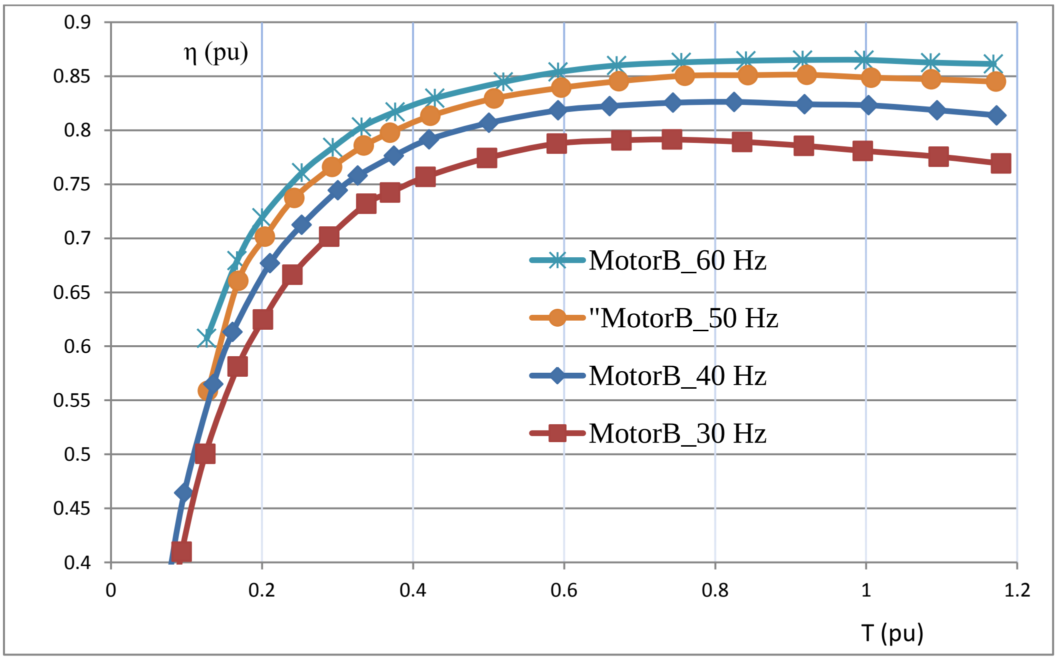

Fig. 4 Experimental results for different frequencies

After that, we have analyzed the feeding voltage variation and experimentally highlighted in which level a change in feeding voltage is an intrinsic characteristic of induction motors efficiency. The voltages choice are made by taking into account practical considerations: i.e. 230 V, and 200 V.

The 230 V is the motor nameplate rated voltage indication, which is in accordance with an industrial normalized 240 V feeding voltage, while the three-phase 120/208 V is frequently used in commercial and institutional sectors. So, the same motors 230/460 V are frequently used and feed from sources 230 V (instead of 240 V) and 200 V (instead of 208 V).

The experimental results illustrated in figure 5 and figure 6 show that direct on line DOL feeding voltage value, as well as drive feeding voltage value, both have an important impact on efficiency value.

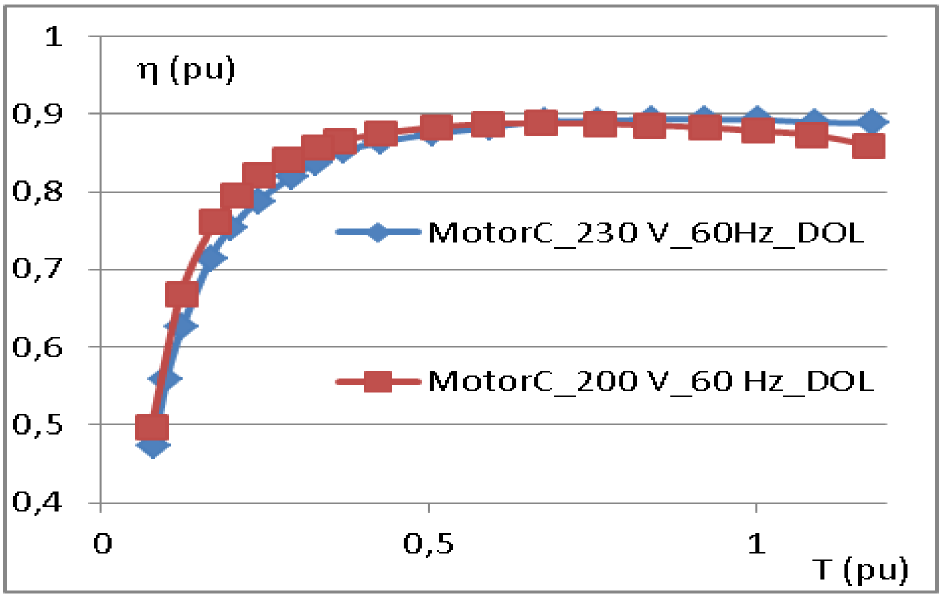

Fig. 5 Direct on line DOL motor C efficiency

When the feeding voltage is decreased from 230 V to 200 V, the motor shows lower full-load efficiency, slips and heats more, and produces less torque. Moreover, the efficiency decrease is more palpable when the motor is overloaded. In contrast, when the motor is under loaded, the efficiency is better when the motor is fed under 200 V voltages. The same results were obtained for motor B.

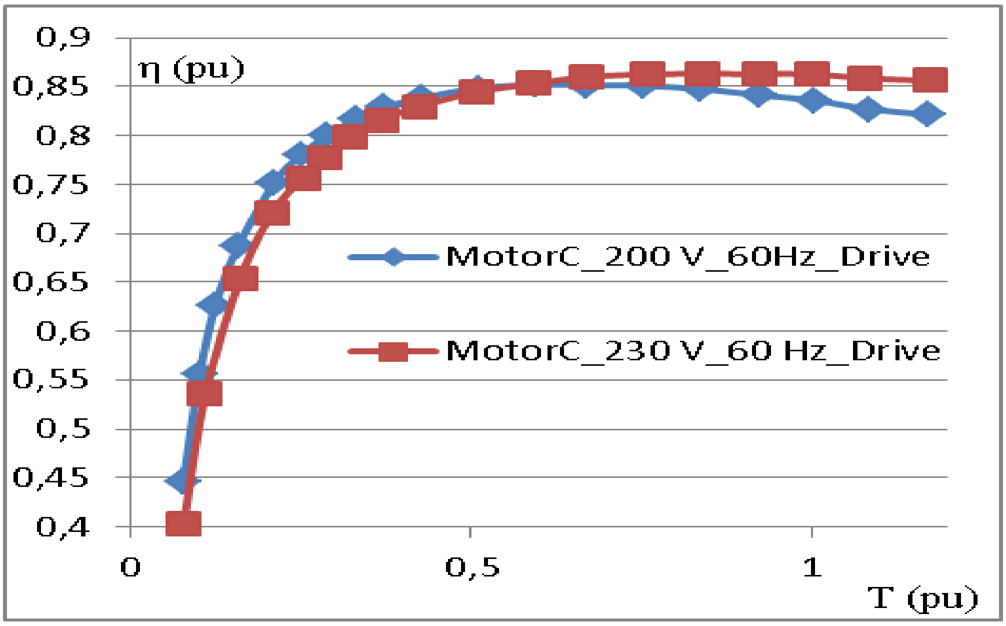

Fig. 6 Drive fed motor C efficiency

As can be seen in figure 7 and figure 8 in the 230 & 200 V line voltage cases, the drive introduces a noticeable reduction of the motor system efficiency in both cases. The decrease is somewhat supply voltage dependent: in the rated regime, it reaches successively 3 % and 4 % with 230 V and 200 V voltage supplies, withdrawing totally in both cases energy savings induced by Premium efficiency motors use.

On the other hand, and as well illustrated in figure 3, despite the very high rated drive efficiency (95 % to 96 %) in the whole useful range of load variation, VFD losses increase the whole system losses by nearly 40 % compared to grid operation.

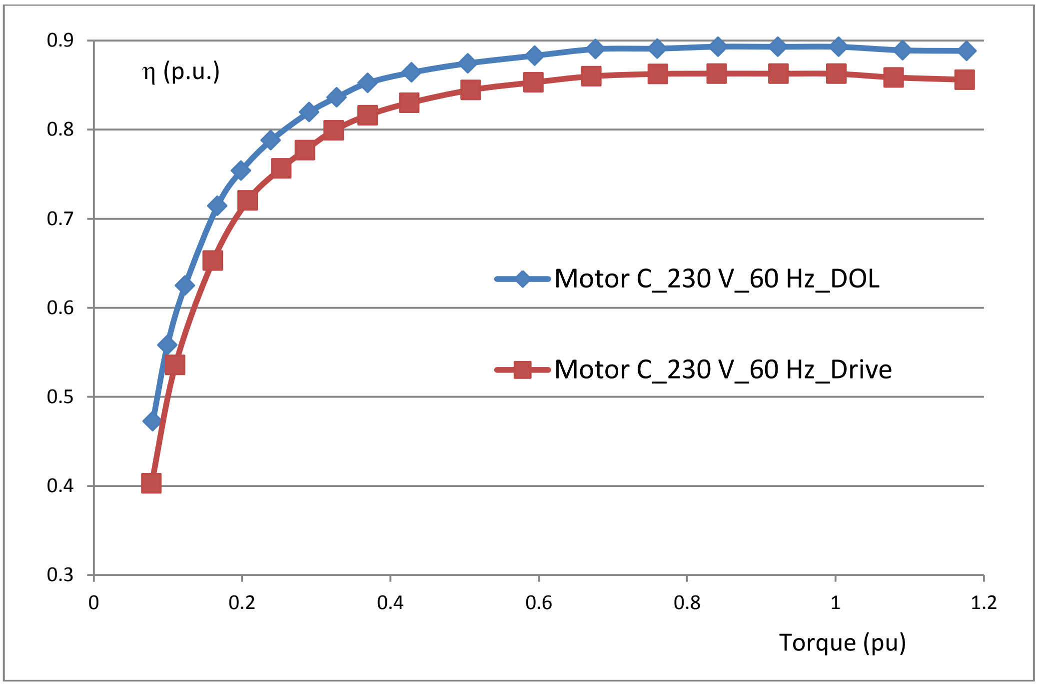

Fig. 7 Motor efficiency

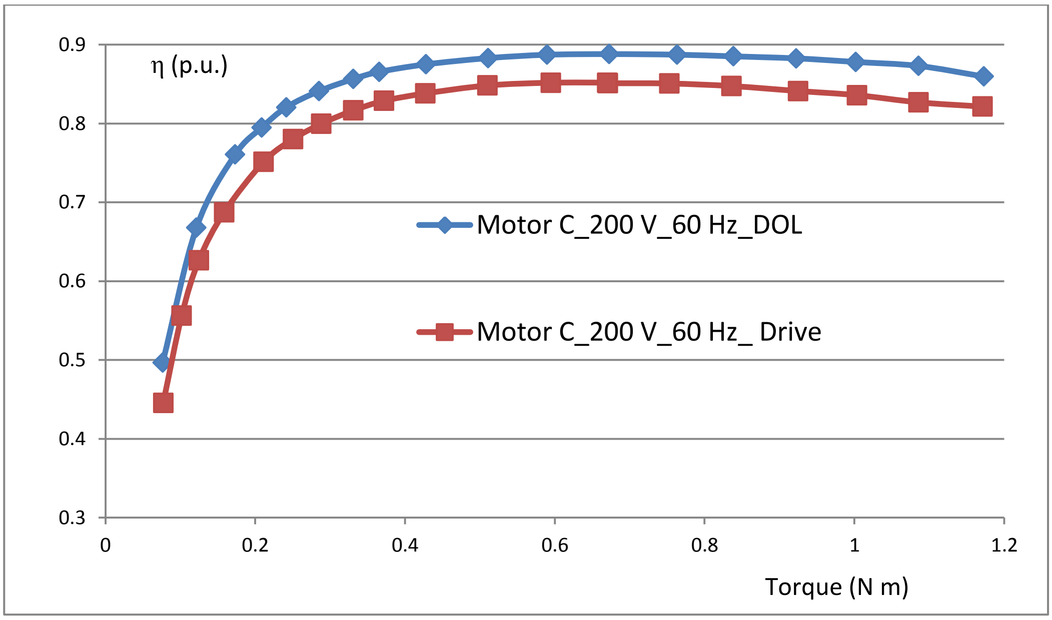

Fig. 8 Motor C efficiency

The results provided in figure 9 and figure 10 show that feeding voltage drop has a significant impact on efficiency value. When the grid feeding voltage is decreased from 230 V to 200 V, the 50 Hz motor driven system shows relatively lower under-load efficiency, but higher full-load than 60 Hz. Moreover, the 50 Hz efficiency bonus is more palpable when the motor is overloaded. Better 60 Hz under-loaded motor is undoubtedly due to no-load current, as watchful analysis of the current waveforms shows that the drive applies lower magnetization values. In addition, although iron, friction and windage losses increase with frequency; these losses usually play a minor role in motors with four poles. In contrast, Joule winding losses are particularly dominant in 3 Hp induction motors when the motor is full or overloaded, and the 50 Hz drive applies relatively lower functioning values.

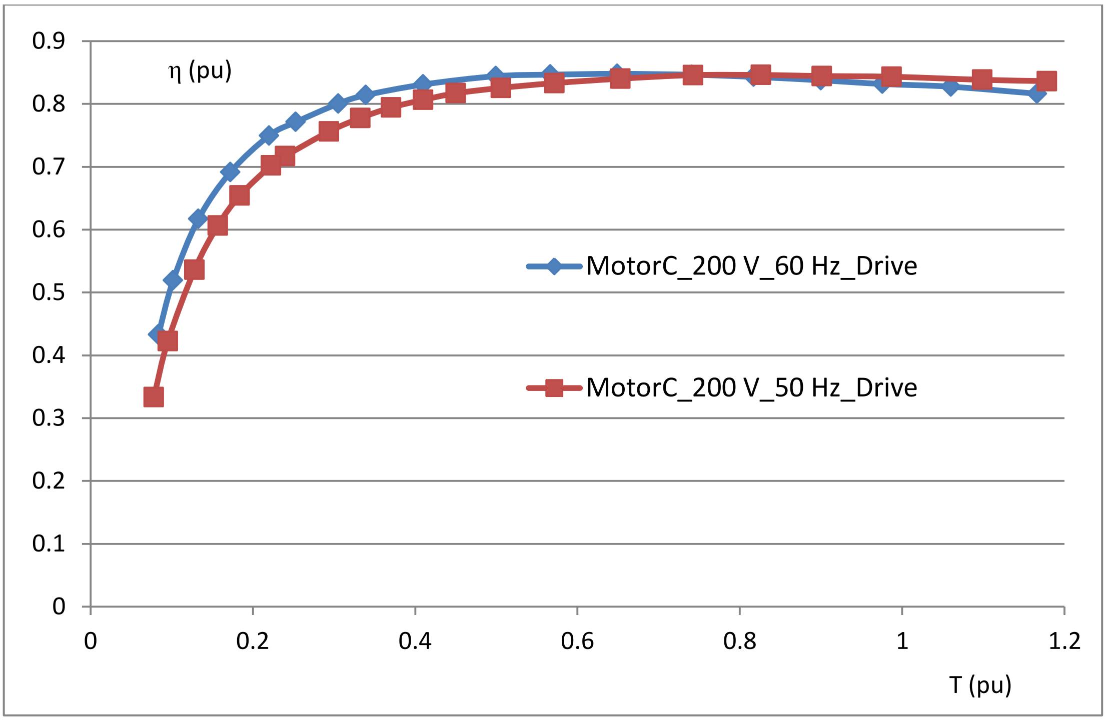

Fig. 9 Motor C efficiency

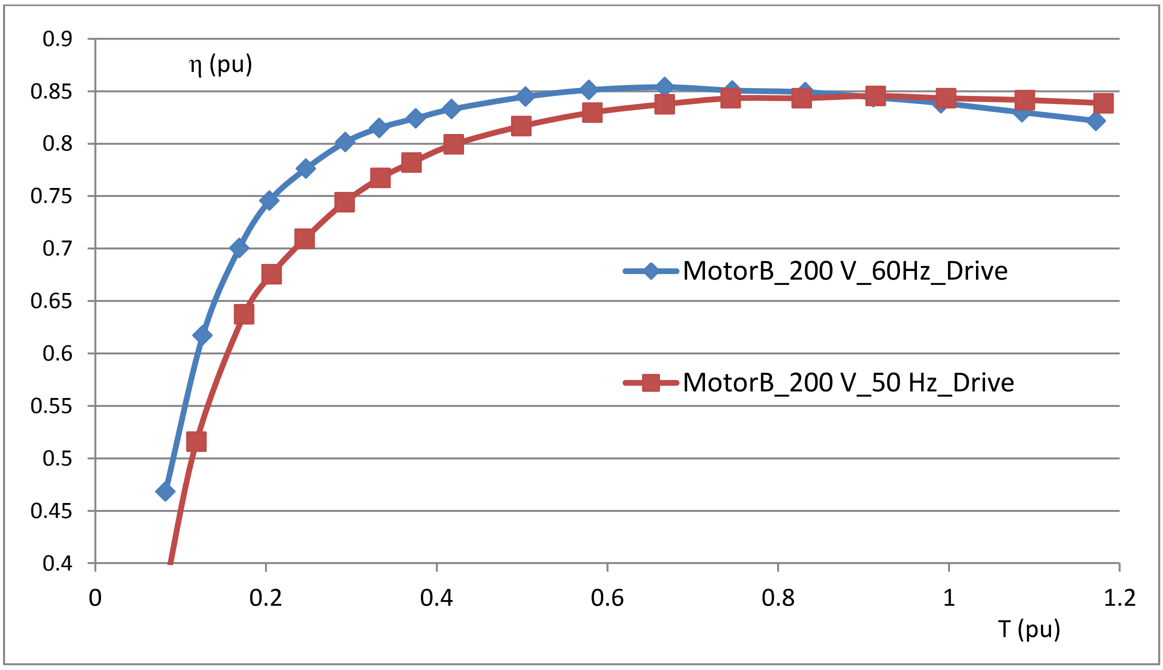

Fig. 10 Motor B efficiency

It seems to be that the provided results are to some extent in contradiction with those provided in figure 4. In reality, they illustrate the importance of voltage drop value. The voltage drop incidence is so important that it can totally withdraw better performances 60 Hz motor driven system efficiency over the 50 Hz one. Moreover, 50 Hz performances are better when the motor is full-loaded or overloaded.

One century and a quarter ago, motor efficiency was not considered as an influencing parameter throughout 60 Hz versus 50 Hz choices. Nowadays new IEC 60034-30 standard establishes tables, clearly showing the 60 Hz superiority. But, taking into account the provided voltage drop incidence, one can deduct that the IEC 60034-30 standard can be enriched.

V. Conclusion

It is highlighted that 60 Hz electric-motor driven systems efficiency in comparison with those of 50 Hz cannot be made just by means of today's eyes, as advantages and impediments of every frequency must be considered, as it was then understood, a century ago.

Experimental evaluation of the performance characteristics of two Premium efficiency 3 Hp induction motors issued from two different manufacturers has been presented.

The experimental results clearly show that feeding voltage has an important impact on efficiency value, as it can totally withdraw 60 Hz efficiency bonus, when compared to 50 Hz one. So, the affirmation that for a given output power and frame size it is easier to reach a high motor efficiency when the motor is operated at 60 Hz supply frequency rather than at 50 Hz must be strongly linked with the feeding voltage. On the obtained results basis, the new IEC 60034-30 standard can be enriched by taking into account the feeding voltage drop.

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Evaluation of efficiency measurement methods for sinusoidal and converter fed induction motors

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Abstract

In recent years, a lot of attention is focused on improving the efficiency of industrial motors which constitute approximately 60-65% of the total industrial electric energy usage. Several alternatives to traditional and widely used induction motors are being proposed and introduced by motor manufacturers, like permanent magnet (PM) motors and synchronous reluctance motors (SynRM). At the same time, more and more induction motors are now supplied by Variable Speed Drives (VSD) because of enormous energy saving potential in applications like pump and fan drives. The percentage of VSDs in industrial environment is rising day by day making it one of the top alternatives to achieve energy reduction targets for industries. This also makes equally important to test and experimentally evaluate efficiency performance of motor drive system using fast and accurate methods. The efficiency measurement standard IEC 60034-2-1 Ed 1.0 describes the test methods only for line fed motors and it does not include testing of VSD motors or motor drive systems. The upcoming standard specification, IEC 60034-2-3[1] is intended to describe test methods and required instrumentation specifications while measuring efficiency of VSD fed motors. The accuracy of measurement setup and methods is more and more important while testing high efficiency systems since slight errors in the measurements can lead to significant deviations in the measured efficiency. But the efficiency measurement setup accuracies are prone to deteriorate while measuring electrical quantities under VSD fed conditions. This can also lead to large uncertainty in measured efficiency while measuring VSD fed motors and the result may be unacceptable if the values are larger than specified tolerance levels for efficiency and losses as per IEC standard 60034-1.

The purpose of this paper is to analyze the direct input-output test methods for faster efficiency evaluation of VSD fed motors using the measuring equipment described by standard specifications. The validity of these results is also investigated by estimating the measurement uncertainties from the accuracy specifications of different instruments used in the test measurements. The electrical efficiency is measured using direct input-output and indirect- summation of losses methods as outlined in efficiency measurement standard under sinusoidal and VSD fed conditions. Then the uncertainty of measurement system at different load conditions is evaluated for sinusoidal as well as VSD supply conditions and compared against the allowable tolerance limits as specified standard specifications.

Keywords: - IEC60034-2-1, IEC 60034-2-3, Direct input-output method of efficiency measurement

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[1] The standard is still in draft stage, the publishing date is scheduled to be in late 2013 http://www.iec.ch

Introduction

The electric motors are most wide spread and convenient means for electromechanical power conversion in industrial environment, and approximately 60-65% of the total industrial electric energy is consumed by electric motors. The main focus in research environment is both on efficiency enhancement of motor systems through design improvements, use of better materials and alternate, more efficient motor technologies like permanent magnet (PM) motors and synchronous reluctance motors (SynRM). The introduction of variable speed drives (VSD) has given a totally different dimension to the energy saving programs in many industrial applications because of enormous energy saving potential in applications like pumps and fan drives. The higher efficiency drives are increasingly replacing conventional motors, thanks to the energy awareness created by many energy efficiency improvement measures and new regulations which will make it mandatory to use higher efficiency motor systems.

This also makes it equally important to experimentally test the efficiency performance of motor drive system using fast and accurate methods. Many standard specifications are specifically formulated to describe the measurement setup requirements and test methods for evaluating the motor efficiencies. For many years there were two main standards (or their subsequent adaptations in local regulations) used around the world to determine these losses: IEC 60034-2 and IEEE 112 method B (or IEEE 112-B). Both standards differ from each other in methods to account for additional stray load losses [9][12]. The efficiency measurement standard IEC 60034-2-1 Ed 1.0 [3] describes the test methods for line fed motors whereas the upcoming standard specification, IEC 60034-2-3 [4][13] is intended for VSD fed motors. The accuracy of measurement setup and methods is more and more important while testing high efficiency systems since slight errors in the measurements can lead to significant deviations in the measured efficiency. The accuracy of measurement setup is prone to deteriorate while measuring electrical quantities under VSD voltage supply. This can also lead to large deviations in measured efficiency values while measuring VSD fed motors. The standard equipment to measure power, for ex. precision power analyzer include special functions like line filters which are used to filter higher harmonic components in the measurement of input quantities. Similarly, other functions like, frequency filters are also embedded into power analyzer to increase the ability of power analyzers to correctly determine the fundamental frequency in the case of VSD supply. But the use of line filter function has adverse effect on the accuracy of power measurement. The result may be unacceptable if the values are larger than specified tolerance levels for efficiency and losses as per IEC standard 60034-1.

The main theme of this paper is thus to analyze change in measurement uncertainties of efficiency measurement setups in VSD supply conditions. The paper is organized in the following manner. First the brief overview of different standard specifications (already published as well as upcoming) for motor efficiency measurements is presented. The alternative arrangements for a typical test facility for motor plus motor-drive system efficiency measurement are presented and different sources of errors in measurements are elaborated. The laboratory measurements are performed on a IE2 efficiency class induction motor using standard test methods under both sinusoidal and VSD supply conditions. The measurement uncertainties for both sinusoidal and VSD supply cases are estimated based on the available accuracies of the measurement equipment. Then the effect of using line filters on measurement uncertainty is analyzed for sinusoidal and VSD supply conditions. In the end, these are compared against the maximum allowable limits defined in standard specifications.

Overview of motor efficiency classes and measurement methods

The International Electrotechnical Commission (IEC) has published an international standard IEC 60034-30 which describes the efficiency classes (IE- code) for standard single phase and three phase motors operated from sinusoidal supply [1][9]. In order to keep pace with the high integration of VSD fed motors in industries, this standard is to be split into two parts - Part 1 will cover all motors operated direct on-line and part 2 will cover motors operated on variable voltage and frequency supplied by VSD [2]. Together with defining the above standard for efficiency classes, IEC has also published a standard for testing the motor efficiency described as *"IEC 60034-2-1 (Ed. 1.0): Rotating electrical machines – Part 2-1: Standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles), 2007*", which describes test methods to determine motor efficiency from measurement tests [3]. As per IEC 60034-2-1 (Ed. 1.0), the motor efficiency can determined in number of ways, for ex. measuring input and output powers directly or measuring the motor loss components separately and the efficiency can be estimated by summing the total losses. Table 1 describes the summary of preferred test methods as per IEC 60034-2-1[3].

Each of above described methods has certain advantages as well as drawbacks with respect to cost, accuracy and complexity of testing. Even with the use of a consistent and accurate efficiency test method, variations in results for the same motor do occur, primarily due to ambient conditions, instrument characteristics and personnel factors in the case of non-automated testing.

Table 1: Preferred methods for efficiency determination of sinusoidal supply fed motors [3]

Ref	Method	Description	Application
2-1-1A	Direct measurement: Input-Output	Torque measurement	All single phase machines
2-1-1B	Summation of losses: Residual losses	PLL determined from residual loss	Three phase machines with rated output power up to 2 MW
2-1-1C	Summation of losses: Assigned value	PLL from assigned value	Three phase machines with rated output power 2 MW and greater

When the motors are supplied with VSD voltages, there is increase in motor losses which is mainly due to additional harmonic losses. Upcoming standard specification, IEC 60034-2-3[2] describes different methods and test procedures to measure these additional losses [6][13]. The standard also introduces the concept of a test converter- which is a VSD voltage source with defined and reproducible harmonic content to supply the motor under test. In this way, it is possible to measure and compare losses for motors being supplied by VSDs from different manufacturers. The scope of this standard is limited only to determine the additional harmonic motor losses resulting from non-sinusoidal power supply- consequently the efficiency of the VSD -fed motor. Thus it does not address methods to determine the efficiency of complete Power Drive System (PDS), this has been the topic for other standards in pipeline to define efficiency of complete PDS [7].

As long as the test methods and measuring equipments are used according to the efficiency measurement standards as described above, the test result shall not exceed the allowed deviation as specified by standard. The required tolerances for different values which are printed on the motor nameplate are defined in IEC 60034-1. This tolerance limits are not only for measurement limits but both variations in manufacturing, material properties together with measurement tolerances. The specified values for motor efficiency and motor losses are shown in Table 2.

Motor or motor drive system manufacturers should now print the IE efficiency class on motor nameplate, together with the actual efficiency values. The manufacturer needs to have the efficiency situation under control by doing type tests per product variant (not on all motors that leave the factory), the possible difference in measured efficiency shall be within the tolerance limit- this accounts for both measurement and manufacturing tolerances. The above requirement puts stringent requirements on the accuracy of measurement equipments and measurement procedures.

Table 2: Tolerance limits for motor loss and efficiency as per IEC 60034-1

Motor efficiency (η) [3] - For machines up to 150 kW (or kVA) - for machines above 150 kW (or kVA)	 -15% of (1- η) -10% of (1- η)
Motor losses for machines above 150 kW (or kVA)	+10% of total motor losses

[2] The standard is still in draft stage, the publishing date is scheduled to be in late 2013 http://www.iec.ch

[3] Tolerance is the maximum allowed deviation between the test result of a quantity and the declared value on the rating plate or in the catalogue. As long as test procedures and test equipment according to IEC standards are used, the test result shall not exceed the allowed deviation independent of test laboratory or equipment.

Requirements for efficiency measurement system in a typical industrial environment

Because of the advancement in the instrumentation and measurement system, the power measurement has been made much easier with introduction of advanced power measurement equipment and systems. There are many suppliers in market like Tektronix, Yokogawa PZ and WT series, Voltech PM Series, who can provide dedicated instruments for power measurement under different operating scenarios. Many of these instrumentation systems offer multiple types of interfaces for electrical and mechanical quantities being measured as per measurement standards. The selection and sizing of the measurement equipment has great impact on uncertainty of efficiency measurements. The discussion henceforth in this paper is focused on measurement system using the precision power analyzers [14] and associated data acquisition accessories. The precision power analyzer allows different alternatives for current measurement. Current measurement by passing current directly through series elements is possible for small motor sizes. But current transformers or transducers have to be used to measure currents of much higher amplitudes than current rating of series element. This will result into the degradation in the accuracy because of the errors introduced by additional shunt or transducer.

Test setup for measurement of motor and drive system efficiency

The test setup for measuring motor efficiency is shown in Figure 1 which employs motor current sensing through use of current transducers. The mechanical arrangement consist of test motor coupled with a load machine with a torque transducer in between for measuring mechanical quantities like load torque, speed and mechanical power.

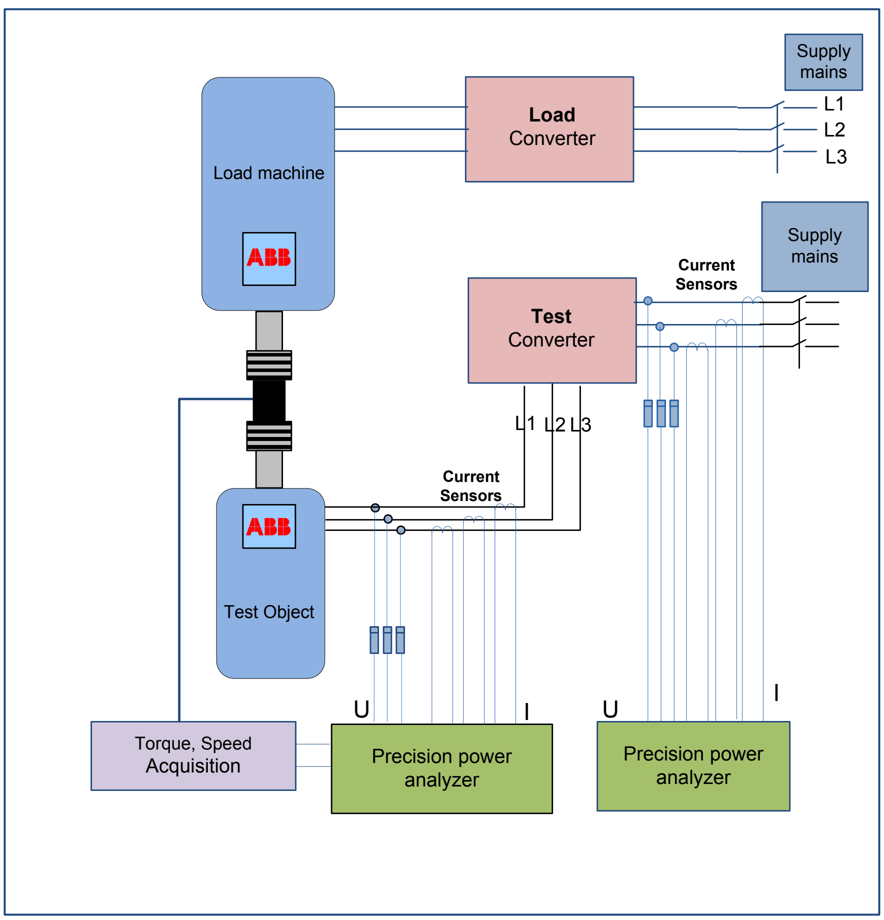

Figure 1: Measurement setup configuration wiring schematic

The load machine is supplied through a VSD (load converter) which controls the load machine to apply specific load torque on the shaft. The test motor is either connected directly to supply mains or through a VSD (test converter) depending upon the measurements. The test converter is used to supply the motor with variable frequency to rotate it at different speeds. The test motor used in this study is 15 kW, IE2 efficiency class (400 V, 50 Hz, 1500 rpm) induction motor. The electrical as well as mechanical power measurement is done by power analyzers since all electrical signal as wells as torque and speed information is input to power analyzers. Thus the power analyzer is capable of directly measuring electrical, mechanical powers, motor losses as well as motor efficiency.

Factors affecting the accuracy of measurement system

The accuracy of the measurement system is of prime important as described in previous sections. For best results, direct interface of motor current and voltage through power measuring instrument is preferred. This measurements system with low instrument count is less prone to large deviations in overall measurement inaccuracies. But using intermediate equipments like current or voltage transducers adds complexity and contributes to its own share of uncertainty in efficiency measurement. Some of the prime factors which should be considered, while selection of measurement setups, are -

- Motor current interface- Insertion of current sensing element directly into current path contributes to least uncertainties in measurement. This results into the best accuracy since the errors associated with current transducers are eliminated. Of course, this is possible only for small motors where the current ratings of motors are sufficiently lower than capacity of current sensing elements of commercially available power analyzers.
- The voltage inputs are directly connected to the power analyzer voltage inputs or through suitable potential divider circuitry when the voltages are higher than rating of voltage rating of power analyzers.
- The torque and speed signal input to the power analyzers are either analogue or digital (or frequency) type, the digital inputs are preferred over analogue inputs for higher accuracy.
- Number and Capacity of test setups

A motor manufacturing facility generally include many motor sizes ranging from few (or fraction) kW to hundreds of kW and it should be possible to test all of these motor sizes. This puts big limitation of the testing infrastructure since practically it is not possible to have test rigs for individual frame sizes. The compromise is generally done with small number of test rigs dedicated to testing certain motors in particular power ranges. The effect of such arrangement will lead to degrading the accuracy of measurement while testing small capacity motor with much higher power capacity test rig. There is always a lower limit of lower power rating of the motor which can be tested on a test rig with accepted levels of measurement uncertainty.

- Precision power analyzers

As today, the power measuring instruments with much higher accuracy than that described in the IEC standard are available in market. But it does not mean that using such instrumentation will always give the efficiency measurement within acceptable tolerance limits. The main reason is that most of the errors are because of deviations in specified ambient conditions under which the instrument is being used, human errors, calculations methods, etc. The power analyzer accuracy levels are function of frequency of supply voltages, often the limits grow linearly with frequency of supply voltages under test. Thus in case of motor efficiency measurement under VSD fed conditions, the uncertainty of the power measurements is often higher, in the order of tens, as compared to the case with sinusoidal supply conditions. This aspect is analyzed in details in later part of this paper for both sinusoidal and VSD fed conditions.

Estimation of measurement uncertainties

This section describes the procedure followed to estimate measurement uncertainty for the measurement setup used in this study. The procedure is similar to one already reported by others [10], with the difference that the actual accuracy levels of different instruments are considered from manufacturers datasheets. The accuracy values are valid under standard environmental condition, like ambient temperature, humidity, calibration state. Deviation from the standard testing conditions leads to the deviation in instrument accuracy. The instrument manufactures generally provide the respective scaling factors to instrument accuracy when the test condition differs from standard operating conditions. The different accuracy specifications and scaling factors for the measurement setup shown in Figure 1 are described in Table 3. The different values shown in Table 3 are obtained from manufacturers catalogues.

Table 3: accuracy specifications for different instruments on the measurement setup

Instrument	measured quantity	Measured quantity	Expression form	Sinus. Supply (50Hz)	VSD supply
Torque transducer	Torque	Accuracy Rotating Speed influence	± (% reading) % per1000 rpm	0.1 0.01	0.1 0.01
	Speed		± (% reading)	0.1	0.1
Current Transducer	Current	Accuracy Conductor position effect	±(% reading + 30 uA) ± % of reading	0.05 0.01	0.05 0.01
Precision power analyzer	Mechanical power	Torque input (Analog) Speed input (pulse)	±(reading error + measurement range error) ±(reading error + mHz)	0.1, 0.1 0.05, 1	0.1, 0.1 0.05,1
	Electrical measurements	Current, Voltage Power	±(reading error + measurement range error) ±(reading error + measurement range error)	0.01, 0.03 0.02, 0.04	0.1, 0.05 0.15, 0.1
	Line filter influence	Current Voltage Power	% of reading % of reading % of reading	0.2 0.2 0.3	0.5 0.2 1
	One year accuracy[4]	% times 6 month accuracy		1.5	1.5
	Temperature coefficient (Valid for range 5 to 18°C or 28 to 40°C)		Add ±0.02% of reading /°C		

The effect of temperature changes after zero level compensation, range change and the effect of self-generated heat caused by current input are neglected in this exercise.

Effect of VSD supply on measurement uncertainty

It can be seen from Table 3 that accuracy limits for precision power analyzers under VSD supply conditions are much higher than the case for sinusoidal supply conditions and thus it will have major impact on the accuracy of efficiency measurements under VSD voltage supply. To highlight the above facts, the overall uncertainty estimation in input power, output power and efficiency of the motor has been performed where motor is operating at nominal load as described in Table 4.

[4] One year accuracy scaling is applicable when the power meters are not calibrated within 6 months

Table 4: example case for determination of measurement uncertainty at nominal operating condition

Current	30.2	A
Voltage	218	V
PF	0.84	
Power	16.65	kW
Torque	98.56	Nm
Speed	1465.4	rpm
Power	15.125	kW

The uncertainily estimation is performed for three situations- “A”, “B” and “C”, these conditions are derived based on the state of different instruments used in the measurement setup. The Table 5 describes such conditions for respective cases.

Table 5: Different scenarios considered for uncertainty estimation

		Scenario A	Scenario B	Scenario C
Electical inputs	Accuracy - ±(reading error + measurement range error)	considered	considered	considered
	Line filter influence - Add 0.5% of reading	considered	Not considered	considered
	One year accuracy- reading error of accuracy at 6 months × 0.5	considered	Not considered	Not considered
Mechanical inputs	Accuracy error- **Analog** ±(reading error + measurement range error)**, Pulse** ±(reading error + mHz)	considered	considered	considered
	Conversion factor deviation from calibration	present	Not present	Not present

Scenario A

Scenario A is the worst case condition, referred to the situation when the current transduceres, power analyzer are not calibrated at intervals specified by manufacturer, line filters are enabled in the measurements and the torque transducer also shows deviation from calibration state. The respective power and efficiency measurements alongwith estimated uncertainity in this situation are shown in Table 6 for both sinusoidal and VSD supply conditions. As expected, the measurement uncertainity is higher with VSD supply conditions. Overall, the uncertainity estimates are much higher than expected limits for such measurements.

Scenario B

Scenario B refers to best case situation where all measurement instruments are calibrated as per specifications. The only influencing factors under this situation are instrument accuracies. The resulting estimation inaccuracies are shown in Table 6. As expected, the efficiency uncertainty is much lower and within acceptable limits.

Scenario C

Scenario C is most likely case similar to scenario B but line filters function in power analyzers is activated in the measurements. Thus the respective scaling factors have to be considered for estimating the measurement inaccuracy. The resulting uncertainty estimates are also shown in Table 6. It is obvious that the added scaling in inaccuracy due to line filters result in much higher uncertainty than the scenario B.

The estimated values under above conditions are tabulated in Table 6, where "+ve and –ve deviation" are the actual maximum values for the respective parameters i.e. the "+ve or –ve Diff" plus actual measurement. "+% and -%" shows the deviation normalized to actual measured value.

Table 6: Estimated measurement uncertainty under different instrument conditions

Instrument scenario			Reading	+ve deviation	-ve deviation	+ve Diff.	-ve Diff.	+%	-%
A	Mech. power		15124.90	15200.14	15049.83	75.24	75.07	0.50	-0.50
	Electrical power	Sinus	16648.27	16746.18	16550.36	97.91	97.91	0.59	-0.59
		VSD	16648.27	16980.46	16316.09	332.18	332.18	2.00	-2.00
	Motor Efficiency	**Sinus**	**90.8**	**91.8**	**89.9**			**1.0**	**1.0**
		VSD	**90.8**	**93.2**	**88.6**			**2.3**	**2.2**
B	Mech. power		15124.90	15184.96	15064.96	60.06	59.94	0.40	-0.40
	Electrical power	Sinus	16648.27	16669.60	16626.94	21.33	21.33	0.13	-0.13
		VSD	16648.27	16718.25	16578.30	69.97	69.97	0.42	-0.42
	Motor Efficiency	**Sinus**	**90.8**	**91.3**	**90.4**			**0.5**	**0.5**
		VSD	**90.8**	**91.6**	**90.1**			**0.7**	**0.7**
C	Mech. power		15124.90	15184.96	15064.96	60.06	59.94	0.40	-0.40
	Electrical power	Sinus	16648.27	16719.55	16577.00	71.27	71.27	0.43	-0.43
		VSD	16648.27	16884.73	16411.82	236.46	236.46	1.42	-1.42
	Motor Efficiency	**Sinus**	**90.8**	**91.6**	**90.1**			**0.8**	**0.7**
		VSD	**90.8**	**92.5**	**89.2**			**1.7**	**1.6**

From the above analysis, the following guidelines should be followed in order to keep the measurements within reasonable accuracy range.

- Torque transducer calibrated (& compensated for error) before start of test
- Ensure zero reading at no load
- Precision power analyzers to be calibrated every six months. The consequence of this is that instrument needs to be taken out from test rig for number of days and thus are not available for measurements.

The line filters have very significant impact on the measurement uncertainties. This is investigated further in details in later part of the paper. Especially the effect of line filters on measurement uncertainty is estimated for efficiency tests performed under sinusoidal and VSD supply conditions and resulting measurement uncertainty are compared against allowable tolerance limits.

Motor efficiency measurement for test motor

The efficiency of the test motor is measured using direct input-output and segregation of loss methods outlined in the IEC standard specifications (IEC 60034-2-1 & IEC00034-2-3). The measurements have been carried out with both sinusoidal and VSD supply conditions.

Motor loss and efficiency determination under sinusoidal supply

Motor efficiency is measured under sinusoidal supply conditions as per the test procedure outlined in IEC60034-2-1. First the heat run test performed at different loading conditions and the efficiency is measured as per direct input-output method. This is followed by indirect efficiency measurement as described in “Method 2- summation of losses, residual losses estimated from stray losses” [3]. The different results from above tests are summarized Table 7 for sinusoidal supply conditions.

Table 7: Measured loss and efficiency under sinusoidal supply

Load torque [%]	Direct input-output method		Indirect method (Method-B)- loss segregation		
	Loss [W]	Efficiency [%]	Loss [W]	Efficiency [%]	
				$(P_{in} - P_L)/P_{in}$	$P_{out}/(P_{out} + P_L)$
115	1892.5	90.2	1836.0	90.5	90.4
100	1523.4	90.8	1464.3	91.2	91.2
75	1053.5	91.6	1016.7	91.9	91.9
50	757.8	91.2	718.2	91.6	91.6
25	598.4	87.3	558.3	88.1	88.0

Motor loss and efficiency determination with converter supply

The efficiency of the test motor is also measured with VSD supply at similar load conditions using direct and indirect test method. The motor is now supplied from a ABB ACS850 industrial drive which operates the motor at rated speed in speed control mode. As outlined in IEC 60034-2-3, “test method 2-3-B summation of losses- Manufacturer specific converter supply, additional harmonic loss determination using final application specific converter” is used to determine motor loss components and “test method 2-3-C Input-Output method” is used to measure motor losses directly [6] (The method is similar to the method 1 Direct input-output power measurement described in IEC 60034-2-1 [3]).

The different results from above tests are summarized Table 7 for sinusoidal supply conditions and in Table 8 for VSD supply conditions. Figure 2 shows the motor efficiency under sinusoidal and VSD supply conditions, whereas the motor losses under different loading condition are shown in Figure 3.[5]

Table 8: Measured loss and efficiency with VSD supply at rated speed of 1500 rpm

Load torque [%]	Direct input-output method			Indirect method (Method-B)			
						η [%]	
	Loss [W]	ΔL [%]	η [%]	Loss [W]	ΔL [%]	$(P_{in} - P_L)/P_{in}$	$P_{out}/(P_{out} + P_L)$
115	1936.2	2.3	89.2	1932.7	5.3	89.2	89.2
100	1692.1	11.1	89.8	1598.6	9.2	90.4	90.3
75	1126.2	6.9	91.0	1084.6	6.7	91.3	91.3
50	797.5	5.2	90.7	775.4	8.0	91.0	91.0
25	601.1	0.5	87.4	558.3	0.0	88.3	88.2

5 As per IEC 60034-2-1, the motor efficiency from indirect loss measurement can be expressed in two ways- first as function of input power and losses and secondly as a function of losses and output power. The first expression is preferred for a motor, the second one for a generator.

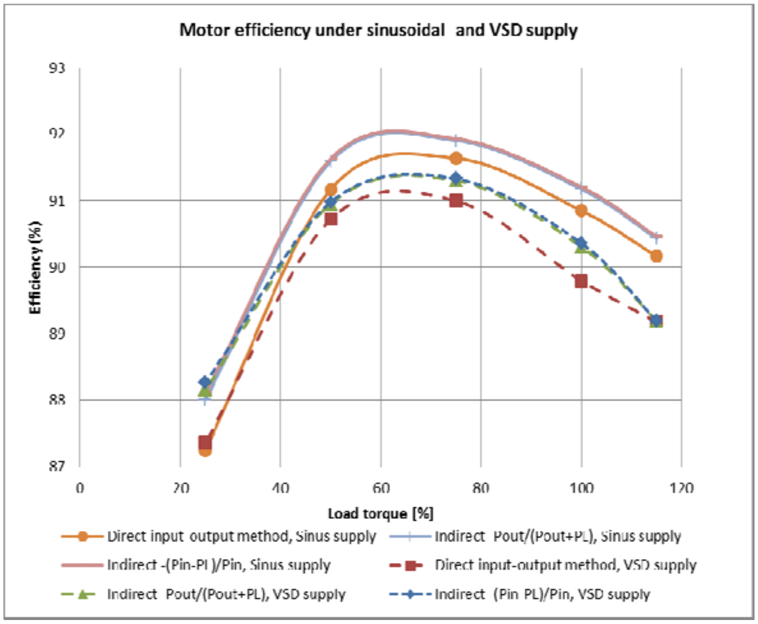

Figure 2: Comparison of motor efficiency under sinusoidal and VSD supply conditions

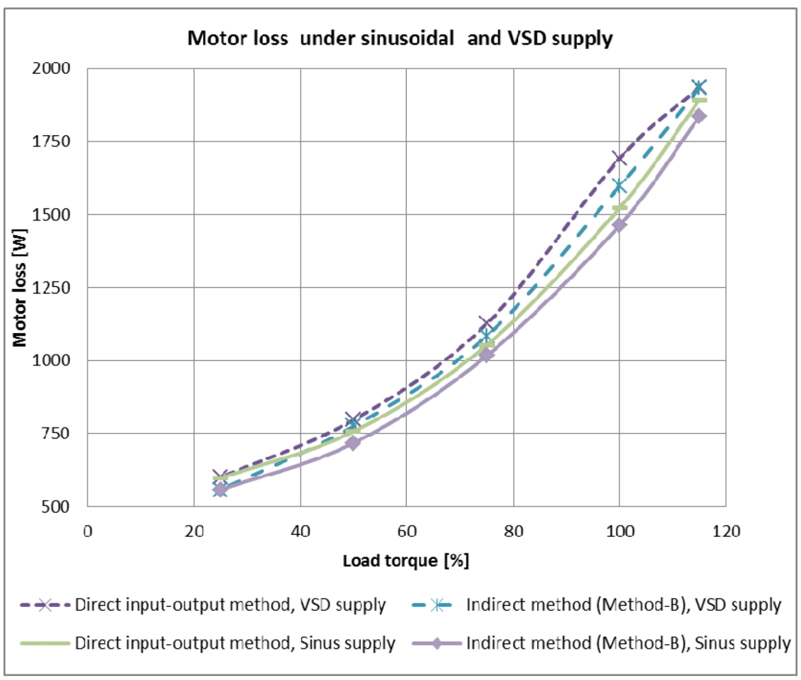

Figure 3: Comparison of motor losses under sinusoidal and VSD supply conditions

It is observed that the efficiency measured with direct input – output method is lower than that determined using indirect method. This is true for both sinusoidal as well as VSD supply conditions. The measured efficiency value at rated load confirm to the IE2 efficiency level under sinusoidal supply condition. The efficiency decreases under VSD supply, owing to the increase in iron losses (additional harmonic losses in the motor iron core, rotor eddy current losses, etc.). The relative increase in losses due to VSD supply is also indicated in Table 8 as a percent of sinusoidal losses at similar load conditions. It is observed from Table 8 that the maximum increase is ~11% and 9 % for measurements using direct input-output method and indirect summation of loss method, respectively. The losses in sinusoidal and VSD supply conditions cannot be compared at 115% load conditions because of the converter voltage limitations at this operating point. The estimation of uncertainty in the above described efficiency values is the main aim of this paper. This has been addressed in next section where the measurement uncertainties are estimated based on the procedure described in previous section and then compared with specified tolerance limits in standard specifications.

Estimation of measurement uncertainties for direct input output method

The procedure for estimation of measurement uncertainties, described in previous section, is carried out for all load conditions for both sinusoidal and VSD supply conditions. To analyze the effect of line filters on measurement uncertainty, the measurement uncertainties are estimated for both the cases – with and without use of filter function (scenario B and C respectively) for sinusoidal and VSD supply conditions. Then the resulting values are compared with tolerance limits to evaluate if the measurement is satisfactory or not.

Uncertainty estimation without line filter (Scenario B)

The measured values of voltage, current and power quantities as well as current range selected by the instruments are used to derive the uncertainties at different load conditions for sinusoidal supply conditions. The results are reported in Figure 4 for efficiency values and in Figure 5 for measured loss values. Similar exercise is also carried out to determine measurement uncertainty for measurement tests with VSD supply conditions. The respective values are also shown in Figure 4 and Figure 5 for efficiency and measured loss respectively. The various scaling factors for different measurement instruments are taken from Table 3 for VSD supply conditions.

Uncertainty estimation with line filter active (Scenario C)

The enabling of line filter function in power analyzers inserts the line filter into the voltage and current measurement input circuit, it directly affects the voltage, current, and power measurements [14]. This results in filtering of input voltage and current signals. High frequency components are filtered out depending upon the selected cut-off frequency. The line filter has minimal effect on measurements in the situation when motor is supplied with sinusoidal voltages, but the measurements in case of VSD voltages are affected by line filter selection. The accuracy specifications of the power analyzers are thus dependent upon line filter state since activating line filter adds additional scaling factor in uncertainty estimation as described in Table 3 .

The effect of line filter on the measurement uncertainty is estimated by considering scaling of power analyzer accuracy values as described in Table 3. The overall uncertainty in motor efficiency and motor losses under sinusoidal supply conditions is shown in Figure 6 and Figure 7, respectively. The measurement uncertainty for VSD supply condition is also estimated as described above and the results are shown in Figure 6 and Figure 7 for motor efficiency and motor losses, respectively.

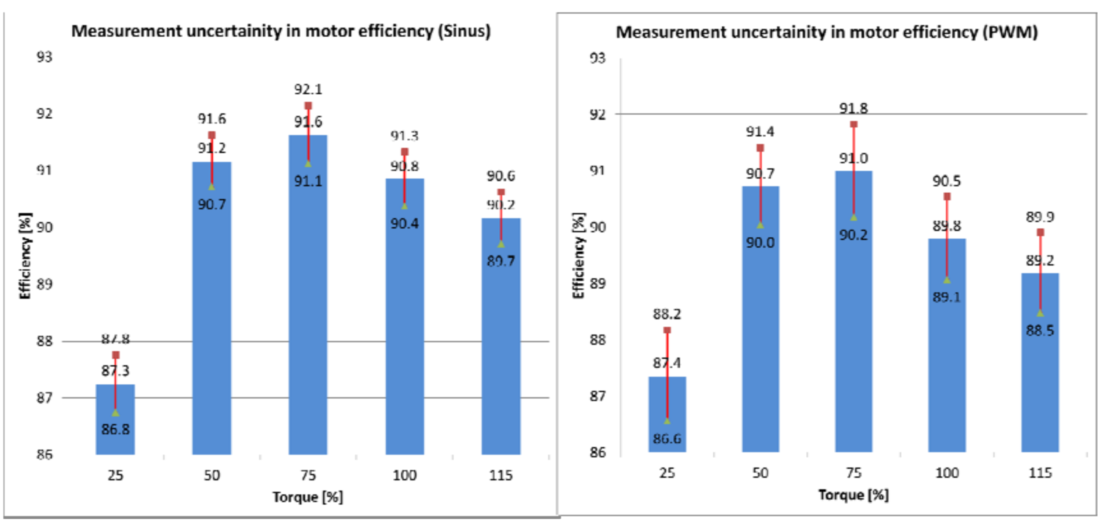

Figure 4: Measurement uncertainty in motor efficiency values without line filters

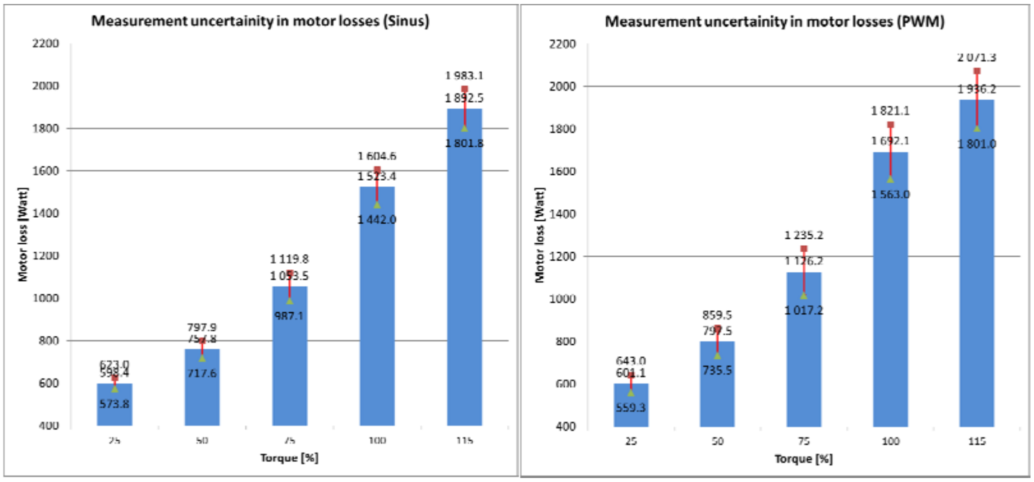

Figure 5: Measurement uncertainty in motor losses without line filters

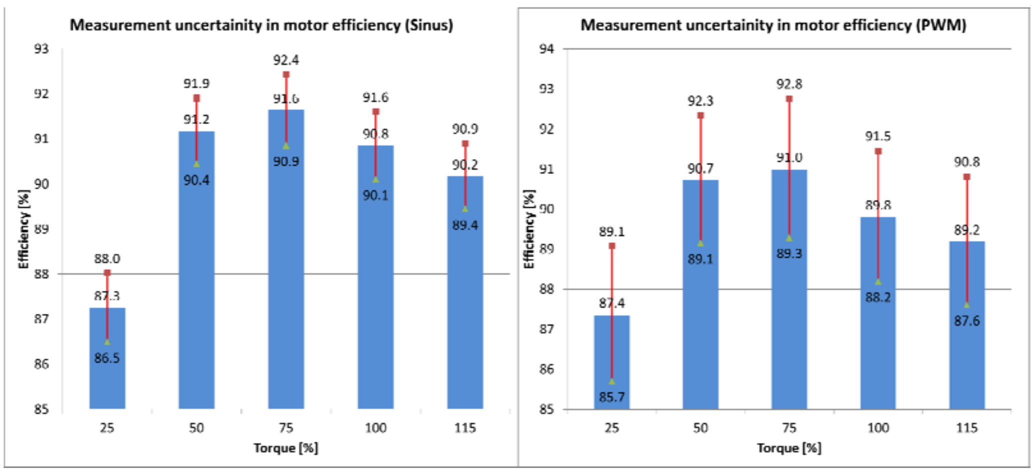

Figure 6: Measurement uncertainty in motor efficiency values with line filters

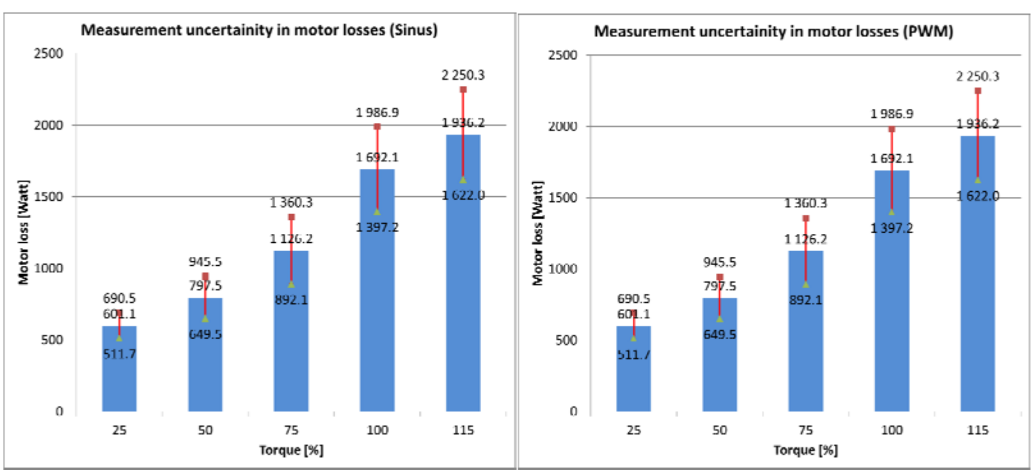

Figure 7: Measurement uncertainty in motor losses with line filters

Comparison of measurement uncertainty with tolerance limits

The recommended error tolerance limits for motor efficiency as per IEC 60034-1 applicable to induction motor of 15 kW power rating is -15% of (1- η). Based on the measured efficiency values at different load conditions the tolerance limits are calculated for both sinusoidal and VSD supply conditions. The results are shown in Figure 8 with dotted lines (blue- sinusoidal supply condition, red-VSD supply). Figure 8 also shows the estimated uncertainty in efficiency from actual measurements for both VSD and sinusoidal supply conditions (continuous blue and red lines). Figure 8(a) shows the comparison of estimated uncertainty when the line filter function was not used. In this condition, the actual uncertainty is well below the maximum tolerance levels for both sinusoidal and VSD supply conditions.

Similar procedure is followed for the case when the line filter function is activated. The comparison between estimated uncertainty and tolerance limits are shown in Figure 8(b). In this scenario, the estimated uncertainty for sinusoidal supply test is lower than the tolerance levels but it exceeds the limits in case of VSD supply conditions. Thus the line filter function is having adverse effects in measurements with VSD supply conditions. The measurement uncertainty is more than manufacturing tolerance limits.

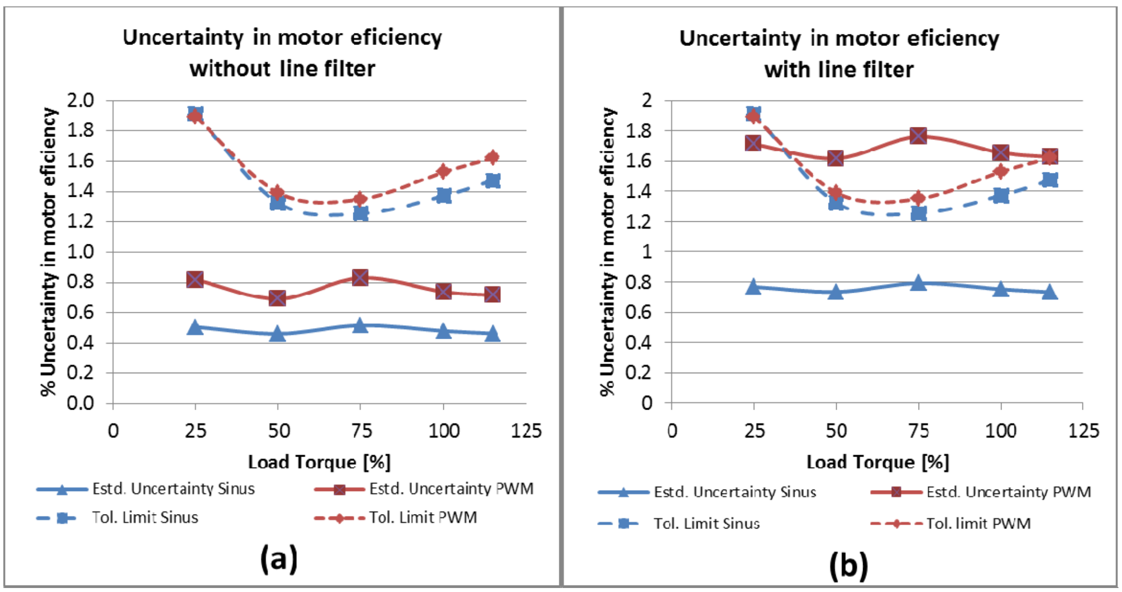

Figure 8: Estimated tolerance limits in motor efficiency at rated speed (dotted curve- maximum tolerance limits - 15% of (1-η) as per IEC60034-1 standard specification)

Similar comparison is also mode for motor losses. Figure 9(a) shows measurement uncertainty (% of total loss) in motor loss for the case when line filter is in disabled condition. The tolerance limits in motor losses are defined as -10% of motor loss as per IEC 60034-1 (for motor rating >150 kW). But for lower than 150 kW motor rating, the tolerance limits are not described. Hence, it is assumed to be equal 15% (tolerance limits for efficiency values). It is seen that the measurement uncertainty in case of sinusoidal supply are well within tolerance limits (<6%), whereas with VSD supply it is much higher (¨7-10%) depending upon load conditions.

The similar procedure is followed for the scenario in which line filter is enabled and the resulting measurement uncertainty values are shown in Figure 9(b). Clearly, line filter has adverse effect under both sinusoidal and VSD conditions. The results for sinusoidal supply conditions are approximately 10%, but for a VSD supply test, the measurement uncertainty is greater than manufacturing tolerance levels (i.e. 15%). The uncertainty in motor loss at 100% and 115% load conditions is lower than respective value at 75% load condition. This is because of the selection of “auto scale mode” of power analyzer which automatically selects the best scaling factor for depending upon the RMS value of measured quantity.[6]

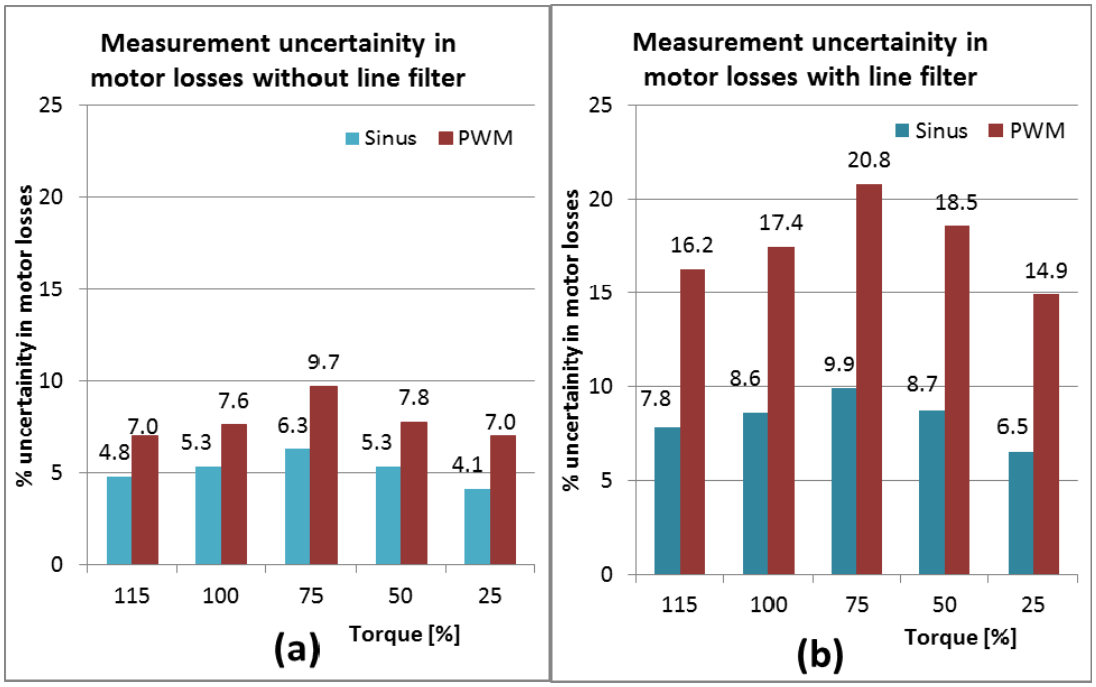

Figure 9: Measurement uncertainty in motor losses

The following conclusions can be drawn from the foregoing analysis of measurement uncertainty estimation-

- It is evident from the foregoing analysis that the measurements under sinusoidal supply conditions are performed while keeping the measurement uncertainty well below manufacturing tolerance levels defined in IEC 60034-1. But the scenario is different when the measurements with VSD supply are performed on same measurement setup. The estimated uncertainties are much larger as compared to sinusoidal supply case.
- Activating line filter function cause the measurement uncertainty go exceed above allowed tolerance limits defined in IEC 60034-1. The use of line filter calls for additional scaling factors while estimating measurement uncertainties. The estimated uncertainty in case of measurements with sinusoidal supply are still within tolerance limits even when the line filter function in power analyzers is activated.
- But with line filter in enabled state, the overall estimation of uncertainties levels actually exceeds the allowed tolerance limits when the measurements are performed with VSD supply conditions. Thus efficiency measurement with VSD supply must be performed **without** enabling line filter function. When the motor efficiency is measured at lower speeds under VSD supply, the voltage, current waveforms contains much higher harmonics. This poses the problems with zero crossing detection of voltage and/or current waveforms and calculation of fundamental frequency becomes difficult. In this situation, it is essential to activate the line filters otherwise the fundamental frequency and thus rest parameters are not calculated properly.
- The motor efficiency measurement under VSD supply conditions is very tricky owing to above conflicting requirements about line filters.

[6] In "auto" scaling mode, the scaling factor is changed to higher value when the RMS value of measured quantity becomes higher than 110% of scale [14].

Conclusions

The paper presents the effect of instrument accuracies on the overall uncertainty in efficiency measurement described as in direct input-output methods as per IEC 60034-2-1. The measurement instrumentation normally has higher error margins for VSD supply conditions as compared to sinusoidal supply. This results in higher values of estimated uncertainty in efficiency during measurement under VSD supply conditions. The efficiency measurement is performed on an induction motor under both sinusoidal and converter fed supply conditions at rated speed. The percentage increase in motor losses during converter fed supply is found to be linearly increasing with respect to load condition. This is very different observation than the assumption made in IEC 60034-2-3 that the additional motor loss due to converter fed supply is independent of motor loading.

Then the uncertainty estimation is performed on measured efficiency under both sinusoidal and converter fed supply conditions. It is observed from estimated uncertainty values are below maximum limits described as per IEC 60034-1 standard specification when measurements are performed with line filter functions in power analyzers is disabled. This is applicable for both sinusoidal and converter fed measurement tests. But measurement uncertainty is much higher when line filters are activated for measurements with VSD supply conditions. In this situation, the estimated uncertainty values are very close or higher than allowed tolerance limits. It is recommended that the use of line filters should be avoided under such situations.

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HIGH SPEED SYSTEM

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ABSTRACT

There is a growing interest in exploiting high-speed machines for industry applications and this is mainly due to the fact that high-frequency design increases power density and reduces the size and weight of the machine for a given power requirements. However, increasing the frequency of the machine brings up major issues such as thermal behavior and the need to increase the switching frequency of the converter. In this paper, we will focus on machines with a fundamental frequency varying between 100 and 1000 Hz.

INTRODUCTION

Permanent magnet synchronous machine (PMSM) is the most widely used concept for high speed applications and the rotor configuration with surface-mounted arc shaped permanent magnet provides the best compromise between the level of the output power and the back EMF THD. In most cases a sleeve provides the containment to prevent centrifugal forces from separating the permanent magnets from the rotor hub. The carbon-fiber offers the highest strength but provides conduction paths for rotor eddy currents induced by time and space stator harmonics which can lead to excessive heating.

PMSM are often fed by a PWM three-phase voltage inverter which generates time stator harmonics and consequently rotor losses. PWM technique used in the modulation process plays an important role in the minimization of these harmonics and high speed drives are generally equipped with an LC output filter of which cut-off frequency is well below the switching frequency of the inverter in order to obtain a quasi-sinusoidal motor terminal voltage. But this solution can cause system instability and is cost and size consuming. Moreover, although the LC filter limits time stator harmonics it does not address the need of increasing the switching frequency of the voltage source ensuring a reasonable switching to fundamental frequency ratio.

Multilevel converters present great advantages compared with conventional two-level converters. The inverter output voltage improves its quality as the number of levels increases reducing the THD of the output waveforms and increasing at the same time the load frequency. Multilevel PWM technique remains a major issue in the minimization of time stator harmonics.

DEFINITION OF “HIGH-SPEED MACHINE”

It seems important at this stage to understand the hidden meaning behind the term “High-speed machine”. In fact there no clear definition!
Generally, a machine is considered high-speed when its design needs to be adapted mechanically or electrically from that of the conventional machine in order to achieve the desired speed range. However there seems to be a consensus when defining a limit between what can be considered as “High-speed machine” and “Super-high speed machine”. As high rotational speeds can be achieved by scaling down the machine as much as the existing technology permits this criterion is not sufficient. The peripheral speed on the outer radius of the rotor is physically limited by the material used to build the sleeve which makes this parameter a good candidate to identify the desired limit but it would favor very large machine operating at low speed.

Regarding the literature it seems to be now admitted that the limit between “High-speed machine” and “Super-high speed machine” can be defined according to the rated power and the rotational speed of a design. An empiric analytical solution has been obtained by Binder and Schneider [2] :

$$\log(\Omega) = 4.27 - 0.275\log(P)$$

Where Ω is the speed in [RPM] and P is the rated power in [W]. This leads to the following approximation

$$P \approx \frac{1}{\Omega^{3.6}}$$

Figure 1 shows this limit and the some existing commercial machines.

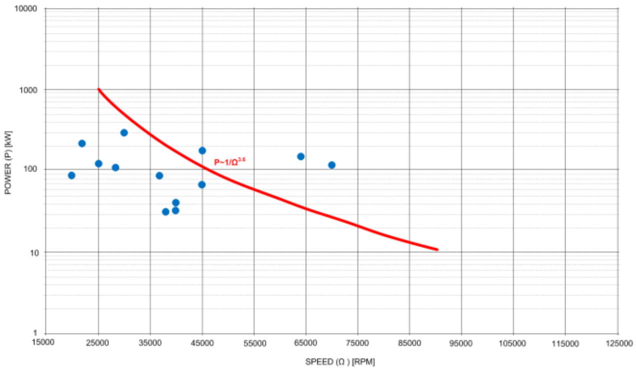


Figure 1 : Limit between high-speed and super-high speed machine

ENABLING HIGH ROTATIONNAL SPEED THROUGH MAGNETIC BEARING

Active magnetic bearings have been available for decades. It uses stator mounted electro-magnets and feedback control to generate forces on the rotor so that it rotates without touching the stator. This technology is particularly suitable for high speed application for many reasons:

- Very low and predictable friction losses,
- Very low vibration,
- No lubrication,
- Able to run in vacuum,
- No gearbox,
- High reliability,
- Adaptable stiffness
- Energy consumption,
- Operate at very high temperature ….

MAGNETIC BEARING

BASIC OPERATING PRINCIPLE

Figure 2 shows the basic operating principle of an active magnetic bearing application. Let's consider a solid part levitated by means of an electromagnet which generates a magnetic force in the opposite direction to the gravitational force. The amplitude of this magnetic force can be modulated by the current coming from the power amplifier. In order to get a closed loop control of the position of the solid part a sensor gives the position feedback signal to the controller. This basic system enables the levitation along only one axis and only in one direction.

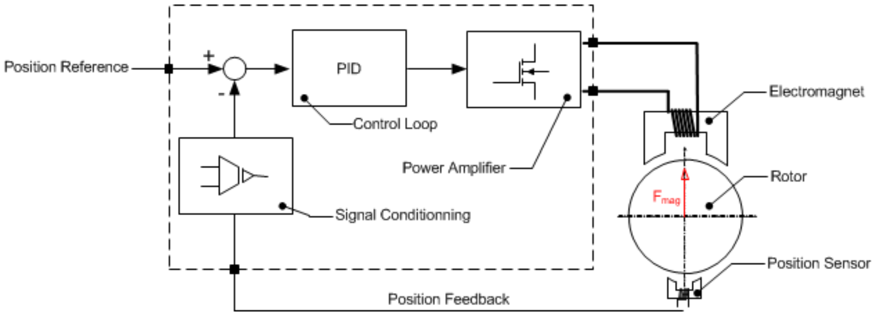


Figure 2 : Basic operating principle of an AMB

AMB SYSTEM DESCRIPTION

In active magnetic bearing systems, several actuators are used in order to control the rotor levitation along at least five degrees-of-freedom: four in radial directions and one the axial direction (See figure 3).

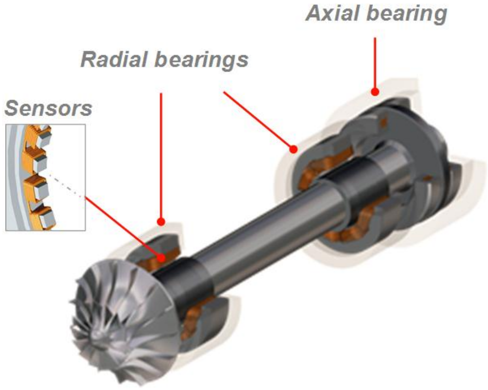


Figure 3 : Rotor mounted on magnetic bearing

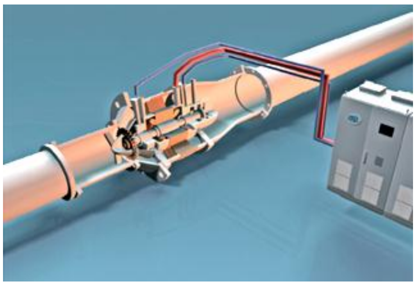
MAGNETIC BEARING APPLICATIONS

Active magnetic bearing technology is going to be widely democratized and is brought to be embedded in many new applications.

Oil and Gas

Oil & Gas companies have recently chosen to move gas compression systems from the platforms to the seabed. Subsea gas compression enables both improved energy efficiency and lower costs to help recover the remaining reserves in the existing gas fields. Active Magnetic Bearings make it possible to operate and control the rotation of the subsea compression units with many advantages: high performance, small footprint, high reliability, no human intervention, and high monitoring capabilities.

Energy



Natural gas comes out of the ground and moves through pipelines at a very high pressure (from 100 to 800 bars). To be used safely by end-users this gas is expanded to only one bar by squeezing it through valves which releases energy that is not being harnessed. Using turbo-expander generator system makes it possible to expand the gas through a turbine resulting in pressure let down and electricity generation. Active Magnetic Bearing allow to design the most compact and efficient solution for this kind of application.

Water and Wastewater

In traditional biological wastewater treatment plants, aeration blower systems represent 40 to 80% of a facility's total energy use. Used to blow air into tanks so that bacteria can break down organic waste, a typical mid-size aeration system operates with two to five air blowers. Reducing the energy requirements of those blowers will help plants cut their energy expenses and CO2 emissions. High-speed motor with Active Magnetic Bearing solutions are helping manufacturers develop a new generation of aeration blower systems to reduce energy use by 10 to 40% compared to traditional lobe-type blowers.

Machine Tool Spindle

Critical grinding processes can be improved by the use of high speed grinding. In order to have the required rotational speeds, magnetic bearing spindles are ideal. They offer a lot of features, which conventional spindles cannot offer: integrated movements and force control. Usually AMB spindles are more powerful than conventional spindles.

HIGH SPEED DRIVE DESIGN

INVERTER

A typical three phase drive application is composed by a passive rectifier, a filter and an inverter which feeds directly the machine as described in figure 4.

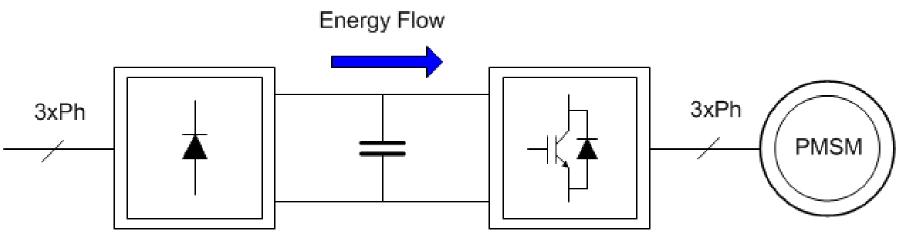


Figure 4 : Typical three-phase drive architecture

The design of a high-speed machine results in a significantly lower synchronous resistance and inductance (a few tens of mΩ and a few hundreds of μH) compared with conventional machine (a few Ω and a few tens of mH). As an example table 1 gives the electrical characteristic of a 330kW/30kRPM machine used in power generation application:

PMSG	
Nominal Speed [kRPM]	30
Power @ Nominal Speed [kW]	330
Phase Resistance [mΩ]	10
Phase Synchronous Inductance [μH]	190

Tableau 1 : Electrical Characteristics of a 330kW/30kRPM machine

This will lead to undesired consequences as increasing the stator current ripple, producing additional rotor losses and decreasing the controllability …

Voltages harmonic frequency components applied to each phase of the machine (a,b and c) can be determined by using the double Fourier integral analysis [3]

$$V_a = \sum_{m=0}^{\infty} \sum_{n=-\infty}^{+\infty} V_{m,n} \cos(m\omega_c t + n\omega_0 t)$$

$$V_b = \sum_{m=0}^{\infty} \sum_{n=-\infty}^{+\infty} V_{m,n} cos\left(m\omega_c t + n\left[\omega_0 t - \frac{2\pi}{3}\right]\right)$$

$$V_c = \sum_{m=0}^{\infty} \sum_{n=-\infty}^{+\infty} V_{m,n} cos\left(m\omega_c t + n\left[\omega_0 t + \frac{2\pi}{3}\right]\right)$$

Where ω_c is the carrier angular frequency, ω_0 is the fundamental angular frequency, m is the carrier index variable and n is the baseband index variable.

The corresponding voltage space vector can be defined using the following definition:

$$\underline{V^s} = \frac{2}{3}\left(\underline{a}^0 V_a + \underline{a}^1 V_b + \underline{a}^2 V_c\right)$$

Where $\underline{a}^0 = e^{j0}$, $\underline{a}^1 = e^{+j\frac{2\pi}{3}}$, $\underline{a}^2 = e^{-j\frac{2\pi}{3}}$ and the index s indicates that the space vector is expressed in the stator fixe frame. This leads to the following result

$$\underline{V^s} = \sum_{m=0}^{\infty} \sum_{n=-\infty}^{+\infty} V_{m,n}\, e^{+j[m\omega_c + n\omega_0]t}$$

The amplitude for a given m and n harmonic space vector will depends on the modulation index M, the DC bus voltage V_{DC}, the carrier angular frequency ω_c, and the strategy of modulation, the fundamental angular frequency ω_0 the strategy of modulation.

The current space vector can then be written as follow

$$\underline{I^s} = \sum_{m=0}^{\infty} \sum_{n=-\infty}^{+\infty} I_{m,n}\, e^{+j[m\omega_c + n\omega_0]t}$$

With

$$I_{m,n} = \frac{V_{m,n}}{|R_s + jL_s(m\omega_c + n\omega_0)|}$$

Where L_s is the synchronous inductance and R_s is the synchronous resistance of the machine.

As the current harmonic is inversely proportional to the synchronous inductance a high speed machine design (which shows lower inductance than conventional design) will necessarily lead to higher level of harmonics. The quality of the signal can be improved by increasing the switching frequency of the inverter but it will be limited by the conduction and switching losses for a given power.
At this stage once can easily understand that the ratio between the carrier frequency and the fundamental frequency is significantly lower for high speed application. Sometimes this ratio can be lower than 9 which make the system complex to be controlled. Generally in this case the machine is driven by an open loop algorithm. The ratio ω_c/ω_0 can be a good candidate to be introduced as a factor to determine the limit of high speed **system.**

ROTOR

Surface mounted permanent magnet synchronous machine is the most used technology in high speed machine levitated by magnetic bearings. The rotor frame is constructed for instance of aluminum, onto which the shaped permanent magnets are glued so that the sinusoidal flux density distribution is achieved in the air gap of the machine. A carbon fiber sleeve provides the containment to prevent centrifugal forces from separating the permanent magnets from the rotor hub (see figure 5).

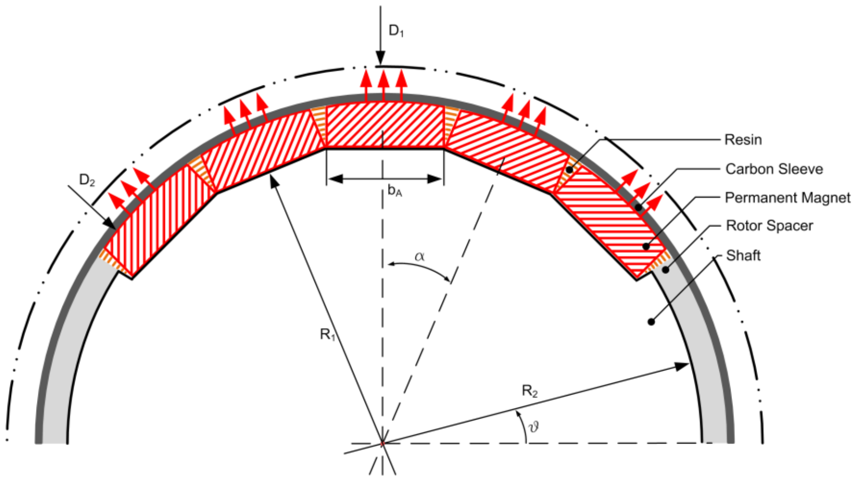


Figure 5 : Surface Mounted Permanent Magnet Rotor

The stator current time harmonics described in the previous section cause eddy current losses in the magnet. When designing high speed permanent magnet machine it is important to know these losses because as the carbon fiber has poor thermal conductivity it make it difficult to remove any losses induced inside the sleeve.
In [4-5] the magnet losses in permanent magnet machines are calculated by considering the magnets as a cylinder of magnet material. In fact many designs use segmented magnet to reduce eddy-current path. In [6] a model a model of the PM machine including the losses due to the time harmonics of the stator current is introduced. This model takes into account the segmentation of the magnets and is represented by a resistance in the equivalent rotating frame.

To reduce these losses most of the commercial solutions use a power converter architecture which introduces a sinus filter between the inverter and the machine to reduce stator current harmonic amplitudes (see figure 6),

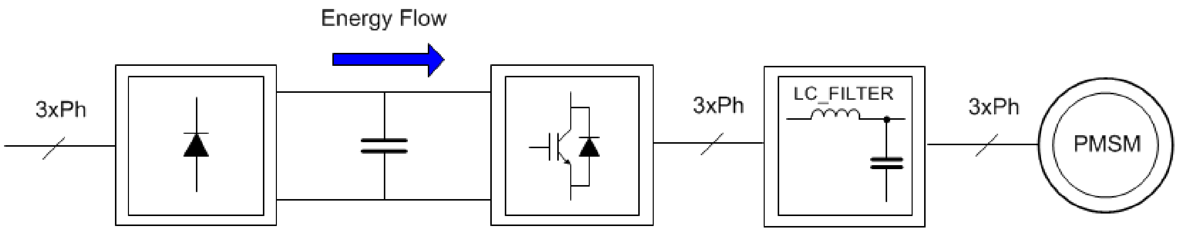


Figure 6 : Three-phase drive equipped with sinus filter

This architecture also reduces electrical stresses (dV/dt) and EMI but it shows many disadvantages:

- Cost/Volume/Weight,
- Non robust closed loop control,
- Modularity,
- Standardization…

MULTILEVEL CONVERTER

A continuous race to develop higher-voltage and higher-current converters to drive high power systems still goes on. Multilevel converters present great advantages compared with conventional and very well-known two-level converters:

- Improvements in the output signal quality → THD ↘
- Increasing voltage range,
- Use of low voltage components which are less expensive and faster,
- Minimizing filter volume,
- Maximizing dynamics by increasing the load apparent frequency,
- Distributing heat by splitting switches,
- Standardizing product ranges by using standardized modules,
- Increasing availability due to splitting and redundancy

The most common multilevel converter topologies are the neutral-point clamped (NPC) converter [7], flying capacitor (FC) converter [8], and cascaded H-bridge converter.

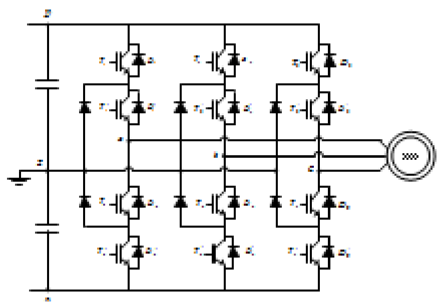


Figure 7 : NPC Converter

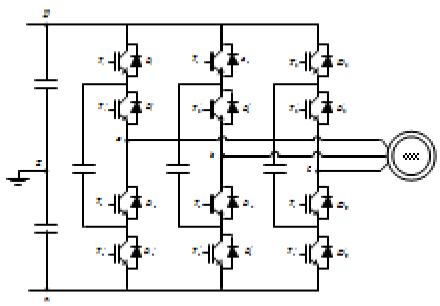


Figure 8 : FC Converter

Other Modular multilevel inverters as the three-phase interleaved dual inverter and the three-phase five-level interleaved dual inverters using interphase transformers are interesting. It should be noted that although the multilevel converters can claim all these advantages is not obvious to implement.

CONCLUSION

In recent years magnetic bearings have unlock the development of high-speed machine which make it possible to increase power density and reduces its size for a given power requirements. AMB technology has significantly impacted the machine design by reaching the physical limit of the magnet and the sleeves material.

Most of industrial application are using conventionnal three phase inverter to feed this kind of machine and they have been recently identify to be an optimization factor for high speed system. Multilevel converters have matured from being an emerging technology to a well-established and attractive solution. Multilevel converter will allow to reduce the footprint defined by the losses, cost, failure mode, volume and weight.

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Sensorless frequency-converter-based methods for realizing life-cycle cost efficient pumping and fan systems

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Abstract

Frequency converters provide means for the energy efficient flow and pressure control in pumping and fan systems by varying the motor speed. Besides speed variation, a modern frequency converter can estimate the state and performance of system operation without additional measurement sensors. This ability provides several possibilities to optimize pumping or fan system operation and the resulting life-cycle costs (LCC) that mainly consist of energy and maintenance costs.

First, information on the present operating state directly informs that how energy efficiently the system is driven, and does the system fulfill the given process requirements. Estimation of the pump or fan operating state can be further applied to determine the surrounding process characteristics, which is essential information for energy audits. This information can also be used for the optimization of the system operation with energy-efficiency-based speed control schemes that are a key factor to LCC efficient pumping and fan systems.

Another, a less studied topic is the detection of lifetime reducing operating states with the frequency converter: it is shown that the occurrence of high flow cavitation, fluid recirculation and fan stalling have an effect on the frequency converter estimates for the motor rotational speed and shaft torque. Correspondingly, mass increase in the fan impeller caused by the contamination build-up can be detected with the converter estimates before the occurrence of impeller imbalance. In both cases, the successful detection of adverse operating state can provide notable cost savings, if the resulting production losses and their effect on the system LCC can be avoided.

This article presents frequency-converter-based monitoring and optimization methods that can be used to optimize pumping and fan system life-cycle costs. The study is done both for commercially available products and for ideas that are verified with laboratory or pilot tests.

Introduction

Pumps and fans are the most common end-use devices driven by electric motors, making them a notable contributor to the global energy consumption [1]. Generally the life-cycle costs of a single pumping or fan system are dominated by its energy consumption, followed by the maintenance and possibly occurring production loss costs. The magnitude of energy costs is practically bound in the design and selection phase of the system and surrounding process, meaning that a change in the investment costs can result in notably larger change in the energy costs over the system lifetime [2]–[3].

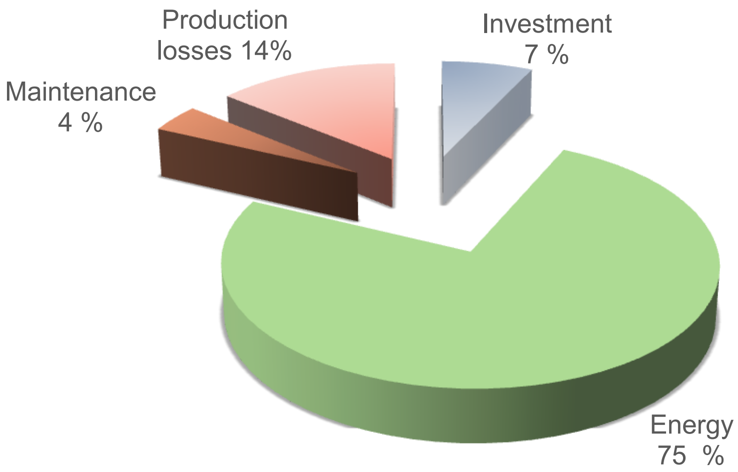

Fig. 1. Calculated life-cycle costs for a pulp pumping system [3].

Variable-speed operation of pumps and fans is one of the key factors to energy efficiently operating systems, as it allows regulation of output flow or pressure without adding hydraulic losses into the surrounding process [4]. Typically the variable-speed operation is realized by using a frequency converter for operating the electric motor at desired rotational speed: the common setup is to have a voltage source inverter and an induction motor that is coupled to a centrifugal pump or fan [1], [5].

Modern frequency converters are versatile devices, providing several application-specific monitoring and control functions for the motor-driven device [6]–[7]. As an example, internal PID controllers and control functions for multi-pump systems are standard features in pump-focused frequency converters [8]. Another increasing trend in frequency converters is to have an integrated programmable logic controller (PLC) that allows modification of the converter, and hence system operation according to specific needs [9]. As these features are nowadays combined with visually appealing user panel interface, converters start to resemble modern PLC systems.

Some frequency converters allow sensorless estimation of the pump or fan operating state, which can be further used for identification and monitoring purposes. This is primarily possible by accurate estimates for the motor rotational speed (n_{est}) and shaft torque (T_{est}), which are commonly available in vector and direct-torque-controlled frequency converters [10]. When these estimates are supplied to the characteristic-curve-based model for the pump or fan operation, for instance the flow rate and specific energy consumption can be determined without additional sensors on the device.

Information on the system operating state can be considered as a starting point for other functions that can improve the pumping or fan system operation in terms of LCC. Also the characteristics of the surrounding process are possible to identify with the frequency converter, and this can be further used by the monitoring and control functions especially in pumping systems. Frequency converters provide also several possibilities for detecting operating states that can make the pump or fan more prone to failure and thus reduce service-life of the system. In the worst case, mechanical failure of the pump or fan can reduce or even temporarily cease production with notable cost effects (e.g. 10 000 € per hour). Together these abilities can affect the main contributors of pumping and fan system LCC as visualized in Fig. 2.

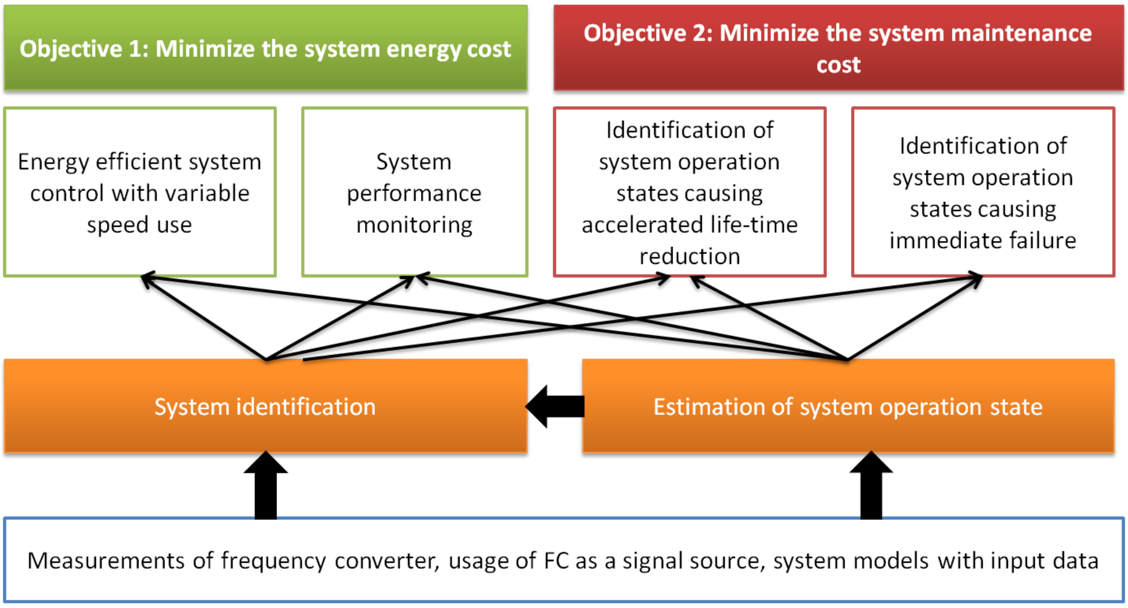

Fig. 2. Functions of a frequency converter in LCC efficient pumping and fan systems [11].

The object of this article is to present frequency-converter-based monitoring and control methods that can efficiently reduce life-cycle costs in pumping and fan systems. The study is done both for commercially available products and for ideas that have been verified with laboratory or pilot tests. Primary focus of the article is in sensorless methods that do not require additional measurement sensors on the pump or fan (later referred to as flow device). Therefore motor optimization methods, such as the flux optimization, are not further discussed in this article although they often improve the system efficiency at partial motor loads [12].

The study is started by revising an existing estimation method for the flow device operating state. After this, identification of surrounding process characteristics and their use in monitoring and control purposes is described. Fourth section describes some existing control schemes that seek to optimize energy efficiency while the pumping task is fulfilled. Finally, possible methods for detecting service-life reducing operating states, such as high flow cavitation and fluid recirculation in pumps, are discussed.

Operating state estimation by a frequency converter

Operating characteristics of a centrifugal flow device are commonly described by their characteristic curves for the flow rate Q vs. head H (or pressure p) and for the flow rate Q vs. shaft power consumption P at the nominal rotational speed n_{nom}. When the latter curve is compared with the present shaft power estimate (P_{est}) adjusted to this rotational speed, converter can determine an estimate for the flow rate (Q_{est}) and further an estimate for the head or pressure (H_{est}, p_{est}). Typically the adjustment of P_{est} or characteristic curves is done with Affinity laws ($Q \sim n$, $H \sim n^2$, $P \sim n^3$), which normally assume constant device efficiency regardless of the change in rotational speed.

When Q_{est} and P_{est} are known, also an estimate for the flow device specific energy consumption ($E_{s,est}$) is provided according to

$$E_{s,est} = \frac{P_{est}}{Q_{est}}, \quad (1)$$

which is also affected by the surrounding process:

$$E_{s,est} = \frac{\rho \cdot g \cdot (H_{st} + k \cdot Q^2)}{\eta}, \quad (2)$$

where ρ is the fluid density, g the acceleration due gravity, H_{st} the process static head, k the friction loss factor, and η the flow device efficiency. If the efficiencies of motor and frequency converter are known, (2) can also be used for the calculation of total system E_s.

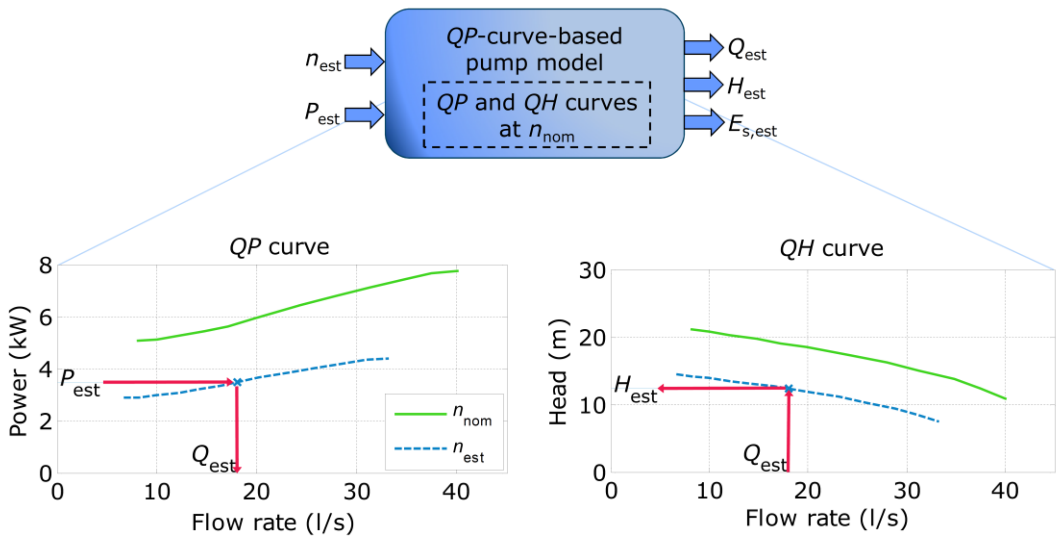

Fig. 3. Estimation of the flow rate and head with adjusted *QP* and *QH* characteristic curves.

Accuracy of this estimation method is primarily affected by the accuracy and shape of the device *QP* curve together with the accuracy of rotational speed and shaft power estimates (see [10] and [13] for further information). Thus the *QP*-curve-based model is primarily recommended for radial-flow flow devices that transfer clean water or air, and it is only available in frequency converters applying the vector or direct torque control method with internal motor model (such as Danfoss VLT 6000 HVAC and ABB ACQ810) [14]–[15].

In addition, some frequency converter models (such as ITT PS200) provide additional functions to check the accuracy of given *QP* curve and exact exponent of the power affinity law with ramp test against a closed valve [16]. In some models (such as Danfoss VLT 6000 HVAC), there is also possibility to provide individual pump characteristic curves to the device memory for several rotational speeds. According to laboratory tests with an accurate *QP* characteristic curve, estimation accuracy of flow rate can be within 5% of the measured flow rate [17]. In practice the estimation results may be less accurate, for instance within 10–20% of the measured flow rate because of the inaccurate or nearly horizontal *QP* curve shape.

Identification of surrounding process

Operating state estimates can be further used to identify the surrounding process, where the flow device is located. This information is for instance needed in the configuration of allowed rotational speed range, so the flow device would not be driven in adverse operating states. The identification data can also be used for predicting system operation at different rotational speeds, as the resulting flow device operating points are always located in the intersection of the device *QH* characteristic curve and the surrounding process curve. Often the surrounding process comprises both static and dynamic head, describing the amount of static (pressure) elevation and friction losses between the start and end points of the fluid flow.

Identification of surrounding process is based on collecting operating state estimates (Q_{est}, H_{est}) at various rotational speeds either during normal operation or during specific identification run, when the surrounding process is known to remain constant. As illustrated in Fig. 4, values for the process static head H_{st} and friction loss factor k can be then determined by finding their best-fit values with the least squares and Simplex methods:

$$H_{process} = H_{st} + k \cdot Q^2 \quad (3)$$

$$S = \sum_{i=1}^{m} \left(H_{est,i} - H_{st} - k \cdot Q_{est,i}^2\right)^2 , \quad (4)$$

which reaches its minimum value (S ≈ 0) when H_{st} and k form the best-fit curve compared with the estimated operating states [13].

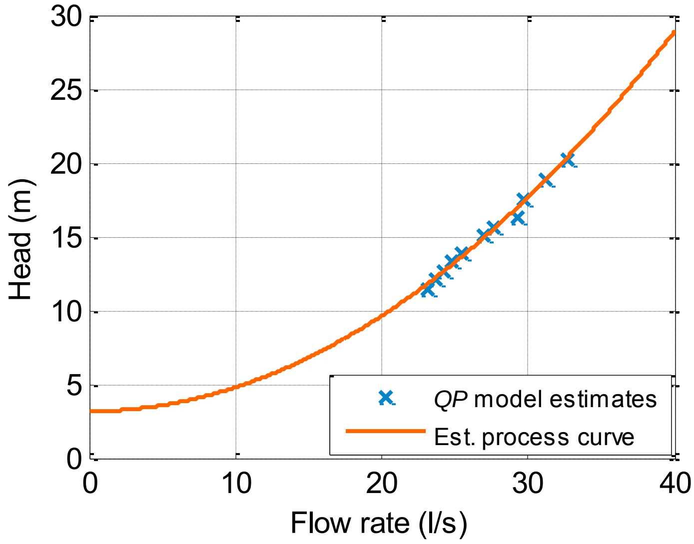

Fig. 4. Estimation of the surrounding process with *QP* model operating state estimates.

As an alternative, just the static head in the surrounding process can be identified with the use of start-up test method described in [18]. In this method, the H_{st}-related minimum rotational speed n_{min} required for the flow production is determined by observing the derivatives of T_{est} or P_{est} as a function of rotational speed. Fig. 5 illustrates an example how the production of flow around 750–800 rpm clearly increases the present torque derivative d*T*/d*n* against its cumulative average, allowing the identification of n_{min} for the pumping system.

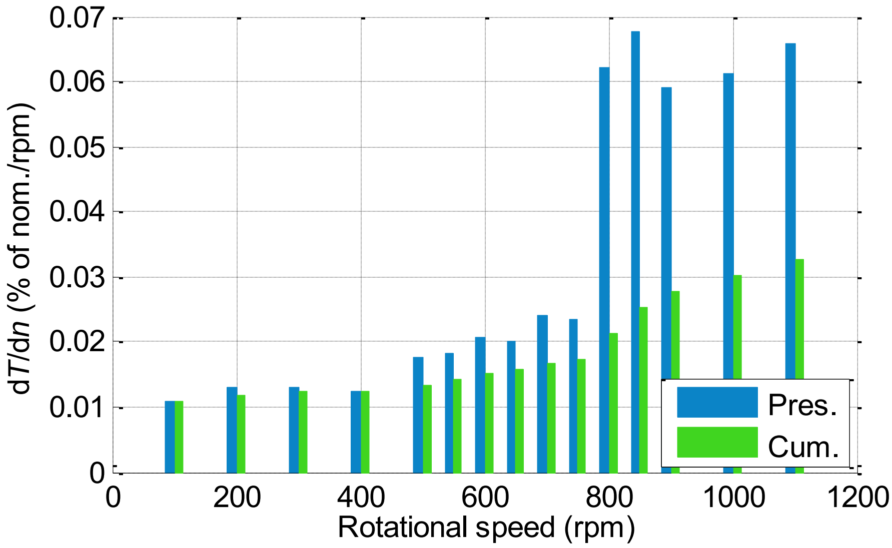

Fig. 5. Identification of n_{min} by observing the present d*T*/d*n* against its cumulative average. The production of flow begins around 750–800 rpm.

When the surrounding process is known, it can be used for several configuration and control purposes. For instance, the flow device operation at zero flow rate condition can be avoided with n_{min}. As another example, the determined H_{st} can be used in the energy audits as reference information.

Information on the surrounding process also allows the determination of the most energy efficient rotational speed for the system by calculating its specific energy consumption E_s (Wh/m^3) at a range of rotational speeds. This utilization of surrounding process information is especially feasible in wastewater systems where reservoirs are periodically drained with level-controlled pumps, and the process static head changes during the reservoir draining [19].

Fig. 6 provides an example how the E_s-related optimum rotational speed is linearly affected by the change in process static head: if the frequency converter is equipped with level measurement sensor or suitable sensorless estimation method, it could be modified to select the applied rotational speed reference according to the present process static head and this kind of H_{st}/E_s-based control curve. Compared with fixed-speed operation, E_s-based rotational speed ramp can provide further energy savings ranging from few to tens of percent. So far, possibility for having a linear speed reference against the measured fluid level has only been available in the additional software package for Vacon NX frequency converters [20], as the level control is commonly performed in a separate PLC. ABB's ACQ810 frequency converter has a dedicated level control macro, but it only allows setting the normal and high level for the rotational speed [15].

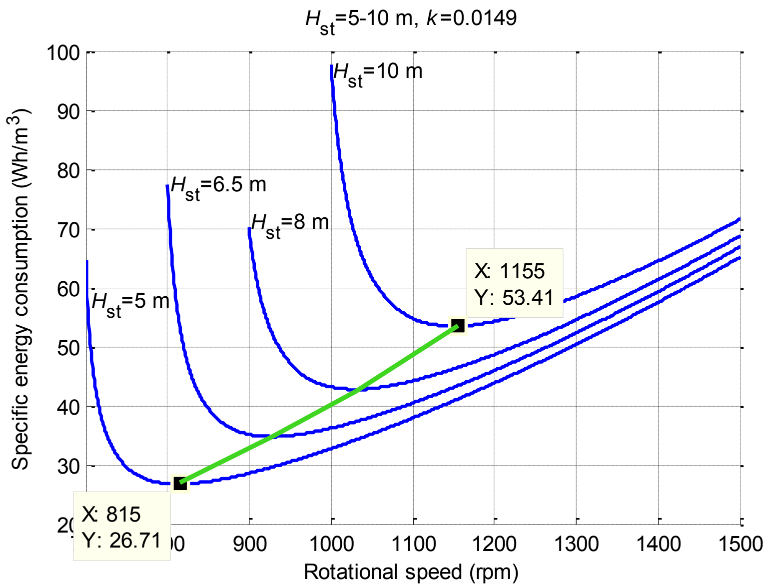

Fig. 6. The effect of process static head on the E_s-based optimum rotational speed.

Third interesting application to use identified process could be in the setting of reference values for the system specific energy consumption that can be monitored by the frequency converter. It has been previously shown how relative E_s could be used as a criterion for determining the best energy efficiency area of the pump. In [21], base value for the E_s was selected according to the pump best efficiency point at its nominal speed, although it should rather reflect the base situation for the pumping system operation in the surrounding process. With properly selected E_s base value and the use of trend monitoring feature, the need for air duct or water piping cleaning and other adverse events can be seen as the increase in the relative E_s.

Energy efficiency optimizing control methods

The use of variable-speed operation instead of valves and bypass lines for flow and pressure control is the first and often the most effective step towards a LCC efficient system. If the system or surrounding process does not possess any degrees of freedom[1], then the required flow rate or pressure can be provided with speed-controlled operation: a laboratory demonstration of the sensorless pressure control with ABB ACQ810 frequency converter is given in [22].

When degrees of freedom are available, even further energy savings are possible with intelligent use of variable-speed operation. In the case of reservoir pumping applications, the previously-introduced E_s-based control of pump operation is often possible, as the pumping task is to empty (or fill) a reservoir without strict time limits. A sensorless method to realize this E_s-based operation is described in [23]. E_s-based control of rotational speeds should also be possible with parallel-connected pumps, where the desired flow rate (or head) can be realized multiple ways. An example of improved control for parallel-connected systems is given in [25], and a similar version of it is available in Vacon frequency converters as the Multifollower PFC application [8].

[1] Degrees of freedom (DoF) allow realization of the given task in various ways. Typical examples are the applied rotational speed, execution time and duration, and the opportunity to use parallel-connected pumps with or without speed control [24].

In some cases, variable-speed operation can be used to optimize both the pumping system and surrounding process operation in terms of energy efficiency. Fig. 7 provides an example of central heating system equipped with thermostats that act as control valves. In these systems, the circulator pump must be able to provide enough pressure to the radiators regardless of the thermostat valve setting. The required pressure for radiators is ensured by operating the circulator pumping system with a constant pressure reference; traditionally this has been realized with the use of a pressure relief valve and currently with the use of variable-speed operation.

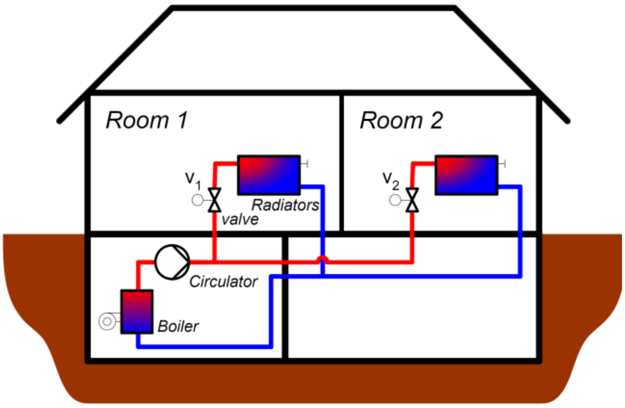

Fig. 7. An example of central heating system having a circulator pump and two radiators equipped with thermostat valves [26].

However, the use of constant pressure reference is not the most energy efficient approach for these systems, where the primary task is to provide flow to the radiators according to the present need, not a constant pressure into the system. Control-wise this means that as thermostat valves close down because of the reduced need for flow[2], rotational speed of the circulator pump can be decreased to result in the opening of thermostats and the reduced flow rate with less power consumption [26]. In circulator pumps this idea was first realized in 1995 by Grundfos [27], and provided as sensorless version in 2003 by Vogel Pumpen/Lowara with the Hydrovar brand (see Fig. 8 for an example) [28]. This feature is nowadays available in several frequency converters under the name advanced pressure control or flow compensation.

Another example of control feature that may save energy is the sleep boost mode that prevents the pump operation at low and inefficient rotational speed during low demand periods. In this feature, only boost runs at normal rotational speed are done periodically to maintain for instance certain pressure in the system. This feature is available for instance in the ABB ACQ810 frequency converter [15].

[2] Closing the thermostat valve increases friction loss factor k. This has a detrimental effect on the system energy efficiency and specific energy consumption E_s, as seen in (2).

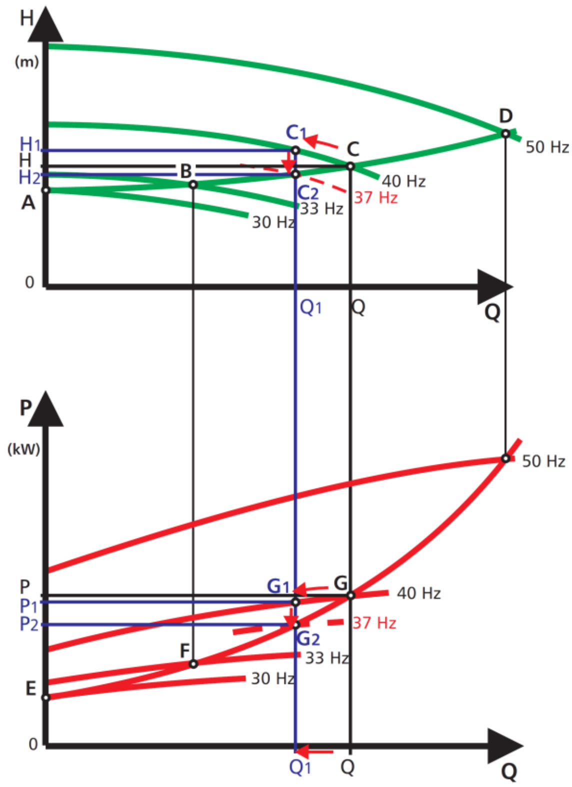

Fig. 8. Graphical example of sensorless pressure control method provided in Hydrovar frequency converters. When flow demand decreases (C→C_1), close of thermostat valves is compensated by decreasing the rotational speed until the pump operates on the desired process curve (C_2, G_2) that is detected by monitoring the converter power estimate [28].

Detection of service-life reducing operating states

Besides realizing energy efficient system operation, a frequency converter can be used as a sensorless condition monitoring unit for the pumping or fan system. Information on the system operating state (Q_{est}, H_{est}) can indicate if the flow device is more prone fluid recirculation, stalling, or high flow cavitation: as a simplified version of this, frequency converters can warn if the power consumption of the flow device too small or high that may indicate a dry running pump or pipe leak, respectively [7], [29].

In the case of centrifugal pumps, both the high flow cavitation and fluid recirculation can also affect the time-domain behavior of n_{est} and T_{est} while the pump is operating in steady state. Hence, the continuous comparison of these estimates (n_{RMS}, T_{RMS}) with their base values ($n_{RMS,N}$, $T_{RMS,N}$) has been proposed to be used for the detection of adverse pumping system operation [30]. Fig. 9 introduces how the relative time-domain variation in rotational speed and shaft torque estimates has acted at different flow rates, when a Sulzer APP22-80 centrifugal pump was driven at constant 1450 rpm. One can see increase in the relative time-domain variations, when the flow rate falls below 7.5 l/s that is the manufacturer-informed limit for continuously allowable operating region.

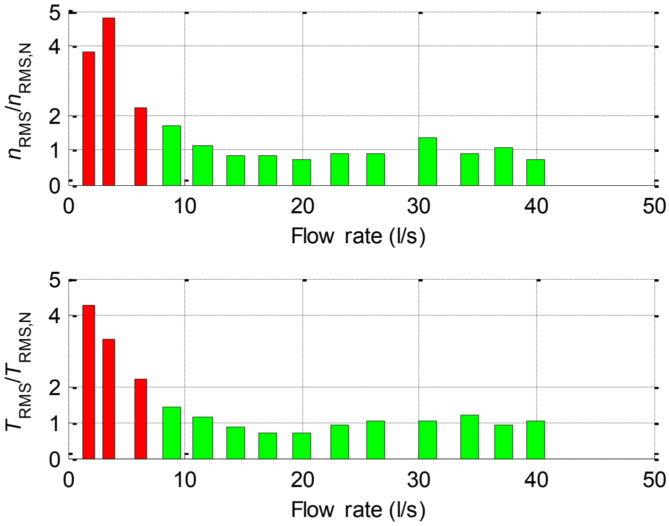

Fig. 9. Detection of fluid recirculation occurrence (red bars) is possible by monitoring relative time-domain variation of n_{est} and T_{est} [30].

This phenomenon is also present when high flow cavitation occurs in the pump, and it has been verified with three centrifugal pumps in [30]. The proposed method has also been verified to be usable with centrifugal fans, where stalling occurs when there is not sufficient air flow through the fan impeller and the flow detaches from the blade surface [31].

A frequency converter can also provide means for the detection of contamination buildup on the fan impeller even before it leads to the imbalance in impeller. In [32], a method is proposed to determine present mass (i.e. condition) of the impeller. It is based on the step-wise torque startup of the fan system and calculation of the fan moment of inertia from the acceleration of the fan. By repeating this startup test periodically, increase in the impeller mass caused by the contamination buildup can be detected in time. Fig. 10 illustrates the possible effect of contaminated (or jammed) impeller on the fan rotational speed, when a step-wise torque reference is applied to rotate the fan.

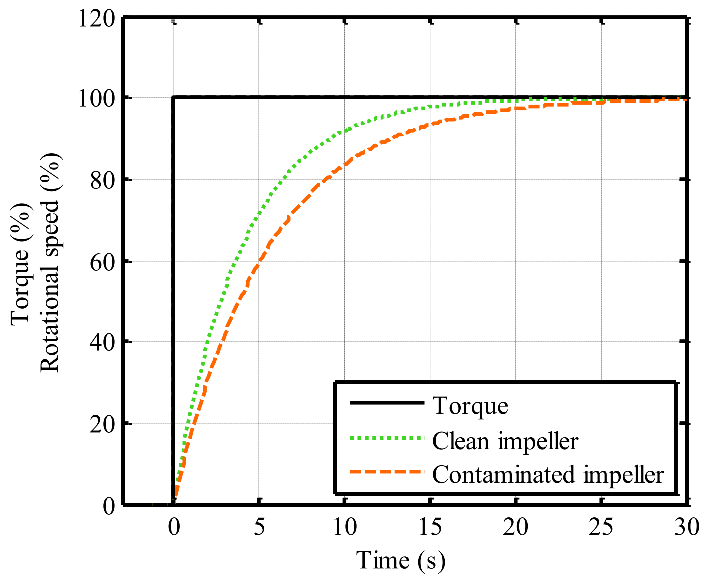

Fig. 10. Effect of impeller contamination on the resulting fan speed, when a step-wise torque is applied [32].

The proposed method has been verified with laboratory measurements for a radial flow fan system that consists of a FläktWoods Centripal EU 4 MD 630 radial blower, an ABB induction motor, and an ABB ACSM1 frequency converter that uses direct torque control. The test setup and portion of the obtained estimation results are illustrated in Fig. 11.

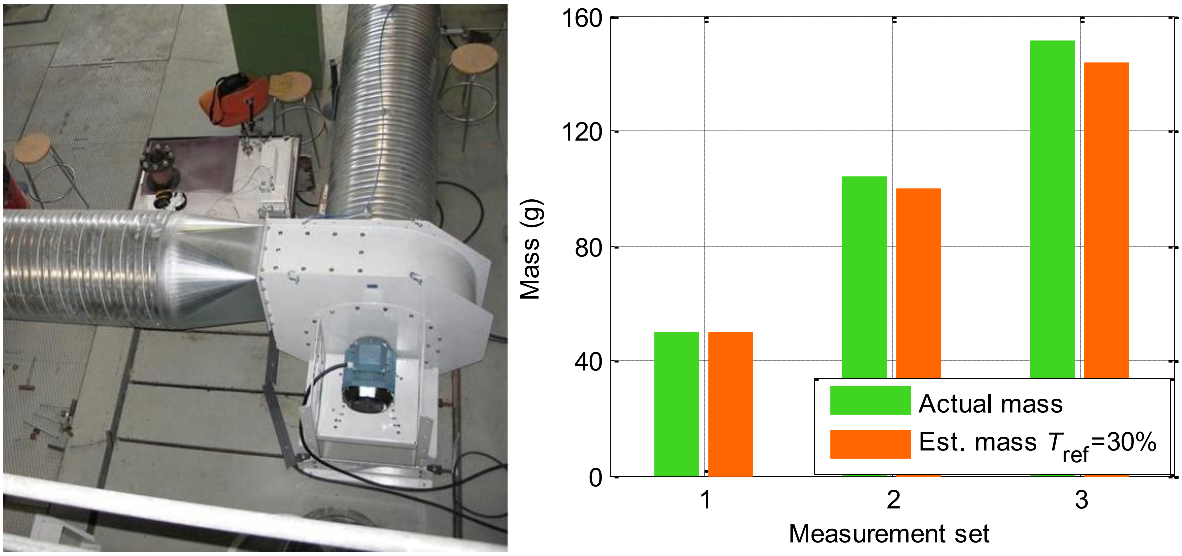

Fig. 11. Laboratory test setup and estimation results for the impeller mass increase [32].

As the sensorless sensing of adverse operating states and different failure modes has been extensively studied with fixed-speed systems and frequency converters allow new possibilities for condition monitoring, authors expect to see more research, such as [33], and also commercial products related to this topic.

Summary

A modern frequency converter can estimate the state and performance of system operation without additional measurement sensors. This ability provides several possibilities to optimize pumping or fan system operation and the resulting life-cycle costs (LCC) that mainly consist of energy and maintenance costs. Especially new, energy-efficiency-based control methods can provide notable cost savings: pressure control in heating systems is a sophisticated example how the rotational speed decrease can improve both the pumping system and surrounding process operation in terms of energy efficiency. In addition to this, modern frequency converter can be used for condition monitoring purposes, allowing optimization of maintenance and production loss costs.

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Efficiency in Boiler Feed Pumps for Industrial Steam Generation

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Abstract

This paper presents some opportunities to improve feedwater system efficiency for industrial boilers, usually consisting of multistage centrifugal pumps driven by three-phase induction motors. There is abundant literature on the efficiency in steam boilers. However, few deal exclusively with feedwater systems.

The total horsepower in boiler feed pumps and the corresponding energy consumption estimated for Brazilian industries are as follows: 110.5 MW_E of motor driven power and a yearly electricity consumption of 442 GWh for a population of 7800 steam boilers, approximately.
It is estimated that there can be an efficiency improvement in feedwater systems for industrial boilers of 30% on average. To a large extent these opportunities reside in older boilers that are very common in the Brazilian industrial sector.

The most common causes for the low efficiency of feedwater systems are: the control loop of the feedwater, oversized boilers and excessive operational pressure set. Sometimes the boiler feedwater system can present more than one problem simultaneously.

Any kind of solution involves some form of intervention in boiler feed pumps, such as: impeller trim, speed regulation, new pump and number of pumps. Each problem may have more than one solution.

Three distinct industrial steam generation facilities were selected in which common inefficiencies are present. The suggested solutions were analyzed. In these three cases, the improvement in efficiency can get to 37%.

Introduction

Steam can be used for power generation, process and space heating. Boilers for power plants are very large and their characteristics are very specific. On the other hand, boilers for space heating are usually small and not used in Brazil. Intermediate boilers are predominant in the industrial sector. The steam produced is used for a wide range of heating processes. In large industries, steam can be used for the cogeneration of electricity.

Steam boilers can be classified by their thermal capacity (MW_T) or by steam production (t/h). Figure 1 illustrates the range of boiler applications [1].

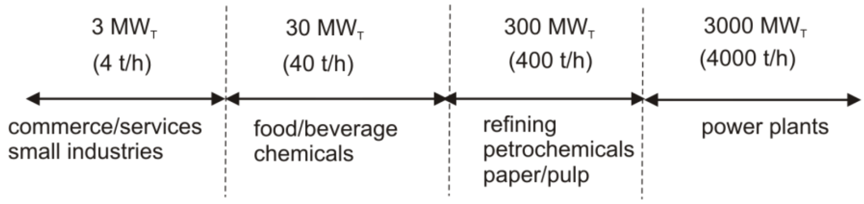

Figure 1. Range of boiler applications.

This paper deals exclusively with industrial boilers. In general, the thermal capacity of industrial boilers ranges between 3 MW_T and 300 MW_T, at some point between 4 t/h and 400 t/h of steam output. Usually, boilers with less than 30 t/h of output are of the firetube type, and while the ones with over 30 t/h are of the watertube type. Feedwater pumps and draft fans are the main apparatuses driven by electric motors in boilers to generate steam for industrial purposes. Both set of equipment have numerous opportunities for improvement in their energy performance. However, in industrial facilities, the thermal efficiency of boiler receives greater attention due to fuel consumption. The efficiency of these systems is considered only in large boilers of power plants. This paper is going to present some opportunities to improve the feedwater system efficiency for industrial boilers, usually consisting of multistage centrifugal pumps driven by three-phase induction motors.

The total installed horsepower in boiler feed pumps and the corresponding energy consumption were estimated for Brazilian industries. There is no such data survey in Brazil. This estimate was performed through relations based on available data from the USA. Basic pieces of information were presented to support the energy efficiency assessment of pumps, including flow control systems. The most common causes of inefficiency were identified. The three main reasons were analyzed based on real situations of different industrial plants. It is estimated that the efficiency improvement in feedwater systems for industrial boilers can reach 30% on average.

Inventory of industrial boilers

An inventory was conducted in the USA. It indicates that there are about 43,000 boilers in the industrial sector with a total capacity of 470 GW_T, [1]. The average capacity of boilers is 11 MW_T. Their energy consumption is estimated at 6,500 TBtu (154 x 10^6 toe*). This represents between 35% and 37% of total fuel consumption in the industrial sector [1, 2].

Approximately 21,000 industrial installations have boilers, i.e. 10% of all installations. About 76% of boilers are over 30 years old. For large boilers, this percentage decreases to 66%. Only 7% of the total capacity of boilers is less than 10 years old, [1].

The boiler market grows quickly during the industrial development of a country and tends to decline to a stable substitution market after the industrialization process. Their growth in sales is currently concentrated in developing countries, especially China and India, [3].

The inventory shows that five industries account for 71% of the total population of boilers and 82% of installed capacity. They are: pulp and paper, chemical, oil refining, food and beverage and primary metals. Another study [2] reports that only four segments account for 88% of total fuel consumption for steam generation. They are: (1) pulp and paper, (2) chemical (3) oil refining, (4) food and beverage. In these industries, the shares of energy with steam generation in relation to the total fuel consumption are 75%, 44%, 31% and 52%, respectively [2, 4]. The graphs in figure 2 show the participation of boilers in each segment with respect to the total population, capacity and consumption of these four industries.

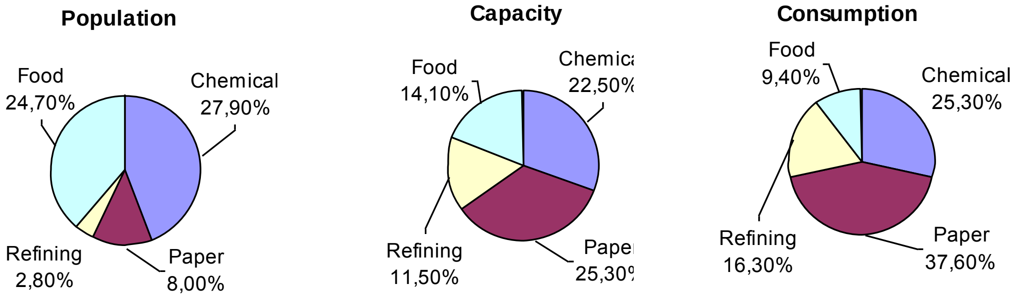

Figure 2. Participation of boilers in the US industrial sector.

In Brazil, there are no reliable statistic terms on steam generation. A rough estimate could be made by applying the data from the U.S. to the actual Brazilian consumption. Table 1 shows the total fuel consumption of four industries in Brazil, [5], and the estimated consumption for steam generation considering the indices of the U.S.

(*) toe: tons of oil equivalent = 42.000 MJ

Table 1. Estimation of energy consumption for industrial steam generation in Brazil.

Industry	Total consumption (10^3 toe)	% steam gen	Cons. Steam gen (10^3 toe)
Paper and pulp	8540	75%	6405
Chemical	5450	44%	2398
Refining[1]	20376	31%	6316
Food and beverage	20630	52%	10727
Subtotal	54996		25846

(1) includes refinery, ethanol plants, natural gas processing, etc. [5].

Assuming that these industry segments represent 88% of the total consumption for steam generation, as it occurs in the U.S., it is concluded that the final consumption is 29.3×10^6 toe, or about 19% of the U.S. consumption.

Based on American studies, [1], with a total capacity of 470 GW_T and an annual consumption of 154×10^6 toe, it follows that the average operational time per year was estimated at 4,000 hours. Likewise, the Brazilian capacity would be 85.5 GW_T. The average capacity of industrial boilers in the U.S. is 11 MW_T. Considering the same average for Brazil, it is inferred that the population of Brazilian boilers would be on the order of 7,800 units.

A thumb rule widely used in Brazil believes that 1 toe generates 15 tons of steam, i.e. the average boilers efficiency is 70%. This represents an average steam production of 110×10^3 t/h (29.3 $\times10^6\times15/4000$). Assuming, as in the case of the U.S., that the medium pressure of steam produced is 2.2 MPa (≈ 22 bar) and the average efficiency of the motor and pump assembly is 65%, the drive power involved would be of about 110.5 MW_E (equation 1), and an electricity consumption of 442 GWh per year.

Boiler feed pump

The motor power (W) to drive the pump is given by equation 1:

$$P_{ele} = \frac{\gamma . Q . H_p}{\eta_p \eta_m} \quad (1),$$

where, γ is the specific weight at feedwater temperature (N/m^3), Q is the flow rate (m^3/s), H_P is the total pump discharge head (m), η_P is the pump efficiency and η_m is the motor efficiency.

The total head required is obtained by adding the following parcels: steam pressure in the boiler (p/γ = cte), head loss in piping ($h_f \approx k.Q^2$), and geometric height difference between the boiler and the deaerator (h_g = cte). The head loss in piping involves losses in flow control valves, check valves, stop valves, fittings, pipes (including passes for economizers and super heaters, if there is any), and other devices. Typically, the steam pressure accounts for approximately 80% of the total head at a nominal pump flow rate.

$$H_b = \frac{p_{vap}}{\gamma} + h_f + h_g \quad (2).$$

The centrifugal pump characteristic curve (H x Q) can be approximated, as equation 3,

$$H_p \cong H_0 - a.Q - b.Q^2 \quad (3),$$

where, a and b are constants for each pump, H_0 is the shut-off head (m) and Q is the flow rate (m^3/s). The system operating point is given by $H_P = H_b$.

Figure 3 shows the characteristic curves of the pump (H_P x Q and η_P x Q), and the feedwater system of an industrial boiler (H_b x Q). The figure on the left shows two distinct points of operation, increasing the valve control opening along the path from 1 to 2. The figure on the right shows the same change in flow produced by a pump speed increase where the valve opening is kept constant. By applying equation 1, it is obvious that the energy efficiency for the flow variation is greater in the second case.

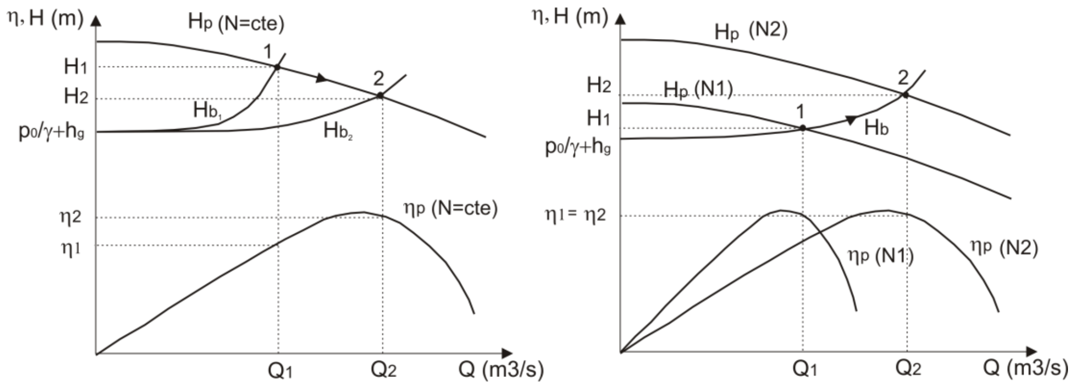

Figure 3. Flow control by throttling and variable speed.

For pump sizing, seven steps should be considered, [6]: number of pumps, feedwater control type, total head of the system (H_b), discharge (Q), NPSH required, protection for minimum flow, and the verification of the conditions established by ASME.

If the steam plant is “base loaded” with very little load swing, one pump may be used to serve multiple boilers. Otherwise, there must be at least one pump for each boiler. The modulating feedwater control should be used. The calculation of H_b has already been explained above. Special attention must be given to the NPSH, since the feedwater is generally at an elevated temperature. A "gap" between the available NPSH and the one required by the pump must be sufficient to avoid cavitation problems. If it is necessary to protect the pump for a minimum flow by recirculation, it should be 20% of the flow at the best efficiency point of the pump (Q_{BEP}), or what is stated by the manufacturer.

The calculation of the net pump flow rate (Q_{nom}) must take into account the boiler evaporation rate (Q_{EV}) and its catch-up capacity (Q_{CT}). The evaporation rate includes the steam flow to the system, purge, and possible diversion to deaerator. The catch-up capacity should be 25% of Q_{EV} for modulating control and 100% of Q_{EV} for on/off control. The ASME Code requires that the pump is able to maintain a flow rate that is equal to evaporation rate at pressure 3% greater than set pressure to the safety valves of the boiler.

Feedwater control

Steam load in industrial facilities is not constant. It varies throughout the day (time variation) and along the year (seasonal variation). So, feedwater flow should also vary. This variation is obtained by throttling the flow control valve or the variable speed pump, as illustrated in figure 3. The control system of the boiler controls these devices. Signals obtained by level sensors are processed by means of an inverse relation, that is, the higher the water level in the boiler is, the lower the flow rate gets, and vice versa. Differential pressure signals may also be used. The water level in the boiler must remain within maximum and minimum limits. Excess water causes flooding of separation moisture devices, causing drag of the liquid phase along with steam into the system. Lack of water can cause overheating of the heat exchange surfaces.

When the steam demand increases, the formation of bubbles in water increases, the average density of the mixture reduces, and it increases the water level in the boiler, even in absence of water intake. This phenomenon is known as "swell". In contrast, if the steam demand decreases, the average density of the mixture increases and lowers the water level in the boiler, which is a phenomenon called as "shrink". These phenomena cause unwanted fluctuations in the boilers feedwater.

There are four modes for boiler level control: (a) turning the pump on/off, (b) through feed control, (c) variable speed pumps, or (d) the combination of the last two. Figure 4 shows a schematic of these modes, [7].

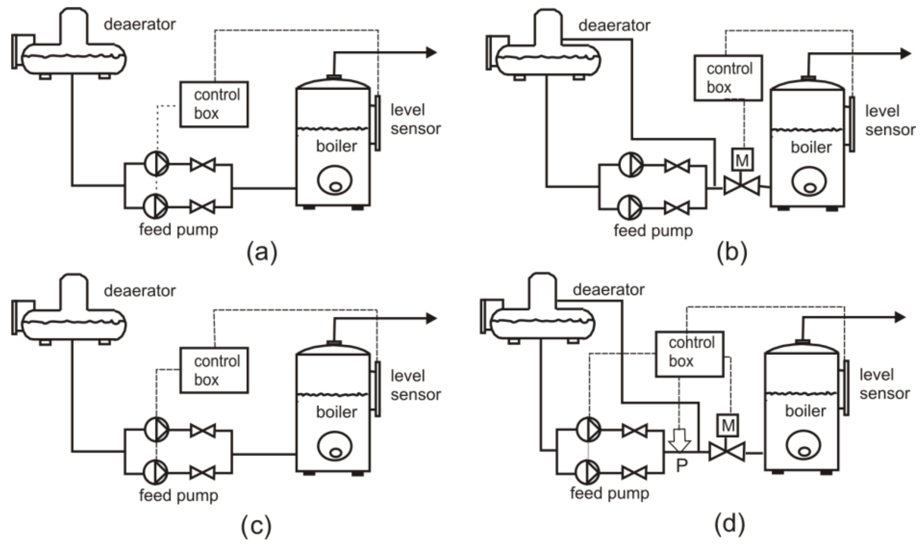

Figure 4. Modes of boiler level control.

For the aforementioned reasons, the on/off control is applied only for small boilers. When the water level falls, the pump starts pumping a large quantity of relatively cold water into the boiler. This will reduce the quantity of steam in the boiler and result in a pressure drop. Water may possibly be dragged along with the steam into the system. The other modes are applied in larger boilers, known as modulating controls. The control loop can have one (level), two (level and steam flow rate), or three elements (level, steam and water flow), [8, 9]. The signal processing of steam and water flow elements allows a smooth oscillation of the boiler feed. In the case of control by means of throttling valves, whether being with or without variable speed pump, the existence of recirculation systems is strongly recommended, i.e. a link between the pump discharge and the deaerator. This ensures a minimum pump flow in order to prevent damage by overheating and other detrimental effects of reduced flow in pumps.

Opportunities for efficiency improvement

There is abundant literature on the efficiency in steam boilers, [10 - 12]. However, few deal exclusively with feedwater system. As it can be seen from equation 1, the input power of the pumps depends on pressure (discharge head), flow rate, and pump efficiency. All these variables are linked to characterize the performance of the pump. Based on studies of various steam generation plants for industrial purposes, it was observed that some inadequacies are present routinely. Usually, there is more than one mismatch in the same plant. A significant part of this situation is due to the age of the facilities with their old projects and equipment. Highlighted, are three very common situations:

- Control loop of the feedwater system. Typically, there are boilers with a modulating control of a single element, namely the control of the throttling valve is done solely with the water level signal of the boiler. The pump flow becomes very swinging, i.e. it fluctuates from very low flows to one beyond the rated condition. Sometimes the pump reaches a shut-off state briefly. This causes severe vibration due to hydraulic imbalance and a severe degradation of mechanical conditions, especially the sealing system. Efficiency is greatly reduced by low flow.

- Oversized boiler. Sometimes the boiler is selected for attending a particular load which was not observed. There are several reasons for this fact. In this case, the pump operates at a very low flow which is far from its best efficiency point (BEP). Thus, the pump efficiency can be dramatically reduced. It is well known that pumps continuously operating with very low flows are subject to a higher failure rate.

- Steam pressure reduction. It is not uncommon to find facilities in which the set pressure of the boiler is higher than the processes needs. As an example, a certain industrial plant had a small boiler (5 t/h) with pressure set to 10 bar_g. The saturated steam in this condition has a temperature of 183 °C. None of the heating processes required temperature that is higher than 164 °C, or pressure of 6 bar_g. Without any major difficulties, [12], the boiler could be set to produce saturated steam at 7 bar_g, which is sufficient to increase the feedwater system efficiency in 30%. Another situation found routinely is the steam consumption in two levels of pressure. Parts of the processes demand 6 bar_g and others 18 bar_g, for instance. In this case, the boiler generates steam in 18 bar_g and the level of 6 bar_g is obtained by pressure reducing valve. Therefore, the energy dissipated in the valve is supplied by the pump.

Three cases of each of the aforementioned situations are presented below.

Cases

Case 1: Inadequate control loop.

Watertube boiler, natural gas, 30 t/h, 2 feedwater pumps (1 stand-by), loop control with 1 element (LIC), 25 years, feedwater at 60 °C.
Note: draft fan motor, 100 cv.

Centrifugal pump, barrel type, 7 stages, gland packing, 3500 rpm, 60 cv.
Design: Q_{proj} = 39 m^3/h, H_{proj} = 268 m, η_{proj} = 66%,
Nominal: Q_{nom} = 30 m^3/h, H_{nom} = 341 m; η_{nom} = 64%.
Characteristic curves (adjusted)

$$H_P = 329{,}5 + 1{,}005.Q - 0{,}0725.Q^2 \quad (4),$$

$$\eta_P = 0{,}0002.Q^3 - 0{,}0658.Q^2 + 3{,}9026.Q - 0{,}1548 \quad (5).$$

Operating time: 24 hour/day.

Monthly steam production (t): see figure 5.

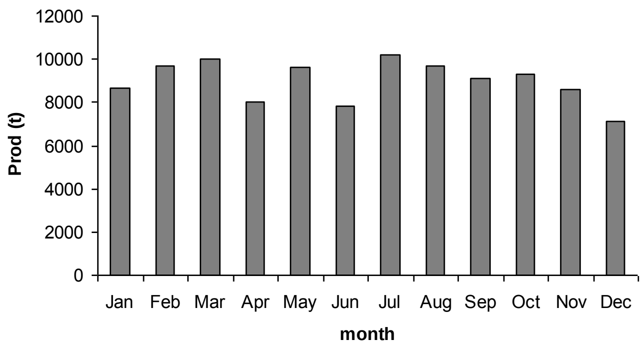

Figure 5. Monthly production (t).

Load of a typical day: see figure 6 and table 2.

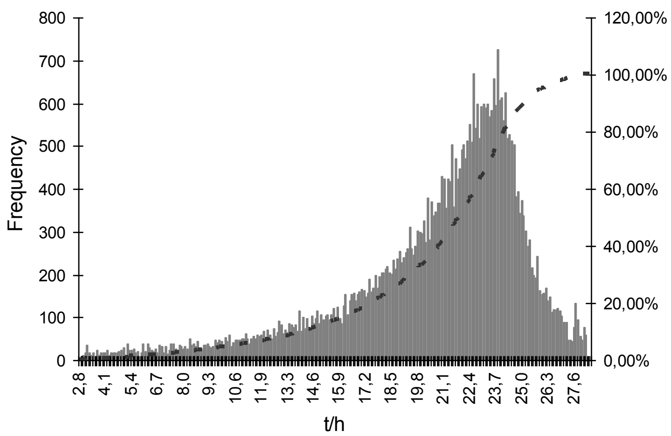

Figure 6. Histogram and cumulative output percentage on a typical day (24 hours).

Table 2. Steam production characteristics on a typical day - average production for bands.

Bands (t/h)	< 15 t/h	15 – 20 t/h	20 – 25 t/h	> 25 t/h
% time	12.2 %	21.3%	55.2%	11.3%
Avg. Output (t/h)	10.76	18.00	22.73	26.17
H_P (m)	331.9	324.1	314.9	306.2
η_P (%)	34.4%	49.9%	56.9%	60.5%
P_P (kW)*	28.3	31.8	34.3	36.1
EE (kWh/day)*	82.86	162.56	454.4	97.9

(*) P_P: pump input power, EE: input energy.

The considered average production of steam during the day was 20.6 t/h. The total energy consumption was 798 kWh. If a control system with 3 elements could ensure a uniform discharge of 20.6 t/h, the total head of the pump would be 319.4 m and its efficiency of 54%. With this, the consumption in over 24 hours would be of 796 kWh. Therefore, there is no energy efficiency improvement to be taken into account.

Figure 7 shows the feedwater flow during 1 hour of a typical day (measurements every 2 seconds).

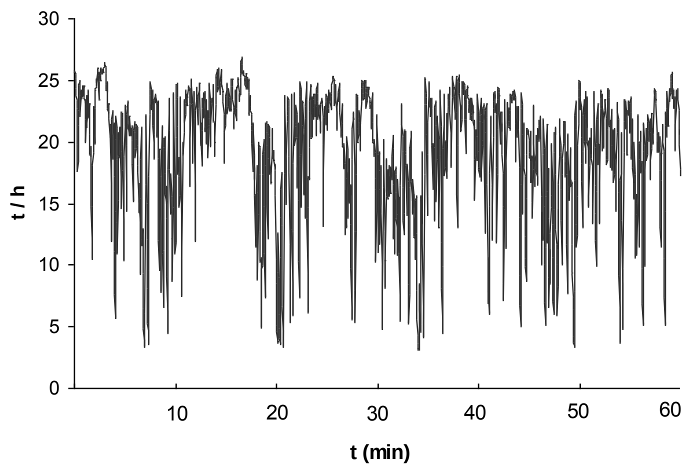

Figure 7. Boiler feedwater flow rate for 1 hour.

The swing of the discharge causes loud noise and vibration in the pump. The gland packing failure rate is quite high. If the production were uniform, the problem of damage to the gland packing would be greatly improved.

It is possible to introduce a frequency inverter under the control loop of 3 elements. In this case, the flow control valve would be kept fully open for operating the pump at design conditions, i.e. Q = 39 m^3/h, H_P = 268 m, η_P = 66%. The static head of the system is 197 m. The adjusted curve is given by equation 6.

$$H_b \approx 197 + 0{,}0467.Q^2 \qquad (6).$$

With the valve open, head H_b is equal to 217 m. Applying Q = 20.6 m^3/h and H = 217 m, the pump shut-off head equals H_0 = 227 m (equation 4). Through similarity ratio (equation 7), one obtains a rotation of 2900 rpm.

$$\frac{H_{01}}{H_{02}} = \left(\frac{N_1}{N_2}\right)^2 \qquad (7).$$

To determine the input power in this case, it is necessary to estimate the efficiency of the pump. For this, the flow of 20.6 m^3/h at 2900 rpm needs to be reflected in the 3500 rpm curve, applying the similarity relations of equation 8.

$$\frac{Q_{1'}}{Q_2} = \frac{N_1}{N_2} \quad (8).$$

This results in a reflected flow of 24.8 m^3/h. With the application of the efficiency equation, its estimated value is 59.2% (equation 5). In this new condition, the input power is 20.6 kW. Thus, the daily energy consumption would be of 495 kWh/day for a uniform steam production. The gain is 38% compared to the previous situation of 798 kWh/day. Figure 8 illustrates this new condition.

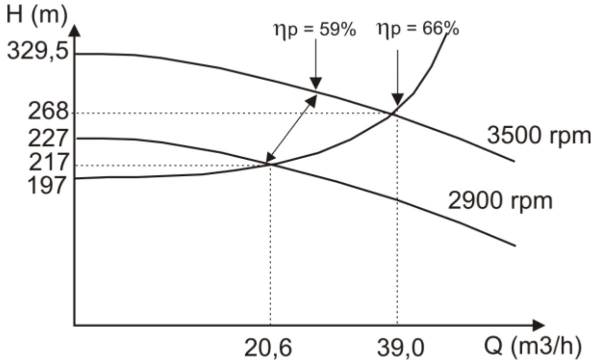

Figure 8. Pump operating conditions for a steam output of 20.6 t/h.

Case 2: Oversized boiler.

Two watertube boilers, sugar cane bagasse, 150 t/h each, 43 bar_g, 410 °C, loop control with 3 elements (LIC, FIC_{water}, FIC_{steam}), feedwater at 110°C.
Note: the power of the primary and secondary fans sum is by 450 cv per boiler.

Two centrifugal pumps, 8 stages, 350 cv each, 3500 rpm, parallel operation,
Design: Q_{proj} = 98 m^3/h, H_{proj} = 608 m, η_{proj} = 72%
Nominal: Q_{nom} = 79 m^3/h, H_{nom} = 656 m, η_{nom} = 68%.
There is a further pump driven by the steam turbine in parallel with the electrical assembly, input power 700 cv, Q_{proj} = 196 m^3/h, H_{proj} = 608 m.

Operating time: 220 days/year, 24 hours/day.

The average output and the included blowdown: see table 3.

Table 3. Average output of each boiler (C1 and C2) and the set*

Boiler	C1 (t/h)	C2 (t/h)	C1 + C2 (t/h)	C1+C2 (m^3/h)
Average	60.6	53.4	112.1	118
Max	71.3	71.3	129.2	136
Min	49.9	41.3	98.8	104

(*) average, maximum and minimum values for each boiler are not concurrent.

The two boilers operate simultaneously. For the average feeding of 118 m^3/h of the assembly, each pump has a discharge medium under the following conditions:
Q_{op} = 29.5 m^3/h, H_{op} = 720 m, η_{op} = 40%.

The input power to drive each pump will be P_{op} = 137.6 kW. In this case, there are four pumps operating simultaneously. The oversizing is evident. It only takes one boiler to meet the demand.

When shutting down one boiler, the operating condition of each pump becomes:
Q_{op} = 59 m^3/h, H_{op} = 680 m, η_{op} = 60%.
The input power for each pump will be P_{op} = 173.3 kW.

The input power in the former situation is 550 kW (4 x 137.6) and in the proposed situation is 347 kW (2 x 173.3). An improved efficiency of 37% is obtained.

Case 3: High pressure (old installations)

Firetube boiler, natural gas, 20 t/h, 18 bar_g, feedwater temperature 50 °C, loop control (LIC, FIC_{steam}), two feed pumps (1 stand-by).

Centrifugal pump, barrel type, 5 stages, mechanical seals, 3500 rpm, 50 cv.
Design: Q_{proj} = 24 m^3/h, H_{proj} = 235 m, η_{proj} = 58%.
Nominal: Q_{nom} = 20 m^3/h, H_{nom} = 240 m, η_{nom} = 53%.

Operating time: 16 hours/day, 6 days/week.
Average output: 16 t/h.
Q_{op} = 16 m^3/h, H_{op} = 243 m, η_{op} = 46%, P_{op} = 23 kW.

The plant consumes 90% of the steam at a pressure of 10 bar_g/183°C and only 10% at a pressure of 18 bar_g/208°C. All the steam is generated at 18 bar_g, and then reduced to 10 bar_g through pressure reducing valve, as illustrated in figure 9. Only one point of the plant consumes steam at 18 bar_g. Strictly speaking, this point should have its own heating system, or else the process should be investigated for the possibility of reducing its temperature from 200 °C down to 180 °C. The elimination of this point, by means of another form of heating, could result in reduced operating pressure of the boiler, and thus increasing the efficiency of feedwater. This new situation can be obtained by installing a new pump assembly or by reducing pump speed, similar to that described in Case 1. In the case of a new pump, it has:

Design: Q_{proj} = 1,2 x 20 = 24 m^3/h, H_{proj} = 130 m, η_{proj} = 52%,
pump KSB WL 40/5 stages, 3500 rpm, P_{motor} = 30 cv.

Nominal: Q_{op} = 0,9x16 = 14,4 m^3/h, H_{op} = 170 m, η_{op} = 46% => P_{op} = 14,5 kW.
Increased efficiency is 37%.

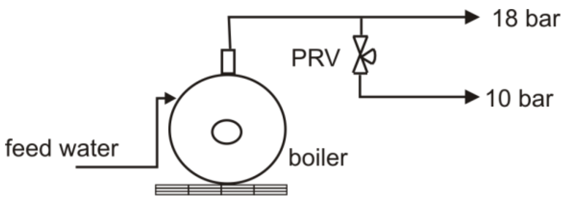

Figure 9. Plant layout.

Conclusion

Feedwater systems for industrial boilers in Brazil have an estimated installed power of 110 MW_E and an energy consumption of 442 GWh per year. There are opportunities to improve the performance of these systems. Three analyzed cases showed a potential efficiency improvement of 37%. To a large extent, these opportunities reside in older boilers which are very commonly found in Brazilian industries. There is no single solution for all cases. Predominant problems focus on control systems level, in oversizing, and excessive pressure. It is not unusual for a boiler to present more than one problem simultaneously.

The efficiency of the boiler feedwater in power plants is widely studied. The same does not occur with the intermediate size boilers to generate steam for industrial purposes. The present Article has not presented any technological innovation. It only sought to demonstrate that there is a significant potential for improving energy efficiency in an application where this issue is commonly ignored. It is expected that it will be able to raise awareness among energy managers of industries with high steam consumption, such as the chemical sector, food and beverage, pulp and paper, sugar and ethanol, in addition of refineries and petrochemical plants. The results obtained in the three cases evaluated are above expectations outlined in international literature. In part, this is due to inattention to the problem.

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The Importance of Calculating the Efficiency of Pumps in Systems with Adjustable Speed Drive

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Abstract

The Brazilian Energy Conservation Program (Procel) is executed by Eletrobras, the main Latin electrical energy company. Procel is split into several sub-programs, which includes *Procel Indústria*, related to industrial energy efficiency. Lots of energy audits are analyzed by *Procel Indústria*'s team. There are many systems and processes in which water flow is variable. In these situations, there is great potential to obtain energy savings by replacing valves (or other flow control device) to Adjustable Speed Drive (ASD). One of the main points to determine the savings, using ASD, is the evaluation of the pump efficiency for new operating points in which the rotational speeds are different from the nominal speed. In most energy audits received for analysis, it is assumed by approximation that the efficiency in the new operating point does not change with the rotating speed and, therefore, is the same at the nominal point. A more appropriate method calculates the efficiency at the new operating point. The purpose of this article is to show that the approximation used in the determination of the efficiency can lead to considerable differences in energy and economic analysis of the pumping system, especially for applications with higher static head.

1-Introduction

1.1-Procel Indústria

The Brazilian Energy Conservation Program (Procel) was created by the federal government in 1985 and is coordinated by the Ministry of Mines and Energy. The program is designed to promote the efficient use of electricity in the country and fight its waste. Eletrobras, the largest power company in Latin America, is responsible for planning and implementation of program activities by providing technical and financial support for its operation.

Procel is divided into nine sub-programs, including *Procel Indústria* (energy efficiency in industry), that considers the industrial sector, responsible for 44% of electrical energy consumption in Brazil [1].

On the other hand, the electricity consumed by motor driven systems corresponds to 62% of the total electrical energy consumed in Brazilian industries [2]. Therefore, the actions in Procel Indústria are focused in motor driven systems.

1.2- Pumping systems: power consumption and efficiency

Pumping systems are responsible for about 18% of energy consumption in industrial motor driven systems [1] and [2]. Considering its relevance in terms of energy, it is one of the five major systems covered by the PNEf (Brazilian National Energy Efficiency Plan) [3].

In Procel Indústria several energy audits on pumping system with variable flow are analyzed. A frequent proposal, presented in various energy audits reports, is the replacement of mechanical control (by means of valve) by electronic (via ASD). A usual approach in these reports is to consider that the pump performance remains constant regardless of the rotating speed. This approach, depending on the conditions of the pumping system, can lead to considerable differences in relation to more precise methodology, in which the efficiency at the new point is modified.

2 - Characteristic curves and operating point

The characteristic curves (obtained in manufacturers' test benches) are diagrams that describe the behavior of a pump, showing the relationship of interdependence existing between the quantities that characterize its operation [4].

Some of the main curves are:

- $H\ vs\ Q$: total head developed by the pump in relation to the flow;
- $\eta\ x\ Q$: efficiency in relation to the flow (for a given rotating speed of the pump);
- $P\ vs\ Q$: power absorbed by the fluid according to the flow;

2.1- Pump curve

Rateaux equations, also known as affinity laws are mathematical expressions which define the relationship between flow and pressure and hydraulic power due to the shaft rotational speed, according to (1), (2) and (3) respectively.

$$\frac{Q_a}{Q_b} = \frac{n_a}{n_b} \tag{1}$$

$$\left(\frac{H_a}{H_b}\right) = \left(\frac{n_a}{n_b}\right)^2 \tag{2}$$

$$\left(\frac{P_a}{P_b}\right) = \left(\frac{n_a}{n_b}\right)^3 \tag{3}$$

It is important to highlight that the affinity laws are only valid for homologous points (having the same efficiency) on the characteristic curves of flow machines and centrifuges and they only replicate pump-system interaction operating conditions for systems with zero geometric height (commonly referred to as static head) [4].

Manufacturers of centrifugal pumps typically provide pump curves ($H\ x\ Q$, $\eta\ x\ Q$ and $P vs\ Q$) for different rotor diameters, but only at nominal rotating speed. Thus, there are different ways to obtain the other curves at different speeds of nominal, presented in Section 4.

The head of the pump is the relationship between energy and the specific weight of the fluid added to the fluid mass passing through the equipment at a given flow rate [4].

The curve of the total head of a centrifugal pump with blades facing backward, at nominal rotating speed (n_a) can be approximated by a second degree polynomial [5]:

$$H_a = a_0 - a_1 Q_a - a_2 {Q_a}^2 \tag{4}$$

Using equation (2), the equation that defines the head-flow curve for any pump rotating speed (n_b) is as follows:

$$H_b = \left(\frac{n_b}{n_a}\right)^2 H_a \tag{5}$$

Thus, by replacing (1) and (4) in (5), we have:

$$H_b = a_0 \left(\frac{n_b}{n_a}\right)^2 - a_1 \left(\frac{n_b}{n_a}\right) Q_b - a_2 {Q_b}^2 \tag{6}$$

2.2- System curve

The head of the system is the amount of energy per unit of specific weight of the fluid that the fluid mass must absorb to overcome the static head, the difference in pressure between the two reservoirs (if present) and the pressure loss in pipes and accessories [4].

With head losses (quantified by ΔH) in the pipes and fittings proportional as the square of flow $(\Delta H \propto Q^2)$ [4] and considering that the reservoirs are open to the atmosphere, the head of the system can be expressed by:

$$H_{system} = H_s + kQ^2 \tag{7}$$

Where, the term (H_s) refers to the static head (or geometric height between the suction and discharge reservoirs) and (k) is a constant which is a function of the system.

2.3 – Operating point

The intersection of the two curves (pump and system) defines the operating point, where for each flow, there is a head developed by the pump equal to that required by the system.

From the coordinates of the operating point (flow, pressure), hydraulic power is obtained according to the equation below:

$$P_{hid} = \gamma . Q . H \tag{8}$$

The shaft input power, also known as BHP (brake horsepower) is obtained considering the pump performance at the operation point, as follows:

$$P = \frac{\gamma . Q . H}{\eta_{pump}} \tag{9}$$

3- Methods to control the flow in pumping systems

Controlling the flow means changing the operating point (Q, H), mentioned in the previous section, which is done by changing the system curve or the pump curve. The most common methods for modifying the curves of the system or the pump curves are: the control by valve or Adjustable Speed Drive (ASD), respectively.

Consider an industrial situation which requires 3 flows $(Q_a > Q_b > Q_c)$ for different operation cycle. In the control by valve, the system curve is modified in order to obtain the corresponding flows, blocking the passage of fluid and increasing the loss of load. In this case, the pump curve remains constant, as shown in Figure 1.

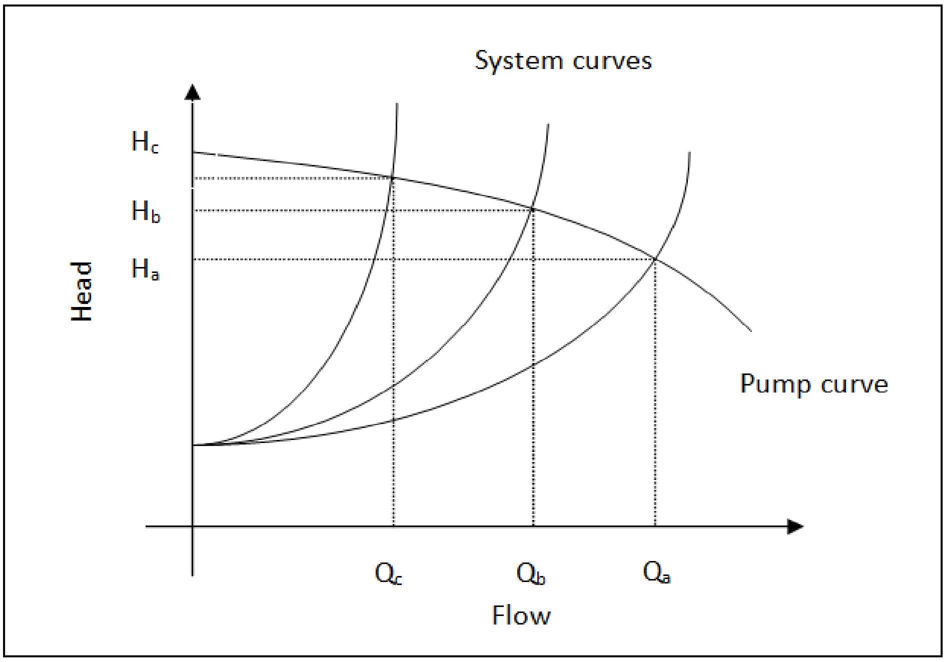

Figure 1: Changing the operating point by valve

The same flows could be obtained decreasing the pump shaft rotational speed $(n_c < n_b < n_a)$ by Adjustable Speed Drive. This device allows the electric motor (alternating current) change the rotating speed of by varying the frequency (f). In [9], the rotation is given by (10), where p is the number of the poles of the motor.

$$n = \frac{120f}{p} \tag{10}$$

By this method only the pump curve is modified, as shown in Figure 2. Analyzing equation (3), valid for centrifugal pumps, it is concluded that decreasing the rotating speed the power absorbed by the fluid is reduced by the cube of the operating speed ratio, bringing great economic and energetic advantage if compared to the control by valves as it will be shown in Section 5. In the control by valve the pump provides an excess of pressure to the system (Hb > H'b and Hc > H'c). It should be noted, however, that the use of frequency converters must be technically and economically analyzed. Disadvantages of these devices are presented in [7].

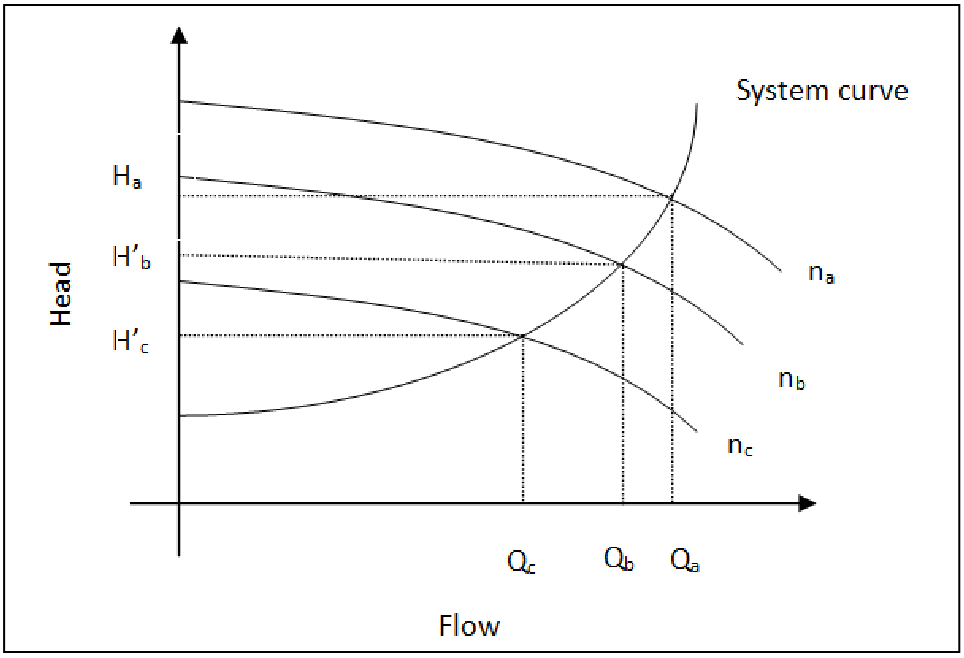

Figure 2: Changing the operating point by ASD

4 - Methodologies for determining pump efficiency operating at different speeds from the nominal

One of the important points in the evaluation of energy savings with the use of Adjustable Speed Drive (ASD) is the determination of pump performance to the new operating points in which the pump shaft rotational speed is different from the nominal. In the majority of energy audits received by Procel Indústria for analysis, it is considered, by approximation that the efficiency at the new operating point does not vary with the change of rotating speed, so the nominal efficiency is often used. This approach can lead to considerable errors in the measurement of economic and energy savings as presented in Section 5.

Consider a pumping system operating initially at a nominal flow Q_a in the nominal rotating speed n_a. With it being necessary to operate at a lower flow Q_b, it is typically decided to use an ASD, by means of which a new rotating speed n_b is obtained, as shown in Figure 3. By approximation, dozens of engineers have been considering that the efficiencies of the points A and B, shown in Figure 3 are the same, whereas mathematically these efficiencies are different, as it will be shown later.

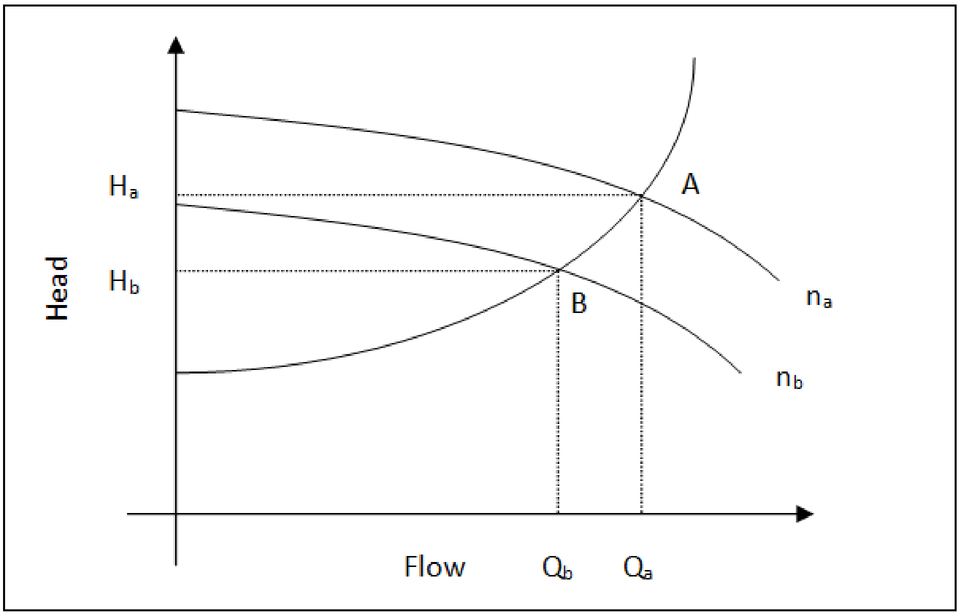

Figure 3: Operating points of the pumping system for different rotating speeds

Applying the affinity law (1) and (2) to obtain the point B:

$$\left(\frac{H_b}{H_a}\right) = \left(\frac{Q_b}{Q_a}\right)^2 \tag{11}$$

As the static head between the reservoirs is not zero, by (7) the equation (11) is not valid because:

$$\frac{H_s + kQ_b^2}{H_s + kQ_a^2} \neq \left(\frac{Q_b}{Q_a}\right)^2 \tag{12}$$

Thus it can be seen that the affinity law may be used only when there is no static head between the reservoirs. Only in this case, the efficiencies of 2 points at different speeds (x, x ') are the same, as (1), (2) and (3):

$$\frac{\eta_x}{\eta_{x'}} = \frac{\frac{\rho g Q_x H_x}{P_x}}{\frac{\rho g Q_{x'} H_{x'}}{P_{x'}}} = \frac{Q_x}{Q_{x'}}\frac{H_x}{H_{x'}}\frac{P_{x'}}{P_x} = \left(\frac{n_x}{n_{x'}}\right)\left(\frac{n_x}{n_{x'}}\right)^2\left(\frac{n_{x'}}{n_x}\right)^3 = 1 \tag{13}$$

So, if the geometric height is not zero the efficiency values of the points A and B, shown in Figure 4, are different [6]. To obtain the correct performance in the new operating point (B) it is necessary to obtain the iso-efficiency line, (using the affinity laws) through the point (B), intercepting the pump curve at nominal rotating speed (point B'), as shown as in Figure 4. So it can be affirmed that $\eta_A = \eta_{A'}$ e $\eta_B = \eta_{B'}$.

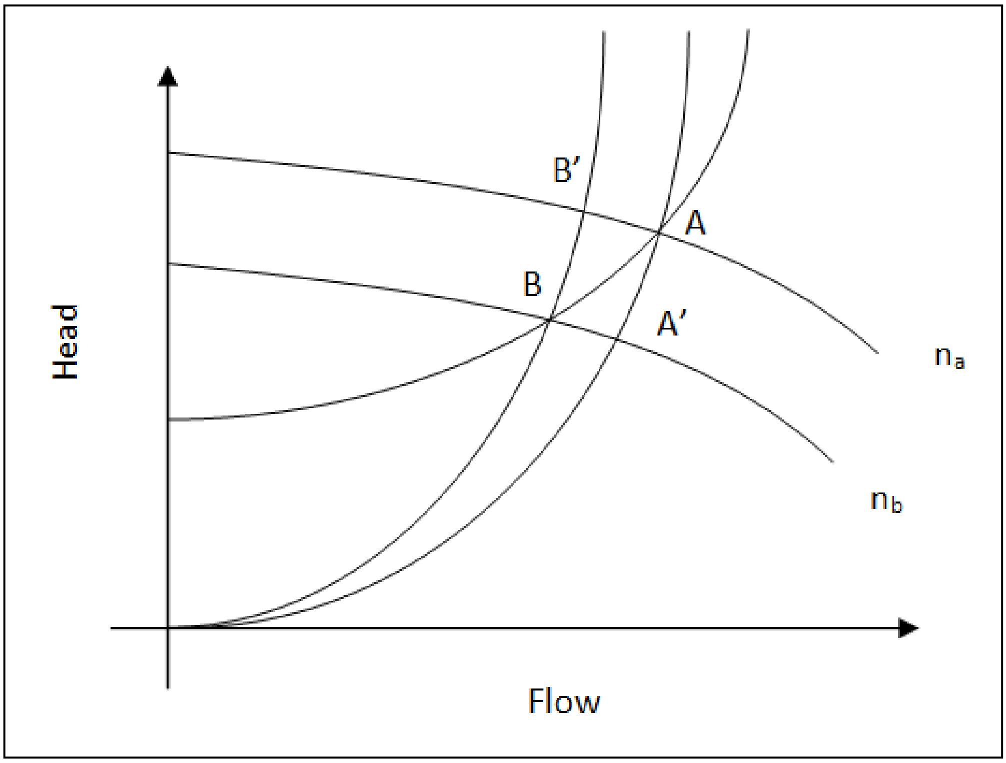

Figure 4: Homologous points

The efficiencies of the points A and B' are known because the pump manufacturer provides the curve $(\eta \ vs \ Q)$ for the nominal rotating speed. In this way the efficiency at the new operating point B is obtained in an indirect manner, as shown in [4].

Another alternative to calculate efficiency of the point B shown in Figure 4, is to employ the empirical equation proposed in [5]

$$\eta_B = 1 - [(1 - \eta_A)] \left(\frac{n_b}{n_a}\right)^{0,1} \qquad (14)$$

Besides the two methods above, according to [8] it is possible to use equation (3) adjusted to obtain the corrected efficiency of the point B (Figure 4), according to (15). This is the method of the Adjusted Affinity Laws.

$$\eta_B = \left(\frac{P_a}{P_b}\right)\left(\frac{n_a}{n_b}\right)^3 \eta_A \qquad (15)$$

The pressures (heads) at points A and B are obtained using equation (7) to the respective nominal flow, so using equation (8) the hydraulic power at each point is obtained. The rotation speed (n_a) is typically the nominal rotation speed of the motor-pump, while the rotation speed (n_b) can be obtained from equation (6) by iterative method. A practical way to obtain the rotation speed (n_b) is the use of the tool “Goal Seek”, of the *Microsoft Office Excel*.

There are errors in each of the three methods above. In the graphical method, it is in the approach to obtain the various points. In the empirical method it is intrinsic. Regarding the method of Adjusted Affinity Laws, the error is due to the physical characteristics of the pump and fluid. For example, physical conditions of the pump and the actual specific weight of the fluid. These aspects also affect other methods.

In this paper we chose to fix the efficiency by Adjusted Affinity Laws method. It will be considered that the pumped fluid is water with a specific weight of 1000 kg / m³, and that the pump is new. These are important considerations for the use of this technique.

5 – Study Case

As seen in the previous section, the only case where the efficiency of the pump could be considered constant, regardless of the operating speed, is the case in which the static head between the reservoirs is zero. As in most pumping systems the reservoirs are at different levels, this consideration (constant efficiency) can result in notable differences in quantifying the benefit of certain action of energy efficiency with respect to the situation in which the efficiency is adjusted, as will be shown in the following example

The pumping system of this example is controlled by valve. The proposal is to install one ASD to make this control. The data were taken from [6] with some modifications.

The economic and energy saving calculations first will be made with constant efficiency of the pump independent of the operating speed, as has frequently been done. After that, the energy saving will be obtained by the proper way, assuming the efficiency of the pump varies with the rotating speed, according to equation (15).

Table 1 presents the technical characteristics of this example;

Table 1: Technical Characteristics of the installation

Technical Characteristics	
Model of the pump	KSB Meganorm 50-160 com rotor 174
Age of the pump	New
Fluid (water)	1,000 kg/m³
Nominal flow of the pump	105 m³/h
Geometric Height between the reservoirs	25 m
Energy cost	R$ 120.00/MWh
Operation time (h/year)	8,000 h/year
Coupling efficiency	95%

The main technical characteristics of the electric motor are in Table 2. In all situations presented in this case, the variation of the efficiency with the load was considered.

Table 2: Technical Characteristics of the electric motor

Technical Characteristics – Electric Motor	
Power	30 cv
Load	Efficiency
50%	89.3%
75%	90%
100%	91%

Table 3 presents the operation cycle of the industrial plant.

Table 3: Operating points

Operating point	**Flow (m³/h)**	**Operation time (h)**
1	50	2,500
2	70	2,500
3	105	3,000

The pump curve provided by the manufacturer is presented in Figure 5.

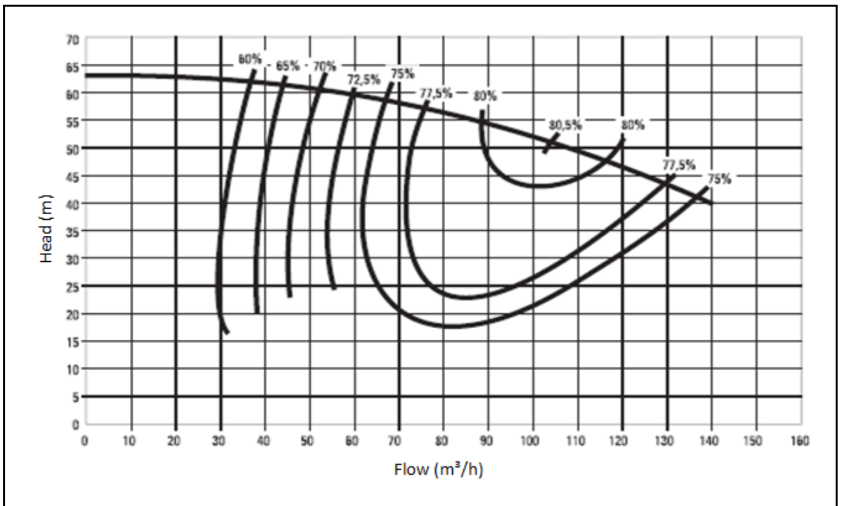

Figure 5: Pump curve provided by the manufacturer

The pump curve and system curve, given by the equation (7), is presented in Figure 6.

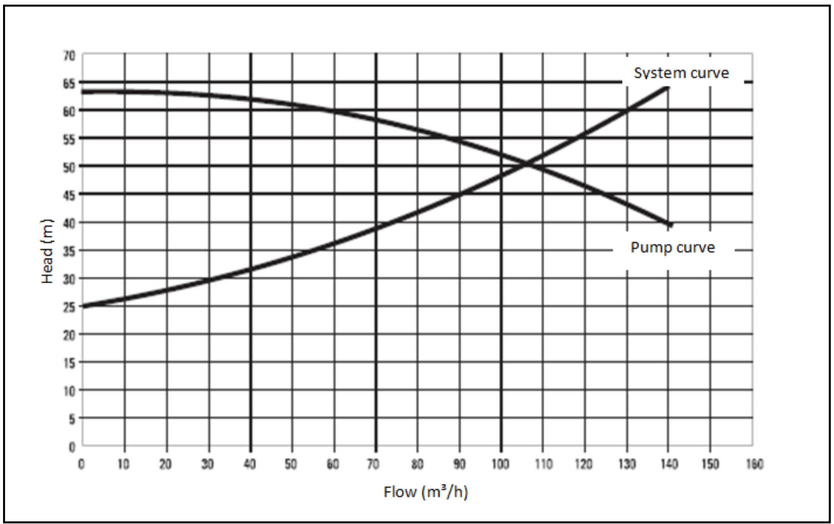

Figure 6: Pump curve and system curve

In Table 4 the values of the main parameters under analysis for the pumping system controlled by valve are presented.

Table 4: Results/ Pumping system controlled by valve

Operating point	**Flow**	**Operation time**	**Head**	**Pump Efficiency**	**Electric Motor Efficiency**	**Electrical power**	**Energy**	**Operation cost per year**
	m^3/h	h	(meters water gauge)	%	%	kW	MWh	R$/year
1	50	2,500	61	68%	90%	13.6	33.99	4,078.00
2	70	2,500	58	76%	91%	16.0	39.96	4,795.00
3	105	3,000	50	80.5%	90%	19.6	58.82	7,058.00
		8,000				Total	132.76	15.931,0

The annual estimated cost of operation of the pumping system considering that the pump efficiency does not change with the rotating speed (incorrect method) is presented in Table 5.

Table 5: Results/ Pumping system controlled by ASD/ constant efficiency

Operating point	Flow	Operation time	Head	Pump Efficiency	Electric Motor Efficiency	Electrical power	Energy	Operation cost per year
	m^3/h	h	(meters water gauge)	%	%	kW	MWh	R$/ year
1	50	2,500	31	80.5%	66%	8.32	20.81	2,497.00
2	70	2,500	37	80.5%	85%	10.81	27.01	3,241.00
3	105	3,000	51	80.5%	89%	21.26	63.77	7,652.00
		8,000				Total	111.59	13,391.00

Considering the variation of pump efficiency with the rotating speed (correct method), the estimated annual cost is R$ 13,222.00, presented in Table 6.

Table 6: Results/ Pumping system controlled by ASD / variable efficiency with speed variation

Operating point	Flow	Operation time	Head	Pump Efficiency	Electric Motor Efficiency	Electrical power	Energy	Operation cost per year
	m^3/h	h	(meters water gauge)	%	%	kW	MWh	R$/ year
1	50	2,500	31	61%	77%	9.48	23.69	2,843.00
2	70	2,500	37	71%	88%	11.83	29.58	3,549.00
3	105	3,000	51	81%	89%	21.26	63.77	7,652.00
		8,000				Total	117.04	14,044.00

So the amount of calculated savings is R$ 2,709.00 when the pump efficiency is adjusted and R$ 3,195.00 when the efficiency is constant by approximation. In other words, the benefits are 18% higher when the approximation is used.

This example was also solved for different static heads and the results are presented in Table 7.

Table 7: Comparison for several static heads

Static heads [m]	Annual cost with valve [R$]	Annual cost with ASD assuming constant (η_{pump}) [R$]	Annual cost with ASD varying (η_{pump}) [R$]	Calculated savings with constant η [R$]	Calculated savings with varying (η_{pump}) [R$]	Error %
0	16,964.00	12,205.00	12,205.00	4,759.00	4,759.00	0%
15	16,964.00	13,102.00	12,833.00	3,861.00	4,131.00	7%
20	16,964.00	13.538,00	13,104.00	3,425,00	3,860.00	13%
25	16,964.00	14,044.00	13,391.00	2,920.00	3,573.00	22%

According to Table 7 it can be observed that the higher the amount of static head, the higher the error in the calculated savings when the efficiency is considered constant as compared to when the efficiency is changed for the new operating point.

6- Conclusion

The correction of pump performance for different operating points is of fundamental importance in the calculation of the energy saved by replacing mechanical control (valve) for the electronic (ASD), especially in systems with high static head. The improper use of the affinity laws can lead to errors in the order of 20% in expected savings, depending on the static head of the system.

The correct quantification of energy and economic saving is important in working with the industries so as not to create false expectations for business managers with respect to the measures implemented, avoiding discredit to the professional auditors. Furthermore, it increases reliability in relation to what is proposed, which is important when a measurement and verification plan is provided.

In this paper it was shown that the usual consideration of efficiency being invariant with change in the rotating speed causes unrealistically attractive results as compared to the reality where the efficiency varies with the rotating speed. Nevertheless, in the example shown in this article, the replacement valve per ASD is economically attractive, as expected.

An additional factor observed is that the use of the ASD can worsen both the pump performance and the electric motor performance, as in the case study presented. However, the total system performance will be lower by performing control flow through the valve due to the large inefficiency of this equipment, so that the power consumption is higher. Other aspects that should also be considered are the performance of the drive and disadvantages of using this electronic equipment, presented in [7].

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Role of Standards in Pump System Energy Reduction

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Colfax Fluid Handling

Abstract

Standards have played a major role in advancing energy reduction in pump-motor systems. This paper identifies organizations involved in the process, it highlights the current universe of standards and importantly suggests where Power Drive System standards are necessary to fill the pump industry's 2015 and beyond needs.

Overview

Standards perform important roles in today's society by enabling commerce, information and processes. Just a few days ago, 14 October, as we do annually we recognized "World Standards Day". Standards in support of pumps with their electric motor drivers have a history of availability. These have primarily dealt with definitions, applications, ratings, operations and dimensions. The role, however, of standards is expanding as regulatory agencies are demanding and users are voluntarily implementing actions to reduce energy consumption for both environmental and economic purposes.

This paper will cover the scope and history of energy reduction pump standards, their content and creation process plus suggest future needs for pump and drive standards which is being created by the extension into energy reduction. It covers:

- Who can write a Standard
- What current Standards leads into pump energy
- What is the direction of pump energy standards
- What current Standards deal with Electric motor and drives
- What Standards are needed beyond 2015.

It is important to initially note that even though ISO, International Organization for Standardization and IEC, International Electro Technical Commission, are powerful global standardization bodies to date most energy standards have been primarily national or regional and this paper focuses on the documented European and North American efforts.

Standard Developing Organizations (SDO)

In simple terms an important first level classification for a standard is Regulatory or Voluntary. Regulatory standards are published by a governmental entity and the standard or companion law defines compliance requirements typically along with penalties for failure to comply.

Voluntary standards are those published without compliance authority. However they are frequently adopted by both parties to a contract and therefore become enforceable under contract law. One also finds instances where a regulatory standard references a voluntary standard. A regulation that references a voluntary test standard might be such an example.

In the United States SDO (Standards Developing Organizations) take on many forms, however, they typically are industry focused organizations established for the purpose of writing standards, relative to the products of its members. Hydraulic Institute is such an organization established in 1917 for education and standards for the pump industry. Their subsidiary organization, Pump Systems Matter, focuses on energy reduction in pump systems education. Still there are a multitude of organizations that can write and publish pump standards in the USA.

Examples of these are API:

– API [1] – American Petroleum Industry standards, a globally recognized set of Standards for equipment serving the oil, gas and process industries.
– ASME [2] – American Society of Mechanical Engineers writing pump standards today focused on Chemical Pumps, power testing and energy audits.
– ASTM [3] – American Standard Testing Materials writing Commercial Marine and Navy pump application standards.

These three are the major US SDO but many more author standards and receive ANSI, American National Standards Institute recognition. Additional examples include:

– AHRI [4] – Air Conditioning, Heating and Refrigeration Institute;
– APSP [5] – Association of Pool & Spa Professionals;
– ASHRAE [6] – American Society of Heating, Refrigeration, Air Conditioning Engineers.

All of the above are voluntary standards which have ANSI recognition. Unlike countries in Europe and elsewhere around the world there is no direct government participation. ANSI recognizes organizations in their area of special interest. Being qualified to produce ANSI standards, however, requires strict compliance to the published processes and an annual audit to confirm compliance. The important elements are transparency and broad participation by users, manufacturers, and interested parties such as educators or engineering consultants. ANSI oversees the creation, promulgation and use of norms and guidelines. Additionally they are the path to ISO participation and accreditation within the USA.

Whereas ISO is based on county memberships, TC 115 (Technical Committee) is the technical committee (consisting of subcommittees) for pumps where representatives of permanent member countries author and process ISO standards.

ANSI therefore is the US representative to ISO. Hydraulic Institute is the US Secretariat for pumps and holds the Chair for Sub-Committee 3 of TC115, Installation and Special Application. The US through its Technical Advisory Group (TAG) for TC115 is active in ISO Standards development, as are others across the globe. TC115 has 21 P (participating) country members and 16 O (observing countries). AFN (of France) holds the TC115 Secretariat, BSI (UK) Chairs SC1, Dimensions and Technical Specification, DIN (Germany) Chairs SC2, Methods of Measuring and Testing.

Pump/Motor Energy Reductions Publications by SDOs
Documents produced by SDO's include Standards (normative), Guidelines, Technical Reports and Books. Not all documents published need to meet the high demands of being normative. Guidelines, Technical Reports and Books group important and helpful information that need not meet the normative and consensus requirement of Standards. An example of this in the pump, motor, drive energy reduction area is the concept leading family of publications developed by Hydraulic Institute and Europump over the past 15 years. The developers should be credited as the leaders in the pump energy reduction movement.

Title	Developer
2001 Pump Life cycle costs	Europump – Hydraulic Institute [7]
2004 Variable Speed Pumping	Europump – Hydraulic Institute [8]
2006 System Efficiency	Europump [9]
2006 Improving Pumping System Performance	US DOE HI [10]
2008 Optimizing Pumping Systems	Hydraulic Institute Pumps, Systems Matter [11]
2013 Power Plant Pumps	Hydraulic Institute [12]

ISO Related Energy Standards
Many of the organizations mentioned have now launched standard development processes covering energy consumption or pump efficiency.

- The ISO 50000 series on Energy Management Systems
  - ISO 50001 – Energy management Standard – June 2011 [13]

Is based on the ISO management system model familiar to organizations worldwide who implement standards such as ISO 9001 (quality management) or ISO 14001 (environmental management) and ISO 50001 follows the Plan-Do-Check-Act process for continual improvement of the energy management system.

- ISO-DIS 50002 – Energy Audits
- ISO-CD 50003 – Energy Management Systems – Requirements for bodies providing audit certification of energy management systems.
- ISO-CD 50004 - Energy management systems – Guidance for the implementation, maintenance and improvement on an energy management system.
- ISO-CD 50006 - Energy baseline and energy performance indicators (EnPls) – General principles and guidance.
- ISO-CD 50015 - Measurement and verification of organizational energy performance – General principles and guidance.

- ISO/DIS 14414 – Pump System Energy Audit
  - ISO/ASME Collaboration For Globalization and Expansion of Core ASME-EA2 Document.

CEN Related Pump Energy Standards

- EN 16297 Part 1, 2, 3
  - European Union – Ecodesign process Circulators. Ground breaking introduction of EEI Energy Efficiency Index Method.
- EU Commission Regulation 641/2009/EC and Amendment 622/2012/EC
  Standards under active development for implementation and market surveillance. Introduction of Industry leading MEI concept. Based on:
  - European Union EcoDesign Directive Lot 11 – Regulation 547/2012for water pumps.

US Energy Related Pump Standard

- ASME – EA2 and Companion and Pump System Energy Audit [2]
- ASRAE 90.1 – 2010 Energy Standard for Buildings except Low Rise Residential Buildings. [6]
- APSP – 15 2012 Standard for Residential Swimming Pool and Spa Energy Efficiency (now a State of CA USA regulatory standard) and qualifies for a voluntary Energy Star Label. [5]

Important Energy Related Pump Activity

- US Department of Energy, Pump Efficiency Rulemaking by the Office of Energy Efficiency and Renewal Energy, Building Technologies Program
  - DOE is in the second year of a five year program to establish Energy Conservation Standards for Commercial and Industrial Pumps. At this point primarily focused on rotodynamic water pumps.
- European Union – EcoDesign Lot 28
  - EcoDesign Preparatory Study on pumps for private and public swimming pools, ponds, fountains and aquariums, as well as clean water pumps larger than those regulated under Lot 11.
- European Union – EcoDesign Lot 29 European Directive 2009 / 125 / EC
  - Ecodesign Preparatory Study on pumps for private and public waste water and for fluids with high solid content.
- ANSI/AHRI Standard 1210-2011 – Performance Rating of Variable Frequency Drives
  - The current performance rating standard for standalone VSDs used in HVAC applications – will soon provide performance maps for VFDs tested with standard NEMA MG-1 Park 31. Performance data is expected to be published in 2014.
- EU Mandates M/470 and M/476
  - Based on these mandates covering motors and drives have led to formation of a joint working group with CEN/TC197 (Pumps) for standard development.

Pump Electric Motor Standards Related To Energy Reduction

- Europe – IEC – 60034 – 30 (2008)
  - Specifies energy efficiency classes for single speed, 3 phase, 2/4/6 pole motors. It provides three efficiency classes for motors – 75 to 375 kW: IE1 (Standard); IE2 (High); IE3 (Premium) in EC IE2 is mandatory, IE3 is mandatory in two steps 1 Jan 2015, 1 Jan 2017 (with exclusions).
  - 5/12/2013 Current World Efficiency Levels: USA IE3, Canada IE3, Mexico IE2, Europe IE2, IE3 2015/17 China IE2, S. Korea IE2, S Africa IE2, Australia IE2.

Comment

In any regulation the test standard becomes a key implementation instrument. This is highlighted in motors with IEEE 112-B, EC 34-2 and JEC 3, being the most important standards. Discussions of their differences have been the subject of learned reviews and are beyond the scope of this paper. The important item here, however, is the estimate that 85 to 90 percent of pump motors are now subject to an efficiency standard.

Pump Test Standards Related To Energy Reduction

- ISO 9906 / HI-ANSI 14.6

As with motors pump testing is an important step in the regulatory process. Harmonization however has occurred in a recent ten year effort and the above standards have provided global consistency. This standard covers hydraulic performance tests for acceptance of rotodynamic pumps (centrifugal, mixed flow, and axial flow pumps.)

Information in the standard may be applied to pumps of any size and to any pumped liquids behaving as clear water. They include six (6) acceptance grades with tolerance bands and being further refined by the US Department of Energy to be a regulatory test standard.

Important Standards For Needs Beyond 2013

To date the body of Standards, Guidelines and Technical Reports primarily focus on components. A broad consensus of users, the industry and regulatory agencies, however agree the greatest energy conservation impact can occur in system operations and improvements beyond the individual component standards. In Europe and North America regulatory standards are primarily directed at manufacturers and not users. This in part because enabling legislation has not been enacting and in part, with the possible exception of building codes, because user standards are considered impossible to enforce.

Because of the above SDO's are promoting a concept titled "Extended Product" (EP). That concept surfaces in scope documents for future EU pump regulations and in the US DOE framework document for efficiency regulations of Commercial and Industrial Pumps. The outcome of these regulatory process will define the avenue and speed at which EP will be aborted. Possibilities include an extension of a regulatory standard or as a companion voluntary standard adopted in a premium labeling standard inclusive of pump and drive control.

Extended Product advantages the centrifugal pump affinity laws where power consumed is the cube of the speed. It is ideal for energy reduction in systems with low static head and a large dynamic head component. Since the predominance of rotodynamic pump applications are variable, or have valve regulation, energy can be reduced through variable speed control.

A proposed Extended Product definition currently consists of an approved rotodynamic pump, a premium efficiency motor, a variable frequency drive and a feedback control to maintain speed (rpm) at or close to the pumps BEP (Best Efficiency Point) that meets the system demand. A second category in level controlled systems may call for a straight forward controlled off and on system.

The variable speed variable frequency operation fundamentally replaces the energy wasteful practice of moving the system curve by valving the discharge. This along with a low flow by pass loop is the historic method typically used for rotodynamic pump control.

Unfortunately, however, users and system designers have insufficient data to adequately determine the overall efficiency of an Extended Product through their operating range and to compare it to other design options such as multiple pumps or system improvements such as larger piping. This is particularly true of systems that have operating points substantially away from the pump rated point because the combined efficiency of motors and drive at reduced speeds is not available. A very common issue is that this arrangement underperforms predictions due to electrical compatibility between the components.

At present there are motor and pump regulatory and voluntary standards with efficiencies at part load but full speed. Missing is a motor and drive combination standard with methodology to accurately determine the power consumption at various operating points, especially low speed operating points. An accurate system efficiency calculation for the pump/motor/VFD packages would then be possible by combining the electrical and the hydraulic component performance maps.

One proposition is a component string test solution but such seems appropriate for only limited applications. When, however, one examines new pump motor drive hybrids beginning to be introduced into the market the physical test solution seems viable for a growing segment.

One, however, today also sees the emergence of work groups for consideration of Standards for VFD and VFD motor combinations:

- ANSI/AHRI Standard 2011 – *Performance Rating of Variable Frequency Drives* – As describe previously in HVACR applications.
- EU Mandates M/470 and M/476
  These mandates covering motors and drives have now expanded to form a joint working group with CEN/TC197 (Pumps).
- CLC/TC22X-WG6 has published a CD: Energy Efficiency for Power drive systems, motor starters, power electronics and driven applications" and "Power Electronics" 22X/123/CD.
- Hydraulic Institute with Europump actively developing an Extended Product Standard based on creating an EEI index for defined pump/motor/drive control configurations. Europump along with motor manufacturers drive manufactures and academics are studying the problems and solutions available.

Conclusion

This paper has tracked the history of pump energy reduction standards. In part because it seems little credit is extended to those hardworking voluntary groups for their efforts in this arena. Equally important is the call for drive and motors organizations to complete the ability to compliment the work done by the pump industry and related organizations.

Clearly pump standards developing organizations have moved beyond their historic scope of application, dimensions and test to embrace energy reduction. It appears that arena will not be theirs alone as energy reduction requirements will flow from government regulations or certification programs.

In this broadened world of standards we will likely see development of blended multi technology standards covering motors / drives / pumps and labeling. And since the current core work is being developed on a regional basis there will be growing demands for globalization.

From the pump viewpoint the extensive use of PDS (Power Drive Systems) will provide the opportunity for industry global product rationalization since electric supply system frequencies will no longer drive a hydraulic design limitation and overall energy will be reduced as now systems can use the energy required for the applications not the energy the pump needs.

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Simplified design method for compressed air network

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1. Abstract

The advantage of using compressed air in industry is undeniable. indeed, pneumatic devices present a good reliability and high durability, simply designed and adapted to be used in harsh environment, this technology is known to be environmental friendly and economic.

Unfortunately, although pneumatic systems possess a lot of advantages, this energy needs another energy source to be produced: an electrical or thermal source drives the compressors that produce this energy. Despite the remarkable performances obtained by compressors and pneumatic components, the overall efficiency of such systems is rather poor. Indeed, air leaks upstream of pneumatic devices and poor design of transport networks are among the main factors which could be better designed in order to improve this efficiency.

Although leakage is one of the most important causes of efficiency losses, this aspect is not covered in this paper. We focus only on the design and calculation of flow through networks to reduce energy losses.

Primary networks of compressed air consist mainly of pipes, elbows, tees and various connections, flow coefficients of these components are not as well known a priori and are rarely available in catalogs. It is developed a simple methodology to calculate the pressure losses of compressed air systems composed by elements in series or in parallel. This method allows knowing the flow rate and the pressure drop of such networks with a good accuracy.

2. Introduction

The production and distribution of compressed air is a very important challenge for a lot of industries, because this energy, unfairly criticized these recent years, provides a very competitive technology compared to others, which can develop similar power [1]. Thus, this technology is still widely employed throughout industry. The inherent cleanliness of the fluid conveying this energy and its availability (atmospheric air) make its essential quality. In recent years, many publications showed interest on energy of compressed air by global calculations based on fundamental laws of thermodynamics. In this paper, we will focus only on the pressure losses due to irreversibilities taking place upstream of pneumatic devices, i.e. in primary distribution networks.

First, the laws governing the calculation of energy losses in the singularities and piping will be analyzed and the rules for determining the energy losses in the upstream networks will be analyzed. Finally, an application will be made on a simplified network to illustrate this approach.

The analysis of the transmission fluid is not a new concern. Historically, professionals have had the desire to create networks in line with the energy they had. This is true also for the delivery of compressed air from the compressor to the tool or machine that provides the useful mechanical

energy.
In a very detailed study presented to the working group of ISO TC 151 WG 4, Hubert et al [2] gives a calculation method using the very useful notion of exergy as a measure of the energy. Indeed, the exergy of a system is the useful energy when a system returns to equilibrium conditions.

A very similar study is also developed by Kagawa et al [3], the energy losses are listed in four major parts: the production of compressed air filtration and drying, transport and the energy lost at the tool. The method to assess the efficiency of each part is developed and analyzed.

Radgen et al [4] published a very important publication where possible actions to improve compressed air network are detailed and it was pointed out the efficiency of each action.

In compressed air network, the flow velocities in the piping is less than 100 m/s, in this range of velocity, the flow is considered as subsonic. However, due to the compressibility of air, equations governing the flow through such components are well described in literature, especially in ISO 6358-1 [6], PR-ISO 6358-3 [6] and standards. The equations described in these standards are widely used when computing networks in series or in parallel.

Historically, when a pneumatic network is in a design stage, flowrate and pressure losses calculations uses flow coefficients issued from incompressible fluid flow theory, in order to achieve the air flowrate calculations. However, compressible flowrate coefficients need precise rules and calculations to be determined from these incompressible parameters. Thus, the work of Wartelle [7] explains in a very didactic publication the how to achieve these calculation and their application to pneumatic components

Recently, the applications of this methodology of calculations give a very satisfactory method of calculation of flow in pipes from only its geometric characteristics and friction factor issued from the literature [8].

In this paper, the elements used to calculate the energy loss in the network will be highlighted, simplified calculations of pressure losses in networks, in series or in parallel, will be explained using rules of calculations of flowrates and pressure drops coefficients in piping and singularities.

3. Energy efficiency in pneumatic network

The electric motor transforms the electrical energy into a mechanical energy available on the shaft; this transformation is achieved with very high efficiency. The compressor connected to this electric motor uses this mechanical energy to produce a flowrate of air at a given temperature and pressure. Generally, at the output of the compressor, the air is at a higher temperature, and then it should be cooled and dried (fig.1).

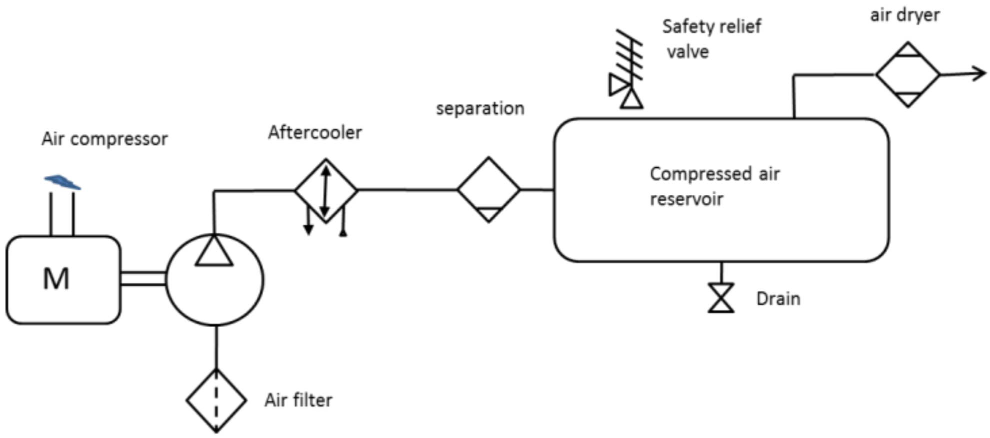

Fig. 1 : Schematic lay out of a compressible air production.

The efficiency of electric motors can reaches more than 90% [8]. This efficiency can be enhanced to more than 94% with high efficiency motors. The energy losses due to internal friction, leakages and insufficient cooling are the greatest part of the overall loss in the compressor installation. They are responsible for 10-20% of mechanical energy losses [9] and vary with compressor type, size and cooling conditions.

Before going further in description of the energy losses in the network let's study briefly the efficiency of the compressor system.

The energy balance of the air through the compressor can be calculated using the following equation of the power :

$$e_T = \dot{m}C_p(T_1 - T_2) + \dot{m}T_a(s_1 - s_2) - \dot{Q}\left(1 - \frac{T_a}{T_f}\right) \qquad (1)$$

Where e_T is the total amount of the power, T1 and P_1 are the inlet conditions, T_2 and P_2 the outlet conditions, T_a the room temperature and T_f are temperature of the coolant fluid.

This pneumatic power is determined from the compression process, where the first term is the enthalpy of the air increase during the compression from state 1 to state 2. The second term represents the entropy change due to raising the pressure. The third term is the entropy change due to raising the temperature

The electric power injected is known so, the overall efficiency is calculated as following:

$$\eta = \frac{\dot{m}C_p(T_1 - T_2) + \dot{m}T_a\left(r\ln\left(\frac{p_2}{p_1}\right) - C_p\ln\left(\frac{T_2}{T_1}\right)\right) + \dot{Q}\left(1 - \frac{T_a}{T_f}\right)}{\dot{W}_e} \qquad (2)$$

As the compression of air is realized very quickly, this process is assumed as adiabatic. Thus the overall adiabatic efficiency is usually taken as the efficiency of the compressor.

The efficiency of the compressor can be determined from the equation 2 and correspond to the increasing of the pressure from the inlet to the outlet of this device. If the compression is isentropic:

$$\frac{p}{\rho^{\gamma}} = \text{constante} \qquad (3)$$

However, Actual efficiency is more near the isothermal efficiency because the air is cooled before using it in the tool. This isothermal efficiency can be easily calculated such as:

$$\eta_{is} = \frac{\dot{m} r T_a \ln\left(\frac{p_2}{p_a}\right)}{\dot{W}_e} \qquad (4)$$

Compressed air must be cleaned by filter before transmitted to pipe network. These filters are used to remove different contaminations (oil, dust, etc). The power loss is determined by the pressure loss through these filters. Flow rate characteristics used to determine pressure losses are often given in catalogue.

In the piping and all the network downstream the compressor, pressure losses and leakage are the two main factors which cause power losses.

The mechanical power loss due to the leakage is given the following relation:

$$e_{lekeage} = \dot{m}_{lekeage} T_a r \ln\left(\frac{p_2}{p_a}\right) \qquad (5)$$

P_a represents the atmospheric pressure. And $\dot{m}_{lekeage}$ the masse flowrate of air leak. The air leak flow rate can be deduced from the loss of pressure when no air is being used.

Theoretical equations for calculating pressure loss in pipes, fittings and hoses exist in literature. Indeed, the mechanical power wasted by this mean can be expressed such as:

$$e_N = \dot{m} T_a r \ln\left(\frac{p_2}{p_2 - \Delta p}\right) \qquad (6)$$

e_n is the mechanical power lost in pipes and fittings constituting the network. The reduction of this mechanical power loss is a very important issue and cannot be achieved without the improvement of this network.

Energy savings measure	% applica-bility (1)	% gains (2)	Potential contribution (3)	Comments
System installation or renewal				
Improvement of drives (high efficiency motors)	25 %	2 %	0.5 %	Most cost effective in small (<10 kW) systems
Improvement of drives (Speed Control)	25 %	15 %	3.8 %	Applicable to variable load systems. In multi-machine installations, only one machine should be fitted with a variable speed drive. The estimated gain is for overall improvement of systems, be they mono or multi-machine.
Upgrading of compressor	30 %	7 %	2.1 %	
Use of sophisticated control systems	20 %	12 %	2.4 %	
Recovering waste heat for use in other functions	20 %	20 %	4.0 %	Note that the gain is in terms of energy, not of electricity consumption, since electricity is converted to useful heat.
Improved cooling, drying and filtering	10 %	5 %	0.5 %	This does not include more frequent filter replacement (see below).
Overall system design, including multi-pressure systems	50 %	9 %	4.5 %	
Reducing frictional pressure losses (for example by increasing pipe diameter)	50 %	3 %	1.5 %	
Optimising certain end use devices	5 %	40 %	2.0 %	
System operation and maintenance				
Reducing air leaks	80 %	20 %	16.0 %	Largest potential gain
More frequent filter replacement	40 %	2 %	0.8 %	
		TOTAL[9]	**32.9 %**	

Table legend: (1) % of CAS where this measure is applicable and cost effective
(2) % reduction in annual energy consumption
(3) Potential contribution = Applicability * Reduction

Table 1 : Possible energy saving measures. (Radgen et al [4])

If the improvement of the motor and compressor is put aside, the most important potential reduction of energy consumption of energy remains the reduction of leakage (16%). The reduction of pressure losses (1.5%), the optimizing of end use service (2%) and system design (4.5) (Table 1). These three points are not negligible and could be improved in the design stage. Indeed, in order to reduce this power the only way is to reduce the pressure drop in the network Δp, this term must be reduced by a properly design of the network in order to minimize the singular and linear pressure losses in the downstream network and in the end use tool. Simple method calculations of pneumatic components assemblies in series or in parallel will be exposed here and could be used for designing compressed air distribution.

4 Flow rate characteristics of pneumatic component

4.1 basic assumptions

When studying the flow of compressed air in piping the basic assumption is to consider the flow as adiabatic [11].The basic equations issued from the mass, the momentum and the energy balance of an adiabatic flow in pneumatic component, are summarized in the following equations.

Equation of mass flow balance

$$\dot{m} = \rho A u \qquad (7)$$

Bernoulli equation or momentum balance

$$p_1 + \delta_1 \frac{\rho u_1^2}{2} = p_2 + \delta_2 \frac{\rho u_2^2}{2} + \Delta p_L + \Delta p_S \quad (8)$$

δ_1 and δ_2 are the kinetic energy coefficient. They are estimated between 1.01 and 1.10 for a tube when R_e > 2000. Δp_L is the linear pressure loss and Δp_s is the singular pressure loss.

The flowrate in the pipes is considered as adiabatic thus the energy balance equation can be written such as

$$C_p T + \frac{u^2}{2} = C_p T_0 \quad (9)$$

The gas state equation for the fluid when considered as an ideal gas:

$$\frac{p}{\rho} = rT \quad (10)$$

The pressure losses in the component are given by the following relations:

$$\Delta p = \Delta p_L + \Delta p_s = \sum_i \xi_i \rho_i \frac{u_i^2}{2} \quad (11)$$

Where, when a pipe of a length L and a diameter D is considered, the coefficient ξ is given by :

$$\xi = \frac{\lambda L}{D} \quad (12)$$

and

$$\lambda = \frac{0.3164}{\mathrm{Re}^{\frac{1}{4}}} \quad (13)$$

λ is the Darcy friction coefficient for linear pressure loss, which depends on the Reynolds number and under certain conditions of the roughness of the pipe (IDEL'CIK [8]).

The Mach number of the flow is given by the following equation:

$$M = \frac{u}{\sqrt{\gamma r T}} \quad (14)$$

When the velocity inside the component is considered as very low, the fluid can be considered as incompressible and the flow rate can be simply determined by application of Bernoulli equation (7):

$$\dot{m} = \frac{A_1 \sqrt{2 \frac{p_1}{r T_1} (\Delta p)}}{\sqrt{\xi}} \quad (15)$$

Let's take coefficient α such as:

$$\alpha = \frac{1}{\sqrt{\xi}} \qquad (16)$$

The equation of the incompressible flow rate becomes:

$$\dot{m} = \alpha A_1 \sqrt{2\rho_1 \Delta p} \qquad (17)$$

For higher fluid velocity, the compressibility of the fluid must be taken into account. The subsonic part of the flow can be therefore approximated by a quadratic equation (quarter of ellipse).

When using the flow rate coefficient α as described below, and by introducing the coefficient of compressibility effect s, the flow rate equations can be rewrite such as:

$$\begin{aligned} &\text{si } \Delta p \geq \frac{p_1}{s} \quad \dot{m} = \frac{\alpha p_1 A_1}{\sqrt{r T_1 s}} \\ &\text{si } \Delta p < \frac{p_1}{s} \quad \dot{m} = \frac{\alpha A_1}{\sqrt{r T_1}} \sqrt{\Delta p \left(2 p_1 - \frac{s}{2} \Delta p \right)} \end{aligned} \qquad (18)$$

When the flow is choked, Mach number is equal to 1 at the exit of the component. By introducing the definition of Mach number in which the flow coefficients are included, the compressibility factor s as a function of the flow coefficient α can be simplified such as [7]:

$$s = 1 + \frac{\alpha}{\sqrt{\frac{\gamma(\gamma+1)}{2}}} + \frac{\alpha^2}{\gamma(\gamma+1)} \qquad (19)$$

Figure 2 here under shows the good agreement between calculation and experimental results.

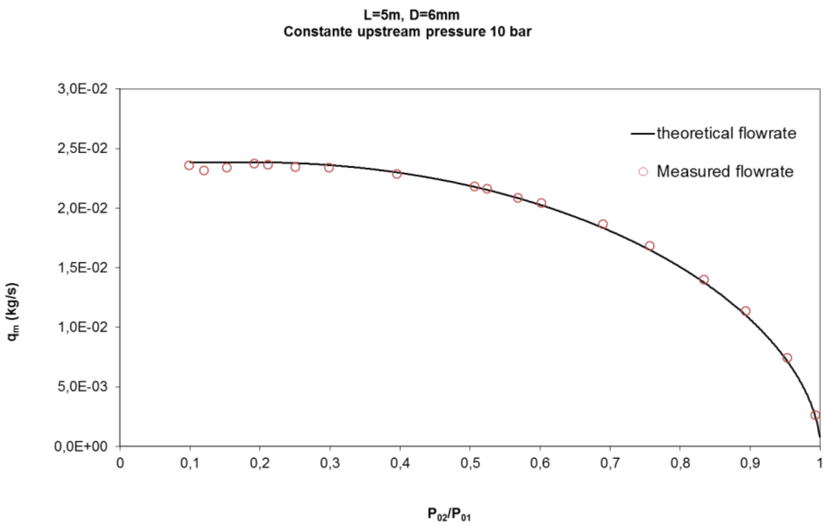

Fig. 2: Theoretical and experimental results obtained for pneumatic pipe.

4.2 method of calculation

By choosing an initial value of Darcy coefficient λ, the coefficient of pressure drop ξ is then calculated (eq. 12). The Flow rate coefficient α and the compressibility factor s are calculated using eq.16 and eq. 19.

If the pressure and temperature conditions are known in the upstream and downstream locations, equation (18) allows determining the initial flowrate value.

Thereby, the Reynolds number is calculated by the following formula:

$$\mathrm{Re}_D = \frac{\rho u D}{\mu} = \frac{4}{D}\frac{\dot{m}}{\pi\mu} \qquad (20)$$

The dynamic viscosity μ depends on the temperature at each location where the Reynolds number is determined. The Sutherland approximation

$$\mu = \mu_0 \left(\frac{T}{T_0}\right)^{3/2} \left(\frac{T_0 + S}{T + S}\right) \qquad (21)$$

can be used with the following parameters for air:

$$\mu_0 = 1.71 \times 10^{-5}\ \mathrm{Pa/s} \quad \text{for} \quad T_0 = 273K$$
$$S = 110.4\ \mathrm{K}$$

In the folowing calculation, it is assumed that the temperature T_1 of the fluid is nearly equal to the stagnation temperature T_{01}. In this hypothesis, it is assumed that the Reynolds number Re_D and the pressure loss coefficient λ do not change along the tube.

This value of Reynolds number is then used again in eq.(20) to evaluate the actual flow rate and this iterative calculation is repeated as long as the flowrate value defined in the following equation is small enough;

$$\varepsilon = \frac{Abs\left(\dot{m}_{actual} - \dot{m}_{previous}\right)}{\dot{m}_{actual}}$$

5. Application to network calculation

As explained in paragraph 3, pressure drop in networks and leakage, represent the main power losses in pneumatic application. The flowing example explains how to calculate very simply, the pressure drop and the flow rate in such network. The example chosen here is rather very simple, but the methodology is applicable whatever the complexity of the network.

Let's consider a pneumatic cylinder a valve and the necessary piping to carrying the compressed air as represented in figure 3.

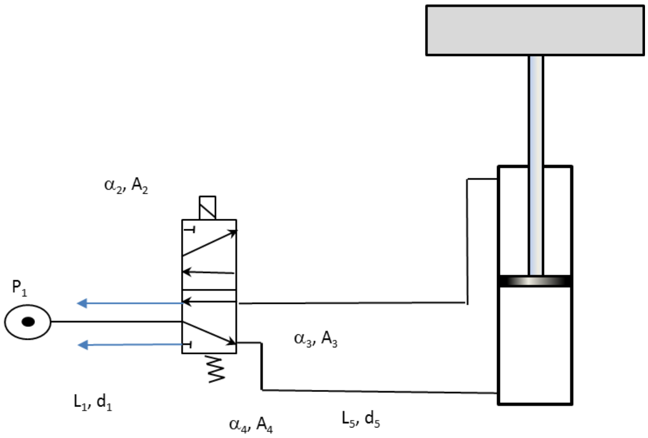

Figure 3 : simplified compressed air network.

The parameters of the components that constitute the circuit, is guiven in the following table

Component N°	pipe		elbow		valve	
	lenght (m)	Diameter d (mm)	ξ coef. (__)	section area mm^2	α coef	section area mm^2
1	0,8	8				
2					0,34	50,24
3			0,98	50,24		
4			0,98	5,,24		
5	1	8				

The parameters of the cylinder are summarized hereunder:

Cylinder Diameter	D_s	0,08	m
Stroke	l	0,2	m
frequency	n	1	Hz
flowrate	$\dot{m}_{cylinder}$	0,015	Kg/s

First, it is important to calculate the air consumption of the cylinder. Air consumption of a double-acting cylinder can be easily evaluated. When the process is known, the flow rate needed is :

$$\dot{m}_{cylinder} = 2n\frac{p_2}{rT_2}A_s l \quad (22)$$

Where, *l* is the stroke of the cylinder and A_s Its section area.

As the he flow rate $\dot{m}$ is known, the flow coefficient α is calculated as following:

1. Equation (13) and (20), (21) allowing to determine Darcy coefficient of the pipes λ and;
2. equation (12) is used to evaluate the pressure drop coefficient ξ of the pipes;
3. flow rate coefficients α of the piping are then determined using equation (16);
4. the overall flow rate coefficient is calculated using the additive property of the flow coefficient:

$$\frac{1}{\alpha_e^2 A^2} = \sum_i \frac{1}{\alpha_i^2 A_i^2} \qquad (23)$$

5. When the equivalent flow rate coefficient α_e is determined, it's easy to determine the coefficient of compressibility effect s_e using(19)
6. pressure drop is the solution of the second degree as following

$$\left(2\Delta p p_1 - \frac{s}{2}(\Delta p)^2\right) = \left(\frac{\sqrt{rT_1}\,\dot{m}}{\alpha A_1}\right)^2 \qquad (24)$$

This last equation can be automatically resolved by iterative computation.

The flowrate and compressibility effect coefficient of the system is summarized in the following table:

Component N°	α	s
1	0,71	1,69
2	0,34	1,30
3	1,01	2,08
4	1,01	2,08
5	0,63	1,61

Thus, as previously indicated, the overall coefficients can be calculated, it is found

$$\frac{1}{\alpha_e^2} = \sum_i \frac{1}{\alpha_i^2} \text{ ; therefore } \alpha_e = 0.257$$
$$s_e = 1 + 0.77\alpha_e + 0.3\alpha_e^2 = 1.607$$

The pressure loss in the upstream line (pipes, elbows and valve) is equal to 0.243 bar for 0.5 Hz and a flowrate of 0.0083 kg/s . For 1 Hz the flowrate is equal to 0.0166 kg/s and the pressure loss is equal to 1.01 bar.

This method allows determining the losses not only by the mean of reduction of pressure loss coefficients (increasing pipes diameter for example) but also by changing the design of the cylinder or its functional parameters.

6. Conclusion

This study highlights the derivation of the power lost in compressed air network by using the calculation of the pressure losses generated by its constituting components. First, the power of compressed air is defined using thermodynamics concept of exergy. The efficiency of each part is analyzed. In air production, the adiabatic and isothermal efficiencies of a compressor are explained and the overall efficiency of compressor is highlighted. In air transmission, the energy losses due to pressure loss in pipe and air leaks are discussed.

The fluid flow model developed in this paper comes from equations of compressible flow, but the mass flow rate is calculated using the friction factor issued from literature. The friction loss coefficient in a pipe also depends on the flow conditions i.e. the Reynolds number. This property is used to obtain very accurate pressure losses in piping and its constitutive components. As pneumatic circuits are generally composed by several components linked by pipes of different diameters, this method can be used in the case where the flow coefficients of these components are not known to obtain a good estimation of the equivalent flow parameters of the circuit and consequently of the mass flow rate through it according to its working condition.

This method of improving pressure losses allows efficiency analysis and discussion which would be helpful to an energy-saving equipment selection and system design.

7. Nomenclature

A	Effective area	[m^2]
A_1	pipe section Area	*[m^2]*
s	entropy -	[J/(kg.K)]
h	enthalpy -	[J/(kg.K)]
C_p	specific heat	[J/kg.K]
d	Internal diameter	[m]
L	Length	[m]
Ma	Mach number	-
p	Pressure	[Pa]
$\dot{m}$	mass flow rate	[kg/s]
r	Constant of gas (r=287 for air)	[J/(kg.K)]
Re	Reynolds number	-
s	Compressibility effect coefficient	-
t	Time	[s]
T	Temperature	[K]
u	Gas velocity	[m/s]
α	Flow coefficient	-
λ	Darcy friction factor	-
μ	Dynamic viscosity	[Pa.s]
ρ	Density	[kg/m^3]

ξ Global pressure loss coefficient of a component -

γ Specific heat ratio -

Subscripts

2 Static downstream conditions

1 Static upstream conditions

01 Total upstream conditions

02 Total downstream conditions

* Choked conditions

a atmospheric

e equivalent

f fluid coolant temperature

L linear

S singular

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An Artificial Intelligence Approach to the Energy Efficiency Improvement of a Pump System

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Abstract

The energy issue is presently in focus worldwide. This work describes the application of modeling, control, and artificial intelligence to improve energy efficiency in pump systems. This Artificial Intelligence approach can be applied to industrial systems in order to reduce the energy consumption. Among the contributions of this work is the description control system based on the combination of an Artificial Neural Network (ANN) and a Proportional Integral (PI) controller that minimizes energy consumption, cost reduction and less emissions using real data. This modeled system was applied in industrial pump systems.

The paper compares energy uses for different control methods such as throttling, using variable speed drives and an Artificial Intelligence approach.

1. Introduction

The need for controlling systems and industrial processes exists and has been increasing over time. The manual control, the first type of control used by the man, is still present in several different processes and needs a human operator with conceptual and often intuitive knowledge of the process as well as of the system. This operator must have huge experience and ability to avoid accidents and obtain the maximum energy efficiency of the equipments. Even the well trained and highly qualified operator can make error that can result in failures in the control process. Currently, factors such as increasing in the system complexity and economic pressure for efficiency and reliability have demanded automatic control system by the industrial sectors [1]. However, with recent advances in technologies, the automatic control systems of industrial processes have become more complex and, some times, inefficient in relation to the energy demand, thus they contrast with others directive of control like as production target that leads the system to operate out of the point of higher energy efficiency. In this regard, there has to be a trade-off between energy efficiency and production target if we want to have an effective control.

This issue emerges in searching for new control methods and strategies such as: multivariable control, adaptive control, predictive control, and control system based on artificial intelligence whose objective is focused on the optimal control. The most common type of control in the industry is the linear PI controller implemented in Programmable Logic Controller (PLC) that allows the development and the inclusion of this control option.

Throttling is effective in reducing flow from pumps, but is not an efficient method because of the energy wasted across the throttle, although it is widely used as a flow setting or controlling technique. Ideally, pumps should be operated within a range of flows centered around peak efficiency flow if problems are to be avoided and high efficiency achieved. Therefore, the range over which throttling should be employed, if it is employed at all, is limited.

Unlike throttling, the speed control does not affect the efficiency of the pump, if there is no static head in the system curve. Frequency converters also allow soft starting and stopping of the pump drives. A decrease in the rotational speed may also have a positive effect on the life time of bearings and other mechanical parts, which favours the use of variable speed drives in pumping applications [2], [3].

In the last three decades, numerous alternative control techniques, such as the ones based on artificial neural network (ANN) and fuzzy logic (FL) theories have been proposed to replace conventional techniques in order to improve industrial control system [4]. In recent years, artificial neural network mainly multilayer perceptron (MLP) with backpropagation algorithm [5], became satisfactory results [6]. This model presents learning and generalization capabilities, remarking their capacity for dealing effectively with nonlinear input-output relationship.

All the necessary procedure to train the ANN was acquired from the experimental water pumping process located at the LEEQE/DEESP-UFPE. Moreover, the process was digitally modeled to allow the identification of the necessary parameters constrained to a reduction in the energy demand of the process.

2. Motivation

In industry, the major part of electric energy is consumed by electric motor applications, which are typically pump, fan, and compressor drives. Hence, increased electricity prices and social awareness of environment have increased the public interest in the energy efficiency of these devices. High energy efficiency can also be linked with improved system reliability stating the importance of operating electric motor applications with high efficiency. Pumps therefore represent the largest single use of motive power in industry and commerce as shown in the breakdown of energy usage by motor driven equipment:

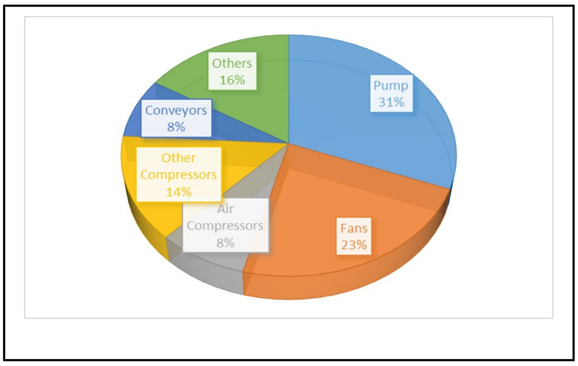

Figure. 1. Estimated distribution motor electricity consumption

In this paper, we propose an automatic control process based on artificial neural network applied to industrial processes aiming for energy efficiency. In addition, we also describe the application of the proposed methodology to a pumping system. The benefits covered include: energy cost savings, simplified pipe systems (elimination of control valves and by-pass lines), reduced maintenance, energy conservation, CO_2 emissions reduction and cost reduction.

3. Arrangement of the pumping system

The experiments were accomplished in the LEEQE /DEESP-UFPE, laboratory specifically developed to research for energy efficiency of motive control systems. In this laboratory, three industrial systems are available to study the control and energy efficiency, such as: water pumping, air compression and exhaustion [7]. Each system, which uses the Siemens WinCC® supervisory program [8], has various options of operation and control. The description of the pumping system is presented in this work.

The LAMOTRIZ didactic system aims to analyze different operation options of equipments usually used in industrial motive systems. As a result, it is possible to develop experiments with new control options and perform comparisons and analyzes between the theory and the practice. Reductions in energy demand can also be realized by comparisons between different techniques, which indicate the maximum possible energy efficiency offering by each process.

3.1 Pumping system

Figure 2 depicts the hydraulic circuit of the pumping system where we can see the following set of components: the flow meter, the pressure meter, manual valves, solenoid-controlled valve, pump motor, torque transducer and velocity sensor.

The main equipments and components of the pumping system are:

1. Manual valve to regulate the water inflow;
2. Controlled valve, from 0 to 100%, to regulate the water inflow;
3. Centrifugal pump;
4. Coupled pump-motor;
5. High performance motor;
6. Drainage manual valve;
7. Controlled valve, from 0 to 100%, to by-pass;
8. Controlled valve, from 0 to 100%, to pump water into the highermperior reservoir; om 0 to 100%, to rise the water from the tanks;
9. Pressure transducer;
10. Manual valve to pour water from the higher tanks;
11. Solenoid valve to pump the water into the 3m high tank;
12. Solenoid valve to pump the water into the 5m high tank;
13. Transducer of the water level from the tank on the ground floor;
14. Manual valve to pour water from the 3m high tank;
15. Manual valve to pour water from the 5m high tank;
16. Flow transducer.

The pumping system is constituted by two water tanks, not showed in Figure 2, which are 3m and 5m high from the floor.

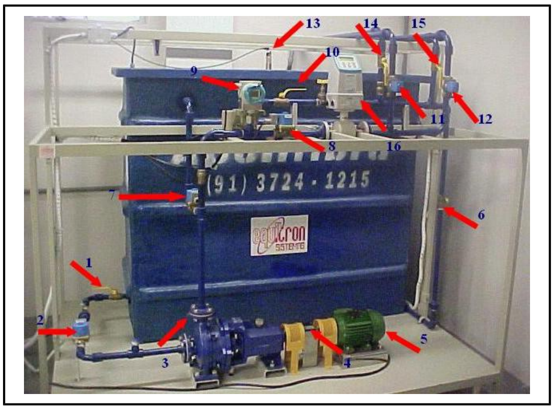

Figure. 2. Hydraulic Circuit from the pumping system

3.2 Supervision and Control Systems

In figure 3, we can see the graphic user interface of the pumping system to realize the experiments by the WinCC® software.

As we can note from Figure 3, the water pumping system allows various options for simulating the water flow control using the proportional valve. The system has three remotely controlled valves which can be opened from zero to 100%. The first valve (FCV-1A-01) is located in water inflow of the pump next to the tank located on the ground floor; the second valve (FCV-1A-02) is used to simulate operations of by-pass, which makes the water to flow in a backward direction to the same tank from which it is being pumped; and the third valve (FCV-1A-03) located in the pipe that joints the both superior and inferior tanks and is used to simulate throttling the output of the pumping system.

The pumping system is completely automated, allowing the water flow be controlled due to the versatile system given by the implementation of control algorithm via programmable software and WinCC® supervisory program which are associated with the PLC that commands the frequency of the converter, varying the pump motor speed, which provides an efficient flow control [7].

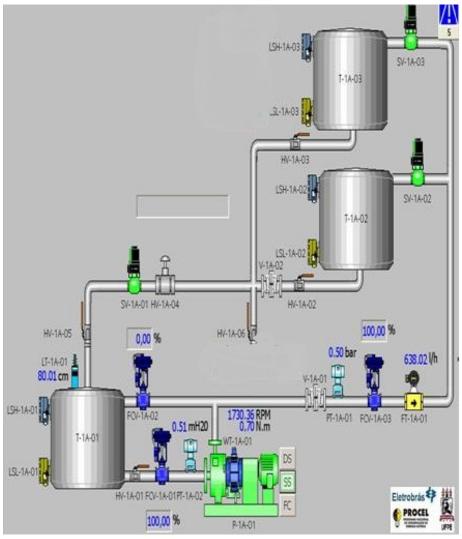

Figure. 3. Graphic User Interface of the Pumping System

4. Methodology

In this paper, we present an application of industrial process control based on ANN aiming for increasing control and energy efficiency in a specific industrial pumping system. The idea, however, can be generalized to other industrial process.

The main points of the control system implementation are presented next.

4.1 Proposed Industrial Process

In many industrial processes, it is necessary to pump defined volumes at a given outflow. In this work, a hypothetical industrial process that needs certain volume "V", as shown in Figure 4, was simulated.

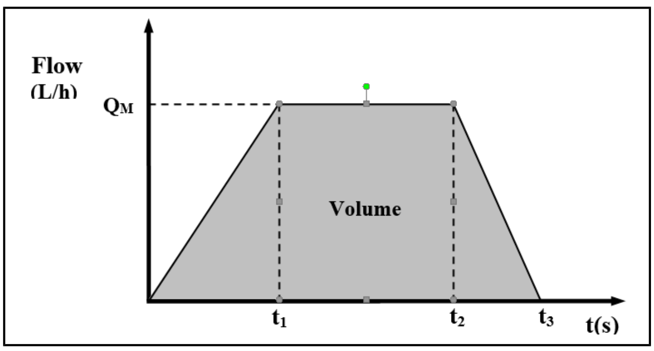

Figure. 4. Hypothetical Curve

As we can note in Figure 4, it is possible to define four variables that clearly describe the proposed process (trapezoidal behavior curve that simulates an industrial process to fill a certain tank).

The total volume pumped in the process can be calculated by Equation (1).

$$V = \frac{t_2 + t_3 - t_1}{2} \cdot Q_M \qquad (1)$$

Where:

- t_1 - Inertia time since the start of the process until its operation in the steady state.
- t_2 - Instant of the beginning of the turn-off process.
- t_3 - Final Instant of the process.
- Q_M - Specified maximum inflow to full the tank.

4.2 Data preprocessing and evaluation criteria

Once the most appropriate raw input data has been selected, it must be preprocessed; otherwise, the neural network will not produce accurate forecasts. The decisions made in this phase of development are critical to the performance of a network.

The first stage of the data preprocessing in this work was to randomly mix the data. Using this process, it is possible turn the data uniform, thus avoiding tendency to false results. After finishing the mixture of the data, the next stage was to normalize them.

Observing that the maximum and minimum magnitudes of each data variable are different, they were normalized individually as in (2):

$$x_{\substack{norm \\ (0,1-0,9)}} = \frac{x - 0,9.x_{mín}}{1,1.x_{máx} - 0,9.x_{mín}} \qquad (2)$$

The data were normalized between 0.1 and 0.9 to avoid saturation of the neurons in the network, making difficult the learning during the training [9].

In this work the data were divided into 50%, 25% and 25% to train, validate and test the neural networks, respectively.

During the neural network training, the calculated error was the mean-squared error (MSE), as shown in (3).

$$MSE = \frac{x_{máx} - x_{mín}}{N \cdot P} \sum_{p=1}^{P} \sum_{i=1}^{N} (x_{pi} - t_{pi})^2 \qquad (3)$$

The simulation results of the networks were evaluated using the percentage mean absolute error (MAPE), as shown in (4).

$$MAPE(\%) = \frac{1}{N \cdot P} \sum_{p=1}^{P} \sum_{i=1}^{N} \frac{|x_{pi} - t_{pi}|}{t_{pi}} \times 100 \qquad (4)$$

Where, x_{max} and x_{min} are the maximum and minimum values of the output coefficient, respectively. N is the number of the network outputs and P is the number of patterns in the data; x_{pi} and t_{pi} are the realized and desired output to each pattern.

4.3 Implementation of the ANN

A wise algorithm implementation to find a proper data set to train an ANN is a decisive factor to define the ANN architecture that best fit the process control system. In this regard, it is highly important that the behavior of the patterns found on the training and test sets closely matches the actual system behavior.

In order to realize the ANN training, experimental data were acquired from the pumping system using the WinCC® supervisory program.

The supervisory program implemented in the pumping system is the WinCC®. This software offers the possibility to implement scripts using the Visual Basic® programming language. Therefore, it is possible to accomplish from simple algorithms, like assignment statement, to more sophisticated ones, like an implantation of an ANN-based controller.

5. Results and Discussions

5.1 ANN architecture

The applied methodology in this work consisted initially of the data preprocessing and the establishment of the best multilayer perceptron neural network (MLP) architecture trained through the RPROP algorithm (Resiliente backpropagation) [11].

ANNs learn from examples and are developed to be able to generalize the knowledge acquired during the training. It is initially important to define the essential input variables for developing the ANN. For the developed system, these variables are V, t_1, t_2, t_3 *and* Q_M, which have been previously defined and depicted in Figure 4. The collected data were thus divided into training, validation and test set as standard procedures to develop neural network architectures [5, 9, 10]. We have used 50% of the data for training, that is, for adjusting the network weights. Half of the remaining data were used as validation set to verify the ANN generalization ability and the other half data were used for testing, i.e., for analyzing the ANN overall performance, since these data were not previously shown to the network.

5.1.1 *ANN training*

The preprocessing input data V (volume) and output data t_1, t_2, t_3 and Q_M were presented to the network. Knowledge of the domain is important in choosing preprocessing methods to highlight underlying features in the data, which can increase the network's ability to learn the association between inputs and outputs. In this work, the data were normalized in the range from 0.1 to 0.9.
The tan-sigmoid and log-sigmoid transfer functions were used in the hidden and output layers, respectively. The criterion adopted to choose the number of hidden neurons was made by training several ANNs with Gradient Descent with Momentum (GDM) algorithmand varying this number from 2 to 6. In this case, the architecture with 3 hidden neurons has provided the best performance (the least mean- squared error) on the validation set with 10

random initializations of the weights. After choosing the best ANN architecture, we searched for the most suitable learning algorithm.

The backpropagation algorithm is commonly used to update the values of the weights and biases in response to the error in the network. Gradient Descent with Momentum algorithm – GDM [12], Resilient Backpropagation algorithm (RPROP) [11] and Levenberg-Marquardt (LM) [13] algorithm are the main optimization techniques applied in the backpropagation learning rules. All these techniques were analyzed by the ANN with three hidden neurons, whose architecture is shown in Figure 5.

Figure. 5. The ANN Architecture

The Best ANN architecture was selected based on the best performance (MSE) on the test set. The LM algorithm provided the smallest MSE among the others algorithms. All the networks were trained using the Matlab®.

5.1.2 Simulation

After finishing the training of the ANNs, the best neural network was chosen and implemented in the Simulink®.

The simulation of the ANN are as follows: a certain volume is given as input to the ANN and it provides four variables (Q_M, t_1, t_2 *and* t_3) that best match the corresponding volume, aiming for high energy efficiency.

5.2 Control

An industrial process control can be made in several ways. Technological advances have made possible the development of many types of controller, but the most common in the industry is the PI controller.

5.2.1 Simulation of the ANN and PI System

With the trained ANN and the complete model of the PI controller system, we can simulate the complete system. The ANN requires a certain volume (V) as input and yields four outputs (Q_M, t_1, t_2 *and* t_3) that are necessary to supply the PI control system, which in turn provides the desired volume constrained by the maximum energy efficiency. From the integration of the outflow graph (Figure 3) through t_1, t_2 *and* t_3, the real volume is obtained and this value is approximately equal to the desired volume. The trapezoid block of Figure 6 controls the simulation time of the system and yields the desired outflow.

We can observe in Figure 6 the outflow graph as a function of time. Two curves are depicted: the curve of the ANN and the one of the controlled system.

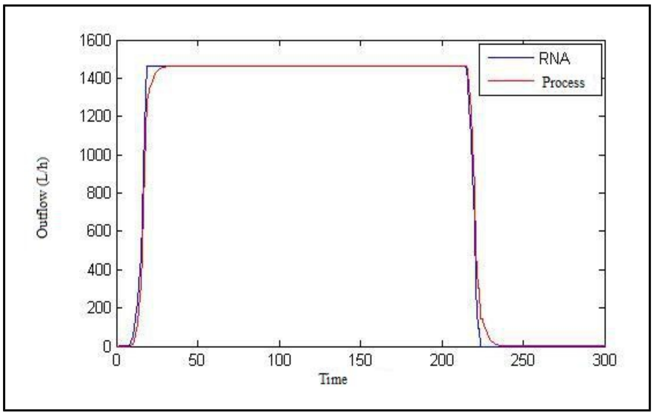

Figure. 6. Outputs: the ANN and the Controlled System

The control system is able to output in a satisfactory way from variable provided by the ANN and, according to Figure 6, it depicts a curve similar to the ANN.

5.3 Experimental Results

Following the methodology presented previously, we implemented in the pump system the PI controller and the ANN-based PI controller. Both controllers were used in order to give experimental results, and so, we could evaluate the practical viability of a pump control system assisted by an ANN.

All implementations were done using Visual Basic® script in the supervisory program.

Table I shows the experimental results of the controllers with and without the ANN. In this table, the energy demand by both systems is presented, as such as, the economy of energy obtained. These results were yielded by different values of pumped volume.

Table 1: Economy of energy demand (Tank at 5 m high)

Volume (L)	Energy (PI) (W.h)	Energy (ANN) (W.h)	Economy (W.h)	%
100	64	47	17	26.6
200	128	101	27	21.1
300	192	151	41	21.4
400	256	202	54	21.1
500	320	254	66	20.6

It is important to point out that the PI controller without the ANN was applied to a desired outflow of 2140 L/h. We point out that the PI controller without the ANN does not search for the maximum energy efficiency, one of the aims of this work. The ANN takes information about the desired volume and provides information about the outflow curve that will reach the maximum energy efficiency.

In this work an ordinary PI controller was used. The use of different types of liner controllers is possible. For example, in the case of a multi-element PI controller, the energy efficiency could be taken into account. However, using the ANN, the control becomes dynamic and adaptable to different situations.

The data obtained by real experiments presented a considerable reduction in energy consumption when the process is controlled by the PI controller assisted by the ANN. By the ANN setting the variables to control the system, the gains are in the order of 20%. We can observe that the economy of energy in absolute value (W.h) increases significantly with the increase in the volume required, i.e., in a large scale systems (thousand of liters), the economy of energy will be significant.

In order to obtain new experimental results, the methodology proposed in this work was also used to the 3m high tank of the pump system showed in Figure 3.

The results validate the substantial gain of the energy efficiency using the proposed methodology as shown in Table 2.

Table 2: Economy of energy demand (Tank at 3m high)

Volume (L)	**Energy (PI) (W.h)**	**Energy (PI+ANN) (W.h)**	**Economy (W.h)**	**%**
100	56	38	18	32.1
200	110	76	34	30.9
300	165	112	53	32.1
400	219	148	71	32.4
500	275	188	87	31.6

The data obtained through real experiments present a sensible reduction in the consumed energy when the process is controlled through ANN. In percentual terms, with the ANN controlling the system, the economy around 30% . It can also be observed that the energy economy increases significantly as well as the increase of the required volume. That means in large scale (thousand of liters) the economy will be significant.

Table 3: Economy of energy demand (Tank at 5 m high)

Volume (L)	**Energy (Throttle Valve)**	**Energy (ANN) (W.h))**	**Economy (W.h)**	**%**
50	40	19	21	52.5
100	85	38	47	55,3
150	121	57	64	52,9
200	169	76	93	55,1
300	242	112	130	53,7
400	325	148	177	54,5
500	415	188	227	54,7

In Table 3, are compared the energy consumed between two different ways of control systems: ANN control and Throttle Valve Control (tank at 5m high). The data obtained through real experiments present a sensible reduction in the consumed energy when the process is controlled through ANN. In percentual terms with the ANN controlling the system, the economy was around 50%.

Table 4: Economy of energy demand (Tank at 3 m high)

Volume (L)	**Energy (Throttle Valve)**	**Energy (ANN) (W.h))**	**Economy (W.h)**	**%**
50	32	13	19	59,4
100	77	29	48	62,3
150	112	43	69	61,6
200	150	51	99	66,0
300	221	75	146	66,1
400	291	98	193	66,3
500	378	129	249	65,8

In Table 4 are compared the energy consumed between two different ways of control systems: ANN control and Throttle Valve Control (tank at 3m high). The data obtained through real experiments present a sensible reduction in the consumed energy when the process is controlled through ANN. In percentual terms, with the ANN controlling the system, the economy was around 60%.

6. Conclusions

In this paper, results presented many examples of how variable speed drives and ANN have saved a tremendous amount of energy, mainly, When pump systems using flow controlled by throttling valves. The plant thus achieved electricity savings 60%, this means CO2 emissions and cost reduction.

The ANN implemented in this work assisted the conventional PI industrial controller, turning it energetically more efficient as verified in the results obtained. The control system becomes more dynamic and adaptable using the frequency converter, which can be applied to various types of systems found in the industry.

Significant economy in the electrical demand of energy will be obtained by large scale system if this controlled system were assisted by an ANN trained using the methodology developed in this work, which aims for the energy efficiency in industrial systems.

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Critical Energy Savings Concepts for Electric Motor Pump Systems

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Abstract

When considering energy efficient operation of motor driven pumps components properly selected and sized for energy efficiency are essential, however, pumps come in a multitude of mechanical configurations. This increases design options but adds selection complexity. Standards created by recognized bodies provide authoritative information to guide one through this universe of options, consequently understanding pump performance and available knowledge resources are increasingly important elements for proper pump and motor drive selections.

Further pumps come in numerous technologies. This presentation outlines the significant items to consider in the application of liquid pumps, highlighting basic selection criteria and providing reference standards for identifying energy savings potentials. Too often energy efficient operation is lost in the selection process and with inclusion of excess flow or pressure requirements. It also discusses frequently overlooked positive displacement pumps for energy savings opportunities.

Overview

Government agencies in both Europe [1] and the United States [2] for over a decade have been engaged in processes to set efficiency standards for liquid pumps. Since there are a vast number of pump types, with ubiquitous applications, making major reduction in energy consumption through component regulation is no simple task.

However in a catch-ball process between users, industry, environmental groups and regulatory agencies the nearly universal conclusion is that the largest energy reduction opportunity appears in the system not in components such as the individual pump or motor drive. Current voluntary standards, such as ISO 50001 Energy Management Systems [3], series reinforce the importance of systems and on organized programs of energy reduction activities.

The numerous supply channels, in which pumps reach the user makes substantiating percentage of driver types by energy source extremely difficult, however, electric motors are clearly dominate and likely are installed in over 90% of pumps. Electric motors have been one of the early industrial products targets for energy regulation and pumps make up 27% of energy used by industrial systems[3]. In studies authoritative agencies such as the US DOE, (US Department of Energy) [4] have reported energy constitutes 40% plus of a pumps life time costs.

Because of the complexity of the pump universe initially regulators have chosen to pursue pump efficiency regulations for rotodynamic pumps but only initially to regulate pumps handling clear water within a defined flow and pressure range. Certainly a reasonable first step since water is the most abundant fluid covering 70%[5] of the earth and clean fresh water is a life sustaining fluid supported by an extensive infrastructure of transport, processing, distribution and multiple use applications. Motor driven pump models are widely available, sold for domestic water services, irrigation, process, thermal transfer, building heating, fire control, cleaning and general purpose applications.

Certainly through regulations there will be energy consumption reductions in future motor driven pump applications. In the European Union there are announced plans for programs over the coming decade to continue the regulation process to additional pumps and liquids. These are positive energy reduction actions; however, this paper will emphasize longstanding application practices which hold immediate opportunities for energy consumption reduction:

- Selection of appropriate pump type[6.]
- Design around BEP, (Best Efficiency Point) / Do not over size pump or driver.
- Stay close to BEP using VFD (Variable Frequency Drive) and feedback control.
- Consider alternate technologies in “crossover” range.
- Expand consideration beyond rotodynamic pumps in selected applications.
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Proper Pump Selection Assistance

There are two technologies that dominate pump applications: Rotodynamic and Positive Displacement. (PD) The categories are established by the manner in which pumps add energy to the working fluid. A positive displacement pump moves a batch of fluid from pump suction to discharge and pressure is developed as fluid is forced into the system.

In simple terms a rotodynamic pump impeller moves a stream of liquid from the pump suction to a discharge cone where velocity is gradually decreased and converted to pressure energy. To date power reduction efforts and regulatory interest have been focused primarily on rotodynamic pumps because they are generally believed to provide the technology for 80% of the pumps in service and 90% of the electrical energy consumed. This technology is well known to users and is the pumping method primarily taught in technical courses. Pump performance is displayed with a very familiar head vs. flow rate curve, with a peak efficiency known as the BEP, Best Efficiency Point. The technology has broad application on water like liquids and in most power ranges can be driven directly by two, four or six pole electric motors.

Within rotodynamic pumps are radial, mixed flow and axial flow impeller designs which impact the shape of the performance curves effecting maximum head capabilities and motor requirements. Of high importance to the selection is the $NPSH_R$ (Net Positive Suction Head Required) curve where NPSH is defined as the head above the vapor pressure of the working fluid. $NPSH_3$[7] another important application factor, is the NPSH at which the pump loses 3% operating head due to cavitation. Although the term cavitation is seen as a hydraulic condition it also may be seen as important to operating life. The same is true of BEP as expanded below.

The fundamental selection criteria for pumps include consideration of: flow rate / inlet pressure / viscosity/ discharge pressure required / liquid / vapor pressure / operating temperature / fluid limitations / available NPSH / driver type / environment area concerns. Viscosity is a primary criterion for a large body of liquids since it enables many positive displacement pumps and may deteriorate performance of rotodynamic pumps.

In addition to these fundamentals, the criteria for selection is often determined by an industry standard Examples would be the API 610)[8] or ANSI/ASME B73,[9] or NFPA-20[10] or ship pump standards from ASTM International[11]. Within their sponsoring industry they set necessary criteria, but some for serve multiple industries. As an example ANSI B73.1 chemical industry standard is seen frequently in general purpose applications because it is a document that provides defined product dimensions making it attractive for inclusion in project specifications. Or API oil and gas pumps are often seen in other industries because of their reputation for robust mechanical construction.

The importance of this is to highlight that proper drive selection is dependent on pump knowledge. Regulators are often tempted to look for niche application slots in which pumps can be categorized, similar to motors, but one can see the many variables in pump application make such almost impossible. For example Hydraulic Institute ANSI Standard 1.3-2009 lists 32 configurations of Rotodynamic Pumps [12].

One can therefore see proper pump selection is based on a myriad of variables. Hydraulic Institute also provides Standards and Guidelines which allow a user to determine which of the configurations provide the best fit for an efficient solution to a specific application. ANSI/HI Guideline 20.3-20.0 [13].

Design around the BEP (Best Efficiency Point)

The most basics of pump system application criterion is that a rotodynamic pump operates at the intersection of the system curve and the pump curve. And that any operation to the left or the right of BEP will lower the pump efficiency. Such does not always increase power (which is a function of head, flow and efficiency), however many studies have shown the adverse mechanical effect on pump life through prolonged operation away from BEP and outside of the recommended operating range.[14]

Stay close to the BEP with a VFD (Variable Frequency Drive with Feedback Control)

One option for this is accomplished by the “Extended Product” solution. Since most energy saving legislation is written to place requirement on pump and motor manufacturers and not users the “extended product” definition provides an opportunity for energy savings by defining a component package with control capabilities.

Configuration falling within this definition range from off - on operation of a tank level controller, to a pump, motor, variable frequency drive and feedback control based on the simple basics of the rotodynamic pump affinities laws:

Flow is proportional to shaft speed $$\frac{Q_1}{Q_2} = \left(\frac{N_1}{N_2}\right)$$

Pressure (Head) is proportional to square of shaft speed $$\frac{H_1}{H_2} = \left(\frac{N_1}{N_2}\right)^2$$

Power is proportional to the cube of the speed $$\frac{P_1}{P_2} = \left(\frac{N_1}{N_2}\right)^3$$

The motor impact in the off-on case is to insure a design with multiple start capabilities which opens consideration of soft starters. With the growing use of VFDs motor manufacturers have expanded VFD compatibility into their standard product offerings. Still VFD selection requires a close analysis of the pump drive, cabling and operating conditions to insure capabilities at all operating points. An example might be sufficient motor cooling at low speeds or minimum operating speeds for PD pumps.

Since the Extended Product (EP) is only supplying the energy required for the application power savings are substantial. The EP minimizes over sizing selections and adapts to seasonal variations but basically is targeted for systems with variable operation requirements and a high component of friction head in its requirement..

Expand consideration beyond Rotodynamic Pumps

To date regulatory and user energy reduction efforts have been focused primarily on rotodynamic pumps since they are considered the most likely candidates for large energy savings. As stated earlier the second major technology for the pumps is Positive Displacement (PD). A positive displacement pump moves a set volume of liquid and pressure is obtained as liquid is forced through the pump discharge into the system thereby converting energy to pressure. The difference between these two pumping technologies is how energy is converted and energy reduction techniques differ accordingly.

Positive Displacement pumps are used in many applications across a multitude of industries because users have found them to be solutions to specifics pumping challenges, however, because rotodynamic pumps provide a much higher flow rate and with their simplicity they are typically first considered for selection. Many properly applied PD pumps operate for decades with only minor maintenance; however, perception often is PD’s require more maintenance than rotodynamic pumps.

“Specialty” is an excellent choice of description for positive displacement pumps and they may therefore have unique motor requirements. Several types have specific characteristics that have made them the preferred product technology in a specific application niche.

Areas of typical PD consideration are high pressure, viscose fluids, sealless designs, self-priming requirements and fragile liquids. Due to their designs they operate at low to moderate flow rates to 3500 m^3/h. In flows above 15 m^3/h they generally are low rpm machines but it would be fair to say the over whelming segment of product is below that flow rate and motor driver selection often requires more attention than rotodynamic pumps. The products have high efficiencies but flow/pressure spill back control historically has lowered their system efficiencies. Today however this is overcome by VSD application.

The PD pump is a constant flow variable pressure device and as such low adoption rates by systems designers, familiar with rotodynamic control philosophies, has limited their application. Today, however, with adoption of concepts such as Extended Product using variable speed that objection is partially overcome. PD pumps however, do not follow the centrifugal affinity laws but change power in direct relationship with flow.

Applications standards have been developed to cover the major PD technologies:

- Reciprocation HI/ANSI[15]]
- Rotary HI/ANSI[16]
- Metering (Controlled Volume)[17]

Contrary to rotodynamic products where core pumping components remain similar, in PD for each basic pumping technology internal component configurations vary widely plus the major technology categories have sub-categories. The area of most cross-over application opportunities is in the Rotary PD group with seven pumping technologies. A Rotary PD is a pump that uses one of the devices below to move liquids from suction to discharge and is built without check valves.

- Vane
- Piston
- Flexible Member
- Lobe
- Gear
- Circumferential Piston
- Screw

In today’s energy focused environment for new installations it is valuable to consider PD pumps in their core applications plus in cross over applications that can be serviced by both rotodynamic and PD technology.

Consider multiple pumping technologies

Cross over applications are herein defined as applications where either PD or rotodynamic technology can provide pumping solutions. Life cycle cost comparison between the two technologies sometimes is not possible due to insufficient historic data. Operating cost however frequently can be calculated around a load profile and in viscous applications the rotodynamic pump power can be calculated using the Hydraulic Institute Guideline ANSI/HI 9.6.7 for Effects of Liquid Viscosity on Rotodynamic Pump Performance.

Heavy viscous fluids have always been the sweet spot for PD pump applications. However, reciprocating and vane pumps have found wide applications on water thin fluids. A true rotary crossover candidate is the screw pump family, both timed and untimed. In a timed unit, clearances between two rotating screws is established by bearings whereas in an untimed screw clearance between three precision screw elements is held by a fluid film based on sleeve bearing technology. The multiple closures and the long length over diameter ratio provide high pressure capability and contrary to other PD pumps allow performance at two or four pole direct drive motors speeds.

The selection options for PD pumps in 24/7 energy sensitive operations are being expanded by material advances, control, monitoring technology and adoption of variable speed drives. One example of such would be in electric motor drive pumps in main line crude oil pipeline transportation applications. Traditionally crude lines have been multistage centrifugals. Because of the following product upgrades consideration is now additionally given to high capacity, high pressure three screw pumps which have been identified as having the highest efficiency Rotary PD designs [18] :

- Concerns of the impact of off spec fluids on untimed screw pumps, which depend on precise internal fluid films, have been greatly reduced, through development of real time fluid monitoring and control technologies in conjunction with variable speed drive technologies.
- Historically limited in flow new extended models of Rotary PD untimed screw pumps today have flow rates capabilities of 955 m^3/h and timed screw pumps have flow rate capabilities of 1910 m^3/h at pipe line pressures and 3400 m^3/h at transfer pressures.
- Improvement in materials and manufacturing processes have extended product life in untimed screw pump applications, but possibly more importantly have allowed for operation on lower viscosity thinner fluids.

Advances in electric driven systems, coupled with the increased flow rate capabilities of untimed Rotary PD screw pumps provide opportunities for substantial energy savings in crude pipe line applications. As an example in a 40,000 BPD (Barrel Per Day) crude oil pipeline handling a product with a viscosity range of 123 cSt min / 325 cSt norm / 415 cSt max, operating at a pipeline pressure of 9928 kPa when equipped with variable frequency motor driven high pressure untimed PD Rotary screw pumps realized a savings of 3090 kW versus the traditional selection. Valued at $.075 a kWh gives the operation a monetary savings of $10.1M over a five year period.

This pumping technology has been used successfully for decades for crude field feeder pipelines but today with the availability of higher flow and pressure designs in both timed and untimed PD rotary screw pumps, it is available for mainline service. Additionally the growing acceptance of variable frequency drives and real time condition monitoring provides the variable flow and a pump protection level which makes this an effective alternate solution to the historic equipment for mainline crude pipelines.

PD pumps efficiencies are impacted by the combination of hydraulic and mechanical losses. In this case the pressure level and fluid result in a unit where mechanical loss is a very small percentage of the total power.

These are clearly impressive savings in this application. HI / ANSI Standard 3.1-3.5 provides helpful general guidelines for cross over applications. “For services that meet product application criteria, users will find opportunities for energy savings in well-designed systems using rotary pumps. This technology has historically found its greatest application at increased viscosities; however, specific designs also handle very thin fluids. Rotary pumps therefore will cover a wide range of services; however, areas of specific attractiveness may be found in applications involving both:

- Fluid with viscosities above 10.3 cSt (60 SSU)
- Differential pressures above 3.5 bar (50 psi)”

Not all applications can show the savings of the above crude pipeline units but in the crossover region the percentage savings can be impressive. In a recent manufacturers study the following energy savings were reported:

Pressure Δ Range	Scope	Rotary Pump Power Savings
5-20 bar	Peripheral Turbine Product Pump vs Rotary Pump	28.9%
20-30 bar	Segmented multistage centrifugal vs Rotary Pump	13.3%
Fluid: Glycol Mix / 10.6 cSt at 20°C /		
Flow Range: 1 to 100 m^3/h		

Here again with these crossover applications the benefits of a variable speed motor drive system allows the pump to meet changing system conditions.

Conclusion

Following the fundamental rules of pump application, applying Extended Product and consideration of the most energy efficient technology in cross over applications create the potential for substantial sustainable energy and environment value enhancement.

Digital control technologies, increasingly efficient motors, variable speed drives and emerging dynamic fluid condition monitoring capability creates the potential for users to make substantial reductions in total energy consumption. Often this value is obtained through the selection of Rotary PD pumps, which as highlighted in this paper, on selected applications can enable a very high level of operating cost savings.

[1] Commission Regulated (EU) No. 547/2012 (25 June 2012) Implementing Directive 2009/125/EC EcoDesign requirements for water pumps.

[2] Energy Conservation Standards Rulemaking Framework Document Commercial & Industrial Pumps, US Department of Energy, Building Technologies Program January 25, 2013.

[3] / [4] Improving Pumping System Performance US Department of Energy, Energy Efficiency and Renewable Energy.

[5] USGS http://ga.waterusgs.gov/edu/

[6] Hydraulic Institute Guideline For Rotodyanamic Pump Efficiency Prediction HI 20.3 – 2010

[7] Hydraulic Institute HI/ANSI 1.3-2009 Standard For Rotodynamic Pumps For Design and Application

[8] API Std. 610 Centrifugal Pumps for Petroleum Petro Chemical and natural Gas. 9/01/2010 Eleventh Edition (ISO 13709: 2009 Identical Adoption)

[9] ASME B73.1-2001 (R2007) Specification for Horizontal Centrifugal Pumps Chemical Process.

[10] National Fire Protection Association NFPA-20. For Installation of Stationary Pumps for Fire Protection.

[11] ASTM – International – F998-12 Standard Specifications for Centrifugal Pumps Shipboard Use, Bilge and Ballast F009-12 Standard Specification for Centrifugal Pump, Shipboard Use

[12] Hydraulic Institute ANSI 1.3-2009 Standard for Rotodynamic Pumps for Design and Application.

[13] Hydraulic Institute ANSI Guideline for Rotodynamic Pump Efficiency Prediction HI 20.3 – 2010.

[14] Hydraulic Institute / ANSI Guideline Allowable Operating Range 9.6.3.

[15] Hydraulic Institute HI/ANSI 6.1-6.5 and HI/ANSI 8.1-8.5 Standard for Reciprocating Pumps for Nomenclature, Definitions, Application and Operation.

[16] Hydraulic Institute HI/ANSI 3.1-3.5 Standard for Rotary Pumps for Nomenclature, Definitions, Application and Operation.

[17] Hydraulic Institute HI/ANSI 7.1-7.5 Standard for Controlled Volume Metering Pumps for Nomenclature, Definitions, Application and Operation.

[18] Hydraulic Institute Rotary Pumps ANSI/HI 3.1-3.5 Page 45

Energy efficiency in water pumping systems used for rice crop irrigation in Rio Grande do Sul – Brazil

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Abstract

The rice culture in Brazil ranges a cultivated area over 2.4 million hectares with 12 million tons of rice production. So, this results in an average productivity of 4,984 kg/ha. The State of Rio Grande do Sul accounts for a planted area, over 1 million hectares and an average annual production of 7.8 million tons, corresponding to an average productivity of 7.35 kg/ha. The process is different, once adopts the irrigation process of plant flooding, in which a 5-10 cm layer of water is held throughout rice growing and maturation. There are three types of mechanized irrigation in terms of a planted area: electromechanical (48%), diesel-mechanical (19%) and natural (33%). Several energy conservation actions are being undertaken by electricity utilities, within their annual programs of energy efficiency, which indicate 40% of real reduction of power and water consumption. This work explores the potential of energy and water conservation due to the adoption of energy-efficiency measures in mechanized irrigation processes in rice crop growing. As reference, it has a sample of the current situation of this type of energy service as well as the performance of several promotion actions for the rational energy usage promoted by energy utilities within their Energy Efficiency Annual Programs. The extrapolated results seek to point out the potential level that glimpses to the rest of the irrigated rice producing regions, once this type of agriculture is now in expansion throughout the country.

Introduction

According to the statistics of the Riograndense Rice Institute – IRGA [7] for the 2012-2013 crop, the rice cultivation in Brazil includes a planted area of 2,420,000 hectares with a production of 12,062,000 tons of rice, resulting in an average productivity of 4,984 kg/ha. The Institute also notes an increase of 4.0% average productivity.

The southern region of Brazil is responsible for a planted area of 1,250,000 (51.6%) hectares, with an estimated production of 9,260,100 tons of grain (76.7%) resulting in an average productivity of 7,408 kg/ha. This Region presents productivity 148.6% higher than the Brazilian average.

The process of cultivation of this rice is differentiated once adopting the process of flood irrigation of crops, being held 5 to 10 cm water throughout the growth and maturation of the plant. In the rest of Brazil's, the rice culture uses a type of rice that no requires permanent irrigation, adapted a traditional cultivation with natural irrigation. However, does not reach the productivity of irrigated rice, with a low aggregate value product not accepted by the consumer market. In 2012-2013, Rio Grande do Sul has a planted area of 1,082,419 hectares (44.7%) with an estimated production of rice 8,067,269 (66.9%) tons with an average productivity of 7,453 kg/ha. This culture in the State is virtually all irrigated rice.

Adopting the data of a detailed survey of crop acreage of Rio Grande do Sul [6] and keeping the same ratio of energy participation in irrigation checked in 2004 we have as result the TABLE 1, with the estimated area cultivated by different forms of irrigation in the different areas of the State.

Table 1: Irrigated rice culture in Rio Grande do Sul – Brazil

Areas	TOTAL		Crop Area					
			Electrical Mechanics		Diesel Mechanics		Natural	
	ha	%	ha	%	ha	%	ha	%
CAMPANHA	151.979	14%	17.642	2%	46.623	4%	87.714	8%
DEPRESSÃO CENTRAL	148.492	14%	48.194	4%	34.158	3%	66.141	6%
FRONTEIRA OESTE	329.473	30%	222.125	21%	74.441	7%	32.907	3%
PLANÍCIE COST. EXTERNA	138.960	13%	76.693	7%	16.197	1%	46.071	4%
PLANÍCIE COST. INTERNA	141.291	13%	65.725	6%	13.560	1%	62.005	6%
SUL	172.225	16%	121.809	11%	24.157	2%	26.259	2%
RS - TOTAL	**1.082.420**	**100%**	**552.188**	**51,0%**	**209.136**	**19,3%**	**321.096**	**29,7%**

We can see the elevated concentration of load already supplied by electricity (51%) and there is still a potential diesel-electric conversion (19.3%). The trend is its conversion as a result of the high costs of diesel use. Verified results indicate more than 60% savings in the conversion process, even having to invest in their own medium voltage networks (23 kV).

Another important point to note is the representation of natural irrigation in rice culture. This is provided through dams with channels or siphons. Are situations, which can be used for hydroelectric power production while the irrigation procedure.

Two electricity distribution utilities serve this market. AES SUL with 58% of the area, mostly on the western border, in the campaign and in the center of Rio Grande do Sul and CEEE-D with 42% in the coastal plain and in the southern part of the State.

The electric power is strongly seasonal, occurring on average 100 days a year, over the months of November to March of the following year. In the period between crop load, the transmission substations and power distribution system of different regions account for at most 20% of the load during harvest.

In face of this problem, the utility AES SUL has been developing actions aimed at diagnosing the rural market and to propose solutions that make it possible to associate the war against waste of electricity, to promote its rational use and its impact on the electric system both the Utility and the Brazilian Electric System.

Diagnosis of the problem

Historically, the electricity sector is faced with a problem on the border West of the Rio Grande do Sul as a result of a seasonal load thereby of pumping water for irrigation of rice crops. The availability of this type of load took place facing the oil crises of 73 and 78 where the electricity sector came to contribute to replace the diesel used in electric motor pumping systems. A whole system of HV and MV transmission, power substations and rural distribution were developed and deployed.

With the privatization of electric power distribution, the new utility sought to prospect effectively the impact of pumping load used in irrigation through a survey of irrigated rice culture facilities [8]. It was made a detailed energy diagnosis in 58 rural farms, evaluating 138 electrical installations of hydraulic pumping, totaling 13,280 CV. This represented approximately 6.2% of the installed power in the region as explained later.

Table 2 summarizes the main physical, electrical and hydraulic points observed in different farms where the geometric heights of high and low pumping Useful Power (Pu) and Installed Power (Pi).

Table 2-- Average values of power Installed for irrigation in Mechanized Rice Culture

Geometric Height	Phisical Location	Power (CV)	Geom. Height (m)	Area (hectare)	Useful Power (CV)	Pu/Pi	CV/ha	CV/m	CV/m/ha	W/ha/m
until 10 m	Direção Uruguaiana-Itaqui	107	7.28	218.94	47.91	42.78%	0.52	14.61	0.07	56.81
	Direção Uruguaiana – Barra do Quara	103	6.99	207.47	43.15	38.39%	0.73	15.19	0.14	103.68
	Direção Uruguaiana – Alegrete	70	6.96	87.34	18.38	32.82%	0.97	11.37	0.15	116.22
	Direção Rosário – São Gabriel	0	0.00	0.00	0.00	0.00%	0.00	0.00	0.00	0.00
from 10 to 15 m	Direção Uruguaiana-Itaqui	128	11.82	172.65	59.51	48.56%	0.77	10.85	0.06	48.93
	Direção Uruguaiana – Barra do Quara	156	11.81	279.71	94.43	61.18%	0.60	13.53	0.05	37.68
	Direção Uruguaiana – Alegrete	90	12.70	96.22	35.72	43.08%	0.99	7.19	0.08	58.10
	Direção Rosário – São Gabriel	58	13.27	69.87	27.01	48.14%	0.87	4.36	0.06	47.77
from 15 to 20 m	Direção Uruguaiana-Itaqui	190	17.80	213.48	111.29	58.81%	0.89	10.69	0.05	36.04
	Direção Uruguaiana – Alegrete	143	17.13	147.92	74.52	52.23%	1.02	8.26	0.06	43.66
More than 20 m	Direção Uruguaiana-Itaqui	225	24.00	278.40	195.99	86.97%	0.81	9.38	0.03	24.90
	Direção Uruguaiana – Alegrete	133	22.00	114.21	72.73	52.73%	1.37	6.07	0.06	46.00
Media		**117**	**12.65**	**157.18**	**65.05**	**47.14%**	**0.79**	**9.29**	**0.07**	**51.65**

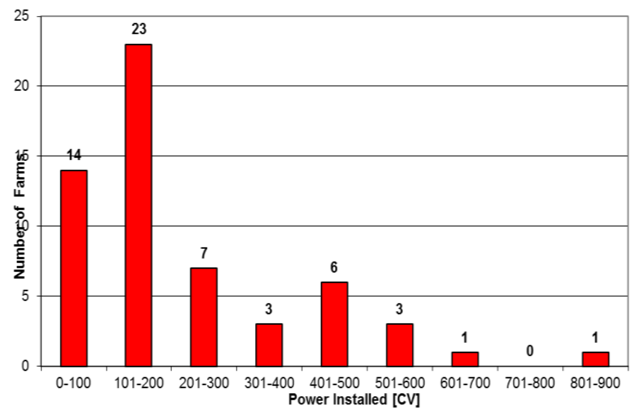

Figure 1: Frequency of occurrence of irrigation power installed

The higher frequency of occurrence of powers installed, as shown in Figure 1 is located between 100 and 200 cv. So, they are easy uprisings aimed at management energy implementation.

Table 3 summarizes the survey, having been diagnosed 11,930 CV in electric motors used in hydraulic pumping, coming up to an estimated reduction to 5,660 .0 CV, which is a 53% average reduction in function of the energy efficiency of crops. This means a reduction of installed power of 4,715 kW during the summer months.

We consider an irrigation period of 21 hours during 120 days, this result in the amount of energy saved of 9,975 MWh per crop.

Table 3 – Energy Efficiency in Pump Motor Drive

Installed Power Pi	Useful Power Pu	Pu/Pi	Location	Height
1,710.0	766.5	45%	Uruguaiana-Itaqui	(até 10m)
1,150.0	535.8	47%	Uruguaiana-Itaqui	(10 – 15m)
950.0	556.4	59%	Uruguaiana-Itaqui	(15 – 20m)
450.0	392.0	87%	Uruguaiana-Itaqui	(> 20m)
1,335.0	561.0	42%	Uruguaiana-Barra	(até 10m)
625.0	377.8	60%	Uruguaiana-Barra	(10 – 15m)
835.0	220.5	26%	Uruguaiana-Alegrete	(até 10m)
1,130.0	464.6	41%	Uruguaiana-Alegrete	(10 - 15m)
1,125.0	580.1	52%	Uruguaiana-Alegrete	(15 - 20m)
400.0	218.2	55%	Uruguaiana-Alegrete	(20 - 25m)
250.0	213.0	85%	Uruguaiana-Alegrete	(> 25)
1,795.0	693.3	39%	Rosário- São Gabriel	(até 10m)
175.0	81.0	46%	Rosário- São Gabriel	(10 - 15m)
11,930.0	**5,660.2**	**47%**	**Média geral**	

This charge deserves special attention in view of the impact which causes the electric power system because of its seasonality and high regional concentration as well as for its typical feature of electric charge, which is used as induction motor's driving force.

Seeking to meet the real electricity requirements with no waste like them identified in diagnoses and provides ways to reducing the seasonality of the load can be the basic premises of any Demand-Side Management action.

The first project for the promotion of Energy Efficiency

Faced with this problem, the distribution utility AES SUL proposed to implement Energy-efficiency measures as financing projects with the electromechanical systems of rice irrigation, seeking to improve the quality of electric energy supply by reducing the waste of energy and improvement of electro-mechanical-hydraulic installations of rice customers. The utility proposed to disseminate widely the success stories with customers belonging to the orizícola segment. For three cycles after the diagnosis, the Company identified, designed, installed and evaluated 32 energy-efficiency operations in the Western border region of the State, where are concentrated the majority of loads. About 18 customers assumed the financing of the energy efficiency of their facilities. During the period of 2004 to 2006 were performed over 70 energy-efficiency actions to reduce the waste of electricity. According to the reports of the PEE / ANEEL, the utility AES SUL invested until 2012 R$ 17,174,262.00 in 46 new projects, predicting a global energy saved 25.525 GWh per year, with 12.64 MW of demand avoided during the principal peak.

Energy and water waste

The process of rice crop irrigation is by flood, occurring throughout the period of cultivation where it should be kept a water slide that ranges from 5 to 10 cm. This is intended to avoid the appearance of weeds and provide the necessary temperature and humidity of soil needed for the growth of the plant. A water pumping station for irrigation of rice, aims to raise a certain volume of water per unit of time (flow (Q)), at a height defined by the gap between the water source to the highest point of the crop, where the water is then distributed by gravity. Thus, to reduce the energy consumed in this process, it is necessary to reduce the flow to be storage and/or the height of the dam. However, these are not the only two elements involved in the process. The installed power and consequently, the energy consumption, also depend on energy losses from water and displacement efficiency of machinery used in the process of pumping (hydraulic pumps and motors).

The ideal situation is where it is not necessary to drive the system because the water supply is in a level higher than the area to be irrigated. In this way, the water is driven by gravity. However, it is known that this is not the most frequent situation. Then it is necessary to optimize the existing pumping plant to reduce the waste of energy and water. Figure 2 shows a part of the waste of water and energy once the pipes are made of cast iron plates and are in the field during the period outside of the crop. The metal corrosion results in perforations, which account for part of the waste of water and energy demand.

Figure 2 – Waste of Water and Energy

It can divide the technologies involved in two parts: mechanical and electrical. The mechanical part comprises the base where the equipment will be immobilized, it may be fixed on the border of the river or dam or floating in liners. It comprises the pump itself, transmission and coupling to the motor and the water drain pipe. The electrical part is the high-voltage network which includes: the switchgear, the fuses, the lightning, the Poles, Sleepers and MV/LV transformer. In the low-voltage network, we have: the cabin control and measurement, cabling, capacitors, starting and switchgears devices, control panels, electric motors and frequency inverters.

The predominance of the facilities found is fixed to the base on the border of the rivers or dams with long pipes of both suction and discharge, which responds in good part by waste of energy due to the loss of the head. The use of rewound motors, couplings for pulley systems, curves and unnecessary diameter variations are frequent.

As technological solutions have been the adoption of systems mounted on barges with pumps working drowned, which eliminates the loss of suction, the use of high-efficiency motors, pipes with low head loss and the use of frequency inverters to adjust the flow according to the crop water requirements.

Figure 4 and 5 show the types of existing facilities and those proposed by design in the pursuit of energy efficiency.

Figure 4 – Energy Efficiency in Pumping System for Rice Irrigation

Figure 5 – Energy Efficiency in Pumping System for Rice Irrigation

Results Achieved

Table 4 stratifies the results achieved in successive periods. We can see that there was increased in the area planted with reduction in demand of electricity and water movement.

Table 4 – Performance of Energy Efficiency – EE Actions [2]

Relationship Installed Power / Irrigated Area							
Period	Before			After EE Action			Reduction
	Area [ha]	Power [CV]	Power / Area	Area [ha]	Power [CV]	Power / Area	%
2002/2003	1,129	950	0.84	1,335	575	0.43	48.8%
2003/2004	845	825	0.98	1,220	490	0.40	58.9%
2004/2005	2,555	2,320	0.91	2,645	1425	0.54	40.7%
TOTAL	**4,529**	**4,095**	**0.90**	**5,200**	**2,490**	**0.48**	**47.0%**

Reduction % = (1 – (Power/Area After EE Action divided by Power/Area Before EE Action)) X 100

Relationship Installed Power / Volume of water Used							
Period	Before			After EE Action			Reduction
	litres / Second	Power	Power / litres/Sec	litres / Second	Power [CV]	Power / litres/Sec	%
2002/2003	2,092	950	0.45	2,218	575	0.26	42.9%
2003/2004	1,807	825	0.46	2,544	490	0.19	57.8%
2004/2005	4,745	2,320	0.49	7,990	1425	0.18	63.5%
TOTAL	**8,644**	**4,095**	**0.47**	**12,752**	**2,490**	**0.20**	**58.8%**

The project achieved a 47% reduction in installed capacity and demanded and less than 58.8% in the volume of water moved. These actions have a strong impact to combat energy waste.

Electric Sector approach

The project was always framed within the criteria of the regulatory agent, in case ANEEL for execution within the Annual Energy-Efficiency Programs. Table 5 summarizes the initial estimation and the accomplishment of the project. Within the return criteria for the electricity sector, one can see the large benefit that such type of project brings. The cost-benefit ratio average achieved in three cycles hit 0.30 in a process of improvement of the R-C/B to each cycle performed. The unit cost of Demand Avoided is 889.7 R$/kW and 203.7 R$/MWh. The Annual Load Factor is 29%.

Table 5 – Energy Efficiency in Rice Crop [1]

	Period			Total	
Initial Estimation	**2001-2002**	**2002-2003**	**2003-2004**		
Total Investiment	**825,000**	**272,244**	**790,905**	**1,888,149**	**R$**
Energy Saved (ES):	**605**	**322**	**2,535**	**3,462**	**MWh**
Avoided Demand (AD):	**378**	**128**	**396**	**902**	**kW**
Annualized investment:	121,130	48,183	139,978	334,173	R$
R-C/B: Relationship Cost/Benefit	**0.76**	**0.70**	**0.36**	**0.45**	
Avoided Investment:	158,477	68,659	394,032	949,674	R$

Accomplishment					
Total Investiment	**526,000**	**350,120**	**709,999**	**1,586,119**	**R$**
Energy Saved (ES):	**1,194**	**714**	**2,755**	**4,662**	**MWh**
Avoided Demand (AD):	**186**	**292**	**589**	**1,067**	**kW**
Annualized investment:	77,230	61,966	125,659	280,718	R$
R-C/B: Relationship Cost/Benefit	**0.53**	**0.40**	**0.23**	**0.30**	
Avoided Investment:	145,738	261,086	545,583	949,674	R$

Client approach

A project to reduce the energy waste and promote its efficient use must necessarily bring benefits to all actors involved [4]. So from the customer's point of view we have as main advantages of tariff impacts, increased competitiveness by reducing costs, the awakening to other sources of existing waste in farming, technological modernization and the highly specialized technical support. This allowed a 62% reduction of installed power by used water, 47% reduction of installed power by irrigated area, the expansion in 10% of the irrigated area due to a reduction in average efficiency of 50% of the invoice value of energy and 6% average reduction of the total cost of production. The average return on investment is 4 crops, which is 16 months. Figures 6 and 7 explain these benefits through the graphical interpretation of the evolution of the electricity bills **[5],[8]**.

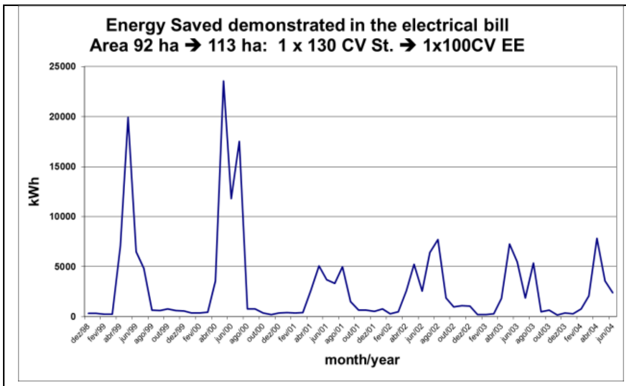

FIGURE 6 – ENERGY BILL [5],[8]

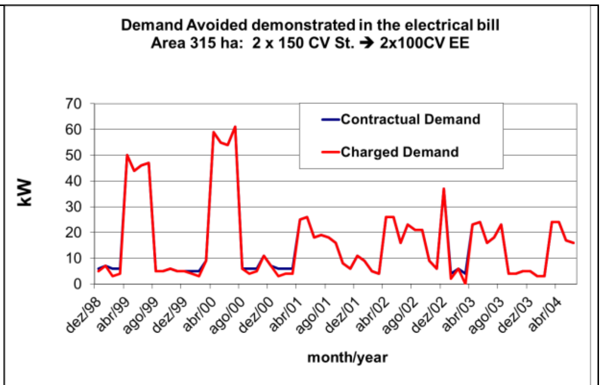

FIGURA 7 – Demand Bill [5],[8]

The Regional impact

It was evidenced in Table 1 the impact of the mechanized irrigation process reaches the entire southern region of the Rio Grande do Sul State, in particular, the concession areas of AES SUL and CEEE – D. It turns out that 72.5% of this service is attended by electrical systems with an additional market economically can be attended also by electric energy representing 22.5%. Table 6 prospects the energy-efficiency potential in both electrical groups as well as diesel of groups. The installed load today reaches 321 MW in electric motors and 96.6 MW using diesel engines, representing 417.6 MW of demanded load. By the energy-efficiency actions in these facilities would have a new demand of 221.1 MW, including the load powered by diesel engines. The demand avoided that would be achieved is of the order of 196.5 MW with an annual Load Factor of 29%. Its operate 120 days a year, 21 hours per day. If the government promotes a global energy-efficiency program, the costs achieved R$ 260,532,589.14 in a Demand-Side Alternative.

If we consider a Supply-Side Alternative, the load is equivalent to a wind power plant equivalent in RGS. The average cost of the last bidding in RGS was R$ 6.853,55 R$/kW. So, the estimation of the investment to install a project by the Supply-Side is R$ 1,346,208,641,66. The Investment Ratio Demand-Side x Supply-Side is 19.35%.

Table 6 – Energy Efficiency in Pumping Irrigation Systems at Rio Grande do Sul Rice Culture

Areas	Electrical Systems			Diesel Systems			Total Irrigation Systems		
	Installed Power		Energy Efficiency	Installed Power		Energy Efficiency	Installed Power		Energy Efficiency
	CV's	kW	kW	CV's	kW	kW	CV's	kW	kW
CAMPANHA	14,015.43	10,255.44	5,431.23	37,038.35	21,530.42	11,402.42	51,053.78	31,785.85	16,833.65
DEPRESSÃO CENTRAL	38,286.31	28,015.03	14,836.64	27,135.63	15,773.96	8,353.82	65,421.95	43,789.00	23,190.46
FRONTEIRA OESTE	176,461.88	129,121.49	68,382.18	59,138.14	34,377.04	18,205.93	235,600.02	163,498.53	86,588.11
PLANÍCIE COST. EXTERNA	60,926.62	44,581.50	23,610.17	12,867.06	7,479.63	3,961.18	73,793.68	52,061.13	27,571.35
PLANÍCIE COST. INTERNA	52,213.98	38,206.25	20,233.86	10,772.53	6,262.08	3,316.37	62,986.50	44,468.33	23,550.23
SUL	96,767.93	70,807.47	37,499.33	19,191.19	11,155.85	5,908.09	115,959.12	81,963.32	43,407.42
RS - TOTAL	**438,672.16**	**320,987.18**	**169,993.42**	**166,142.89**	**96,578.99**	**51,147.81**	**604,815.05**	**417,566.17**	**221,141.23**

Conclusions and recommendations

Having as reference the data evaluated, it can be considered that this type of project gives good results and benefits for all actors involved, like the farmers, the utility, the national electric sector and society as a whole. Whereas it is not just to promote the fight against waste of electricity, but also to avoid the misapplication of water, it can be concluded that environmental conservation is an additional justification for its achievement.

It was evidenced that measures such as these presented compete strongly with actions by the supply side of energy, even though these based on renewable resources. The mechanized irrigation is part of most agricultural processes soon results as the currently obtained certainly may encourage other utilities to prospect potential in their concession areas. The size and the structure of the process are equivalent to those found in pumping systems for public sanitation, so the results can serve as a reference for this socio-economic segment.

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Sensorless specific energy optimization of a variable-speed-driven pumping system

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Abstract

Increasing energy efficiency is one of the key methods when aiming for sustainable energy use. Pumping systems are responsible for a significant part of the industrial electricity consumption, which has increased the interest in finding energy saving opportunities in the pumping applications. Usually, the greatest energy saving potential in pumping systems can be found by optimizing the system control. This is because increasing the efficiency of an individual component can seldom reduce the energy consumption as efficiently as setting the delivered output according to the process needs. Tapping this energy saving potential requires not only appropriate control methods, but also easily implementable and sufficient monitoring solutions. Rotational speed control with a variable speed drive (VSD) has proved to be an energy efficient way to control the pumping system operation.

After implementing the rotational speed control to a pumping system, the optimization of the control procedure is usually left for the pump operator. In many cases, the information required to fulfill the pumping task in the most energy efficient way is not available or has to be gathered manually by start-up measurements with separate metering equipment. For these reasons, full optimization of the pumping task is often neglected. As modern VSDs are also able to monitor the output of the pumping system without additional metering, these monitoring data can be used in the system control to ensure optimal energy use.

This paper shows how variable-speed-driven pumps can monitor the energy efficiency of the pump and set the rotational speed according to the lowest specific energy consumption. The method does not require any additional start-up measurements or identification runs, excluding the pump performance curves required for sensorless pump monitoring. The operation of the control strategy is presented and the operation of the strategy is validated by simulations and tests for an actual pumping system.

Introduction

The importance of energy efficiency both in industrial and municipal processes has increased the interest in finding energy saving solutions for pumping applications [1]. Energy efficient operation in a pumping system is often accomplished by applying the rotational speed control of pumps with variable speed drives (VSDs) [2, 3]. In variable speed pumping processes, where precise flow adjustment is necessary, energy efficient pumping can be enabled by adjusting the rotational speed of the pump so that the pump performance varies according to the desired process output. In steady-state processes, the energy saving potential of the rotational speed control can be achieved even with an ON-OFF control scheme, if the rotational speed of pump is first optimized according to the system characteristics.

Optimizing the energy use in variable speed pumping requires certain information on the pumping system. For instance, if the total head of the system as a function of flow rate is determined, the resulting operating points in variable speed operation can be calculated using the pump performance curves, and the most energy efficient operating conditions can be found. This information can be gathered by analyzing the system data available or by using separate start-up measurements for example as in [4], where the measurements are made for the system and the system is optimized once with these data. Optimization of the energy efficiency of a pump based on the monitored output and system data is described for instance in [5] and [6], where the system is optimized by applying measurements of flow rate and head, respectively. However, the requirement of sufficient system data often limits the feasibility of the optimized control strategies: the pump operator is not necessary aware of the details of the system, or changes have been made to the system characteristics [7]. In addition, real-time process information is often limited, since the direct measurement of the pump output is rarely available. To avoid direct metering in variable speed pumping, the pump operating point and the energy efficiency of the pumping can be determined using the pump performance curves and the VSD's internal estimates for the torque, rotational speed, and power [8]. Moreover, these monitoring data can be used for control purposes, and the operating state of the pump can be optimized without startup measurements or detailed system data.

This study describes a method suitable for optimizing the operation of a variable-speed-controlled pumping system. The method calculates the specific energy consumption of the pump using the sensorless monitoring of the pump operating point available in modern VSDs and determines the operating state with the lowest specific energy use. The only information required from the pump operator is the *QH* and *QP* characteristic curves of the pump. The simplified block diagram of the method is illustrated in Fig 1. As the control algorithm is completely software based, the implementation of the method to the VSD controlled pumping systems is simple and inexpensive. The presented method can be applied especially in systems, where the pumping task is related to lifting a certain volume of liquid from one place to another without strict limitation for the duration. An example of such systems is a reservoir filling task, in which the main concern is typically related to sufficient fluid level in the inlet our outlet reservoir. In addition, the flow rate in such systems is not a direct reference for the control. However, the applicability can be limited if the pumping tasks has requirements for minimum pump output pressure or flow rate.

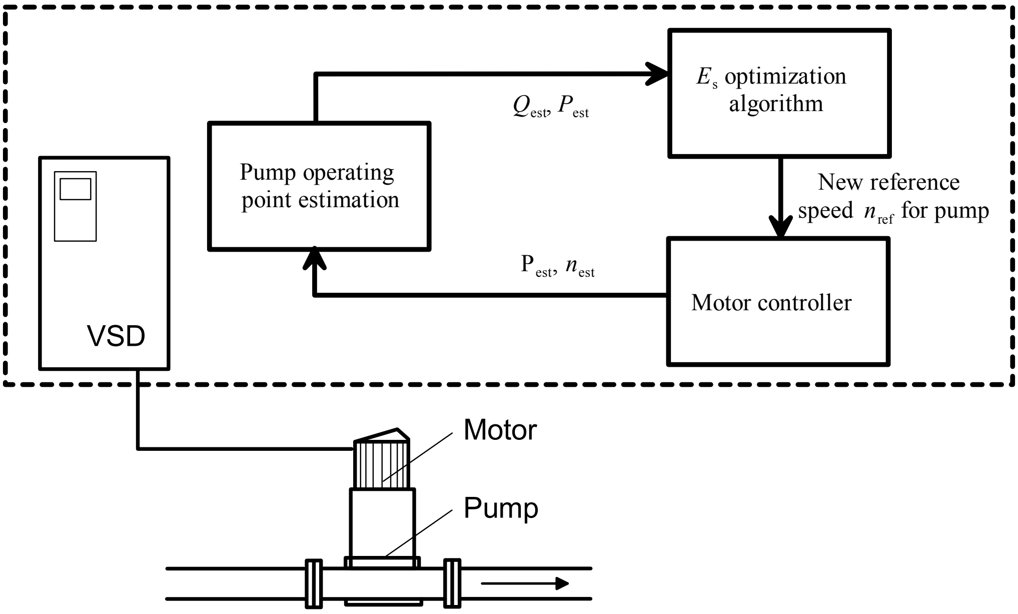

Fig 1 Optimizing the rotational speed of the variable-speed-driven pump based on monitored specific energy consumption. The subscript 'est' denotes the estimated values.

The structure of the paper is as follows. First, the method of determining the operating point by applying a VSD and the criteria selected for energy efficient operation is reported in brief. After this, the method suitable for optimized specific energy consumption is introduced. The viability of the proposed method is demonstrated by laboratory measurements. The paper is concluded in the last section.

Sensorless pump operating point estimation

The output of the variable-speed-driven pumping system can be monitored by using sensorless operating point estimation with VSDs [9, 10]. The estimation is based on the variable speed drive estimates for the motor rotational speed and mechanical power, which are used as inputs to the estimation method. Pump characteristic curves, given as total head and pump power as a function of flow rate (*QH* curve and *QP* curve), are used as a model of the pump, and the operating point is estimated with this model and the inputs. As the pump characteristic curves are usually given only for the nominal rotational speed, an approximation of the operation of the pump at other rotational speeds can be obtained by the affinity laws

$$Q = \left(\frac{n}{n_0}\right) Q_0 \tag{1}$$

$$H = \left(\frac{n}{n_0}\right)^2 H_0 \tag{2}$$

$$P = \left(\frac{n}{n_0}\right)^3 P_0 \tag{3}$$

where the subscript 0 denotes the values at the nominal rotational speed, *n* is the rotational speed, *Q* is the flow rate, *H* is the pump head, and *P* is the pump mechanical power. A graphical example of this estimation method is given in Fig 2.

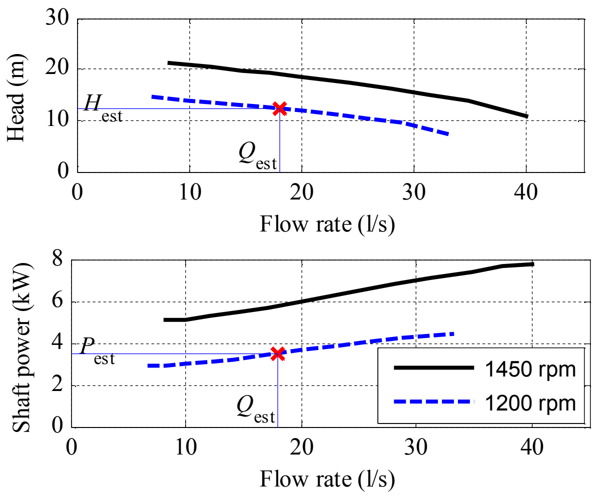

Fig 2 Flow rate vs. head (*QH*) and flow rate vs. shaft power (*QP*) characteristic curves of a centrifugal pump; an example of the pump operating state determination with the shaft power estimate P_{est}.

The sensorless operating point estimation can assess the output of the pump with sufficient accuracy in many cases. The accuracy of the estimation may decrease in situations where there is a substantial difference between the performance curves and actual operation of the pump in a system. In addition, the shape of the characteristic curves has a clear effect on estimation accuracy; for instance in the case of a flat *QP* curve, even a small error in the estimated power can result in a more significant error in the estimated flow rate value. The feasibility and accuracy of the operating point estimation methods applying a VSD are discussed in more detail in [8, 10, 11].

Minimum specific energy

The total head of a pumping system can be divided into a static head and a dynamic head. The static head H_s comprises the geodetic head and the pressure difference between the inlet and outlet sections of the system. The dynamic head H_d consists of the difference in the velocity heads and the friction head. In open systems, the total head is usually referred to as the sum of the elevation difference and the friction head only, and is written

$$H = H_s + H_d = H_{geo} + kQ^2 \tag{4}$$

where H_{geo} refers to the geodetic head and *k* is the dynamic head coefficient depending on the liquid and the characteristics of the piping.

Specific energy consumption defines the amount of energy needed to pump a unit of liquid. It can be considered an appropriate criterion for energy efficiency in systems where the sole purpose of the pumping process is to transfer liquid to a higher level. Specific energy consumption E_s can be calculated by

$$E_s = \frac{E}{V} = \frac{P}{Q} \tag{4}$$

where E is the energy consumed by the pumped volume V.

In variable speed pumping, the minimum specific energy consumption for a pumping system, having a static head H_s and a flow resistance coefficient k, can be determined at a single operating speed n of the pump. Correspondingly, if the dynamic flow resistance coefficient k remains constant, a higher static head results in a higher optimal rotational speed at which the minimum E_s is found. Further, the required minimum E_s increases with a higher static head, because the delivered output has to be lifted to a higher elevation. An example of the behavior of the specific energy consumption as a function of rotational speed at four different static head values is given in Fig 3.

The curves plotted in Fig 3 represent a series of operating points where the rotational speed of the pump is raised from zero to 1500 rpm. The pump can deliver flow only after overcoming the static head of the system. In this case, the rotational speed at which the pump starts to deliver flow is approximately 700 rpm for the static head of 5 m. The minimum E_s for the pumping in the illustrated system case is ~29 Wh/m^3 when the static head is 5 m, and this operating state is achieved when the rotational speed of the pump is ~800 rpm. Correspondingly, if the static head of the system is 10 m, the minimum E_s (52 Wh/m^3) can be achieved at the rotational speed of 1150 rpm (Fig 3).

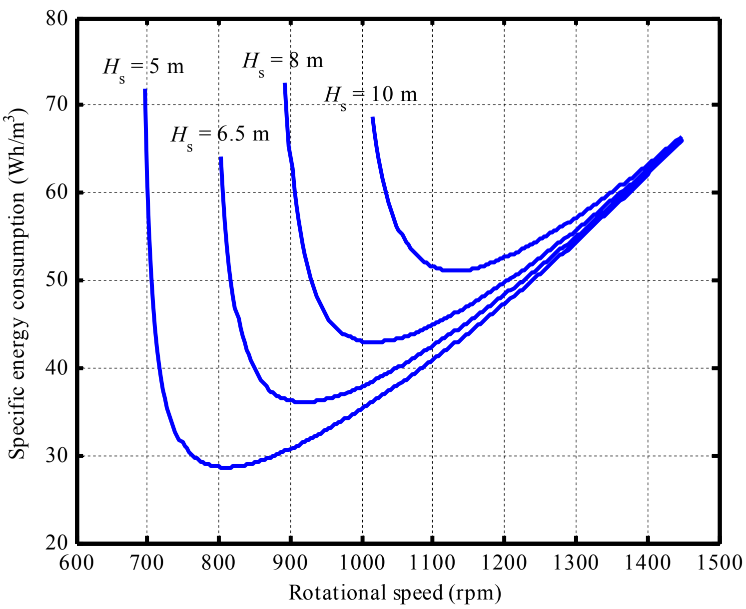

Fig 3 Specific energy as a function of rotational speed and static head for a system with a constant dynamic flow resistance k = 0.0143. The specific energy consumption is calculated for four different static heads.

The purpose of the proposed pump control algorithm is to find the optimal rotational speed by using only the sensorless pump operating point estimation methods and track the optimal rotational speed in systems where the system characteristics change over the pumping task, for example the static head changes during a reservoir filling task. The suggested control can be fitted according to the process requirements, for instance, if there is a certain time limit for the reservoir filling task. The minimum required output can also be included in the suggested control algorithm as a limiting factor to the rotational speed.

Optimization method

The specific energy optimization method is based on the sensorless operating point estimation and the option to control the pump rotational speed by the VSD. The rotational speed is changed in a stepwise manner, and the rotational speed with the minimum specific energy is selected as the optimal rotational speed. The algorithm that can accomplish this is presented in Fig 4. First, the pump is operated at the nominal rotational speed, and the specific energy consumption is estimated with this speed. Then, the rotational speed is reduced, and if this reduced rotational speed results in a lower specific energy consumption than the previous value, the rotational speed is reduced again. If the rotational speed reduction results in a higher specific energy consumption, the rotational speed is increased to see if the increased rotational speed will result in a lower specific energy consumption. The search for the optimal rotational speed is continued until the algorithm is stopped.

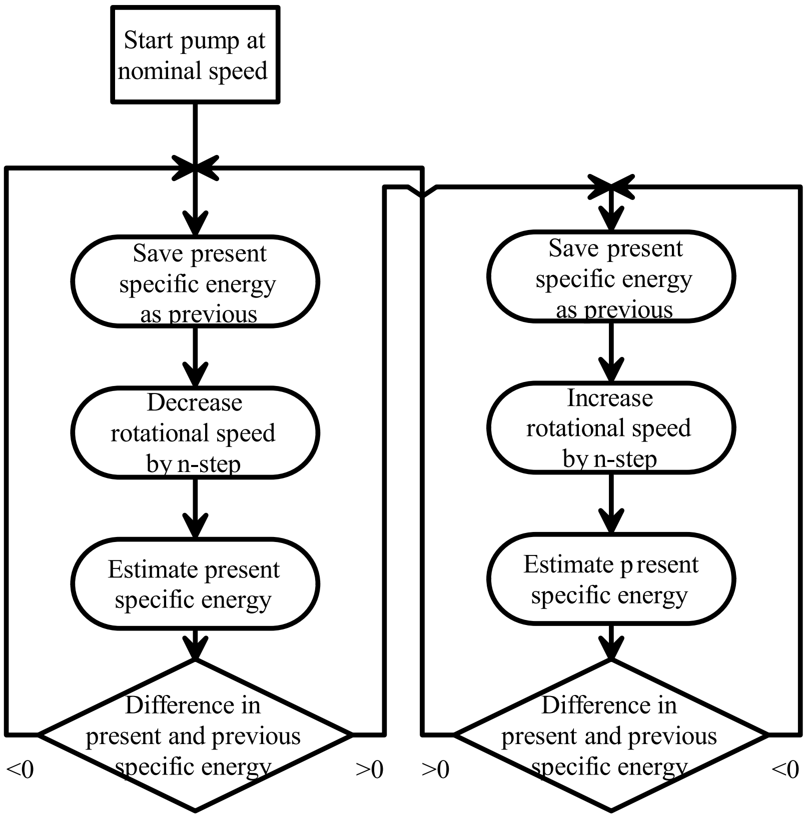

Fig 4 Simplified flow chart of the algorithm that can be used to minimize the specific energy consumption of a pumping system. *n-step* refers to a rotational speed step, which is used in the search for the minimum specific energy.

As can be seen in Fig 4, the simplified flow chart has no stop state. Hence, the rotational speed will move constantly ± one n-step around the optimal rotational speed in this simplified example. The control can nevertheless be stabilized, because in many actual pumping applications stability of the pumping is preferred. For example, in systems where the system characteristics are constant the determined optimal rotational speed can be used as a constant rotational speed reference to eliminate the oscillation.

To demonstrate the behavior of the suggested control, the algorithm in Fig 4 was simulated with a system consisting of a 5 m static head and a dynamic flow resistance factor of 0.0143. The behavior of the rotational speed and the specific energy as a function of time is illustrated in Fig 5. The control procedure is started approximately at time 1 s. The rotational speed is decreased from 1450 rpm to 795 rpm with 15 rpm steps. At this point, the algorithm detects that the specific energy consumption at 810 rpm was lower than with 795 rpm and increases the rotational speed. At 825 rpm the algorithm again detects that the specific energy consumption at 810 rpm is lower than at 825 rpm and starts to reduce the rotational speed. This is continued until the simulation is stopped. The algorithm finds the optimal rotational speed within the accuracy of the rotational speed step, which is 15 rpm in this case, but the step can be fixed depending on the nominal rotational speed of the pump and the desired resolution. The selected control interval in the simulation is 0.5 s, but it can also be fixed to ensure steady operation between steps and to avoid rapid rotational speed changes of the pump.

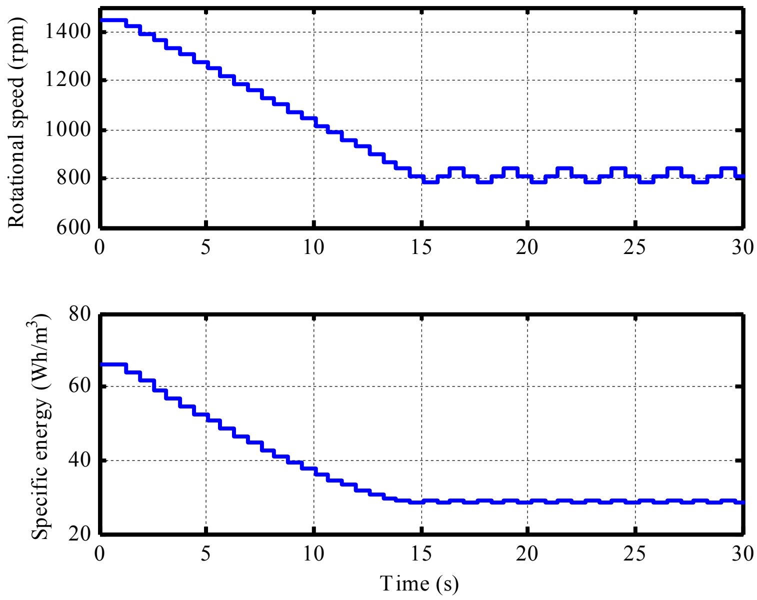

Fig 5 Behavior of the algorithm in a simulation where a pumping system has a 5 m static head and a dynamic flow resistance of 0.0143. The optimal rotational speed is approximately 810 rpm in this example, and it is found approximately at 15 s.

Laboratory measurements

The proposed control method was tested with a laboratory test setup consisting of a water container, various piping, and a Sulzer APP22-80 centrifugal pump driven by an ABB 11 kW induction motor and an ABB ACS800 variable speed drive equipped with a sensorless flow estimation method. The static head in the system was approximately 5 m and the dynamic flow resistance coefficient could be controlled with valves. The laboratory measurement setup is shown in Fig 6. The control interval was 25 s and the rotational speed step was varied between 30 rpm and 60 rpm.

Fig 6 Laboratory test setup comprises a water tank, various piping, a centrifugal pump, an induction motor, and a frequency converter.

First, the control algorithm was tested with a valve setting, which was selected so that the flow rate produced at the pump nominal speed was 90 % of the nominal flow rate. The results for the rotational speed and the estimated and measured specific energy consumption as a function of time can be seen in Fig 7. The figure shows that the optimization method control reduces the pump rotational speed as long as the monitored specific energy consumption keeps decreasing (0−240 s). When the pump rotational speed is decreased to 720 rpm at 240 s, the specific energy starts to increase, as a result of which the rotational speed reference is increased in the next control round. The rotational speed varies from 720 to 900 rpm between 240 and 500 s as the control tries to determine the optimal rotational speed based on the minimum E_s.

To determine the optimal rotational speed more accurately, the rotational speed step was changed from 60 rpm to 30 rpm at 500 s. Hence, the rotational speed starts to fluctuate between 780 rpm and 900 rpm (500−900 s). In this region, there is only a small variation in the measured and calculated E_s values. The minimum value for E_s in this measuring sequence is ~35 Wh/m^3, and it is achieved when the pump is operated at approximately 810−840 rpm (Fig 7).

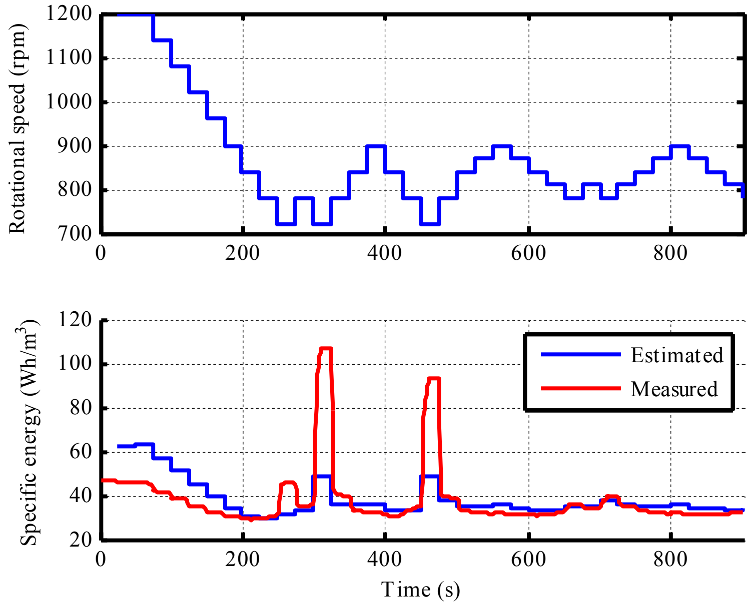

Fig 7 Rotational speed, estimated and measured specific energies as a function of time. The minimum specific energy is more accurately determined after 500 s when the rotational speed step size is reduced from 60 to 30 rpm.

The results of the same measuring sequence can also be seen in Fig 8, where the estimated and measured specific energies are shown as a function of rotational speed. It can be seen from Fig 8 that the E_s values when operating between 780 rpm and 900 rpm are very close to each other, which suggests that this region is the most energy efficient speed region in terms of specific energy consumption. Fig 8 also shows that there is a notable difference between the estimated and measured E_s in certain operating points, which is mainly caused by a divergence between the estimated and measured flow rate. Despite this, the region where the minimum E_s is obtained is found in the same rotational speed region.

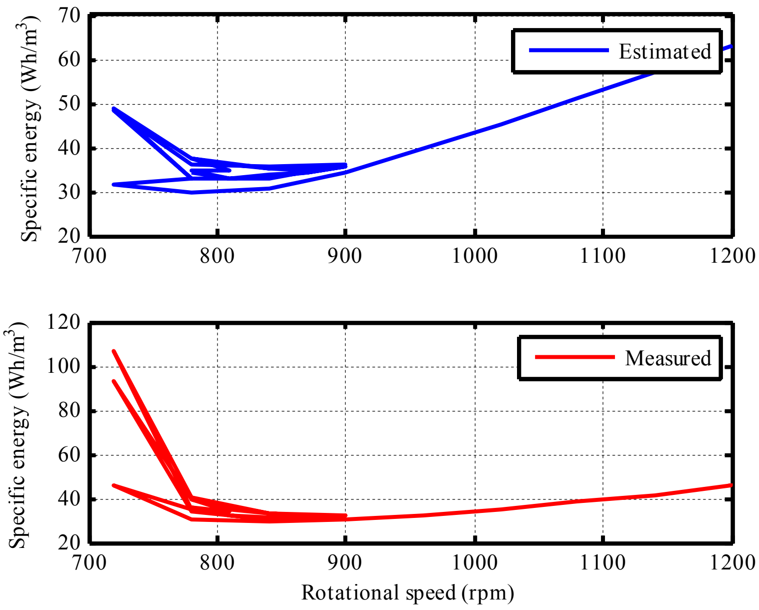

Fig 8 Measured and estimated specific energies as a function of rotational speed in the 90 % relative flow region. The minimum specific energy is found when the pump is operated at 810−840 rpm.

Similar results were obtained in a measuring sequence in which the pump was operated in the 100 % relative flow region. The rotational speed step used in this sequence was 30 rpm. The resulting specific energy consumption as a function of rotational speed is depicted in Fig 9. Similar to the previous sequence, the control algorithm varies the rotational speed of the pump and determines the rotational speed at which the estimated E_s is at the minimum level according to both the measured and estimates values. Fig 9 shows that both the estimated and measured E_s are at lowest when the pump is operated approximately at 840 rpm.

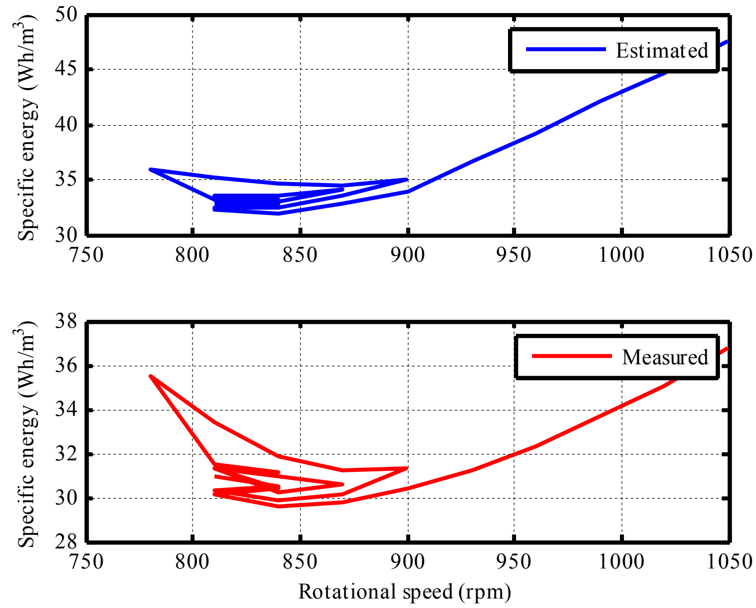

Fig 9 Estimated and measured specific energies as a function of rotational speed in the 100 % relative flow region. The minimum specific energy is found when the pump is operated at 840 rpm.

The results show that the suggested control method is able to determine a rotational speed range in which the E_s is at lowest. When the pump is operated near the minimum E_s, the changes in the specific energy consumption after each control step can be so small that the optimal rotational speed is difficult to define accurately. According to the tests, the optimal rotational speed with the minimum E_s was demanding to determine even with the measuring equipment, since the value for the measured minimum E_s was not always the same. In addition, because of the inaccuracies in the flow estimation, the algorithm cannot always determine a single optimal rotational speed, but varies the speed of the pump with two to three steps near the optimal E_s value. As shown in Fig 7, the selected rotational speed step also has a strong influence on the determination of the optimal rotational speed.

Conclusion

In this paper, a method was presented to optimize the specific energy consumption of a pumping system without sensors. The method uses the well-known model-based estimation for pump flow rate to assess the specific energy consumption of the pumping system, and by stepwise control of the rotational speed of the pump, the method finds the minimum specific energy consumption.

The laboratory measurements show that the algorithm is able to find the optimal rotational speed to minimize the specific energy consumption. According to the results, the absolute values of the estimated and measured specific energy consumption differ from each other. However, determination of the optimal rotational speed with the suggested method is based on the change in the estimated specific energy consumption according to the rotational speed. Hence, the exact accuracy for the E_s values is somewhat irrelevant and the rotational speed for the minimum E_s can be determined. The suggested control can be seen as an appropriate method to increase energy efficiency for instance in reservoir filling pumping tasks, where there are no strict time limits for the pumping.

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General Methodologies of Determining the Energy-Efficiency-Index of Pump Units in the Frame of the Extended Product Approach

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Abstract

Quantifying the energy efficiency of pump units across markets is a tough task: These units mostly consist of rotodynamic pumps driven by motor systems either without or with variable-speed drives, the latter being called power drive systems (PDS). To evaluate the energy efficiency of such arbitrary pump units in the frame of the Extended Product Approach (EPA), the Energy-Efficiency-Index (EEI) is introduced as a normalized weighted average of electrical power input of a pump unit operated at different duty points of a standardized load-time profile. If the unit is equipped with a variable-speed drive, the duty points also have to be adjusted according to a standardized pressure control curve. The EEI is therefore a measure of energy efficiency and represents simultaneously the quality of the Extended Product "pump unit" and the characters of the standardized load-time profile and the standardized pressure control curve. The two general methodologies to determine the EEI presented in this paper are valid independently of a particular standardized load-time profile or pressure control curve.

Besides determining the EEI experimentally, an alternative methodology is necessary to establish a market-wide EEI determination with reasonable effort for manufacturers, system integrators and customers. The alternative approach described in this paper is capable of modeling the part load behavior of the pump unit's components with sufficient accuracy. To achieve this, the methodology rests upon physically based semi-analytic models of the components of the pump unit. The models are adapted to the corresponding real components by means of a small amount of well-defined data. The methodology is reported in its general form in this paper, treating the underlying semi-analytic models themselves as black-boxes. The approach is developed and experimentally validated within the scope of a EUROPUMP project carried out at Technische Universitaet Darmstadt, Germany.

Introduction

The political goal to increase the sustainability of the energy production and utilization inside the European Union, especially to reduce the emission of CO_2, has led to the ecodesign directives 2005/32/EC [1] and 2009/125/EC [2]. These were intended to increase the energy efficiency of energy using and energy related products. Starting from preparatory studies and accompanied by a consecutive exchange of information with the association of European pump manufacturers (EUROPUMP), the European Commission has passed two pump-specific regulations on a legislative level which came into force on January 1st, 2013.

The first of these regulations [3] applies to circulator pumps for heating and hot water circuits. The second regulation [4] applies to rotodynamic clean water pumps of specified types within a scope of nominal data (c.f. [5]). These pumps are classified in respect to energy efficiency by a so called Minimum-Efficiency-Index (MEI), a classification system of lower limits for the pump's efficiency at three specified flow rates: one at 75 % part load, one at 110 % over load and one at best efficiency point (BEP). The classification according to the MEI is standardized in a coming EN standard [6] while the corresponding legislative regulation [4] specifies the minimum values of MEI that have to be fulfilled to allow the product to be placed on the market. Comparable regulations exist in the field of asynchronous motors: The system of IE classes that was adopted in 2008 [7], classifies asynchronous motors with respect to their efficiency at nominal load condition.

Both the regulation affecting the water pump market [4] and the system of IE classes [7] affecting the market of asynchronous motors can be summarized under the keyword "Product Approach". The energy savings of measures in the frame of a Product Approach result from forced increases of the product efficiency. This way of reducing the energy consumption requires high effort by the manufacturers as the design of the product in relation to its efficiency and the manufacturing technologies etc. have to be improved. Furthermore, the question whether the product is applied in an energy efficient way is blinded out completely by a Product Approach.

These reasons have motivated to extend the Product Approach to a concept called Extended Product Approach (EPA) that includes both the efficiency and the application of a product. In respect to pumps, the Extended Products consist of a pump and a motor system. The latter is an electric motor with or without a Variable Speed Drive (VSD).

The Extended Product Approach has already been successfully introduced in the field of circulator pumps in the European Union by regulation [3] mentioned above, where the determination of a value called EEI (Energy-Efficiency-Index) is mandatory for every circulator pump since January, 2013.

To also apply the EPA on rotodynamic clean water pumps and to assess them by an adequately defined EEI-value is problematic since there are serious differences between typical circulator and clean water pumps that need to be addressed. Circulator pumps are generally sold as fully integrated products where all the product’s components (rotodynamic pump and electric motor without or with variable-speed drive) are technically aligned to each other by one manufacturer and the customer is not intended to combine these on his own. Therefore the determination of EEI is clearly allocated to one accountable institution.

In contrast to that, the combination of individual components (which also might be delivered by different manufacturers) to complete pump units by a system integrator company is an important case in the field of clean water pumps and therefore cannot be neglected. Neither the responsibility nor the methodology to determine the EEI of such Extended Products in the field of clean water pump units is straightforward. A market-wide experimental determination of the EEI would additionally cause high effort to manufacturers and/or system integrators. An alternative determination methodology is therefore desirable or – even more – urgently necessary to enable the energy efficiency qualification of rotodynamic clean water pumps according to the EPA across markets.

This paper describes an experimental as well as a so-called semi-analytical methodology to determine the EEI for clean water pump units in the frame of the EPA. The main focus in this paper will be on the semi-analytic methodology.

The Extended Product Approach

The Extended Product Approach (EPA) for rotodynamic clean water pump units (c.f. Fig. 1) focuses presently on pump units of different types and sizes that are widely applied in the field of clean water pumping. The pumps are driven by asynchronous motors without or with Variable-Speed Drives (VSD), the latter being called Power Drive Systems (PDS). In the sense of European legislation and standardization, these fixed-speed and variable-speed pump units are “Extended Products”.

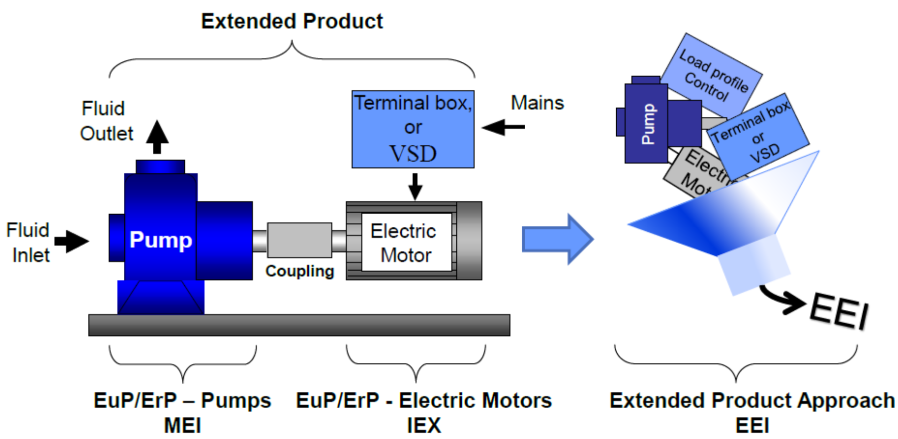

Fig. 1: The Concept of the Extended Product Approach

Adapted from [8] with kind permission of the authors

Basic feature of the EPA is the consideration of an energy efficient application of the Extended Product in addition to the product efficiency alone as it is the case in a Product Approach. To reach this, a load-time profile and a pressure control curve (c.f. below) need to be incorporated in the methodology. Result of the EPA is the EEI, a value representing both the efficiencies of the Extended Product's components and its suitability in terms of energy efficiency for the load-time profile and pressure control curve the determination of the EEI is based on (cf. Fig. 1).

Ideally, a load-time profile would represent the particular application a pump unit needs to be chosen for in the best way possible, but two serious problems prevent the realization of this: Firstly, the customer respectively system integrator would need to apply the EPA and determine an EEI for every available pump unit in the market on his own in order to find the most energy efficient one for any particular application. Secondly, a load-time profile representing sufficiently well the particular application is costly to determine and therefore in most cases not available.

To overcome these problems, to enable a market-wide determination of EEI values and to maintain comparability between different pump units despite of the different applications they are used in, standardized load-time profiles are established for different types of applications. The intention of these standardized load-time profiles is not to represent particular applications in the best way possible. In fact, they shall constitute representative applications – that are not too far from typical load-time profiles in the particular types of application – only for the purpose of applying the EPA and thus determining the EEI.

The introduction of these standardized load-time profiles as common bases enables a sufficiently accurate prediction of the relative differences in terms of energy efficiency between different pump units for various types of applications: The better the EEI of a pump unit based on the standardized load profile for a particular type of application is, the more energy efficient this pump unit will most likely perform in the real application of the same type, too. Thus a further aspect of competition is introduced to the market via the EPA.

It should be pointed out that the standardized load-time profiles exclude any idle time of the pump unit: Only the performance of the running extended product is considered. This is reasonable, because the interaction of the extended product with the application or system it is used in (e.g. on/off-switching controlled by level switches) is not intended to be included in the qualification in terms of energy efficiency in the sense of the EPA. Future concepts e.g. in the sense of system approaches might be able to include the interaction of extended products with the applications or systems they are used in into one measure of energy efficiency qualification. In contrast to that, the EPA is intended to qualify pump units as extended products that could be taken out of a box and installed into an application or system afterwards.

At the time this paper was written, different standardized load-time profiles representing different types of applications were considered by the EUROPUMP working group developing the EPA. For detailed information on the status of these discussions as well as further information on the concept of the EPA in general, it is recommended to refer to [8]. In the present paper, the so called Heating-Ventilating-and-Air-Conditioning (HVAC) load-time profile is generalized for closed loop applications of clean water pumps. It is used in this paper as standardized load-time profile for demonstration and explanation of the methodologies to determine the EEI in the frame of the EPA (cf. Fig. 2). It should be noted that this restriction clearly affects the numerical values used to illustrate the methodical procedures in the course of the paper. Nevertheless, the general methodologies to determine the EEI presented in this paper are valid independently of a particular load-time profile.

The load-time profile for closed loop applications is characterized by the rated flow rates $Q_i / Q_{100\%}$ where the subscript 100% denotes the nominal operating point of the pump (corresponding to the pump's best efficiency point at its nominal rotational speed $n_{100\%}$) and time weights $\Delta t_i / t_{tot}$ listed in Tab. 1. The time weights represent which fraction Δt_i of the total operating time t_{tot} (excluding the time the unit is switched off) the pump unit is operated at the individual value of flow rate. The load-time profile as it is listed in Tab. 1 has been determined by [9] and is internationally accepted as being representative for the very important application field of building technology. It should be noted that according to Tab. 1 a load-time profile is only characterized by values of flow rate and time weight for each duty point and not by values of the pump head H .

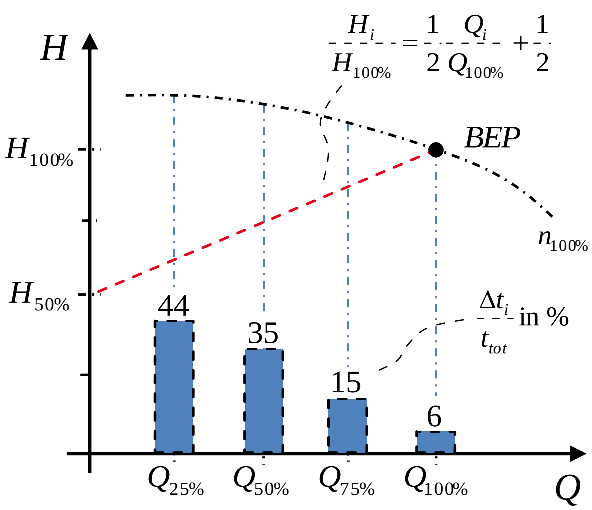

Fig. 2: Standardized load-time profile and pressure control curve for closed loop applications

Tab. 1: Standardized load-time profile for closed loop applications

Rated Flow Rate $Q_i/Q_{100\%}$	**Time Weight** $\Delta t_i/t_{tot}$
1	6 %
0.75	15 %
0.5	35 %
0.25	44 %

In case of fixed-speed pumps (pump units driven by asynchronous motors without VSD) the relevant duty points for determining the EEI are straightforward: The rotational speed of the asynchronous motors of these pump units fed directly by the electric grid is determined by the constant frequency of the electric grid f_1 according to Eq. (1)

$$n = n_{synch}(1-s) \tag{1}$$

where $n_{synch} = f_1/N_P$ is the synchronous speed, N_P is the number of pole pairs of the asynchronous motor and $s = (n_{synch} - n)/n_{synch}$ is the slip. As the slip only slightly varies with the duty point and generally is much smaller than unity, the rotational speed of fixed-speed pumps can be assumed as being approximately constant $n \approx n_{100\%}$. In order to fix the nominal rotational speed $n_{100\%}$ that strongly influences the hydraulic performance of the rotodynamic pump for the purpose of EEI determination and to maintain comparability between different products, the nominal rotational speeds are defined in the frame of the EPA as

$n_{100\%} = 2900\ \mathrm{rpm}$ in case of units equipped with 2-pole motors and

$n_{100\%} = 1450\ \mathrm{rpm}$ in case of units equipped with 4-pole motors. (2)

These values of the nominal rotational speeds have grown historically in European legislation and standardization: The EUROPUMP working group responsible for the development of the EPA defined the nominal rotational speeds of pumps in the frame of the EPA according to Eq. (2) to be in line with the MEI classification system for water pumps. For this classification system, nominal rotational pump speeds had to be defined to establish comparability between different pumps as well (c.f. [6]).

In contrast to fixed-speed pump units, the relevant duty points for determining the EEI of a variable-speed pump unit (pump unit driven by asynchronous motor with VSD) are not straightforward. Due to the ability of varying the rotational speed by varying the motor stator frequency e.g. via a frequency converter, these units are able to be operated at duty points distributed over a wide range of the Q-H-plane (c.f. Fig. 2).

In many applications where highly varying flow rates are demanded as is the case for the closed loop load-time profile used as example in this paper (c.f. Fig. 2 and Tab. 1) the smaller values of flow rate could easily be delivered by the pump with decreased pump head, too. To exploit this potential of saving energy and reduce the pump head compared to the corresponding value on the pump characteristic at $n_{100\%}$ the rotational speed needs to be reduced at reduced flow rate.

Generally, manufacturers and system integrators use their own control strategy following which the rotational speed is reduced according to decreasing flow rates. Furthermore, these control strategies can often easily be changed by changing the software settings of the VSD (e.g. frequency converter). To reach comparability of EEI values of variable-speed pump units across markets in spite of such individual control strategies, standardized pressure control curves are established for various types of applications.

As is the case for the standardized load-time profiles mentioned above, the purpose of the standardized pressure control curves is not to represent individual applications in the best way possible, but to provide representative control curves as a common base. These standardized control curves are defined in a form that is not too far from typical pressure control curves used in the particular types of applications. They serve only for the purpose of determining the EEI in the frame of the EPA. At the time this paper was written, different standardized pressure control curves belonging to different types of applications were considered by the EUROPUMP working group developing the EPA. For detailed information on the status of these discussions it is recommended to refer to [8].

In the present paper, the pressure control curve (as shown in Fig. 2)

$$\frac{H_i}{H_{100\%}} = \frac{1}{2}\frac{Q_i}{Q_{100\%}} + \frac{1}{2} \qquad (3)$$

is used to illustrate the determination of EEI for variable-speed pump units. The pressure control curve according to Eq. (3) is illustrated in Fig. 2 as a red dashed line and takes into account that in typical real applications some static head needs to be maintained even if the flow rate is reduced to very small values. It should be noted that although the restriction to this pressure control curve clearly affects the numerical values of EEI, the general methodologies to determine the EEI presented in this paper are valid independently of a particular pressure control curve.

Energy-Efficiency-Index

The Energy-Efficiency-Index (EEI) is the result of the qualification of pump units in terms of energy efficiency according to the EPA described above. The EEI is defined in such a way that a dimensionless value representing the energy efficiency of the performance of a fixed- or variable-speed pump unit used in a particular type of application is established. Thus, also an additional aspect of competition is introduced (in comparison to a system of minimum required efficiencies only, e.g. MEI- [6] and IE-classes [7]) by showing the effect of the whole configuration of a pump unit on its energy consumption in different types of applications.

The EEI is defined as

$$EEI = \frac{P_{1,avg}}{P_{1,ref}} \quad (4)$$

where $P_{1,avg}$ is a weighted average of the electrical power input of the actual pump unit (either fixed- or variable-speed) and $P_{1,ref}$ denotes a reference electrical power input of a reference fixed-speed pump unit (c.f. Fig. 3). The wording “actual pump unit” denotes the really existing pump unit the EEI shall be determined for while “reference pump unit” denotes a virtual pump unit that is used to normalize the power consumption of the actual pump unit for the purpose of EEI determination in this paper.

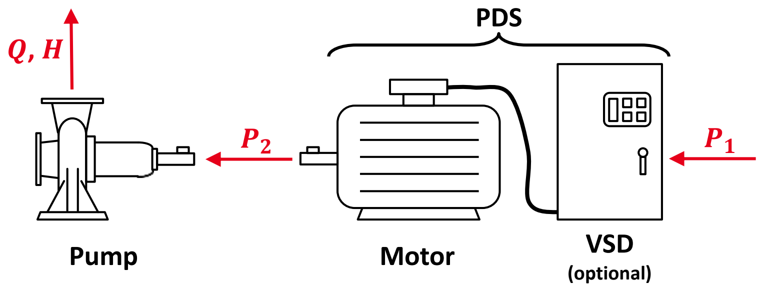

Fig. 3: Conversion of power between the components of a pump unit

The averaged electrical power input of the actual pump unit in the nominator of Eq. (4) is defined as the sum of the electrical power input values $P_{1,i}$ of the actual pump unit at each duty point of a load-time profile where the value of each duty point is weighted by the time fraction $\Delta t_i / t_{tot}$:

$$P_{1,avg} = \sum_i \frac{\Delta t_i}{t_{tot}} P_{1,i} \ . \quad (5)$$

Generally, two methodologies for determining the electrical power input of the actual pump unit $P_{1,i}$ in Eq. (5) are possible. These experimental and semi-analytic approaches are described in chapters following below.

The reference electrical power input $P_{1,ref}$ in the denominator of Eq. (4) is established upon a (virtual) reference fixed-speed pump unit (without VSD). It is defined in a way to be independent from technical particularities of individual (existing) pump units and serves to normalize the values of the EEI in order to compensate physical and technological differences on maximum attainable energy efficiencies. Hereby pump units of different type, size and nominal data, but of the same quality of energy efficiency, will have comparable numerical values of EEI for the same load-time profile and pressure control curve.

The EPA has been developed (and is still under development) for very different kinds of product groups, e.g. circulator pumps, clean water pump units (equipped with one rotodynamic pump) or booster stations (equipped with more than one clean water pump unit). As these different kinds of extended products generally require specific measures of normalizing the EEI, the reference electrical power input $P_{1,ref}$ in the denominator of Eq. (4) needs to be defined separately for each of them. For the product group “clean water pump units (equipped with one rotodynamic pump)” covered by this paper, the reference electrical power input is defined as

$$P_{1,ref} = \frac{P_{2,ref}}{\eta_{Mot,ref}} \tag{6}$$

where $P_{2,ref}$ is a reference mechanical shaft power of a (virtual) reference pump unit while $\eta_{Mot,ref}$ denotes the efficiency of a (virtual) reference asynchronous motor. The reference mechanical shaft power in Eq. (6) is derived from a reference hydraulic power $\rho g\, Q_{100\%}\, H_{100\%}$, characterized by the nominal flow rate and the nominal head of the (existing) actual pump unit (which are identical to the values at the best efficiency point at nominal rotational speed $n_{100\%}$ of the actual pump), and the efficiency of a (virtual) rotodynamic reference pump $\eta_{Pump,ref}$:

$$P_{2,ref} = \frac{\rho g\, Q_{100\%}\, H_{100\%}}{\eta_{Pump,ref}}. \tag{7}$$

The efficiencies of the (virtual) reference pump $\eta_{Pump,ref}$ and motor $\eta_{Mot,ref}$ in Eq. (6) and Eq. (7) are determined according to already existing product-specific efficiency standards to incorporate well established efficiency values of these components as base of the (virtual) components the (virtual) reference fixed-speed pump unit is composed of. The reference pump efficiency

$$\eta_{Pump,ref} = \eta_{Pump,ref}\left(Type,\, MEI,\, n_{100\%},\, Q_{100\%},\, H_{100\%}\right) \tag{8}$$

is derived from equations defined in a legislative regulation and a coming EN standard which concern the Minimum-Efficiency-Index (MEI) for clean water pumps ([4], [6]). The coefficients used in the equations therein and hence the reference pump efficiency as their result depend on the type of the (existing) actual rotodynamic pump (e.g. single-stage pump, multistage pump, inline pump), its nominal rotational speed $n_{100\%}$ and hydraulic quantities $Q_{100\%}$ and $H_{100\%}$ and a fixed value of the MEI the (virtual) reference pump shall exactly fulfill. The reference motor efficiency

$$\eta_{Mot,ref} = \eta_{Mot,ref}\left(\, f_1,\, N_P,\, IE,\, P_{2,ref}\right) \tag{9}$$

is derived from the calculation procedures defined in an IEC standard that concerns the IE classes system for asynchronous motors [7]. The procedures therein and hence the reference motor efficiency depend on the frequency of the electrical grid supplying the (existing) actual pump unit f_1, the pole pair number of the (existing) actual asynchronous motor N_P, a fixed IE class the (virtual) reference motor shall exactly fulfill and the reference shaft power $P_{2,ref}$ that has to be determined according to Eq. (7) in advance.

The EUROPUMP working group developing the EPA for clean water pumps has not finally fixed the MEI value and IE-class the (virtual) reference components shall exactly fulfill in the definitions of $\eta_{Pump,ref}$ and $\eta_{Mot,ref}$. According to a proposal of the working group, a MEI value of 0.4 and class IE3 are used to evaluate $P_{1,ref}$ in the numerical examples in the subsequent chapters of this paper. Although these restrictions clearly affect the numerical values used in the examples, the general procedure to determine $P_{1,ref}$ is valid independently of particularly chosen MEI values and IE classes.

The definition of the reference electrical power input $P_{1,ref}$ can be summarized as follows:

The reference electrical power input $P_{1,ref}$ is the electrical power input to a (virtual) reference fixed-speed pump unit (without VSD). The reference unit has the same nominal rotational *speed ($n_{100\%}$) and hydraulic quantities (pump type, $Q_{100\%}$, $H_{100\%}$) as the (existing) actual fixed- or variable-speed pump unit the EEI shall be calculated for. The reference unit consists of state-of-the-art components as they are defined by means of existing product-specific standards (MEI, [6] and IE, [7]).*

The reference electrical power input $P_{1,ref}$ is the electrical power input to this established (virtual) reference fixed-speed pump unit when its operation at nominal hydraulic conditions (characterized by $Q_{100\%}$ and $H_{100\%}$ of the existing actual pump unit) is considered. Hence, the reference electrical power input $P_{1,ref}$ rests upon nominal information on the rotodynamic pump of the (existing) actual fixed- or variable-speed pump unit only. It can be determined entirely based on information given in the product documentations as consequence.

Experimental Approach

The experimental approach to determine the EEI is straightforward: The fixed- or variable-speed pump unit to investigate has to be installed on a test bench. For the tests to be done, suitable measurement equipment to determine the electrical input power P_1 and the hydraulic output power characterized by the flow rate Q and the pump head H has to be available. Besides these primary measurement quantities, additional measurement equipment might be necessary to prove that standardized test conditions are fulfilled which will be described in future standards on EEI.

The duty points $Q_i / Q_{100\%}$ of the load-time profile (e.g. the load-time profile for closed loop applications, c.f. Fig. 2 and Tab. 1) must be adjusted by throttling and in case of variable-speed pumps additionally by adjusting the rotational speed in order to follow the standardized pressure control curve (e.g. the pressure control curve according to Eq. (3) and Fig. 2). For each duty point the electrical power input to the actual pump unit $P_{1,i}$ must be measured. Afterwards, the averaged electrical power input $P_{1,avg}$ can be determined from the measured $P_{1,i}$ values according to Eq. (5).

To use Eq. (4) and calculate the EEI, the reference electrical power input $P_{1,ref}$ has to be determined as well. The only information necessary to determine $P_{1,ref}$ is the nominal data of the rotodynamic pump of the actual fixed- or variable-speed pump unit. This information serves to establish the (virtual) reference fixed-speed pump unit belonging to the (existing) actual fixed- or variable-speed pump unit and can easily be found e.g. in the product documentation. As no measured data is necessary to establish $P_{1,ref}$, this reference value could also be calculated before the experimental investigation.

In the last step, the EEI for the (existing) actual fixed- or variable-speed pump unit can be calculated by means of Eq. (4).

This experimental approach is straightforward, but causes high effort especially when an actual pump unit equipped with components delivered by different manufacturers is considered.

Semi-Analytical Approach

The main motivations for the development of the semi-analytic methodology as an alternative to experimentally determine the EEI were

- to reduce the experimental effort to establish a market-wide EEI determination for pump units and
- to enable (or ease) generally a systematic determination of EEI values for units consisting of components delivered by completely different manufacturers.

The aim of the general procedure is to determine the electrical power input values $P_{1,i}$ to the actual pump unit at each duty point of the load-time profile by means of semi-analytic models (SAM). This method is developed within a project carried out at the Technische Universitaet Darmstadt. The project was initiated and is supported by EUROPUMP. It aims at the theoretical elaboration and experimental validation of the SAM method in the frame of the EPA for pump units.

When applying this method, the performance of the actual pump unit – and finally its electric power consumption – is mathematically synthesized using modeling of its particular components and taking into account the physical interactions of the components. The model of the pump unit is called semi-analytical because the mathematical correlations used describe the performance in a principal form that reflects the underlying physical processes and influences, but only needs a small amount of well-defined data from the separate components. These so-called supporting points serve to "calibrate" the principal equations describing the performance of both components (rotodynamic pump and PDS) to the investigated components.

The general calculation procedure by means of the SAM of the pump unit as well as the location of the supporting points of pump (blue upward-triangles) respectively PDS (purple downward-triangles) are illustrated in Fig. 4. The SAM of the pump unit consists of a SAM of the pump that is based on physical knowledge (affinity laws for rotodynamic pumps) and an empirical interpolation procedure for the losses of the PDS.

In case of the pump, the three supporting points correspond to the three duty points defined in the frame of the MEI (c.f. [6]), namely one at 75 % part load, one at 110 % over load and one at best efficiency point (BEP) of the pump. In case of the PDS the supporting points are different: They correspond to three out of eight supporting points which will be defined by [10] that form the corners of a characteristic triangle in the n-T-plane containing the typical operation conditions of rotodynamic pumps. The supporting points of the PDS will be available (i.e. indicated in the product documentations) or at least calculable for each PDS on the market in the future.

In the end, the main purpose of both the SAM of the pump and the interpolation procedure for the losses of the PDS is to enable a prediction of the performance of both components at the duty points of the load-time profile on base of only these three supporting points per component. The physical and empirical knowledge about the components' part load behaviors representing the basement of the modeling enables sufficiently accurate predictions despite of the low numbers of supporting points. Although validation of the SAM methodology has not been finally accomplished at the time this paper was written, latest results in determining the EEI by means of the SAM methodology show deviations from experimentally determined EEI values only in the order of magnitude of typical total (systematic + statistic) measurement uncertainties.

The SAM calculation procedure is presented very basically in this paper: The SAM of the pump and the interpolation procedure for the losses of the PDS are treated as black-box models (input-output models) without giving detailed information about their internal mathematics (c.f. Fig. 4). At the time this paper was written, such details about the SAM of the pump respectively interpolation procedure for the losses of the PDS were still under consideration by the EUROPUMP working group developing the EPA for clean water pumps and will be described in a future standard on EPA for pump units once they are finally validated. Nevertheless, the general procedure of determining the EEI by means of the SAM method has been fixed by the working group so that further changes of details inside the black-box models of pump and PDS will improve the accuracy of predicting the numerical value of EEI but not affect the general procedure presented here.

In the following, the principal calculation procedure to determine the EEI of a pump unit by means of the SAM methodology will be explained in a numerical example. For this purpose, a fictitious variable-speed pump unit is utilized. The unit's nominal data is listed in Tab. 2 for convenience. Especially note that in case of the SAM method, a strict distinction between the nominal values of the pump and the nominal values of the PDS needs to be utilized. To facilitate the distinction, the subscript $100\%,Pump$ will replace the subscript 100% used above for nominal values of the pump and $100\%,PDS$ will indicate nominal values of the PDS in the following. The fictitious pump unit used in this numerical example does not correspond to any pump unit investigated at TU Darmstadt within the EUROPUMP project.

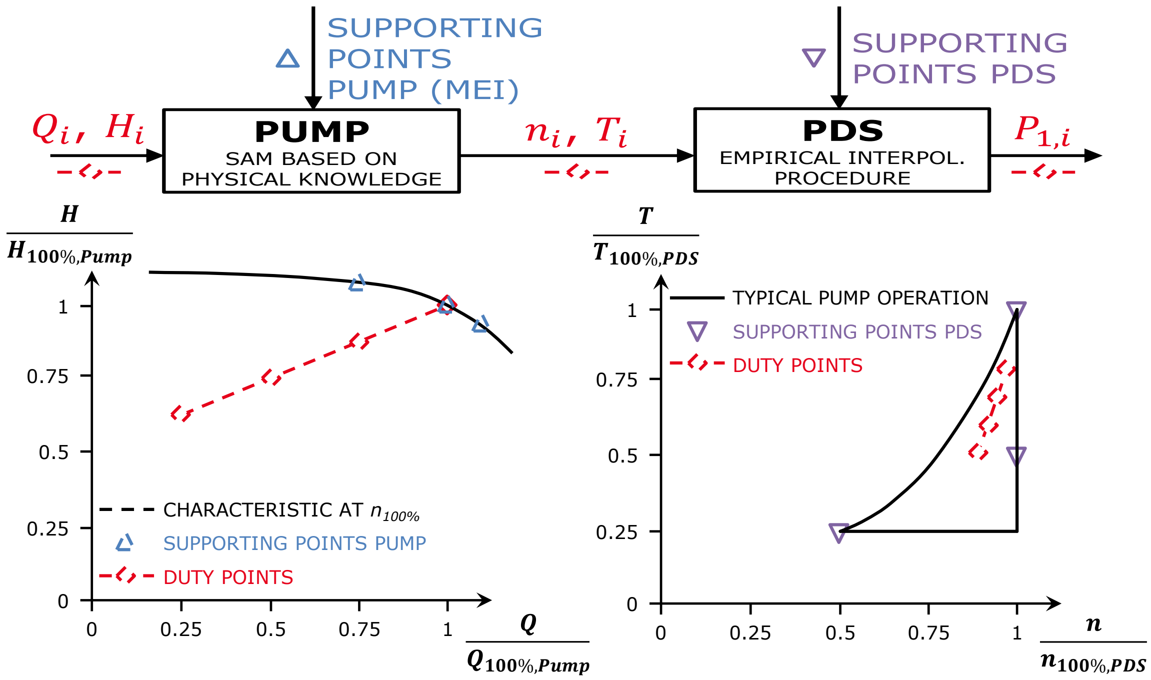

Fig. 4: Structure and supporting points of the semi-analytic methodology

The fictitious pump unit is equipped with a so-called “vertical multistage” (MS) pump with 3 stages and a 2-pole asynchronous motor. Because of the 2-pole asynchronous motor $(N_P = 1)$, $n_{100\%,Pump} = 2900\,\text{rpm}$ has to be chosen as nominal rotational speed of the pump according to Eq. (2).

In contrast, the nominal rotational speed of the PDS corresponds to the nominal load condition of the PDS where the nominal mechanical power $P_{2,100\%,PDS}$ and nominal torque $T_{100\%,PDS}$ of the PDS are delivered simultaneously. Therefore, $n_{100\%,PDS}$ represents a design value of the PDS and is individual for each PDS. The nominal data of the fictitious PDS used in this numerical example is listed in Tab. 2, too.

The EEI in this numerical example will be determined on base of the closed loop load-time profile (c.f. Fig. 2, Tab. 1) and, as a variable-speed pump unit is considered, the pressure control curve defined by Eq. (3).

Tab. 2: Nominal data of fictitious variable-speed pump unit

Pump Type	$Q_{100\%,Pump}$	$H_{100\%,Pump}$	$n_{100\%,Pump}$	$T_{100\%,Pump}$	$P_{2,100\%,Pump}$
MS ($N_{Stages} = 3$)	$49.7\ m^3/h$	54.7 m	2900 rpm	38.2 Nm	11.6 kW

N_P	**Variable Speed Drive?**	$n_{100\%,PDS}$	$T_{100\%,PDS}$	$P_{2,100\%,PDS}$
1	yes	2926 rpm	49.0 Nm	15.0 kW

The supporting points for the components of the fictitious pump unit which need to be available for application of the SAM method are given in Tab. 3. The three supporting points of the pump (defined by the rated flow rate $Q/Q_{100\%,Pump}$) are given in the left table, while the three supporting points of the PDS (defined by the relative speed $n/n_{100\%,PDS}$ and relative torque $T/T_{100\%,PDS}$) are given in the right table. The performance-characterizing values of the pump that need to be known for each supporting point are the rated head $H/H_{100\%,Pump}$ and the rated mechanical power $P_2/P_{2,100\%,Pump}$, the respective values of the PDS are the so-called related losses $p_{L,PDS} = P_{L,PDS}/P_{2,100\%,PDS}$. These are dimensionless values that indicate the magnitude of the absolute losses of the PDS $P_{L,PDS}$ at an operating point in relation to the nominal mechanical power of the PDS $P_{2,100\%,PDS}$.

Tab. 3: Supporting points of pump and PDS of fictitious variable-speed pump unit

$Q/Q_{100\%,Pump}$	$H/H_{100\%,Pump}$	$P_2/P_{2,100\%,Pump}$	$n/n_{100\%,PDS}$	$T/T_{100\%,PDS}$	$p_{L,PDS}$
0.75	1.14	0.91	1	1	17 %
1	1	1	1	0.5	9 %
1.1	0.93	1.03	0.5	0.25	4 %

Application of the SAM of the Pump

In a first step, the values of rotational speed n_i and torque T_i corresponding to the load points Q_i and H_i defined by the closed loop load-time profile and pressure control curve defined by Eq. (3) need to be determined. For this purpose, the SAM of the pump is adjusted to the actual pump of the fictitious pump unit by means of the pump's supporting points listed in Tab. 3. After this, the mechanical representation of the load points can be calculated by means of the SAM of the pump. This is given relative to the pump's nominal point in Tab. 4.

Tab. 4: Results of the SAM of the pump

$Q_i/Q_{100\%,Pump}$	$n_i/n_{100\%,Pump}$	$T_i/T_{100\%,Pump}$	$P_{2,i}/P_{2,100\%,Pump}$
1	1	1	1
0.75	0.90	0.78	0.70
0.5	0.80	0.55	0.44
0.25	0.72	0.35	0.25

Application of the interpolation procedure of the PDS

The values of speed n_i and torque T_i calculated by the pump SAM serve as input data to the interpolation procedure of the PDS. As the nominal points of the pump and the PDS are defined in different ways, the mechanical load points given in a representation relative to the pump's nominal point in Tab. 4 have to be converted to a form relative to the nominal point of the PDS first:

$$\frac{x_i}{x_{100\%,PDS}} = \frac{x_i}{x_{100\%,Pump}} \frac{x_{100\%,Pump}}{x_{100\%,PDS}} . \qquad (10)$$

In the next step, the related losses $p_{L,PDS,i}$ have to be determined for the mechanical load points. For this purpose, the interpolation procedure for the losses of the PDS is adjusted to the actual PDS of the fictitious pump unit by means of the supporting points of the PDS given in Tab. 3. The results of the interpolation scheme of the PDS as well as the mechanical load points in their representation converted according to Eq. (10) are given in Tab. 5. Note that for better orientation the rated flow rates are still given in their form relative to the pump's nominal point in Tab. 5.

Tab. 5: Converted mechanical load points and calculated losses of the PDS

$Q_i / Q_{100\%,Pump}$	$n_i / n_{100\%,PDS}$	$T_i / T_{100\%,PDS}$	$p_{L,PDS,i}$
1	0.99	0.78	13.8 %
0.75	0.89	0.60	10.7 %
0.5	0.79	0.42	7.6 %
0.25	0.71	0.27	5.1 %

Combination of the Results

To finally determine the electrical power input $P_{1,i}$ at each load point n_i and T_i respectively Q_i and H_i, the results from the SAM of the pump (Tab. 4) and the interpolated losses of the PDS (Tab. 5) have to be combined. Note that the respective nominal values the individual results are referred to have to be considered during this combination:

$$P_{1,i} = P_{2,i} + P_{L,PDS,i} = \frac{P_{2,i}}{P_{2,100\%,Pump}} P_{2,100\%,Pump} + p_{L,PDS,i}\, P_{2,100\%,Mot}\,. \quad (11)$$

The combined results respectively the searched electrical power input values $P_{1,i}$ to the fictitious pump unit for each load point of the closed loop load-time profile and for the pressure control curve defined by Eq. (3) are listed in Tab. 6.

Tab. 6: Combined results of the calculations for the pump and the PDS

$Q_i / Q_{100\%,Pump}$	$P_{1,i}$
1	13.7 kW
0.75	9.7 kW
0.5	6.2 kW
0.25	3.7 kW

From these results, the averaged electrical power input to the fictitious variable-speed pump unit can be determined as

$$P_{1,avg} = 0.06\, P_{1,100\%} + 0.15\, P_{1,75\%} + 0.35\, P_{1,50\%} + 0.44\, P_{1,25\%} \approx 6.1\,\text{kW}\,. \quad (12)$$

Calculation of the Energy-Efficiency-Index

The reference electrical power input $P_{1,ref}$ of the (virtual) reference fixed-speed pump unit corresponding to the fictitious actual variable-speed pump unit investigated in this numerical example must be calculated before the EEI can be determined for it. Note that the determination of $P_{1,ref}$ is based on nominal information on the actual rotodynamic pump only. These can easily be found e.g. in the product documentations. Hence, the value of $P_{1,ref}$ could have been calculated before the determination of $P_{1,avg}$ as well.

The procedures to determine $\eta_{Pump,ref}$ and $\eta_{Mot,ref}$ inside the calculation of $P_{1,ref}$ would lengthen this paper obviously and are therefore left out here. They are described in detail in [6] and [7]. Along with the intermediate results $\eta_{Pump,ref} \approx 70.7\ \%$ (calculated by means of [6]), $P_{2,ref} \approx 10.5\ \mathrm{kW}$ (calculated by means of Eq. (7)) and $\eta_{Mot,ref} \approx 91.0\ \%$ (calculated by means of [7]), the reference electrical power input corresponding to the actual pump unit investigated in this numerical example can finally be determined as $P_{1,ref} \approx 11.5\ \mathrm{kW}$

With the averaged electrical power input determined by means of the SAM and the reference electrical power input calculated just before, the EEI determined on base of the closed loop load-time profile and the pressure control curve defined by Eq. (3) can finally be calculated for the fictitious actual variable-speed pump unit as $EEI \approx 0.530$ in this numerical example.

Outlook

After European legislative regulations started ascertaining and prescribing minimal levels of the efficiencies of pumps within the frame of the Product Approach in January, 2013, the European energy efficiency strategy might aim at the very often used combinations of rotodynamic pumps and asynchronous motors with and without Variable Speed Drives (e.g. frequency converters) in the frame of the Extended Product Approach in the future. If the Extended Product Approach will be introduced in European legislation and standardization, the methodologies to determine the EEI presented in this paper might be applied by manufacturers or suppliers of pump units to determine the EEI-values of the pump units they place on the market or put into service.

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Estimating Pump Internal Wear Ring Clearance Leakage Losses and the Impact on Pump Efficiency

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Abstract

Rotodynamic pumps as designed and manufactured typically have relatively tight internal clearances between rotating and non-rotating parts at what is known as the wear ring areas. These clearances serve to separate pump higher pressure areas from lower pressure ones, in order to restrict the internal circulation of pumped fluid back to the suction side of the impeller. With respect to pump performance, this circulation is a leakage loss that affects volumetric efficiency and therefore the pump efficiency. While performance characteristics of a new pump determined by test reflect the design clearances, as pumps operate, wear in these clearances can occur that causes increased internal leakage loss and reduced pump efficiency. A relatively straightforward approach is provided to estimate the leakage loss of a pump due to increased wear ring clearances, and the resulting impact on pump efficiency.

Introduction

By necessity, rotodynamic pumps with enclosed impellers (having shrouded vanes) use relatively tight running clearances between rotating parts (impellers) and non-rotating parts (casings) to separate higher pressure areas from lower pressure areas. When new, a relatively small amount of leakage occurs through these clearances due to the internal pressure differential produced by the pump. This leakage flow is included in the total flow rate produced by the impeller (which impacts the pump input power required), but because it flows back to the suction side of the pump to be re-pumped and not out the pump discharge, it does not contribute to the pump performance, but is instead considered a volumetric efficiency loss that affects the efficiency of the pump.

These clearances can increase during the course of normal pump operation, resulting in increased internal leakage loss, reduced pump performance, and reduced efficiency. This is especially true with applications having abrasive materials or grit present in the pumped media, and clearances in such instances should be routinely evaluated and maintained for best results. In anticipation of potential wear in these important clearances, many pumps are equipped with wear rings so as to easily facilitate this process.

This paper provides a method to estimate the internal leakage losses due to wear and the resulting impact on pump efficiency, using information found in classic pump reference materials.

Wear Ring Description

Wear rings of various designs are available to pump designers, with the plain, straight-type ring being the most commonly used. Refer to Figures 10.1 and 10.2 from Stepanoff [1]. This paper is concerned with plain, straight-type rings as commonly found in end suction, vertical inline, and split case pumps that use volute casings and enclosed impeller types (having shrouds adjacent to the vanes), although the methodology presented herein may be adapted to other ring styles. It also may be adapted to vertically suspended type pumps and other types that utilize diffuser casings. Other methodologies not addressed herein apply to pumps with open impellers (having vanes unshrouded or shrouded on one side only).

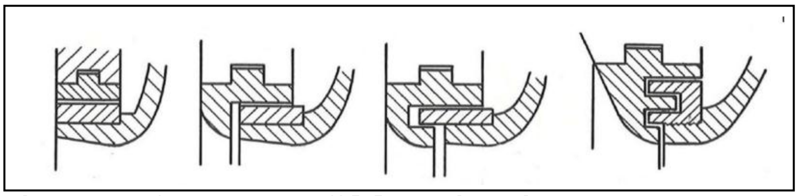


Figure 10.1 from Stepanoff [1] Wearing Ring Types

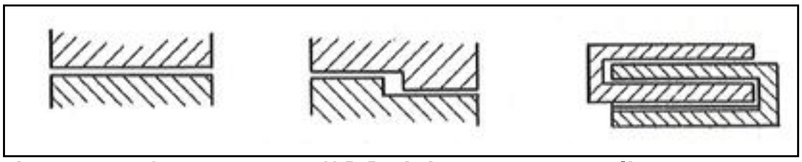


Figure 10.2 from Stepanoff [1] High Pressure Sealing Arrangements

Mathematical Model

Volumetric Efficiency

Volumetric efficiency from Jekat [2] page 2.8, equation (18) is:

$$\eta_V = \frac{Q}{(Q + Q_L)}$$

Where:

Q = pump flow rate, GPM

Q_L = leakage flow rate, GPM

η_v = volumetric efficiency

Pump Efficiency

The effect of volumetric efficiency on pump efficiency may be seen by the following equation (19) from Jekat [2]:

$$\eta = \frac{1}{\left(\frac{1}{(\eta_h \cdot \eta_v)} + \left(\frac{P_{df}}{P_w}\right) + \left(\frac{P_m}{P_w}\right)\right)}$$

Where:

η = pump efficiency

η_h = hydraulic efficiency $\eta_h = \left(1 - \left(\frac{0.8}{Q^{0.25}}\right)\right)$ per equation (46) of Jekat [2] for average (or standard) hydraulic designs

η_v = volumetric efficiency

P_{DF} = disk friction power loss

P_m = mechanical power loss (bearing and seal friction)

P_w = water horsepower

Therefore it can be seen that by knowing the variance in leakage loss (and hence volumetric efficiency), with the other losses kept constant, the impact on the pump efficiency may be determined.

The above equation may be rearranged into a more familiar form:

$$\eta = \eta_h \cdot \eta_v \cdot \left(\eta_m - \left(\frac{P_{DF}}{P_S} \right) \right)$$

Where P_S = Pump shaft input power

However, Jekat [2] provides guidance for the values of $\left(\frac{P_{df}}{P_w} \right)$ and $\left(\frac{P_m}{P_w} \right)$ in the previous version of the equation, and for the purpose of this paper the former version is chosen.

Pressure at the Wear Rings

Stepanoff [1] page 187, equation (10.6) provides an empirical formula for the pressure at the wear ring for the pump best efficiency point (B.E.P.) flow rate:

$$H_L = \frac{3}{4} \frac{u_2^2 - u_1^2}{2g}$$

Where H_L= head at the wear ring, feet

U_2 = peripheral velocity at the wear ring diameter, ft/sec

U_1 = peripheral velocity at the vane entrance tip (impeller eye), ft/sec

For convenience in calculating U_1, the diameter of the vane entrance tip (impeller eye) may be estimated as 85% of the wear ring diameter.

Internal Leakage Losses

H_L is also recognized as the head loss across the wear ring when subjected to the leakage flow rate. The head loss may be calculated using the following equation, derived from equations (10.2) and (10.3) of Stepanoff [1] page 183:

$$H_L = \left(f \left(\frac{L}{a} \right) + 1.5 \right) \frac{v^2}{2g}$$

Where H_L= head across the clearance, feet

f = friction coefficient, dimensionless

L = width of the wear ring surface

a = diametrical clearance, feet

By inspection it is seen the multiplier of the velocity head ($v^2/2g$) in the equation above represents the sum of the classic square-edge inlet loss coefficient (1.0), the sudden expansion loss coefficient (0.5) and the internal friction loss coefficient (f L/a). Therefore it remains to solve for the flow rate to determine leakage losses.

However, it is also seen by inspection that the terms f and v are derived from the flow rate, and of course that leakage flow rate is not yet known. Therefore an iterative process is necessary as follows:

1) First, consider the leakage losses for the ring clearance in the as-new condition.

2) Assume a leakage flow rate Q_L, for convenience, as a fraction of the new pump best efficiency point (BEP) flow rate, say 0.015 x BEP flow rate

3) Calculate v through the as-new annular clearance, as follows:

$$v = \frac{Q_L \times 0.321}{A}, \text{ ft/sec}$$

Where A = annular area, square inches

$$A = \pi \cdot \left(\frac{D}{2}\right) \cdot a$$, and D = average diameter of the ring surfaces, inches

4) Calculate Reynolds number, as follows:

$$N_{Re} = \frac{v \frac{a}{(12)} \cdot \rho}{\mu}$$

Where ρ = fluid density, lbm/ft^3

μ = fluid absolute viscosity, lb_m/ft sec

5) The equation correlating Reynolds number and friction factor f is complex and uses f in multiple places, therefore use an iterative process to determine f for the fixed value of Reynolds number, starting with f_{est} = 0.001, obtaining a value for f which is used in the next iteration as f_{est}. Convergence is usually obtained on the third iteration, which therefore fixes the value of f.

$$f = \left[\frac{1}{-2 \cdot \log\left[\left(\frac{0.000250}{3.7 \cdot a}\right) + \frac{2.51}{N_{Re}\sqrt{f_{est}}}\right]} \right]^2$$

(Author note: The above equation and the corresponding iterative process are presented here, however it has been suggested to the author that simplified equations may be available that eliminate the need for the iterative process to determine f.)

6) Using f, and rearranging the equation for H, a calculated value of Q_L can be obtained:

$$Q_L = \frac{A}{0.321}\left(\frac{H_L \cdot 2g}{f\left(\frac{L}{a}\right) + 1.5}\right)^{1/2}$$

7) Steps 1 through 6 are then repeated, with convergence reached typically on the third iteration, with the result being that an estimate of the internal leakage loss Q_L is now known.

Note, however, Q_L is the leakage for one wear ring as applicable a single suction end suction pump or vertical inline pump fitted with one wear ring (no wear ring behind the impeller with balance holes to reduce the axial thrust). If the pump is double suction or a single suction (end suction pump or vertical inline) pump fitted with a wear ring on th suction side of the impeller and also a wear ring behind the impeller with balance holes to reduce the axial thrust, the value of Q_L must be doubled.

8) The volumetric efficiency for the as-new condition may now be calculated as follows using a modified equation to account for the number of annular wear ring openings producing leakage losses:

$$\eta_V = \frac{Q}{Q + (Q_L) \cdot \text{(No. of Annular ring passages)}}$$

9) Now, consider the leakage losses for the ring clearance in the worn condition. Use steps 1 through 8 above, substituting the worn value of ring clearance in the appropriate equations. The result is the volumetric efficiency for the worn condition considered.

Using the previously equation (19) from Jekat [2] the effect of volumetric efficiency on pump efficiency is found by the following:

$$\eta = \frac{1}{\left(\frac{1}{(\eta_h \cdot \eta_v)} + \left(\frac{P_{DF}}{P_W} \right) + \left(\frac{P_M}{P_M} \right) \right)}$$

Jekat [2] offers typical values for (P_{df} / P_w) and (P_m / P_w), however, for the purposes of evaluating the new-to-worn condition ring clearances and associated leakage losses, calculation of estimated mechanical power losses and disk friction losses is not essential as they may be considered constant.

Therefore,

$$\eta = \frac{1}{\frac{1}{(\eta_h \cdot \eta_v)} + K}$$

Where K = a constant, $= \left(\frac{P_{DF}}{P_W} \right) + \left(\frac{P_M}{P_W} \right)$

Now, using the known new condition value of pump efficiency η, hydraulic efficiency η_h, and volumetric efficiency η_v, K may be determined.

$$K = \frac{1}{\eta} - \left(\frac{1}{\eta_h - \eta_v} \right)$$

To calculate the pump efficiency in the worn condition, use the previous value of hydraulic efficiency η_h, the worn volumetric efficiency η_v, and K in the equation below.

$$\eta = \frac{1}{\frac{1}{(\eta_h \cdot \eta_v)} + K}$$

Experimental Results

The methodologies presented herein have been used successfully by the author for a couple of decades with the results typically predicting the efficiency degradation within one or two percentage points, however most of these instances have not involved substantial deviation from the new ring clearances, which may be typically on the order of 0.001 to 0.002 times the ring diameter.

For experimental purposes in exploring the effects of more extreme ring clearance wear, a convenient pump was selected to subject to the progressive opening of the ring clearances, with subsequent tests associated with each case. The pump chosen was an 8” x 6” double suction, dual volute, axially split case pump (Figure 1). This particular pump has a low-NPSH impeller design (hydraulic efficiency η_h = 0.85 est.) which is a special-case characteristic not particularly conducive to the highest efficiency values obtainable, but the pump was deemed suitable for the experiment. The new ring clearances were approximately 0.0015 times the ring diameter.

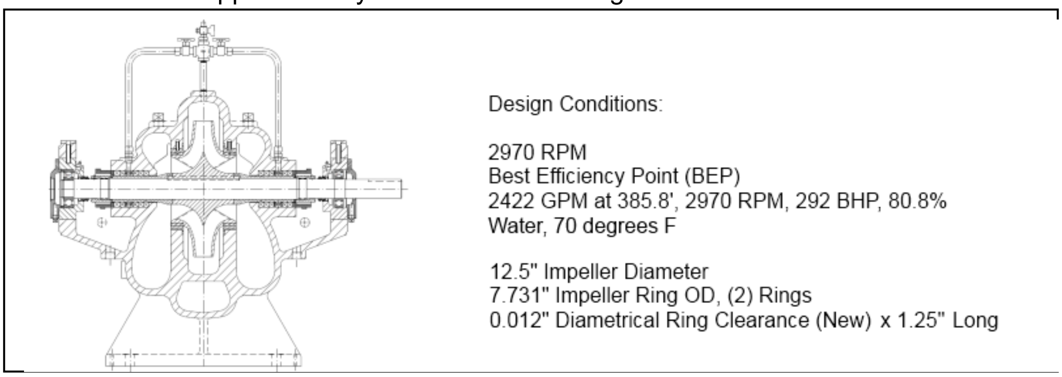


Figure 1 Test Pump

The pump was tested at 2970 RPM with subsequent ring clearances of 0.0023, 0.0048, 0.0071, and 0.0094 times the ring diameter, and the methodology applied to each case. Table 1 below shows a spreadsheet of calculations performed for the with the 0.0094 times the ring diameter case as an example. Table 2 is a tabulation of the calculated and test results obtained for each ring clearance scenario. Figure 2 shows the plotted test results.

Table 1, Example of Spreadsheet Results (for Clearances Opened from 0.0015 to 0.0094 times the Wear Ring Diameter)

Input Data	
RPM	2970
H, feet	385.75
Q, GPM	2422
No. of Annular Ring Passages	2
Ring Length, inches	1.25
Impeller Ring Diameter, inches	7.731
Impeller Front Shroud Dia., inches	12.5
New Ring Clearance, inches	0.012
Worn Ring Clearance, inches	0.073
New Pump Efficiency With New Ring Clearances	80.78%

New Straight Ring Clearance Calculations		Worn Straight Ring Clearance Calculations	
U2f	162.12	U2f	162.12
U1	85.23	U1	85.23
Hloss	221.49	Hloss	221.49
Center of New Annular Opening	7.737	Center of Worn Annular Opening	7.768
Area of New Annular Opening	0.1458	Area of Worn Annular Opening	0.8907
Qloss1	36.33	Qloss1	36.33
Annular Velocity	79.96	Annular Velocity	13.09
Reynolds Number	7571	Reynolds Number	7541
First Guess Friction Factor	0.001	First Guess Friction Factor	0.001
Friction Factor1	0.0778	Friction Factor1	0.0663
Friction Factor2	0.0533	Friction Factor2	0.0355
Friction Factor3	0.0540	Friction Factor3	0.0379
Friction Factor4	0.0540	Friction Factor4	0.0376
Friction Factor5	0.0540	Friction Factor5	0.0376
Qloss2	20.33	Qloss2	226.32
Annular Velocity	44.74	Annular Velocity	81.56
Reynolds Number	4236	Reynolds Number	46979
First Guess Friction Factor	0.001	First Guess Friction Factor	0.001
Friction Factor1	0.0961	Friction Factor1	0.0375
Friction Factor2	0.0555	Friction Factor2	0.0293
Friction Factor3	0.0573	Friction Factor3	0.0296
Friction Factor4	0.0572	Friction Factor4	0.0296
Friction Factor5	0.0572	Friction Factor5	0.0296
Qloss3	19.87	Qloss3	233.96
Annular Velocity	43.74	Annular Velocity	84.32
Reynolds Number	4141	Reynolds Number	48566
First Guess Friction Factor	0.001	First Guess Friction Factor	0.001
Friction Factor1	0.0970	Friction Factor1	0.0372
Friction Factor2	0.0556	Friction Factor2	0.0293
Friction Factor3	0.0574	Friction Factor3	0.0295
Friction Factor4	0.0573	Friction Factor4	0.0295
Friction Factor5	0.0573	Friction Factor5	0.0295
Qloss4	19.85	Qloss4	234.03
Annular Velocity	43.69	Annular Velocity	84.34
Reynolds Number	4137	Reynolds Number	48580
First Guess Friction Factor	0.001	First Guess Friction Factor	0.001
Friction Factor1	0.0970	Friction Factor1	0.0372
Friction Factor2	0.0556	Friction Factor2	0.0293
Friction Factor3	0.0575	Friction Factor3	0.0295
Friction Factor4	0.0573	Friction Factor4	0.0295
Friction Factor5	0.0573	Friction Factor5	0.0295
Qloss5	19.85	Qloss5	234.03
Annular Velocity	43.69	Annular Velocity	84.34
Reynolds Number	4137	Reynolds Number	48580
First Guess Friction Factor	0.001	First Guess Friction Factor	0.001
Friction Factor1	0.0970	Friction Factor1	0.0372
Friction Factor2	0.0556	Friction Factor2	0.0293
Friction Factor3	0.0575	Friction Factor3	0.0295
Friction Factor4	0.0573	Friction Factor4	0.0295
Friction Factor5	0.0573	Friction Factor5	0.0295
Qloss6	19.85	Qloss6	234.03

Estimated Hydraulic Efficiency (Low NPSH)	0.85

Calculated Data	
New Straight Ring Leakage Loss, GPM	19.85
New Ring Total Pump Leakage Loss, GPM	39.70
New Ring Pump Volumetric Efficiency	98.39%
K	0.04218
Worn Straight Ring Leakage Loss, GPM	234.03
Worn Ring Total Pump Leakage Loss, GPM	468.06
Worn Ring Pump Volumetric Efficiency	83.80%

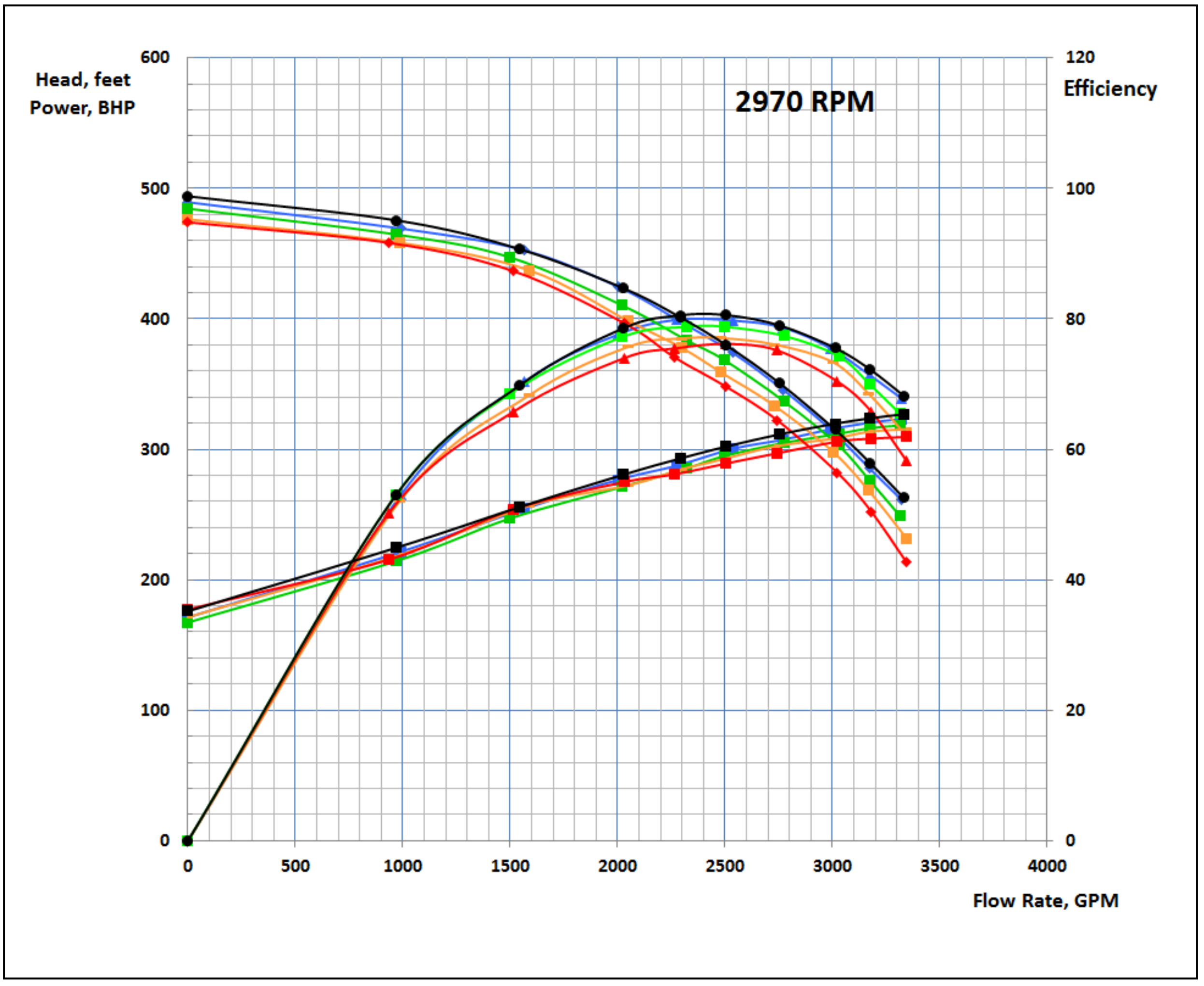
Output Data - Straight Ring Design With Worn Clearances	
Pump Efficiency	69.16%

For Information Only	
Pdf/Pw per Jekat Eq. (51) p. 2.23	0.0329
Pm/Pw per Jekat Fig. 15	0.0077

Table 2, Test Result Comparisons for Various Clearances

	New	Worn			
Clearance/Wear Ring Diameter	0.0015	0.0023	0.0048	0.0071	0.0094
Diametrical Clearance (in)	0.012	0.018	0.037	0.055	0.073
Total Leakage Loss (GPM)	39.7	74.04	202.52	333.91	468.06
Volumetric Efficiency	98.39%	97.03%	92.28%	87.88%	83.80%
Pump Efficiency	80.78%	79.71%	75.93%	72.42%	69.16%
Tested Pump Efficiency	80.78%	80.11%	79.02%	77.35%	76.26%

Figure 2 Plotted Test Results



Discussion of Test Results

As can be seen from Table 2, the calculated deterioration of the pump efficiency is greater than actually experienced in the test pump, and it is apparent that further research is needed to explain the variance.

In the interim, the use of an empirical efficiency correction factor may be useful, shown plotted vs. the Diametrical Clearance/Wear Ring Diameter ratio in Figure 2, below.

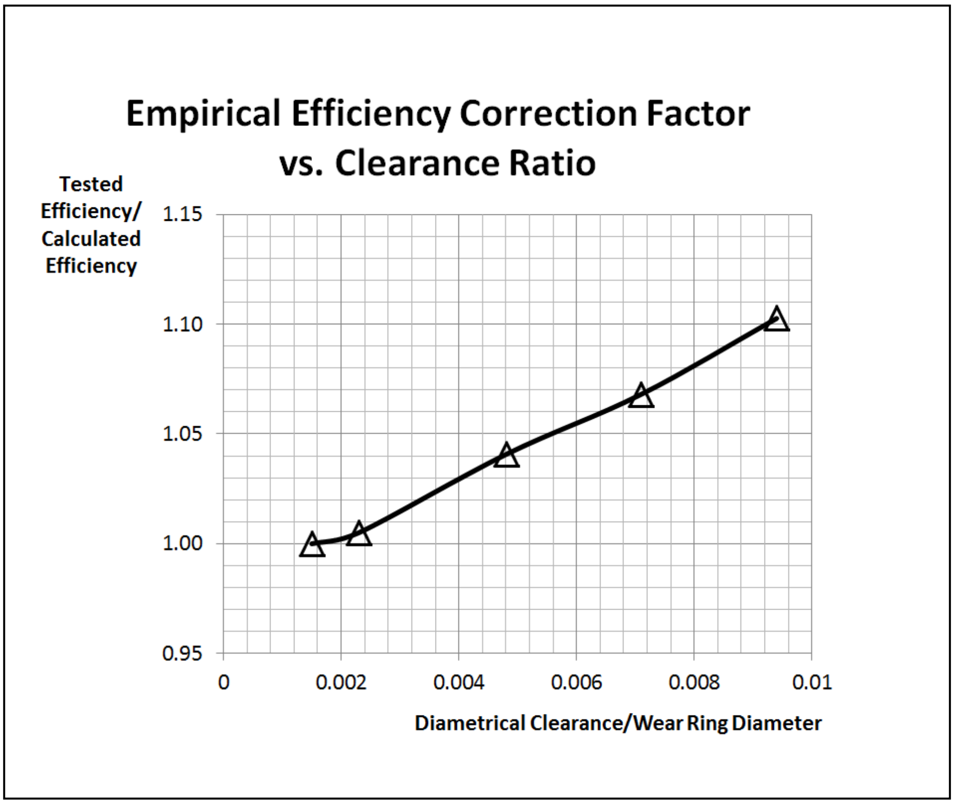


Figure 2 Empirical Efficency Correction Factor

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Deducing Efficiency of an Electric Submersible Pump Function in Wellhead Pressure and Reservoir Parameters

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Abstract

The Electric Submersible Pump (ESP) is one of the most important artificial lifting systems used in oil and water wells, Its operational parameters often remains unknown until necessity to pull the pump string out of hole hopefully before getting damage for either motor and/or pump assembly. This paper presents a method to determine pump overall efficiency (η_o) which reflects on overall performance of ESP assembly. The motor is monitored by observing amperage chart. However there is no direct method to determine pump efficiency. This important parameter determines whether the ESP is working properly within the operating range or if there are low flow problems causing impeller down thrust or if pump is above the operating range causing impeller upper thrust, leading to excessive motor loading and causing burn out.

Introduction

The rated efficiency of a pump may differ considerably from the actual installed efficiency. This is for the following reasons:

- The magnitude will vary from pump to pump as some pumps will spend much of the time running below rated point, where the efficiency is likely to be much reduced. Users should be strongly encouraged to take more care in specifying pumps to ensure that they are not over-rated for the actual duty.

- Pump efficiency will deteriorate over time, and the actual efficiency of a pump will not match that of the pump when new. This is a very important issue concerning both the average efficiency and maintenance costs of a pump. Also improperly selected motors may not deliver adequately input power to the pump. Options to improve pumping efficiency include adjusting impellers, repairing or replacing worn pumps, replacing mismatched pumps and converting to energy efficient motors. The effect of these options on energy was evaluated using data collected over the past twenty years from numerous pumps.

1. Effect of changing system curve on the obtained pump flow rate

As seen in Fig.1, total head of system curve equals tubing hydraulic friction losses plus static head, as friction losses increases, the resultant will be a reduction in the obtained pump flow rate ($Q_1 > Q_2$), also increase in head exerted on pump ($H_1 < H_2$), subsequently more power to be consumed, which reflects on overall pump efficiency as shown in Fig.2 where ($\eta_1 > \eta_2$).

2. Analysis of ESP overall performance

The basic tool for ESP troubleshooting is the ammeter chart. Field engineers analyze this chart, they read amperage magnitude but the most important information in the chart is the pattern's shape. Normal and many abnormal operational conditions can be identified by just looking and recognize the patterns. One of those typical patterns is trace associated with the automatic restart sequences performed by the Variable Speed Driver (VSD) due to under and over load protection. However, troubleshooting can be a difficult task if no typical pattern matches with the field chart or failure chart or the failure is not regular, for example the well can run for ten days and fail, or just few hours. With this erratic behavior the operator can not stay at the well to wait for a failure and check the VSD operating conditions in that instant. Pump operation and hence efficiency is determined by two principal parameters (head and flow rate), in addition to other factors such as fluid properties, impeller design and motor speed selected. ESP overall efficiency is not affected significantly by changing either impeller diameter, keeping fixed r.p.m. or changing r.p.m, keeping fixed impeller diameter, based on the following affinity laws:

First: with fixing r.p.m. and changing impeller diameter:

$Q_2 = Q_1 (\phi_2/\phi_1)$ $H_2 = H_1 (\phi_2/\phi_1)^2$ $\Pi_2 = \Pi_1 (\phi_2/\phi_1)^3$ (1)

Second: with changing r.p.m. and fixing impeller diameter:

$Q_2 = Q_1 (N_2/N_1)$ $H_2 = H_1 (N_2/N_1)^2$ $\Pi_2 = \Pi_1 (N_2/N_1)^3$ (2)

The above principles are applied for real pump performance charts, where in Fig.3, pump performance is shown at constant r.p.m. and varied impeller diameter, this analysis is shown in Table-1. In Fig.5, pump performance is shown at constant diameter and varied r.p.m., this is analyzed in Table-2:

Table-1: The calculated data are plotted in Fig.4

Q_1, gpm ϕ = 6.5"	H_1, ft at ϕ = 6.5"	Hydraulic Π_1, HP ϕ = 6.5"	Brake Power, HP ϕ = 6.5"	η_o, % ϕ = 6.5"	expected Q_2, gpm ϕ = 8"	expected H_2, ft ϕ = 8"	expected Hydraulic Π_2, HP ϕ = 8"	Brake Power HP ϕ = 8"	expected η_o, % ϕ = 8"
100	190	4.80	8.88	54.1	123.0	287.8	8.96	16.7	53.7
132.5	180	6.03	10.00	60.3	163.0	272.7	11.24	18.3	61.4
142.5	175	6.30	10.40	60.5	175.4	265.1	11.75	18.75	62.7
167.5	165	6.78	11.20	60.5	206.2	250.0	12.64	20.83	60.7

Table-2: The calculated data are plotted in Fig.6

Q_1, lit./s r.p.m. = 300	H_1, mt r.p.m. = 300	Hydraulic Π_1, kw r.p.m.= 300	Brake Power kw at r.p.m. = 300	η_o, % r.p.m. = 300	expected Q_2, lit./s r.p.m. = 450	expected H_2, mt at r.p.m. = 450	expected Hydraulic Π_2, kw r.p.m.= 450	Brake Power kw r.p.m.= 450	expected η_o, % r.p.m. = 350
560	61.8	339.5	665	51.9	840	139.1	1145.8	2290	50
880	61	526.6	790	66.7	1320	137.3	1777.3	2700	65.8
1125	59.5	656.66	900	74	1688	133.9	2216.2	3020	73.4
1490	59	862.4	1067	80.8	2235	132.8	2910.6	3630	80.2

Used Equations are:

In Table-1, hydraulic power, HP = (sp.gr).* 62.4 * [Q / (60 * 7.48)] * (H/550)

= (sp.gr.) Q * H / 3956 (3)

In Table-2, Hydraulic power, kw = 0.00981 Q * H (4)

Brake power = hydraulic power / η_o (5)

3. Mathematical model of ESP efficiency calculation

The subject is treated for a reservoir has the steady state condition as seen in Fig.8 as per following steps:

- Simulating IPR curve of the well as (Q-P) curve of the pump.

- Drawing the system curve represents the TDH (equation-6).

- Operating point is the intersection of IPR & TDH curves.

(Q-P) curve of the selected ESP as shown in Fig.9 where operating point to be at best overall pump efficiency:

IPR equation [1]:

$P_e - P_{wf} = [141.2\ \beta\ Q\ \mu / (k\ .\ h)] * [\ln (r_e/r_w) + S]$ (6)

VLP equation:

$P_{wf} = WHP + P_{hyd.} + (constant * f * L * Q^2 / d^5)$ (7)

Solving (6) & (7) yields:

$[Constant * f * L / d^5]\ Q^2 + \{[141.2\ \beta\ \mu / (k\ h)] * [\ln (r_e/r_w) + S]\}\ Q + (WHP + P_{hyd} - P_e) = 0$ (8)

Equation (8) can be re-written in the form:

$A\ Q^2 + B\ Q + C = 0$ (9)

Where:

$A = constant * f * L / d^5$ $B = [141.2\ \beta\ \mu / (kh)] * [\ln (r_e/r_w) + S]$ $C = WHP + P_{hyd.} - P_e$

$f = 1.325 / [\ln (E/3.7/d) + 5.74 / Re^{0.9}]^2$ for $5000 \le Re \le 10^8$ (turbulent flow) and $10^{-6} \le (E/d) \le 10^{-2}$ **[2]**

$Re = \rho\ V\ d / \mu = 92.248\ sp.gr * Q / (\mu\ d)$ **[3]**

Based on: $Q = 0.5\ [-B + (B^2 - 4\ AC)^{0.5}] / A$ (10)

& $P_{wf} = WHP + P_{hyd.} + 0.25\ A^{-1}\ [-B + (B^2 - 4\ AC)^{0.5}]^2$ (11)

$NDL = (0.433\ sp.gr.* D) - P_{wf}$ (12)

$TDH = [(0.433\ sp.gr.* D) - P_{wf}] + [WHP] + \{constant * f * sp.gr.* L * A^{-2}\ [-B \pm (B^2 - 4\ AC)^{0.5}]^2 / d^5$ (13)

$HHP = constant * TDH * Q$ (14)

$IPHP = (\eta_m\ MHP) - LHP$ (15)

$\eta_{OPE} = HHP / IPHP$ (16)

The above model is solved accurately in the excel calculation sheet, found here-in under. In which, (Q) is initially assumed (line No.28), relating Reynolds number (Re1-line No.59), which must be equal or too closed to the Reynolds number (R2-line No.73) corresponds the calculated (Q), line (No.71).

3.1. Tubing sizing for liquid transportation

Optimum velocity for liquid transportation is 5 ft/s **[4]**. So, the following equation determines flow rate at any selected diameter: $Q = 419.6\ (I.D)^2$ Where: Q: bbl/d & I.D: inch

Velocity may be raised up by increasing pumping pressure, but to which limit. The answer is to just before reaching erosion velocity; $Ve = 100 / (\rho)^{0.5}$ **[5]** … where (ρ): is mixture density, Ibm/ft^3. Assuming that it's required to transport a liquid flow rate as 12,500 bbl/d; with 20 % water cut & 80 % oil cut where 1.05 & 0.85 are the sp.gr. for water and oil respectively. Now, (ρ) is 55.54 Ibm/ft^3. Knowing that two tubing sizes are available as: 3 ½" (2.992" I.D) & 4 ½" (3.958" I.D):

As: $V = Q / [83.925\ (I.D)^2]$ … V: velocity, ft/s (17)

For: 3 ½" tubing: V = 16.6 ft/s & Ve = 13.4 .. i.e. $Ve < V$ ….it's not recommended to be used.

For: 4 ½" tubing:V = 9.51 ft/s & Ve = 13.4 .. i.e. $Ve > V$ ….it's recommended to be used.

4. Calculation of annual cost of power consumed by pump motor

4.1. If driver is an electric engine

Hydraulic Power (P) = sp.gr. * Q * H

Brake power (BP) = sp.gr. * Q * H / η_o

Input Motor Power (IMP) = sp.gr. * Q * H / (η_o η_m)

Annual cost of power consumed by motor, C = sp.gr. * Q * H * U * T / (η_o η_m) ….. $/year

Where:

- Q: gpm

- H: ft.

- η_o & η_m: pump overall efficiency and motor efficiency respectively, %

- T: power cost, $ / (kw. hr.)

- U: utilization factor (working hours/year), %

$\therefore$ C = 1.6526 sp.gr. * Q * H * U * T / (η_o η_m) …… $/year (18)

4.2. If driver is a diesel engine

IMP = 39.7 q DEE…. Kw (19)

The fuel consumption can be measured by disconnecting the fuel line from the fuel tank, placing it into a container filled with a known volume of fuel and measuring the time it takes to fill the container with fuel. The discharge end of any bypass fuel line should also be inserted into the container. The input power of a diesel engine may be three to four times that of an electric motor because of difference in engine efficiency. However, both are rated based on the brake or shaft power. An electric motor rated at 75 kw produces the same power as a 75 kw diesel engine.

5. Conclusion

The subject paper presents an analytical method simulating ESP performance chart, in addition to the excel program solves the derived model. Its application is easy and gives accurate results regarding pump assembly and power economics.

6. Technical contribution

1- Developing new equation gives ESP performance as a function of reservoir parameters and well data.

2- ESP performance can be checked frequently by easy forecast for overall pump efficiency.

7. Economic contribution

1- The subject paper presents the method by which, driving ESP motor can be saved from burnt out by stopping the system at the proper time.

2- The derived equations can be easily run using simple Excel calculation sheet, so its usage is economic.

8. Appendices

Appendix-1: derivation for some of the used equations

Derivation of Eq. (18)

Power = sp.gr. * 1.0 * Q * (1/7.48/60)*$(30.48)^3$ * H * (30.48) * 981 …... (dyne. cm) / s = erg / s

= [sp.gr.*1.0 *Q* (1/7.48/60)*$(30.48)^3$ * H * (30.48) * 981] / (10^7) …... Joule/s = W.s / s

= [sp.gr.*1.0 x Q*(1/7.48/60)*$(30.48)^3$ *H*(30.48)*981* 3600*24*365 / 3600] / (10^7*10^3)

(kw. hr.)/ year

C = [10^{-10} *(1/7.48/ 60)*$(30.48)^4$ * 981* 3600 * 24 *365 / 3600] * sp.gr. * Q * H * U * T / (η_o η_m)

Derivation of Eq. (19)

IMP = DCV*252 (cal./gal.) * 4.186 (Joule/cal.) * q (gal./hr.) * DEE

= 135,500*252 (cal./gal.)*4.186/(1000*3600) (kW hr./cal.) * q (gal./hr.) = 39.7 q DEE…. kW

Appndix2: Excell calculation

Input Data	No.	G
Re, ft	2	6000
Rw, ft	3	0.2917
Beta oil	4	1.1
D, mid of perforation depth, ft	5	6000
K, permeability m.d.	6	50
h, net pay thickness, ft	7	100
S, skin effect	8	0
Ln (re/rw)	9	9.771635421
Pe, psi	10	3500
Phyd. psi	11	=g5*.433*g8
WHP, psi	12	157
PY	13	3.1415926
PY^2	14	=G13^2
g, ft/s^2	15	32.2
Pump Depth	16	
Km	17	0.63
M	18	=G17*1000
Ft	19	=1000
Mile	20	=G19/5280
Pipe Roughness	21	
In.	22	0.005
Mm	23	=G22*25.4
Relative Roughness	24	
In./in.	25	=G22/G40
mm/mm	26	=G22/G40
Assumed Flow Rate	27	
bbl/d	28	600
gpm	29	=G28*42/1440
cu.m/day	30	=G28/6.289

Lit./s	31	=((100^3)/1000)*G28/(6.289*3600*24)
Specific Gravity	32	
Oil Degree API	33	29.0
oil sp.gr.	34	=141.5/(G33+131.5)
water sp.gr.	35	1.08
water cut, %	36	1
oil cut, %	37	0
composite sp.gr.	38	=G34*G37+G35*G36
Diameter	39	
In.	40	2.992
Nominal pipeline flow rate, bbl/d	41	=(3.1415926/4)*(G40/12)^2*5*3600*24/5.615
Mm	42	=G40*25.4
Cm	43	=G40*2.54
Flow Velocity	44	
cm/s	45	=G28/(2.7533*G40^2)
ft/s	46	=G45/30.48
Erosion Velocity	47	
ft/s	48	=100/(G38*62.4)^0.5
cm/s	49	=G48*30.48
Viscosity	50	
c.P.	51	3
c.St.	52	=G51/G38
Utilization factor, %	53	
power cost, $/(kw.hr.)	54	0.02
working hours	55	7920
utilization factor, %	56	=G55/(365*24)
Results:	57	
Reynolds Number	58	
(Re1) with viscosity in c.p.	59	=G38*G45*G40*2.54/(0.01*G51)
with viscosity in c.st.	60	=2.54*G40*G45/(0.01*G52)
Friction Loss Factor	61	
Friction factor, for RE over 2300	62	=1.325/(LN((5.74/G59^0.9)+(G25/3.7))^2)
Hydraulic Friction Losses	63	
Hydraulic friction losses, m	64	=8*G62*G18*(G30/3600/24)^2/3.1415926^2/9.81/(G40*0.0254)^5
Hydraulic friction losses, psi	65	=(G64*3.281*G38*62.4/144)
A = 8 fl/(PY^2*g*d^5)	66	=(G38*62.4/144)*(5.615/24/3600)^2*(8*G62*G19)/G14/G15/(G40/12)^5
B	67	=141.2*G4*G51*G9/G6/G7
C	68	=G12+G11-G10
B^2	69	=G67^2
4AC	70	=4*G66*G68
Q	71	=(-G67+(G69-G70)^0.5)/(2*G66)
velocity, cm/s	72	=30.48*(G71*5.615/24/3600)/(0.785*(G40/12)^2)
(Re2), with viscosity in c.p.	73	=G38*G72*G40*2.54/(0.01*G51)
PWF1	74	=G10-(G67*G71)
PWF2	75	=G12+G11+(G66*G71^2)
PWF, ft	76	=G75*144/(G38*62.4)
NDL, ft	77	=G5-G76
NDL, psi	78	=G77*62.4*G38/144
Hf, psi	79	=(G38*62.4/144)*(5.615/24/3600)^2*(8*G62*G19)/G14/G15/(G40/12)^5
TDH, psi	80	=G12+G79+G78
HHP	81	=G80*G71/58771.15
Motor efficiency	82	0.85
overall pump efficiency	83	0.65
input HP to pump	84	=G81/G83

HP for seal, separator, .. etc.	85	6.0
Total HP required	86	=G84+G85
Motor name plate HP	87	=G86/G82
Annual power cost, $/year	88	=1.6526*G38*(G29)*(G56*G80*144/G38/62.4)*G54/ G82*G83)

Nomenclatures	**Meaning**	**Unit**
P	Pressure	psi
d	tubing diameter	in.
D	perforation depth	ft
DEE	Diesel Engine Efficiency (27-37%)	%
DCV	Diesel Calorific Value	BTU/gal.
E	pipe roughness	in.
f	friction factor	-
g	gravitational earth	32.2 ft/s^2
h	formation net pay thickness	ft
H	Pumping head	ft, mt
HP	Horsepower	-
IPHP	Input Pump Horse Power	-
IPR	Inflow Performance Relationship	bbl/d/psi
Bbl	barrel = 159 litres = 42 gallon	-
HHP	Hydraulic Horsepower	-
k	permeability	m.d.
m.d.	milli darcy = 10^{-3} darcy	-
Darcy	Permeability ≈ 10^{-8}	cm^2
kW	kilowatt	-
L	Length of tubing string	ft
LHP	Lost Horse Power	-
ln	logarithmic for base natural number	-
MHP	Motor Horse Power	-
NDL	Net Dynamic Lift	psi
PIP	Pump Intake Pressure	psi
Q	Flow rate	bbl/d
q	Fuel consumption	gal./hr.
gal.	gallon = (1/42) barrel	-
hr.	hour	60 minutes
cal.	Calorie = (1/252) BTU	-
BTU	British Thermal Unit	-
r	radius	ft
r.p.m.	revolutions per minute	
Re	Reynolds number	-
S	Skin factor effect	-
sp.gr.	specific gravity (60^{o}F/60^{o}F)	-
TDH	Total Dynamic Head	psi
V	Velocity	ft/s
VLP	Vertical Lift Performance	-
WHP	Well Head Pressure	psi

Greek letters

β	oil formation volume factor	reservoir bbl/surface bbl
μ	dynamic viscosity	c.p.
η	efficiency	%
Π	Power	HP or kw
ρ	Density	g/cm^3

ϕ	Pump impeller diameter	in.

Subscripts

e: drainage

m: motor

o: overall

w: bore

hyd.: hydrostatic

wf: bottom hole formation

OPE: Overall Pump Efficiency

1, 2: denotes condition (1) & condition (2)

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4. http://www.engineeringtoolbox.com/copper-pipes-water-velocities-d_1081.html
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Useful conversion factors

bbl x 5.615 E+00 = ft^3
Centipoise x1.0E-02 = 1.0 poise
ft x 3.048*E-01 = m
Ibf x 4.448222E+00 = N
HP x 746 E-03 = kw
in x 2.54*E+00 = cm
Liter x 1.0E-03 = m^3
psi x 6.894757E+00 = kPa
poise x 1.0E+00 = gm/cm/s
Stoke x 1.0E+00 = cm^2/s
* Conversion factor is exact

Biography

Hesham A. M. Abdou is a general manager in operations department, Agiba petroleum Company, Egypt. He holds B.Sc. Degree in petroleum engineering, from Al-Azhar University (1982), awarded

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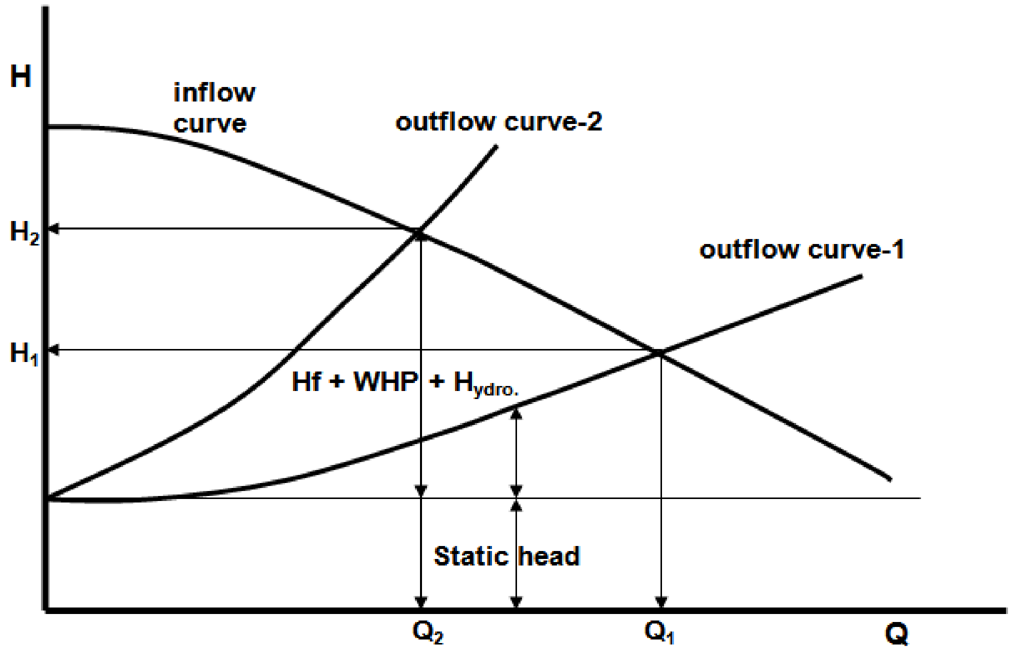


Fig.1 Pump performance versus system curves

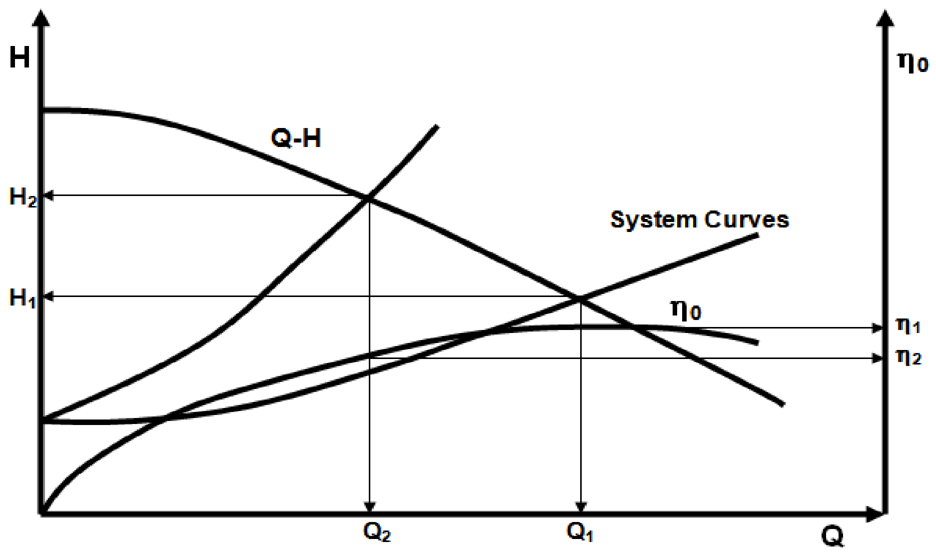


Fig.2 Flow rate versus Head & Efficiency curves

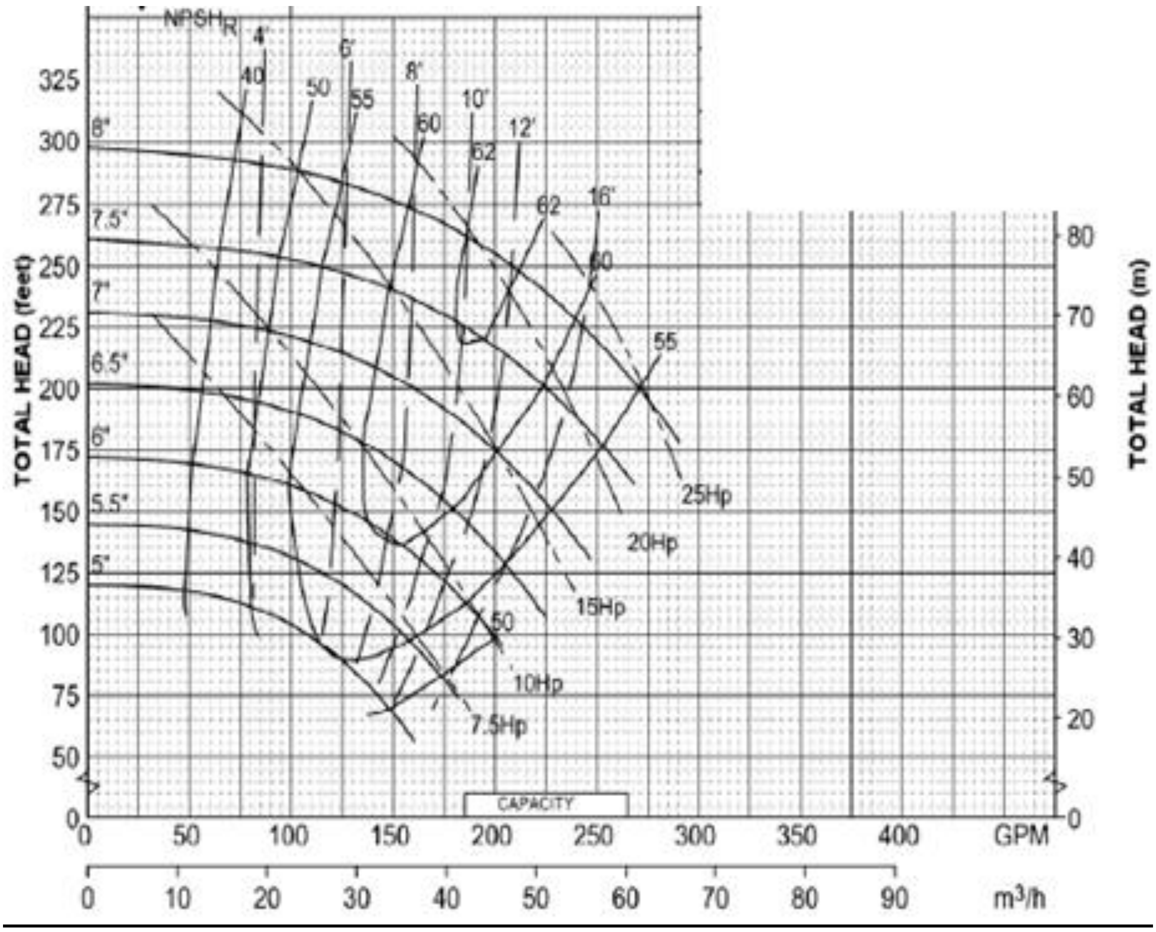
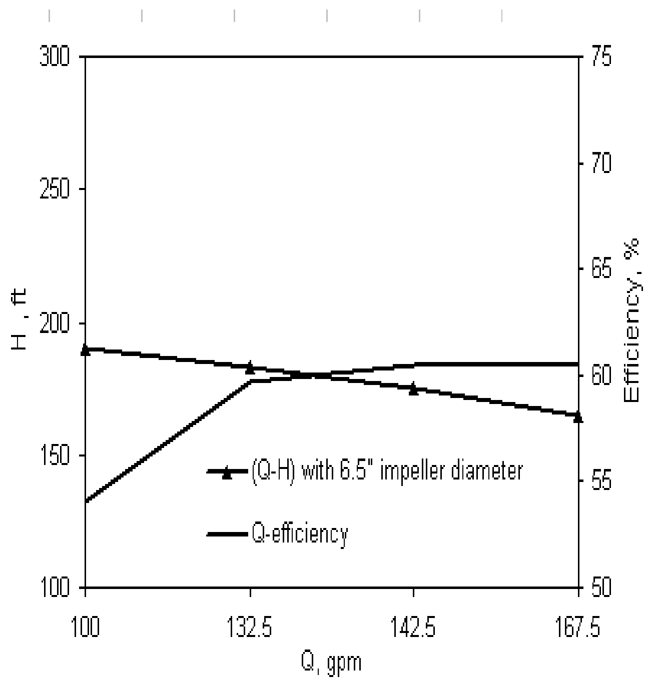


Fig.3 Pump performance with constant r.p.m. and varied impeller diameter



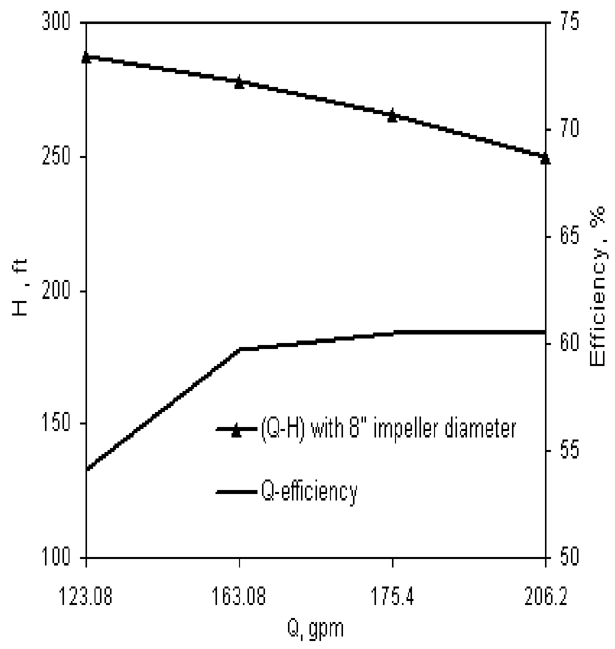


Fig.4 Pump performance with constant r.p.m. and varied impeller diameter

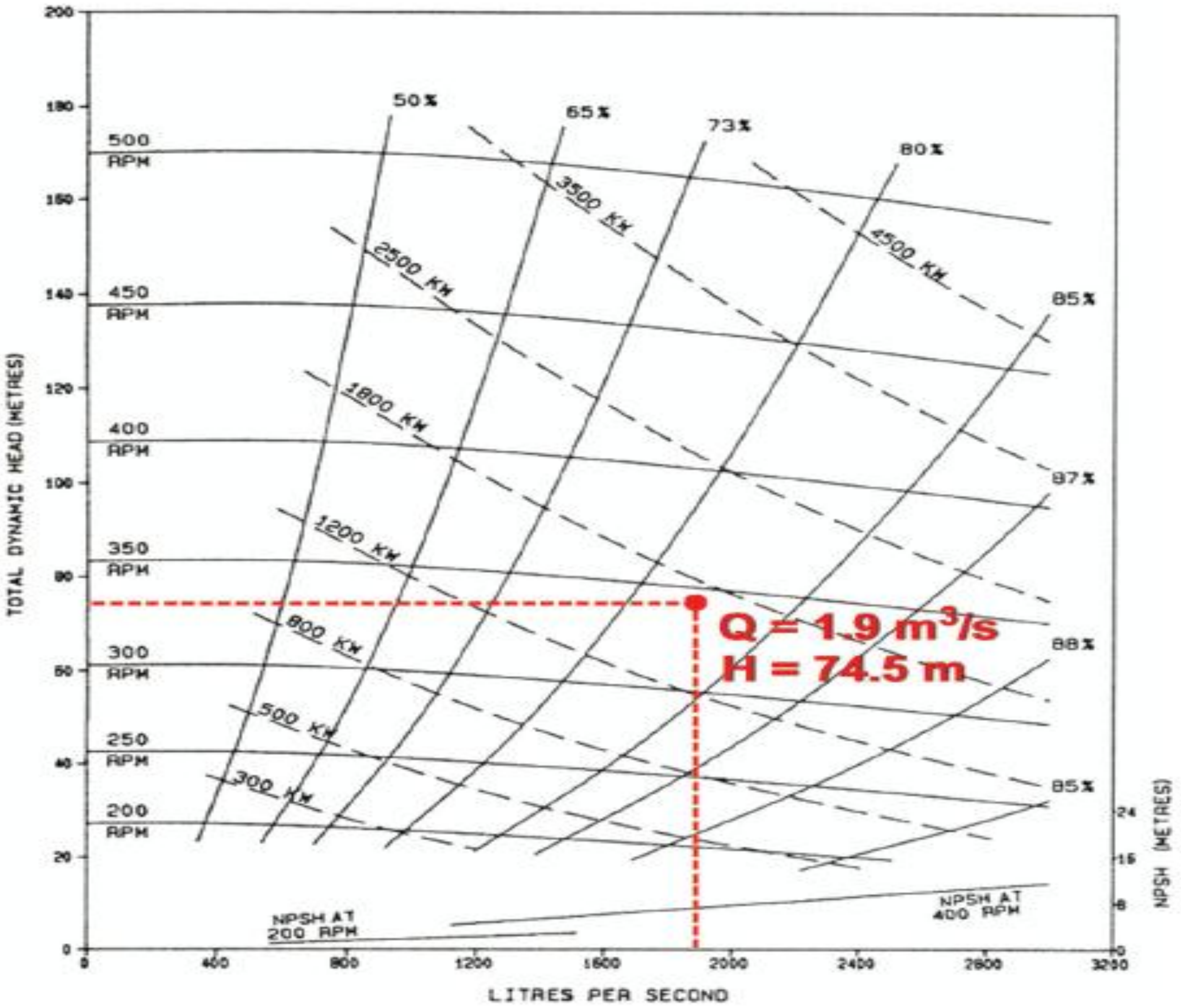


Fig.5 Pump performance with constant impeller diameter and varied r.p.m.

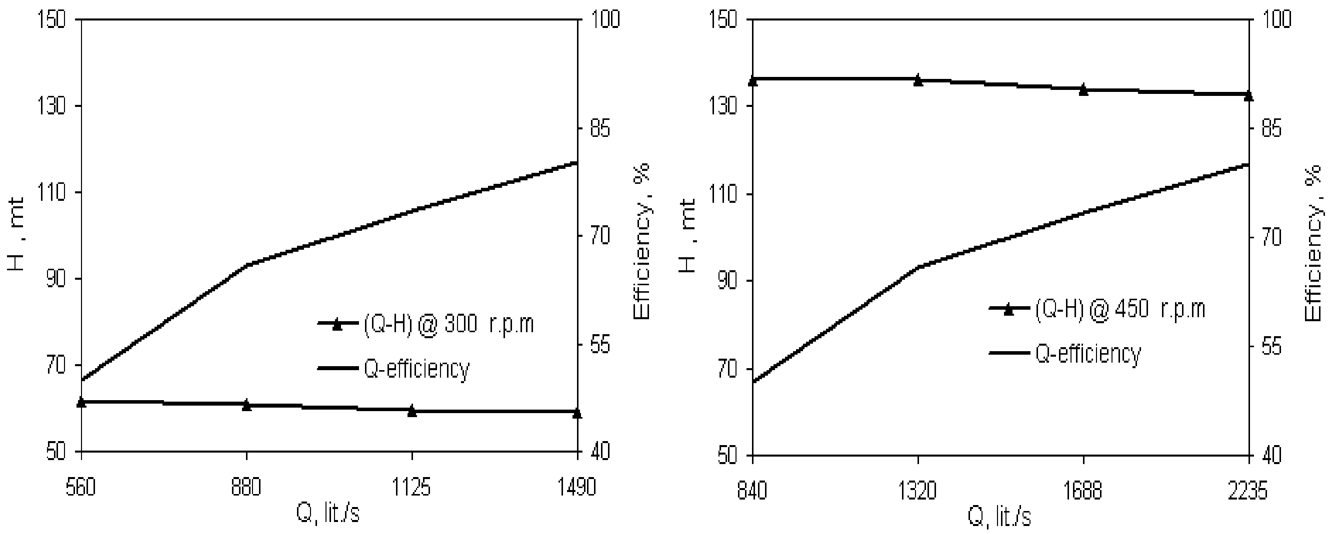


Fig.6 Pump performance with constant impeller diameter and varied r.p.m.

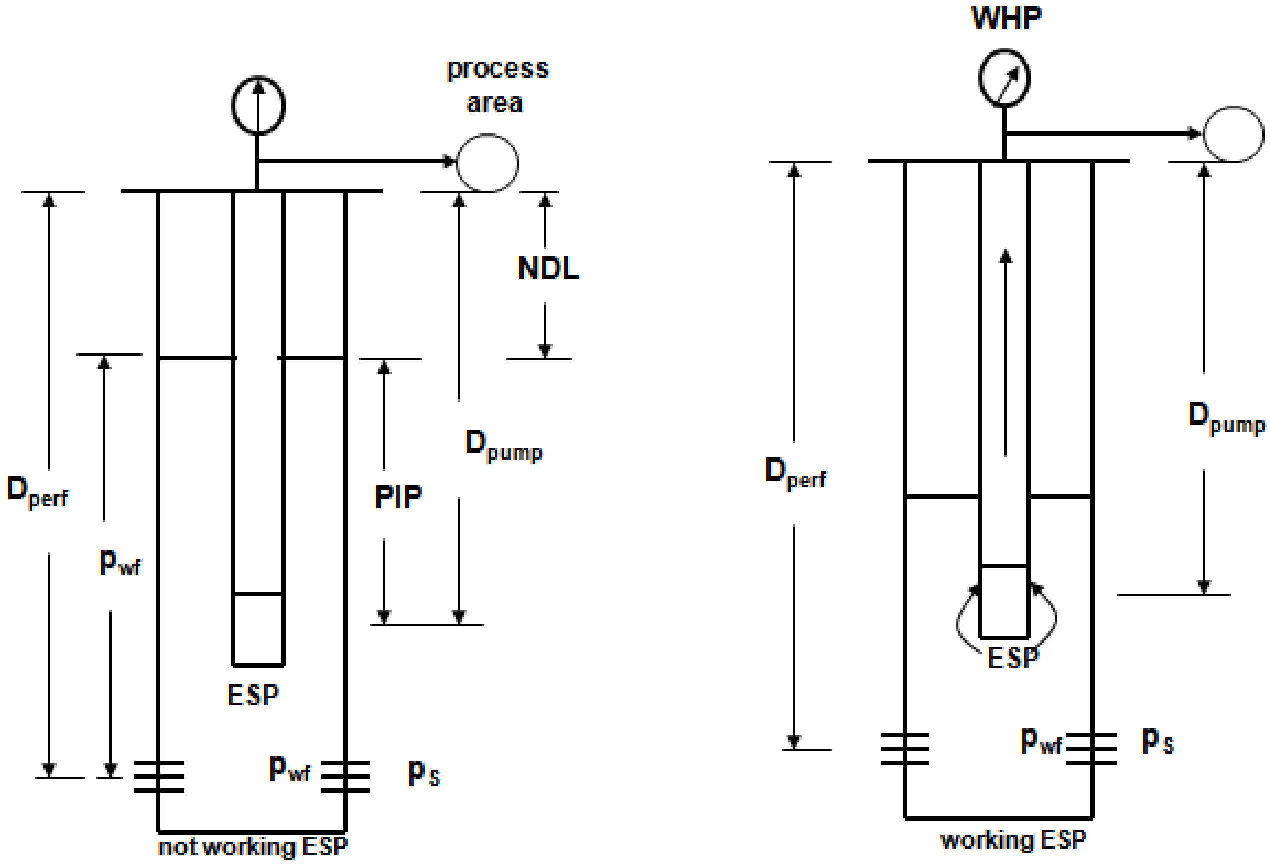


Fig.7 ESP and well geometry

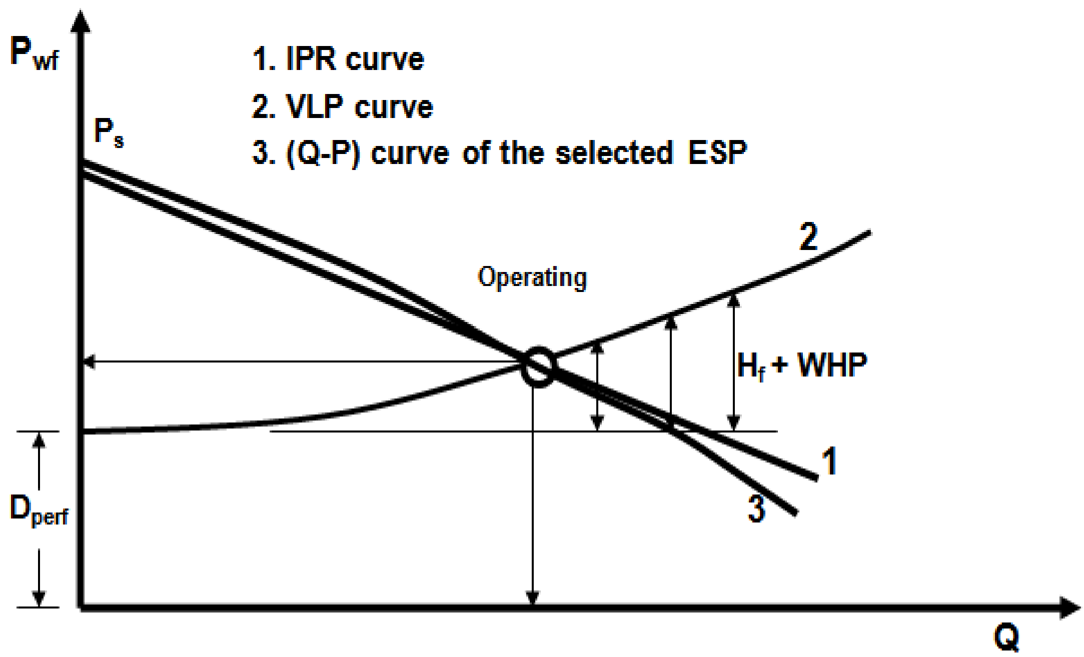


Fig.8 IPR versus VLP gives operating point

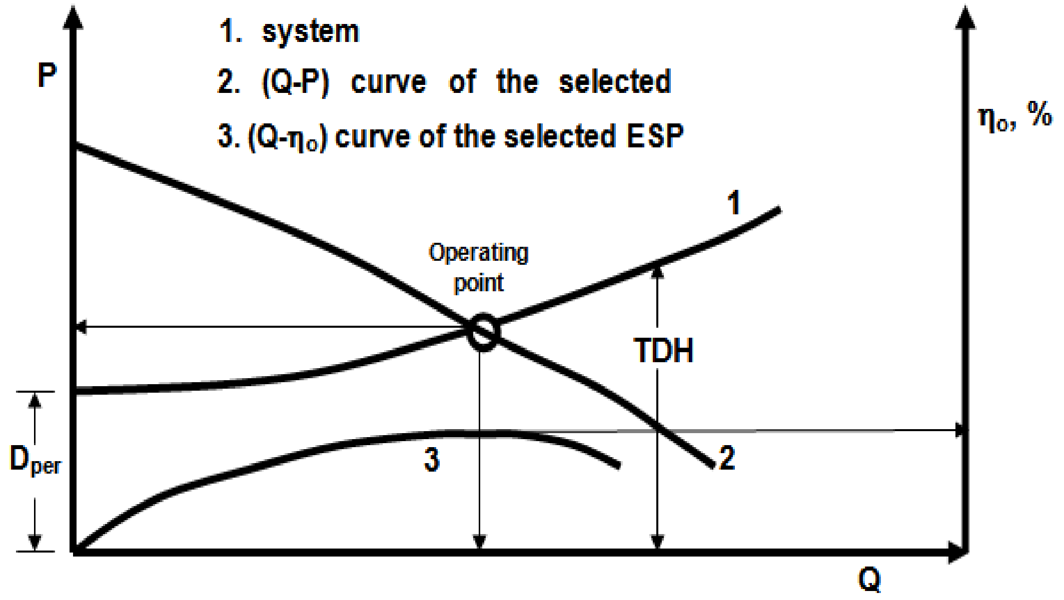


Fig.9 Performance chart of the selected ESP

Energy efficiency optimization of a dust extractor: An industrial case study

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Abstract

The Eco-design directive published by the European Union aims at 34TWh of annual savings with industrial fans by the year 2020. This is about 10% of the total saving aim of 366TWh. Electric motors are still responsible for over 40% of the planned savings with 135TWh of annual savings by 2020.

These aims are translated into European directives to guide the market towards more energy efficient systems. An evolution within those regulations is the fact that directives are not only focusing on one particular part in the drive system (e.g. the induction motor), but consider the entire system with all its parts to rise the overall system energy efficiency. Examples of this total system approach are the latest EU directives on circulator pumps [1] [2], air conditioning systems [3], domestic comfort fans [3] and industrial fans [4].

This system approach demands a thorough analysis of all the different parts of the drive system in order to make a sound technical and economical choice on which part to invest to rise the overall system efficiency.

This paper describes a practical case study carried out on an industrial dust extractor in preparation of a new research project proposal in which o.a. the EU-directive 327/2011 [4] will be investigated. The different drive parts were analyzed based on their efficiency and replaced if technically and economically feasible. Research and test bench results of previous and on-going research projects on energy efficiency were used to predict the potential savings. At each step energy consumption measurements were carried out before and after to validate the estimated savings.

Measurement procedure

The case consists of an industrial dust extractor used to extract dust from shearing carpets. The axial fan has backward placed fins and is driven by 3xSPB2000 V-belts connected with a ratio of 1/1.47 (fan runs faster) to a 30kW, 4 pole induction motor with no indicated efficiency class. Taking into account the age of the setup, the efficiency class can be Eff3 or even lower (**Figure 1**).

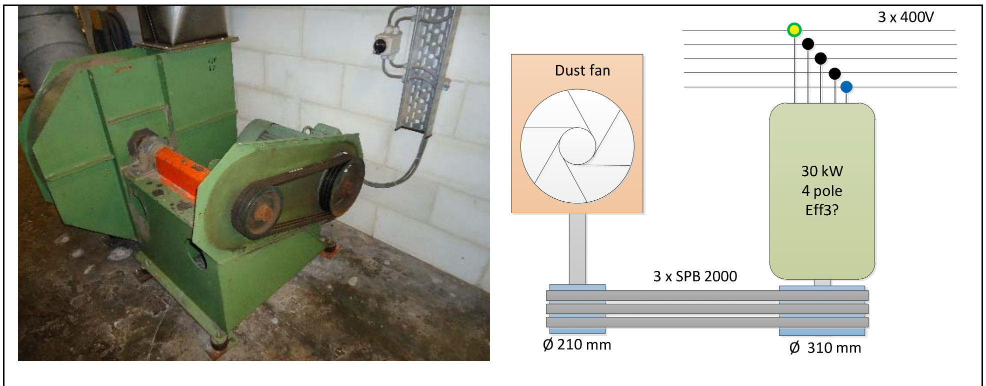

Figure 1: Original test setup: industrial fan

The optimization procedure was carried out in different sequential steps. Before and after each step an electric energy measurement on grid side with suitable power measurement devices was done to quantify the improvement. Because at some steps rather small improvements were expected, an energy logging was done during several days at each step in order to detect even small efficiency improvements.

The following steps were taken during the measurement procedure:

1. Reference energy logging no.1
2. Maintenance: belt tension / pulley alignment / greasing
3. Energy logging no.2
4. Redimensioning and implementing new electric motor
5. Energy logging no.3
6. Implementing speed control and optimizing speed
7. Energy logging no.4
8. Maintenance : cleaning air ducts and fan
9. Energy logging no. 5
10. Redimensioning drive train : implementing direct drive principle
11. Energy logging no. 6

A general remark regarding drawing conclusions on energy efficiency improvements for these kinds of practical cases is the need for a continuous load during the tests. If the production process results in a non-continuous load, it is quite difficult to draw closing conclusions on energy efficiency improvements. If this is the case, tests under controlled conditions in a lab on a test bench can help to confirm practical measurements. In this particular case, measurements have shown that the load could be considered as quite continuous, but even then some steps in the optimization procedure are based on previous laboratory tests in our facilities.

Step 1: Reference energy logging no.1

A first reference energy logging was carried out during about 170h. This measurement gave an average active power drawn by the motor from the grid of 19.38 kW. (**Figure 2**) This result was found after eliminating all the standstills during the test. Furthermore, it can be noticed that the load can be considered to be quite stable, which is a prerequisite to draw closing conclusions on further improvement steps.

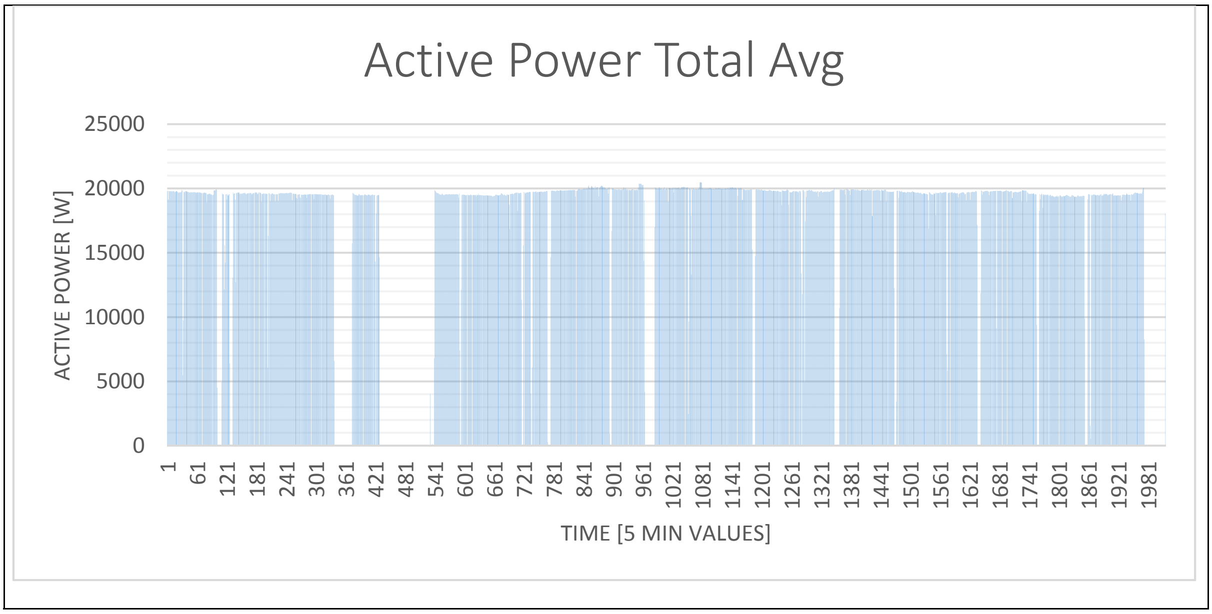

Figure 2: Reference energy logging no. 1

Step 2: Maintenance

In this step the effect of some maintenance activities on the energy efficiency was investigated. One of the goals of this step was to determine the effect of applying a correct belt tension and pulley alignment during maintenance activities. In the past, this was checked completely manually every 3 months, without using some adequate equipment. In this step, the correct belt frequency was calculated and applied using an optical belt frequency measurement device and the pulley alignment was checked using laser equipment (**Figure 3**). Also the bearings of the drive shaft were greased.

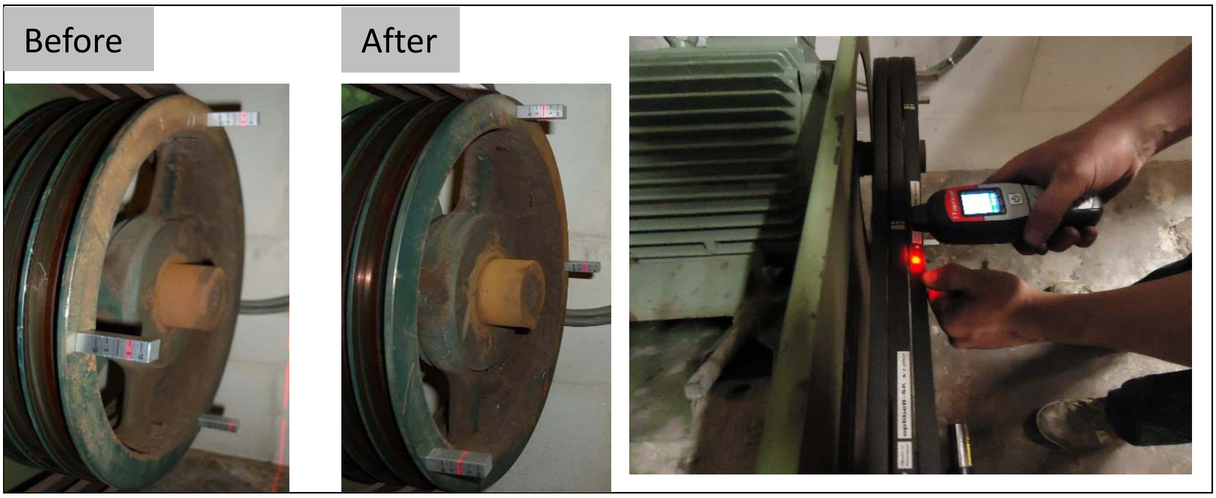

Figure 3: Pulley alignment and checking belt tension using adequate equipment

Although the belt tension was checked manually in the past (just by “feeling” the tension), this test showed the belt frequency was nearly perfect. The calculated belt frequency was 39.07Hz. Before the maintenance a belt frequency was measured of 38Hz in average. This is mainly due to the experience of the maintenance personnel in the company. The pulley misalignment was about 5mm before maintenance and was corrected using the laser equipment device.

Step 3: Energy logging no. 2

A new measurement was started for about 170h and after filtering standstills and startups out of the results a reduction of 0.05% in average active power was measured. Taking into account the measurement errors this can be considered as negligible. This result was within the expectations regarding the rather small adjustments, which had been made during the maintenance activities.

Step 4: Redimensioning electric motor

Based upon the energy measurements one can conclude that the induction motor of 30kW is over dimensioned for the driven fan. The average measured input power was 19.38kW. This means the motor is loaded for about 60%. Because of the lack of information on the efficiency of the present motor, the efficiency in that working point was very conservatively estimated at 91.1%. This is based on measurements and extrapolations done on a 4pole, 15kW IE1 induction machine at our test facilities and catalog data.

With an estimated shaft power of 17.7kW (19.38kW x 0.911) the 30kW machine can be replaced by a 22kW IE3 4 pole induction motor which has an efficiency of 93.1% according to the IEC60034-30 [5].

Especially with fan applications, one should take care when replacing older motors by newer, high efficient motors. One of the typical properties of induction motors with a higher efficiency label is the lower slip value compared to older motors due to the lower rotor resistance. Affinity laws claim a cubic relation between speed and power drawn by a centrifugal fan. This can result in considerably higher input power on motor side although the higher efficiency of the motor. In most cases this is not the intention and results in an even higher energy bill in comparison to the situation with the old motor. To take this effect into account, speed was measured before and after the replacement of the motor.

Step 5: Energy logging no. 3

After implementing the new 22kW IE3 4 pole motor a new energy logging resulted in an average active power of 17.3kW. In comparison to the 19.4kW before this is a reduction of about 11%. This result shows the estimated 2% (93.1% - 91.1%) was indeed very conservative. The reason for this high energy gain can be found in several points:

- Estimations were made based upon measurements done on an IE1 induction machine in our lab which can be more or less compared to the old Eff2 efficiency class. Regarding the fact there was no information on the efficiency on the nameplate, it is very likely to assume the efficiency class of the old motor was even far below the old Eff3 efficiency class.

- The old motor was only loaded for 60%, which has a negative impact on the efficiency of the motor in that working point. The new motor is now loaded for about 75%. Measurements in our test lab show the efficiency often tends to maximize in that point [6] (**Figure 4**).

- The effect of a changed speed has to be considered too because of the cubic relation between power drawn and speed of a centrifugal fan. A speed measurement was done before the replacement and resulted in 1486 rpm. After installing the new 22kW the speed dropped slightly to 1482 rpm. Taking into account the cubic relation this results in a reduction of power drawn at grid side of about 1%.

Conclusion at this point is that the reduction in active input power of 11% due to the replacement of the 30kW motor is mainly due to the higher efficiency of the 22kW motor in it's working point (+10%). Considering the total installation costs for the new motor, an energy price of 0.09 €/kWh and about 5800 working hours per year this investment has a payback of less than 1 year with a yearly saving potential of about €1000 per installed fan.

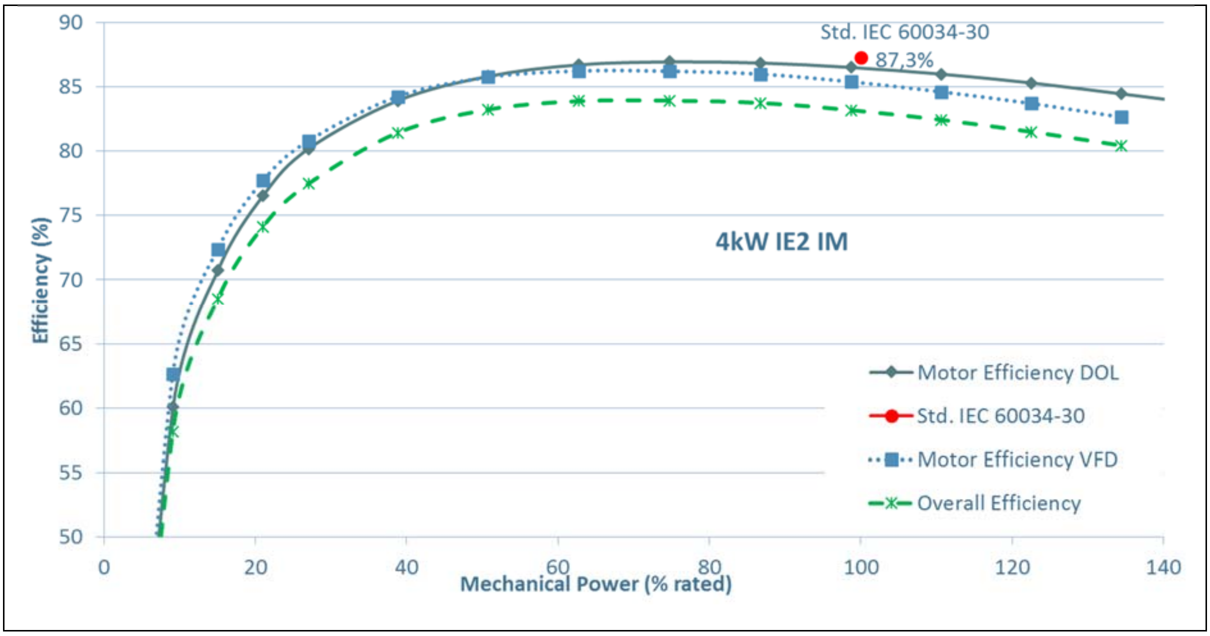

Figure 4: 4kW motor and overall (motor-drive) efficiency at DOL and VSD operation with maximum efficiency typically reached around 75% [6].

Step 6 & 7: Implementing speed control

When it comes to centrifugal loads, the step towards speed control to reduce the energy cost is often obvious. Again, because of the cubic relation between speed and power drawn, even a small drop in speed can result in substantially lower input power. Of course the quadratic relation between speed and pressure has to be considered regarding the fact the fan is used to extract dust for a shearing machine.

A speed control was implemented on the new 22kW motor and several speed setpoints were tested during a long time to ensure the dust was still sufficiently extracted from the shearing machine.

In a first trial, frequency was drastically dropped to 30Hz. In this case, according to the affinity laws, the input power theoretically drops to about 20% of the initial value. Very soon there was a visible loss of quality at this low speed so speed had to been increased again (**Figure 5**).

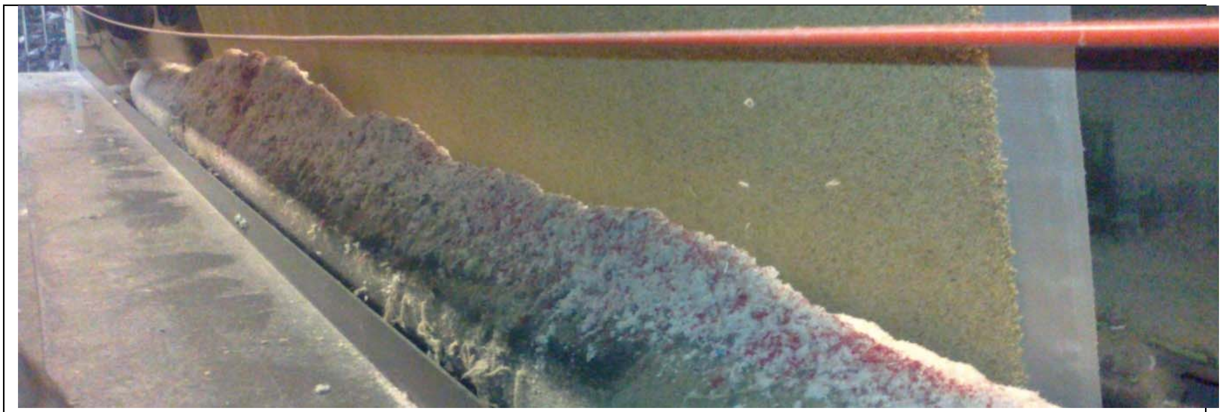

Figure 5: Visible quality loss of the dust extraction performance of the fan at 30 Hz

The frequency was then increased to 39Hz. Measurements show a reduction of measured input power of 50%, but this also resulted in a quality loss after a few hours. With a frequency of 45Hz, the input power dropped 20% in comparison to the DOL situation, but again there was a little quality loss after a few days (**Figure 6**).

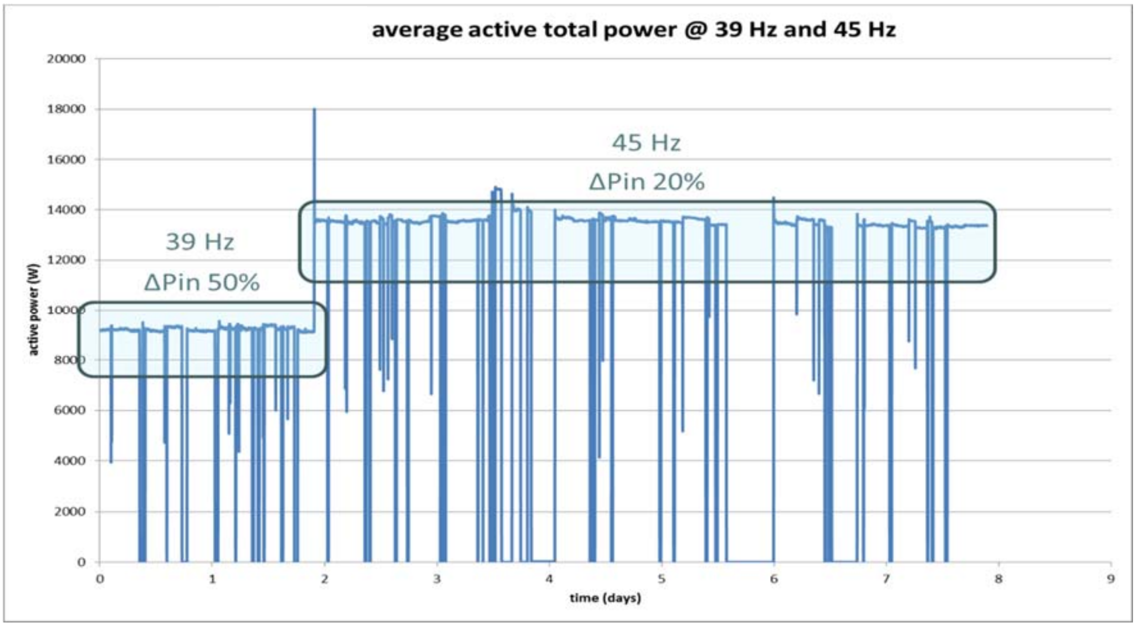

Figure 6: Average active power drawn by the motor fan at 39Hz and 45Hz

Eventually, in consultation with the company, the frequency was set at 48Hz for this motor without any visible quality loss so far. The resulting average input power was now 15.9kW which is still a reduction of 8% in comparison to the DOL-situation of 17.3kW in step 5. This does not entirely match the theoretical affinity laws, which predicts a reduction of 11.5% with a pure centrifugal load.

When integrating a speed regulating drive into the system one should take into account the drive itself is responsible for an extra loss in energy efficiency of 2 to 3%. But even then this step in the optimization process confirms again that speed control, especially at quadratic load profiles such as fans, is often a very energy saving solution, even for small reduction in fan speed.

Considering the total installation costs for the new drive, an energy price of 0.09 €/kWh and about 5800 working hours per year this investment has a payback of about 1,5 year with a yearly saving potential of about €730 per installed fan.

Step 8 & 9: Maintenance: cleaning air ducts

Prior to this step, the drive was removed from the system again so the fan motor operated again DOL.

The dust which is extracted from the shearing machine has the tendency to stick very easily to the side of the air ducts due to lubrication oil present in the dust. Every six months all the air ducts in the system and the fan itself are cleaned. The dust reduces in some cases the opening in the air duct by more than 50%. Measurements before and after the cleaning of the air ducts were performed to determine the effect on the overall energy performance.

After cleaning the installation and performing a new energy measurement during several days, the average active power was 18.7kW which is a rise of 1.4kW in comparison to the DOL operation before the cleaning.

This is a typical phenomenon which is sometimes underestimated in industry. Because of the cleaned system, a new working point becomes active in the system curve with a higher pressure drop and a higher flow. This also means the fan needs more power at the shaft side (**Figure 7**). Of course in most cases the higher flow is not needed because the installation was working fine before the cleaning and in fact we now have an installation which is over dimensioned.

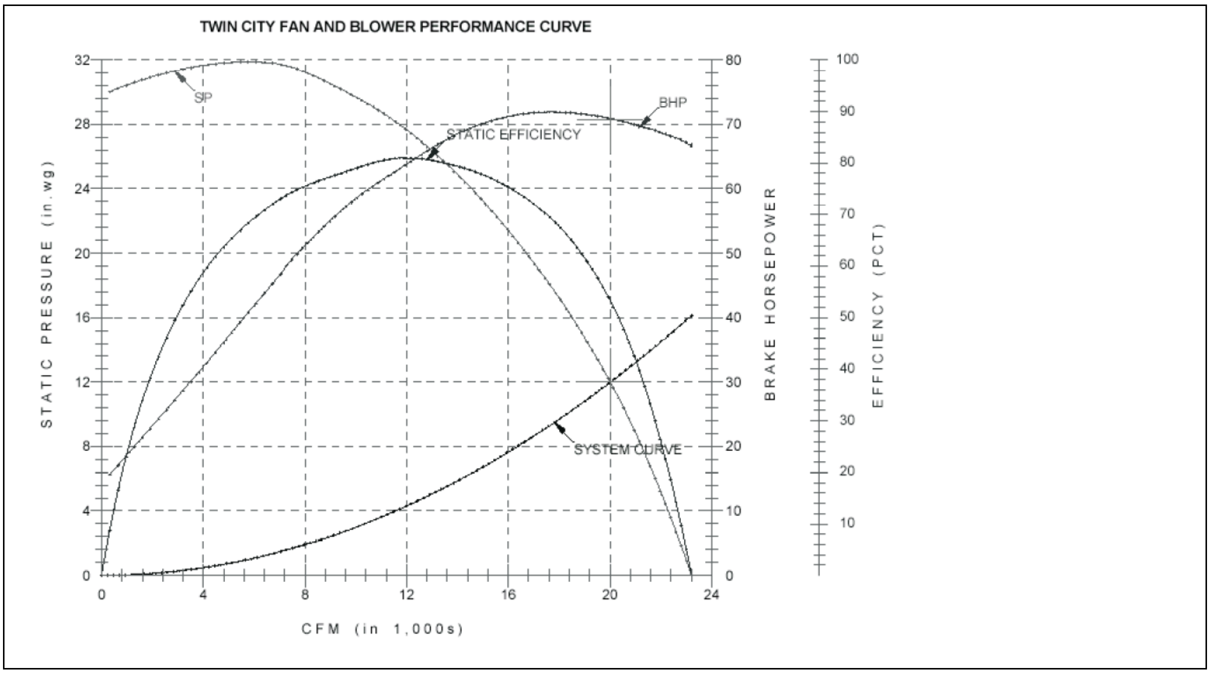

Figure 7: Typical fan characteristics [BEE India, 2004]

This confirms again the need for a drive to regulate the speed of the fan according to the system demands. The fan speed can automatically be adapted using a flow sensor in the air ducts as feedback for the speed control of the system.

Step 10: Redimensioning the drive train

At this point in the process, the entire drive train concept is questioned and the possibility of leaving out the belt drive concept is considered (**Figure 9**). Using input information of measurements done at our facilities, the possible impact on the efficiency was estimated.

In the original set up, the fan is driven by 3xSPB 2000 V-belts. Using belt calculation software at a service factor of 1.4, the power which can be transmitted with these three belts is 57kW! With an average input power of 16kW after implementing the speed controlled high efficiency motor this means an over dimensioning of more than 70%.

Measurements done at our test lab on a SPA 1682 with a ratio of 0.56 have shown an efficiency of 96% at about 30% of the nominal torque. As can be seen on the iso-efficiency contour, speed has no real impact on the efficiency of the belt [7]. The output torque is the determining factor for the efficiency (**Figure 8**).

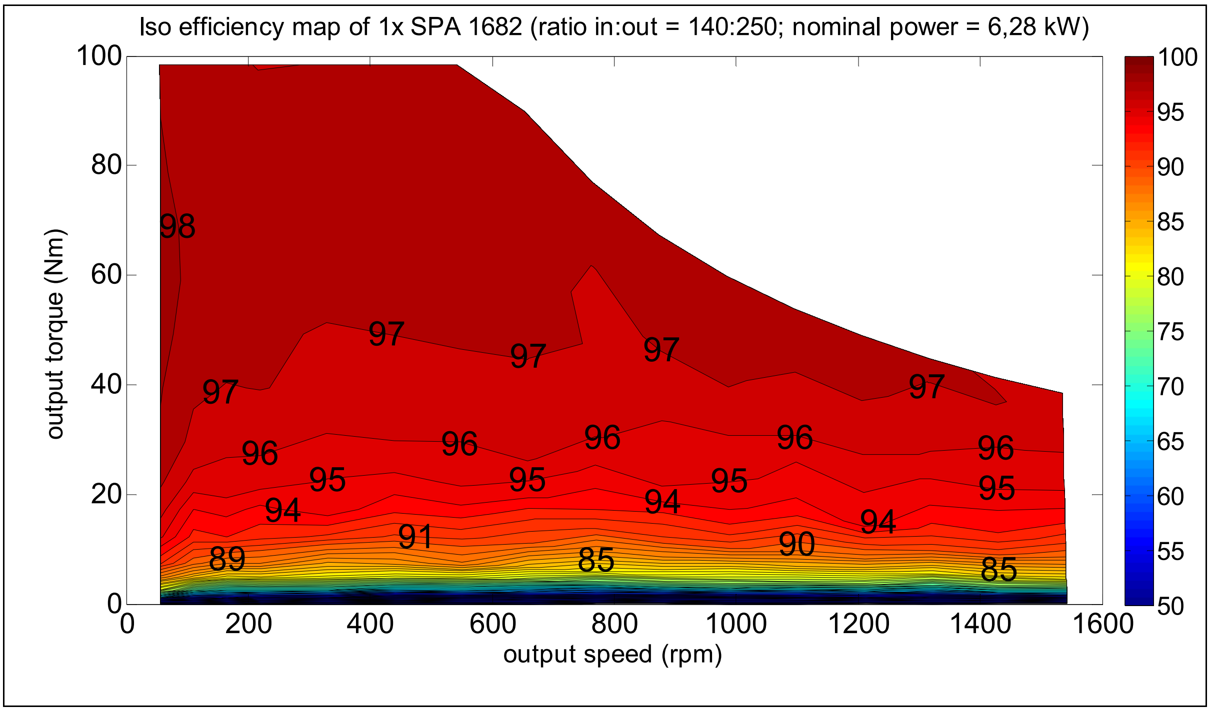

Figure 8: Iso-efficiency contour of 1xSPA 1682 V-belt [7]

By omitting the driving belts, an estimated energy saving of about 4% can be predicted based on these measurements. Also maintenance costs are reduced by leaving out the belts out of the drive train.

Belts are often used at industrial fan installations for mechanical safety reasons. At startup, the belt can shortly slip to reduce the mechanical stress on the drive train. In case of a stalled fan, the belt again can act as a mechanical safety factor. By implementing a drive however, the startup is now established by providing an adapted ramp-up time and a stalled motor will quickly be shut down by the drive itself because of the overload of the output bridge of the drive.

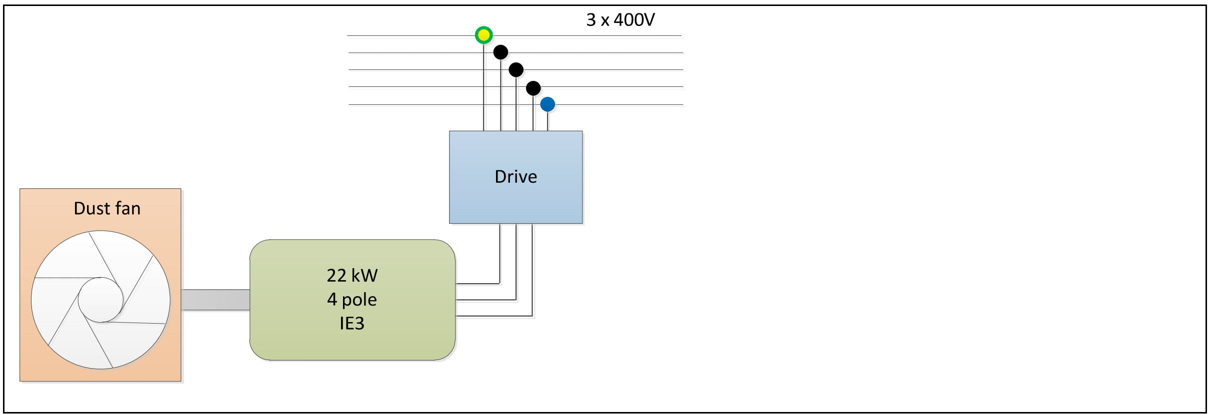

Figure 9: Applying direct drive principle to dust fan

By omitting the belts however, the motor has to turn 1.47 times faster at a speed of about 2178rpm by using the drive. Experience has shown this is not a problem for the motor itself and the mechanical effects on the motor are negligible. On the contrary; measurements done at our test facilities indicate that the overall efficiency of a speed regulated induction motor does not reach maximum efficiency at nominal load and speed, but always around 120% of nominal speed and 60% of nominal load [6](**Figure 10**). In this case, the motor will run at a speed of 147% of nominal speed and about 66% of nominal torque. Relying on our experience and based on the contour beneath (**Figure 10**) the efficiency should stay at about the same level as at nominal speed and load.

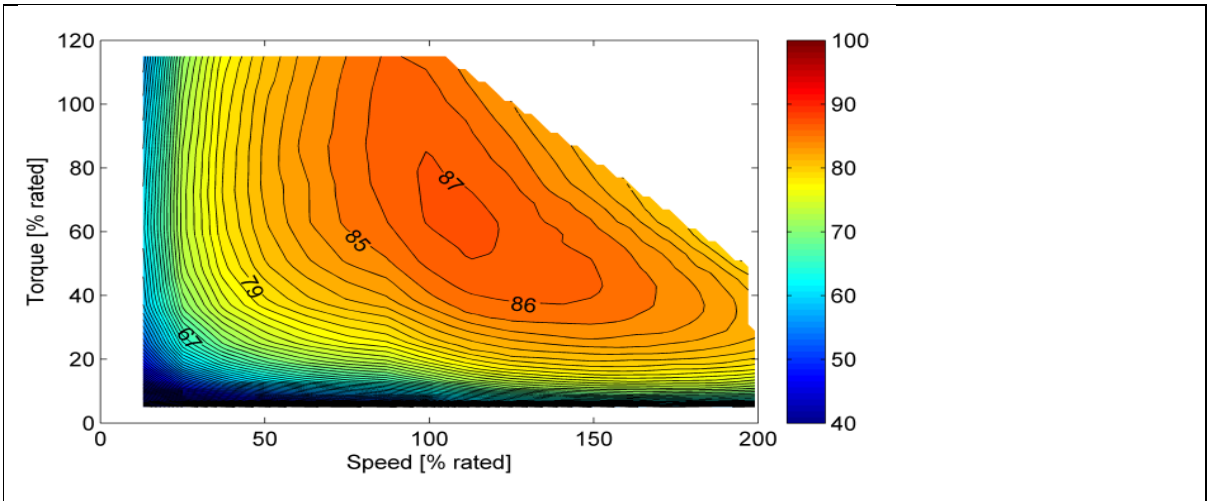

Figure 10 : Iso-efficiency contour 11kW 4 pole IE2 IM + drive [6]

This last step has not yet been implemented by the publishing date of this paper, but energy logging results of this last step will be presented at the Eemods 2013 conference.

Conclusions

Regulations on energy efficiency tend to evolve to a total system approach to reach a certain minimum overall system efficiency. The EU-directive 327/2011 for industrial fans is an example of such a total system approach. This case was set up as an example to determine the possible measures to rise the overall system efficiency of an industrial fan installation. Regarding the several steps which have been taken during the optimization process, the following conclusions can be made;

1. In this case, maintenance performed on the belts using adequate equipment resulted in a negligible effect on the energy efficiency. The belt tension was already correct and the correction of the misalignment did not result in a change of input power. The cleaning activities on the air ducts and fan however resulted in a higher flow and pressure, but also in a not

intended input power rise of 8% which shows the need for a speed regulated system to adapt the speed to the system condition.

2. Older motors (without any efficiency labeling at all) should be replaced by newer, high efficient alternatives. In this case, an energy saving of 10% was reached with a payback of less than a year. Take care however when replacing the motor to maintain same speed of the fan.

3. Speed regulation has shown again to be an interesting step with industrial fans. Even a small reduction in speed of the fan can result in substantial energy savings because of the affinity laws. In this case an energy saving of 8% was reached by reducing the frequency by 2 Hz. To optimize the savings, a flow sensor feedback has to be installed which controls the speed regulator of the drive.

4. Reconsider the whole drive train. As in many industrial fan applications, belts were used to drive the fan. The applied belts were over dimensioned by 70%. By omitting the belts and drive the shaft of the fan directly using a frequency convertor, an extra 4% in energy savings can be expected in this case. Also, the overall maintenance costs go down by leaving the belts away.

After performing these optimization steps, an overall system efficiency gain was reached of 22% (-24MWh/year). With an average of 5800 working hours a year and an energy price of € 0.09/kWh this equals about €2150 of yearly savings per installed fan in the company and a payback time of around 1 year.

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Influence of Radial Fan Efficiency in Sound Pressure Level of Electric Motors

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Abstract

The objective of this work is to present, by means of experimental, analytical and numerical techniques that sound pressure level generated by radial-bladed centrifugal fans of electric motor cooling systems may be expressed by a logarithmical ratio of the peripheral velocity of rotor, volumetric flow and efficiency of the fan. The proposed methodology proved to be efficient and simple in the prediction of generated noise by radial-bladed centrifugal fans of TEFC motors with accuracy of ± 3 dB.

Introduction

Electric motors are used to convert electric energy into mechanical energy. The losses generated in this process can be separated into electrical losses and mechanical losses. The mechanical losses are distributed in frictional losses and ventilation losses, which correspond to the power absorbed by the motor fan and comprise the focus of this work.

Specific references [1] estimate that electric motors were responsible for approximately 46 % of the global electricity demand in 2006 (15700 TWh/year). Considering that, on average, cooling fans alone consume around 0.5 % of the energy absorbed by the motor, this results in nearly 36 TWh/year being consumed by the motor fans, what represents 38 % [2] of the production record of Itaipu station, the world's largest hydroelectric power plant as regards the generation of electric energy.

In general, two main reasons to pursue energy conservation are environmental sustainability and cost reduction. However, in the case of electric motors, beyond these well-known advantages, efficiency increasing also means noise decreasing.

The effort to control the noise emitted by electric motors increases due to legislation requirements such criteria defined in the NR – 15 [3] and EPA 550/9-74-004 [4], industrial standards such as the IEC 60034-9 [5] and NEMA MG 1 [6], and customer needs. Currently, to assure competitive products in the market low noise levels are fundamental, for example, in applications as electric vehicle motors, air conditioning and others.

In totally enclosed fan cooled (TEFC) motors noise is generated by electromagnetic, mechanical and aerodynamic effects. Among these, the aerodynamic noise portion is paramount in most cases and is focused in this work. Aerodynamic noises are generated by rotation of fan rotor that induces the air flow over the motor. This work shows that the motor noise level can be related to the performance of the motor cooling fan.

Fan Sound Level Prediction Techniques

Currently, the fan sound level prediction may be divided in two main areas analytical and numerical techniques, where the first uses analytical equations experimentally calibrated and performance parameters of fan and the last uses computational numerical techniques, which requires large computational capacity what makes it impractical for most of the cases.

There are many works available in literature as the presented by references [7] up to [13] that use analytical techniques to estimate sound level generated by fans, however all of them focus on conventional fans as some examples the presented in the **Figure 1**.

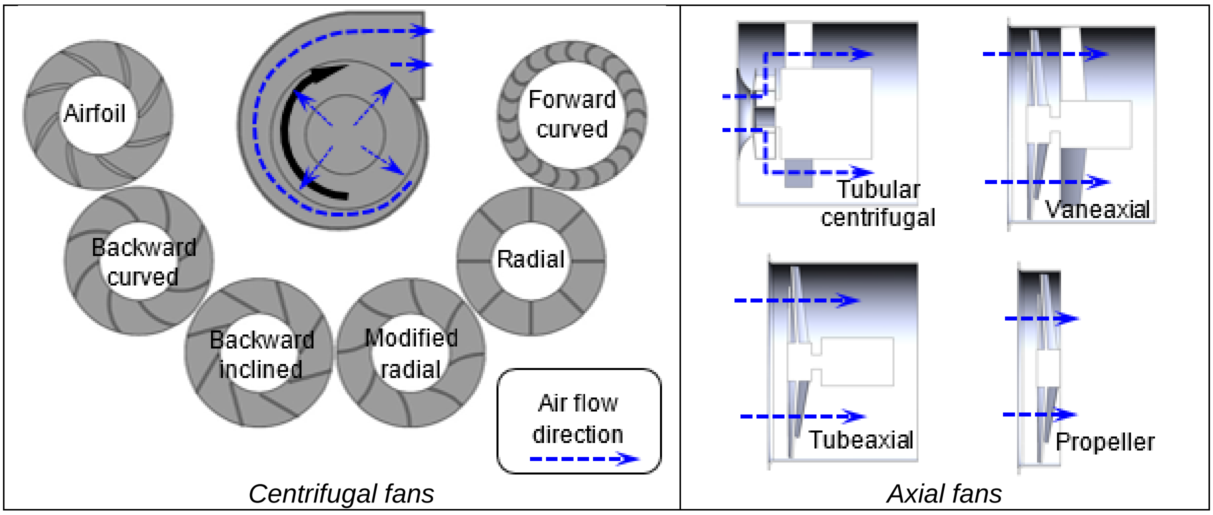


Figure 1 – Conventional fans

In the **Figure 2** is showed the air flow direction generated by radial-bladed centrifugal fan over a TEFC motor, where the flow behavior is similar to tubular centrifugal (Figure 1). However, in case of TEFC motors the air inlet and outlet are directly in contact with atmospheric pressure (free delivery) this means that according to the ANSI/ASHRAE 51-07 [14] the static pressure is equal to zero. In most cited references, which concern noise prediction, static pressure or total pressure are basic parameters in the noise prediction, for convenience peripheral velocity of rotor will be used instead these parameters.

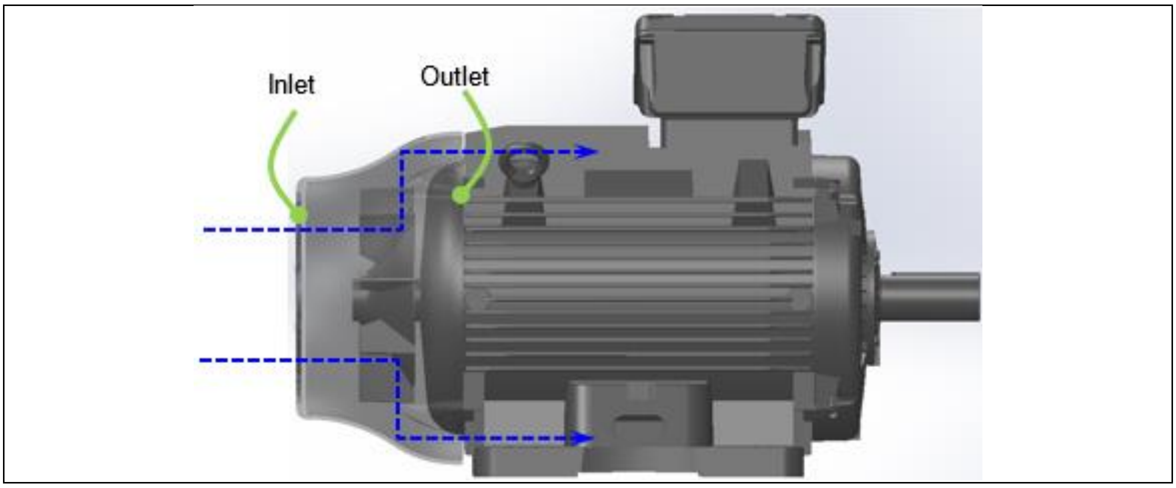


Figure 2 – Air flow direction over TEFC motor

Specifically, these fans need to work in both rotation directions generating axial flow over motor, wherefore its rotor is centrifugal and comprise radial blades. Some works such as [15] and [16] have advantages like low noise and low absorbed power of the axial fans over the radial-bladed centrifugal fans, however axial fans do not meet to work in both rotation directions.

In [17] is presented a methodology based on [12] to estimate the sound pressure level emitted by TEFC electric motors, where the errors obtained between the experimental and predicted results are of the order of ± 6 dB(A), this is high error to be considered in design phase.

Publications as [18], [19] and [20] comprise computational aeroacoustics (CAA) methods to predict the noise generated by fans, however these methods have high computational costs and high simulation time.

Therefore, due to the disadvantage of existing methodologies and the shortage of information available about noise prediction of radial-bladed centrifugal fans motivate the development of this work. Mainly to improve the accuracy and processing time of the noise prediction in the design phase allowing to include the noise level as design variable in optimization processes of this fan type.

Dimensionless Analysis

The references [9], [10], [11] and [21] use the Buckingham pi theorem [22] to develop a dimensionless acoustic parameter. Similarly as presented in these references, it is proposed initially a dimensionless sound power parameter to obtain an expression which allows the representation of the sound power level generated by fan. Following is presented the sequence of determination of the power dimensionless parameters.

The fan losses (W_{Loss}) may be calculated by following equation:

$$W_{loss} = W_{abs} - W_h \qquad (1)$$

where,

W_{abs} is the power absorbed by the fan;

and W_h is the hydraulic power, which is a function of fan total pressure (ΔP_t) and fan air volumetric flow ($\dot{V}$).

$$W_h = \Delta P_t \dot{V} \qquad (2)$$

The absorbed power can be written as a function of the fan efficiency (η).

$$W_{abs} = \frac{W_h}{\eta} \qquad (3)$$

Then, substituting the equations (2) and (3) in equation (1).

$$W_{loss} = \Delta P_t \dot{V} \left(\frac{1}{\eta} - 1 \right) \qquad (4)$$

Considering that the emitted sound power (W_s) has a relation with peripheral velocity of rotor external diameter (V_p), volumetric flow, total pressure and fan efficiency, it is proposed the following new acoustic dimensionless parameter (A_0):

$$A_0 = \frac{W_s}{W_{loss}\eta} \quad => \quad A_0 = \frac{W_s}{\Delta P_t \dot{V}(1-\eta)} \qquad (5)$$

According to Groff [10] dimensional analyses have shown that the sound power generated by fan is related with the following dimensionless parameters:

Pressure coefficient:

$$\psi = \frac{2\Delta P_t}{\rho {V_p}^2} \quad => \quad \Delta P_t = c_1 \rho {d_5}^2 n^2 \psi \qquad (6)$$

Flow coefficient:

$$\varphi = \frac{\dot{V}}{\pi V_p \frac{{d_5}^2}{4}} \quad => \quad \dot{V} = c_2 n {d_5}^3 \varphi \qquad (7)$$

Mach number:

$$Ma = \frac{V_p}{c_s} \quad => \quad Ma = c_3 \frac{nd_5}{c_s} \tag{8}$$

where,

ρ is the fluid density;

d_5 fan rotor outer diameter;

n fan rotational speed;

c_1, c_2, … are constants;

and c_s is the speed of sound.

Now, substituting the equations (6) and (7) in equation (5) it is obtained the next equation:

$$A_0 = \frac{W_s}{c_4\rho(1-\eta){d_5}^5 n^3 \psi\varphi} \quad => \quad W_s = c_4 A_0 \rho(1-\eta){d_5}^5 n^3 \psi\varphi \tag{9}$$

In Neise [23] is presented the three basic aerodynamic generation mechanisms of fan noise, these sources are monopole, dipole and quadrupole. As showed in Chanaud [21] the sound powers emitted by these mechanisms are respectively proportional to:

$$W_m \ \alpha \ {d_5}^6 n^4 \tag{10}$$

$$W_d \ \alpha \ {d_5}^8 n^6 \tag{11}$$

$$W_q \ \alpha \ {d_5}^{10} n^8 \tag{12}$$

Therefore, it is possible to define dimensionless parameter to these three mechanisms as the ratio of the A_0 and Ma. The dimensionless parameter for monopole source is:

$$A_m = \frac{A_0}{Ma} \quad => \quad W_m = c_5 \frac{A_m \rho(1-\eta){d_5}^6 n^4 \psi\varphi}{c_s} \tag{13}$$

Similarly to the monopole source, dimensionless parameters for dipole and quadrupole sources are, respectively:

$$A_d = \frac{A_0}{Ma^3} \quad => \quad W_m = c_6 \frac{A_d \rho(1-\eta){d_5}^8 n^6 \psi\varphi}{{c_s}^3} \tag{14}$$

$$A_q = \frac{A_0}{Ma^5} \quad => \quad W_m = c_7 \frac{A_q \rho(1-\eta){d_5}^{10} n^8 \psi\varphi}{{c_s}^5} \tag{15}$$

As presented by Groff [10] these considerations accomplished for the three sources may be incorporated in a single dimensionless parameter to represent the fan sound power, this model assumes the following generalized dimensionless parameter.

$$A_\alpha = \frac{A_0}{Ma^{2\alpha-1}} \quad => \quad W_\alpha = c_8 \frac{A_\alpha \rho(1-\eta){d_5}^{2(\alpha+2)} n^{2(\alpha+1)} \psi\varphi}{{c_s}^{2\alpha-1}} \tag{16}$$

Where the parameter α is equal to 1, 2 and 3 for monopole, dipole and quadrupole source, respectively.

The peripheral velocity of rotor is calculated as:

$$V_p = \frac{2\pi}{60} n \frac{d_5}{2} \quad => \quad V_p = c_9 n d_5 \tag{17}$$

Hence, working the equations (7), (16) and (17), the fan sound power can defined as:

$$W_s = a_s \dot{V}(1-\eta){V_p}^{2\alpha+1} \tag{18}$$

where,

$$a_s = c_{10} \frac{A_\alpha \rho \psi}{{c_s}^{2\alpha-1}} \tag{19}$$

This term is a function of geometric, point of rating and fluid properties, however may be considered as a constant for a given geometric family of fans.

The equation (18) can be expressed in decibel form, thus the sound power level:

$$SWL = 10\log\left(\frac{W_s}{W_0}\right) \tag{20}$$

The reference sound power (W_0) is equal to 10^{-12} W.

Sound power levels of noise sources can be determined using the sound pressure as defined by ISO-3744 [24] and ISO 3745 [25], considering a hemi-anechoic room the converting of sound power level into sound pressure level (SPL) is given by following equation.

$$SPL = SWL - 10\log(2\pi r^2) \tag{21}$$

where r is the radius of the test hemisphere surface.

Introducing,

$$\beta = 2\alpha + 1 \tag{22}$$

Incorporating the equations (18), (20)19, (21) and (22) in a single equation the *SPL* can be estimated as:

$$SPL = K_1 + 10\log(\dot{V}) + 10\log(1-\eta) + 10\beta\log(V_p) \tag{23}$$

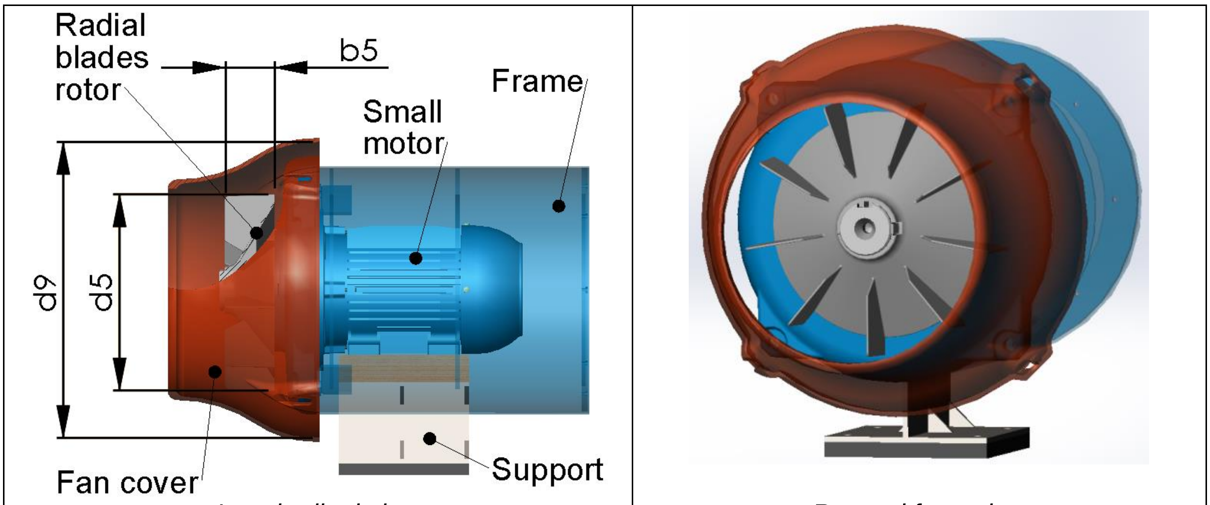
Where the K_1 and β are empirical parameters and may be determined by means experiments.

Experiments

Fan noise experiments

The determination of K_1 and β requires the variation of the following geometric parameters: external diameter of rotor (d_5), blade width (b_5), number of blades (Z), which are related to the rotor and the diameter of the fan cover (d_9) in the air outlet region, the **Figure 3** presents these parameters. The last parameter analyzed is the fan rotational speed, the analyzed parameters are known as design variables.

The focus of the work is only the aerodynamic noise generated by fan of electric motor, therefore a simplified device was developed to simulate an electric motor of the type TEFC, which is constructed with a radial-bladed centrifugal fan on the rear shaft of the self-motor and is covered by a housing knowing as fan cover. The motor frame is composed by cooling fins, terminal box, feet, flange, eye bolt and others, which were not incorporated on the device, as showed in the Figure 3. To avoid the electromagnetic and the mechanical noise, the fan driver was exchange by a small TEFC motor without fan and enclosed by a steel housing. Further, the protection grid in the air inlet region of the fan cover was removed.



Longitudinal view *Rotated front view*

Figure 3 – Simplified device and analyzed parameters

The noise tests were accomplished in accordance with the methods specified by international standards ISO-3744 [24] and ISO 3745 [25], the hemi-anechoic room was used as test environment to simulate the free field over a reflecting plane.

The microphone position were verified to ensure that the measurements were accomplished in the free-field regions avoiding: near-field, region where the source proximity is too closed that the *SPL* may vary significantly with a small change in sound level meter position and reverberant-field, region where errors may be introduced by room walls proximity, as defined in [26].

Noises generated from all sources other than the noise of concern source are known as background noises and must be isolated, in is this case the difference between the total (concern source and background) sound pressure level and the background sound pressure level was at least 10 dB. In the background noise was included the device operating noise without fan.

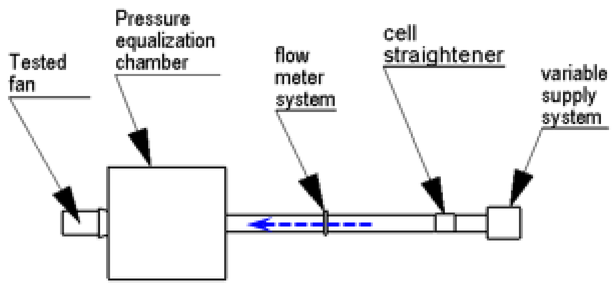
Fans typical noise comprise a wide range of frequency, for this case will used a range between 125 Hz up to 5 kHz, because this corresponds to the main portion of total generated noise by fan. The range of sound pressure level meter was selected from 30 dB up to 110 dB.

Fan Aerodynamic experiments

Currently, as demonstrated in Verardi [27] computational fluid dynamics (CFD) techniques can be used reliably to estimate aerodynamic parameters as volumetric flow, fan total pressure and absorbed power. With focus on reducing the time of determination of the fan aerodynamics parameters CFD was used to calculated these values, however to show the CFD technique reliability some validations using experimental methods were accomplished.

Experiments of the fan aerodynamic parameters were accomplished as specified in ANSI/ASHRAE [14], the **Figure 4** presents the test facility, defined in ANSI/ASHRAE [14] as Inlet Chamber, which is basically composed by a variable supply system, cell straightener, flow meter system, pressure equalization chamber and tested fan. The calculations of volumetric flow and efficiency present in equation (23) are estimated as ANSI/ASHRAE [14], volumetric flow is obtained directly of the experimentally measured values conversion and fan efficiency is a quantity indirectly calculated by equations (2) and (3).

Test facility



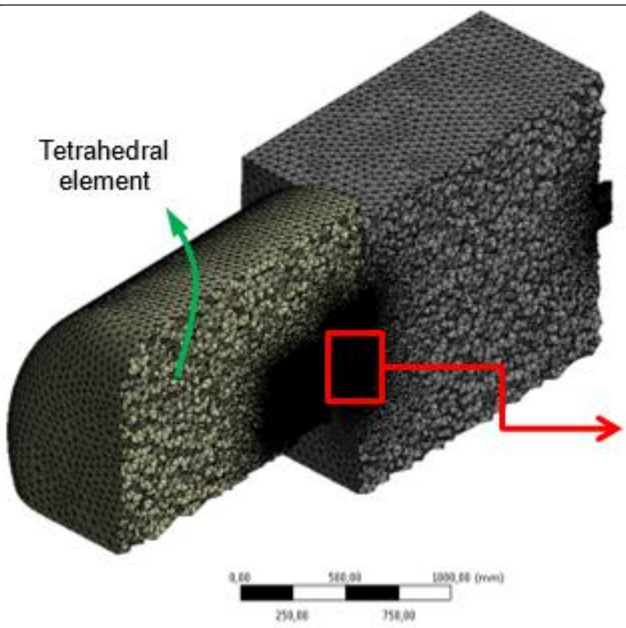
Inlet chamber schema

Figure 4 – Test of the fan aerodynamic performance

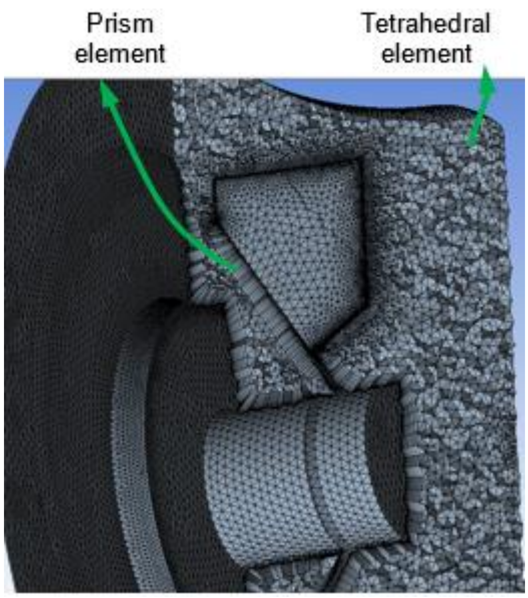
CFD analyses

CFD analyses were carried out with support of commercial software *Ansys CFX – Version 14.0* where the mesh presented in the Figure 5 is composed by 2,820,998 of nodes. This mesh was simulated to compare numerical with experimental results of the volumetric flow and absorbed power. Following are mentioned the main parameters used in the CFD simulations:

- Analysis: steady state;
- Fluid: incompressible, isothermal (air at 25 °C);
- Turbulence model: Shear Stress Transport (SST) [28];
- Residual rms: 1.4 x 10^{-4};
- And accumulated time step: 400 iterations.



Complete domain of simulation



Detail view of rotating domain

Figure 5 – CFD mesh

In the Figure 6 are presented results of validation for volumetric flow and absorbed power. Three rotational speeds are compared for volumetric flow where 4.5 % was the maximum error found and for absorbed power two rotational speeds are compared with the maximum error of 5.2 %, note that values of rotational speeds used to the measurements are different between volumetric flow and absorbed power this occurred due to a restriction of measurement system. In both validations are presented values of uncertainties, where experimental uncertainties are calculated as defined in ANSI/ASHRAE [14] and numerical uncertainties represent minimum and maximum values relative to the numerical oscillations.

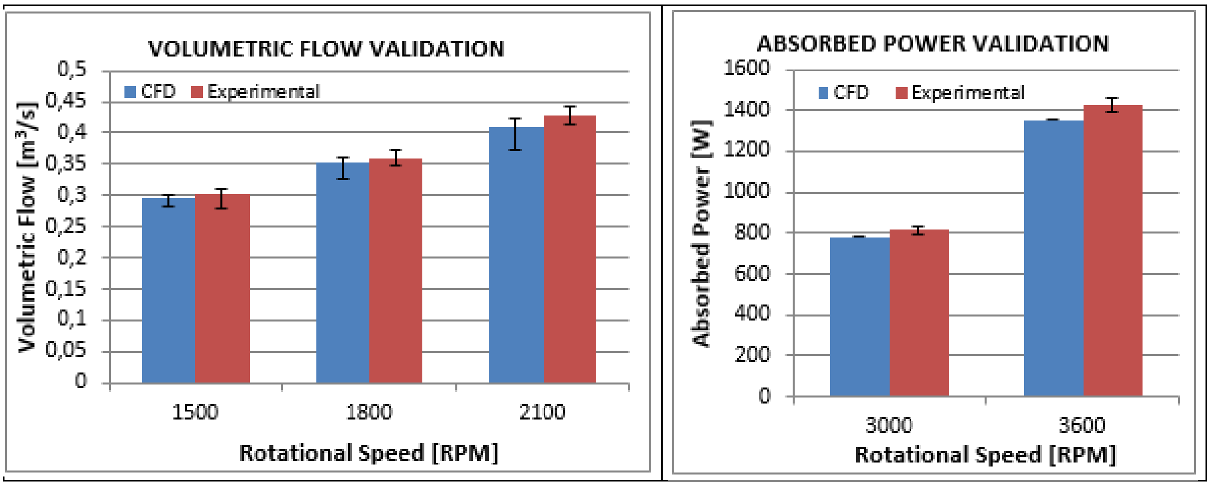


Figure 6 – Results of CFD validations

Determination of K_1 and β

As presented in Montgomery [29], the value of design variables was chosen using a central composite design (CCD) technique for fitting the second-order model ensuring more reliability of the experiments, specifically was used a face-centered cube to define geometric parameters arrangement. Each design point of the rotor geometric parameters was tested in three rotational speeds: 1800, 2400 and 3000 RPM, in three diameter of the fan cover: 432, 456 and 563 mm and were replicated three times, resulting in a total amount of 405 tests. Table 1 shows the randomized matrix of the CCD accomplished for the rotor geometric parameters.

Table 1 – Design points of the rotor geometric parameters

Test Sequence	d_5	b_5	Z
	[mm]	*[mm]*	*[-]*
10º	312	58	5
13º	251	39	5
3º	190	77	3
8º	312	77	9
2º	190	39	9
6º	312	39	9
14º	251	58	9
4º	190	77	9
7º	312	77	3
5º	312	39	3
12º	251	77	5
15º	251	58	3
11º	190	58	5
9º	251	58	5
1º	190	39	3

To obtain the experimental parameters K_1 and β was used least squares method [30] to fit the estimated results by equation (23) to the sound pressure level experimental results. To supply known values of volumetric flow and efficiency of the equation (23) CFD results were used, values of peripheral velocity were calculated by equation (17) and observed sound pressure level were obtained by means of experiments as previously described.

Results

The results of the least squares method to experimental parameters were $K_1 = 21.0$ and $\beta = 4.5$ where the maximum absolute error found was equal to 3.4 dB using the equation (23) and the respective values of K_1 and β. **Figure 7** presents percentage of occurrences versus error range in dB. The horizontal bars represent in percentage of occurrences inside of error interval, for instance, the graph shows that 70 % of the design points presented the maximum error between calculated and experimental of ± 1.5 dB.

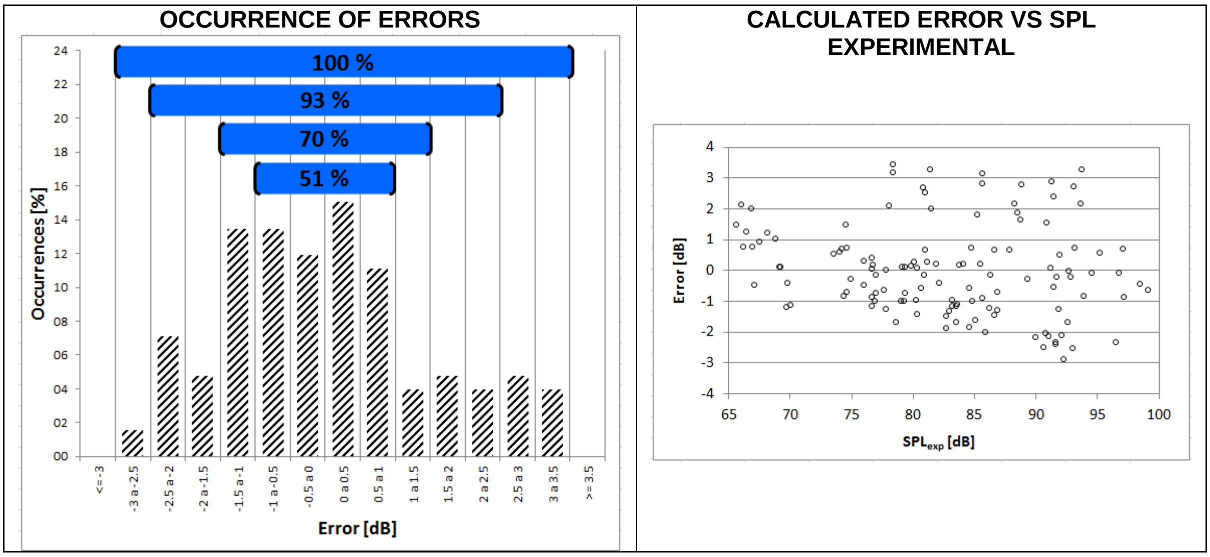


Figure 7 – Distribution of errors

In **Figure 8** are presented the individual effect of each parameter in sound pressure level using the proposed methodology for the analyzed range. The peripheral velocity is the paramount parameter in the sound generated, the volumetric flow performs moderated effect and fan efficiency has minimal influence in the sound generated.

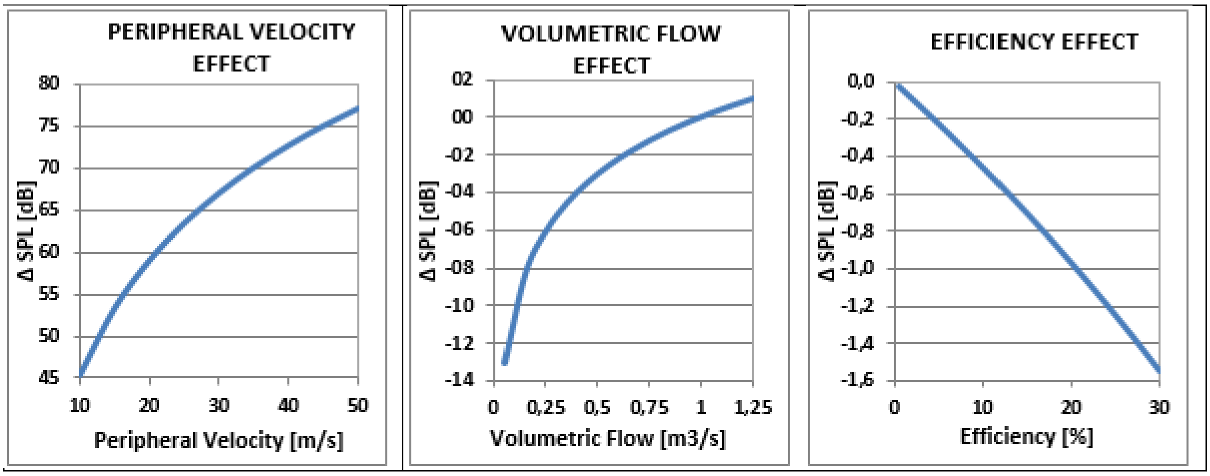


Figure 8 – Effect of parameters in SPL

Conclusions

Noise prediction is an important parameter in design phase to development fans used in electric motors mainly those that require low noise levels, however the information about noise prediction are scarce due the phenomenon complexity of fan noise generation.

The proposed methodology proved to be efficient and simple in the prediction of generated noise by radial-bladed centrifugal fans of TEFC motors with accuracy of ± 3 dB. The dimensionless analysis supplied a simple equation based on parameters easily achieved as peripheral velocity of rotor, volumetric flow and fan efficiency, which may be obtained by means experimental tests or numerical simulations.

CFD techniques is a powerful tool to achievement aerodynamic performance parameters of fans as was presented in validation tests where the error between experimental and numerical was approximately of 5 % for the volumetric flow and absorbed power. Wherefore, the CFD analysis combined with presented methodology of noise prediction may be used in optimization processes of fans in design phases reducing costs, number of prototypes and development time.

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MODERNIZATION OF ESCALATORS WITH FOCUS ON ENERGY EFFICIENCY AND SUSTAINABILITY: A case study for feasibility analysis

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Kron Electrical Instruments LTDA. Management of New Business

Abstract

This case study aims to evaluate the feasibility of upgrade the equipment of mass transportation "Escalator", using concepts of energetic efficiency, sustainability, financial analysis, among others, to propose the modernization in the Companhia do Metropolitano de São Paulo.

The research method defined what, where, how, and for how long to measure the equipment's based in the international protocol "Measurement and Verification M&V". After analysis of the M&V protocol a duty cycle of one week was elllected, to collect electrical and operational data of two representative escalators. With the data obtained it was possible to correlate the electrical parameters, statistical analyzes and financial considerations.

The analysis and conclusions from this study suggest that modernization is feasible in many aspects

1) Social: reduction of incidents among elderly, and the increase of jobs opportunity.

2) Technical: the use high performance motor and regenerative frequency drive will improve the Mean Time between Failures (MTBF) proposals; generation of historic data of functional deviations.

3) Budget / Finance: the modernization project will save energy, making it possible to generate funds, with Payback MIRR (Modified Internal Rate of Return - MIRR) at maximum of 10 years;

4) Legal: to accomplish federal and state laws in the area of energetic efficiency and sustainability;

5) Environmental: Reduction of CO_2 emissions, estimated at three hundred ninety-seven tons per year (397 Ton. CO_2/year).

I. Introduction

With the promulgation of Decree No. 58,107, on June 5th , 2012, , Geraldo Alckmin, governor of São Paulo State instituted the "Strategy for Sustainable Development of the State of São Paulo in 2020", and gives related measures. This governmental program, motivated the present study that targets to search “motrizes” systems and energetic diagnoses in order to propose modernization at the Companhia do Metropolitano de São Paulo, Metrô. The São Paulo Company of the Metropolitan – Metrô was formed on April 24th, 1968. Today, the São Paulo Metro has four lines in operation, 65 kilometers of network and 58 stations.

In this Decree 58.107/2012, we have the following articles related to this study:

"Article 1 – Is established the “Strategy for Sustainable Development of the State of São Paulo in 2020”, which aims an agenda for sustainable development of the State of São Paulo, with sectorial goals that define the action of the State Government of São Paulo by 2020 under the Annex terms of this Decree.

Article 2 - The Strategy, conceived in the context of the UN Conference on Sustainable Development - Rio +20, to be held in Rio de Janeiro in June 2012, is guided by the main themes of this conference, namely the green economy in the context of sustainable development, eradication of poverty, and the institutional framework for sustainable development. "

The most important aspects of it for the present study:

"Reduction of 20% of carbon dioxide emissions, the set point is the based on the year 2005, for the State Policy on Climate Change.";

"Modernization and expansion of the existing subway lines, from the current 74.2 km to 244.2 km in 2020.";

In Storasta (the Electricity Sector Magazine, June 2012), is possible to analyze projections of energetic consumption (Figure 1) in two scenarios: base consumption (solid line); consumption with estimated energetic efficiency (dotted line)

Figure 1 - Projected Energy Consumption - Source MME - PNEF

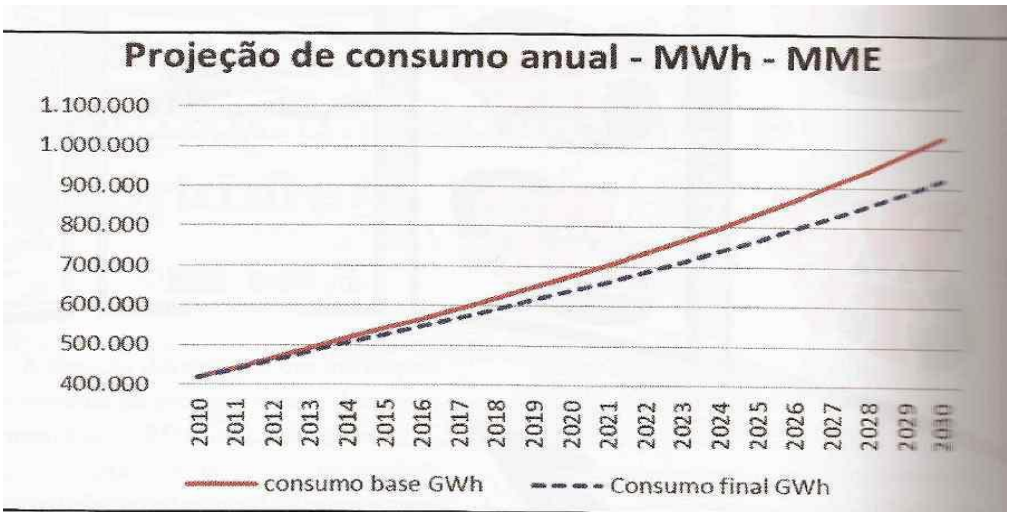


Figura 1 – Projeção de consumo anual de energia e participação da eficiência energética.
Fonte: MME-PNEf.

The study "Modernization of Escalators ..." was the result of an applied field research in two escalators representing the entire set of escalators of the enterprise in order to check the feasibility of a potential project to modernize these types of equipment and others with similar scope.

Using the concept of applied technology of regenerative frequency drive, adjusting the expenditure of energy as the mechanical load on the tip of the motor shaft powered by this it follows that the greater the variability of shaft load the greater the potential for energy savings. The higher the quantity the same type of equipment and the greater the power of their motors greater the potential for energy savings and lower spending on planning and design. So, just modeling the modernization of the equipment and replicate this model for all others of the same type.

The AC motors have an estimated life time between 15 and 20 years. Beyond this life the motors gradually lose their ability to serve the various types of conjugated and can present various deviations of functioning. According to the Brazilian Maintenance Association (ABRAMAN) the average age of the national industrial facilities in 2011 was 16 years.

II. Present Situation of the Target Equipments

It possible to observe 385 escalators intended to (Table 1) be modernized. From this total 99 were manufactured by the Otis company (Figure 2) and 286 by the Villares company. The scope of each escalator is contained in the range mentioned in this table. The measurement unit CV (cheval vapeur) consists in 735.5 Watt.

Figure 2 - Motor, Reducer and Control Panel Otis Escalator

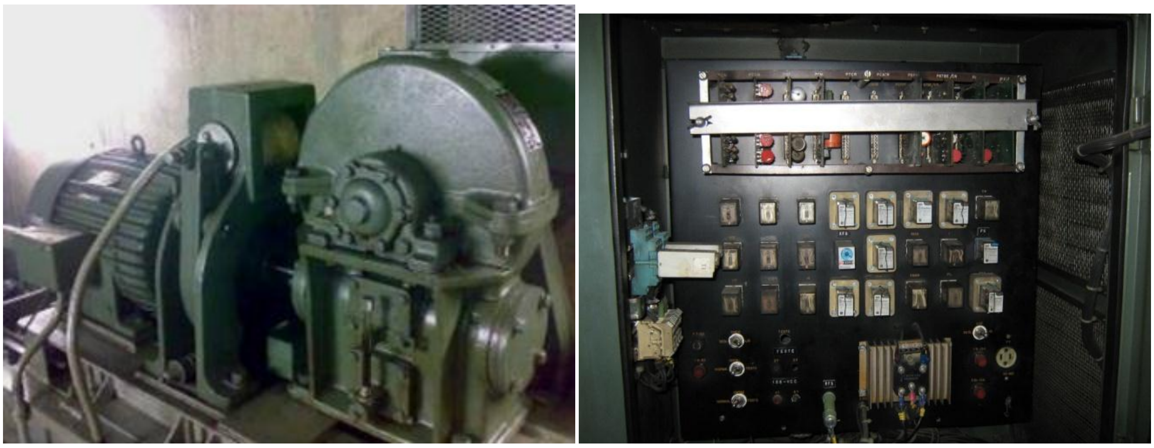


Table 1 - Powers in CV, Elevation and Motor Quantity

MOTOR CAPACITY	ELEVATION [m]	QUANTITIES		TOTAL
		OTIS	VILLARES	
15 CV	de 3,4 a 4,4		88	88
20 CV	4,5	5		5
25 CV	de 5,0 a 6,5	18	179	197
30 CV	de 6,6 a 7,2	45		45
40 CV	de 7,5 a 12,5	31	19	50
TOTAL QUANTITIES		99	286	385

In table 2 we can observe that the start of operation of each of these subsets have at least 20 years of operation.

Table 2 - Motors Quantity and Beging Operation Date

BEGINNING OF OPERATION	QUANTITIES					
	15 CV	20 CV	25 CV	30 CV	40 CV	TOTAL
1974	20		14			34
1975	45		34		14	93
1977	3		20			23
1978			14			14
1979				4	2	6
1980	3		4	11	5	23
1981			19		4	23
1982			19	8	2	29
1983			16	1		17
1984			1			1
1986			8	2	5	15
1988	15		40	16	9	80
1989	2		2	1		5
1991		4	3		8	15
1992		1			1	2
1992			3	2		5
TOTAL	88	5	197	45	50	385

III. Purpose of Modernization

The modernization of escalators has as premise on the renewal of the motors of 385 equipment. Since they were installed more than 20 years ago, more than the standard life time (15 years) is expected to save about 5% of the daily used energy, installing high performance motors.

Identifying the variability load at the shaft end and the use of regenerative frequency drives regenerative economy will save around 30% of the energy due to: optimization of magnetic current adjusting the power needed every moment on the shaft load regenerating energy when the escalator is going down with people, improving the power factor.

The use of PLC (Programmable Logic Controller) enable: replacement of the interlock circuits and logic control of operation and safety of escalators; deployment timetable of operation so that in times of peak escalator works with its rated speed (around 0.6 meters per second which represents around 90 steps per minute) and schedules worth around 50% of that speed. With the implementation of this timetable esteem up saving around 30% of the energy currently used. Another major potential benefit of this deployment timetable will reduce the number of incidents in times of little movement of passengers on subway, especially with older people who usually have problems with balance.

IV. Baseline and Procedures Case Study

The weekly period measurement was choosing as the "baseline”. This pattern of use of escalators is repeated weekly and procedures defined in the Operations Management. These procedures were developed after observing the use of this equipment has weekly cycle and varies during the hours of rush time , in both directions in every day.

The choice of “Option A - Retrofit Partly Isolated” Chapter 4 of the Guide to Measurement and Verification PROCEL, - because the creation of the "retrofit” depends of the approval and continuity of this case study.

These specific escalators were chosen due to its high loading, ER22 and ER28 were the Corinthians Itaquera Station. These escalators have eight pole motors, the load average yield of 88.6% and slipping around 1.7%. The motor nameplate data is shown bellow in Table 3.

Table 3 - Nameplate of the escalators ER22 and ER28

ER22 e ER28	DATA	UNIT
Model	365T20486	
Motor Power	30	CV
Voltage	440	V
RPM	885	rpm
Current	43	A

The instrument used in the measurements was the "Portable Analyzer MPK NG" Company Kron Meters. This analyzer performs three-phase power quality measurement standards as IEC61000-4-30 Class S, IEC61000-4-7 and classifies events according to module 8 of PRODIST. This instrument is equipped with mass memory, allowing storage of up to ten historical electrical quantities. Has a sampling rate of 128 points per cycle. It also has memory for storing events. This unit was installed as photographs 8 and 9. The accuracy of the device is: Voltage: ± 0.5% (± 0.2% typical) Frequency: ± 0.05 Hz; Current: ± 0.2%. In the case in question was chosen Current Probe 100 Amps with measurement range of 1 to 100 Amps, since the plate current of the motor is 43 Amps at 440 Volts. Figure 3 shows the same installed to the process of measuring electrical quantities of escalators.

Figure 3 - Installation of Power Analyzers Panel of ER 22 and ER 28

V. Results Obtained

The results of measurements on escalators 22 (runs to upper level, the paid area) and 28 (runs downhill towards the paid area) at Station Corinthians Itaquera (ITQ). Thus, the users entering or leaving the station use escalators to go up or down (where a ticket is needed) and mezzanine boards where there is paid area or free circulating area. With these handsets Kron installed on escalators, 10.017 events were registered (or rows in Excel spreadsheet) with values of parameters electrical varies, useful for the referred search. Parts of these records and reports provided by the system were presented below in Tables 4, 5, 6 and 7. These tables show the various electrical quantities measures, noting for example: the value of low Power Factor (PF) found; energy consumption over the period of a week with a running time of approximately 155 hours.

Table 4 - Measurement of Electrical Parameters in ER22

DATE	TIME	VOLTS U1-U2	VOLTS U2-U3	VOLTS U3-U1	AMPS U1	AMPS U2	AMPS U3	POWER FACTOR	THD VOLTS U1	THD VOLTS U2	THD VOLTS U3
30/05/12	12:10:00	477,0	476,0	475,8	16,3	16,3	15,8	0,7	5,0	5,4	5,0
30/05/12	12:11:00	477,4	477,1	477,0	16,9	17,0	16,7	0,7	3,0	3,1	2,8
30/05/12	12:12:00	480,4	479,9	480,0	17,3	17,3	17,0	0,7	3,8	4,0	3,5
30/05/12	12:13:00	480,2	479,6	479,8	15,3	15,3	15,2	0,7	4,5	4,8	4,5
30/05/12	12:14:00	477,0	476,3	476,2	16,5	16,5	16,2	0,7	5,8	6,2	5,8
30/05/12	12:15:00	480,7	480,5	480,9	16,8	16,8	16,8	0,7	2,6	2,6	2,4
30/05/12	12:16:00	472,8	472,1	472,0	17,9	17,9	17,5	0,8	4,0	4,3	4,0
30/05/12	12:17:00	478,9	478,4	478,4	14,7	14,7	14,4	0,6	4,0	4,4	4,1
30/05/12	12:18:00	477,5	477,3	477,2	17,8	17,9	17,7	0,7	2,9	3,0	2,7
30/05/12	12:19:00	480,3	479,6	479,8	16,4	16,4	16,2	0,7	3,6	3,7	3,5
30/05/12	12:20:00	481,8	481,2	481,3	12,5	12,6	12,4	0,5	4,1	4,1	4,0
30/05/12	12:21:00	476,0	475,3	475,2	17,5	17,5	17,2	0,7	3,2	3,4	3,2
30/05/12	12:22:00	481,8	481,2	481,4	16,2	16,1	15,9	0,7	4,6	4,8	4,5
30/05/12	12:23:00	480,7	480,2	480,4	15,0	15,0	14,8	0,6	3,2	3,3	2,9
30/05/12	12:24:00	482,1	481,7	482,2	14,4	14,5	14,4	0,6	3,5	3,6	3,4
30/05/12	12:25:00	483,5	483,1	483,4	14,3	14,3	14,2	0,6	3,4	3,4	3,2

Table 5 - Energy Consumption in ER22 in a Week

ENERGY CONSUMED	
EA+..:	"972.810 kWh"
EA-..:	"-2.791 kWh"
ER+..:	"1310.713 kVArh"
ER-..:	"-0.037 Varh"

Table 6 - Measurement of Electrical Parameters in ER28

DATE	TIME	VOLTS U1-U2	VOLTS U2-U3	VOLTS U3-U1	AMPS U1	AMPS U2	AMPS U3	POWER FACTOR	THD VOLTS U1	THD VOLTS U2	THD VOLTS U3
30/05/12	12:10:00	476,9	478,0	476,9	11,9	12,4	12,4	0,3	5,1	4,8	5,3
30/05/12	12:11:00	477,7	478,2	477,8	12,2	12,5	12,4	0,3	2,8	2,9	3,0
30/05/12	12:12:00	480,7	481,6	480,8	12,2	12,6	12,5	0,3	3,5	3,6	3,8
30/05/12	12:13:00	480,0	480,6	480,0	12,1	12,5	12,4	0,3	4,8	4,5	5,0
30/05/12	12:14:00	478,2	479,1	478,3	12,0	12,4	12,3	0,3	5,9	5,5	6,1
30/05/12	12:15:00	482,0	482,2	481,6	12,4	12,7	12,4	0,3	2,4	2,5	2,5
30/05/12	12:16:00	474,1	475,1	474,2	12,0	12,5	12,3	0,3	4,2	4,0	4,3
30/05/12	12:17:00	479,0	479,9	478,8	12,0	12,5	12,3	0,3	4,2	3,8	4,3
30/05/12	12:18:00	478,2	478,6	478,1	12,0	12,3	12,1	0,3	2,8	2,7	3,0
30/05/12	12:19:00	480,6	481,1	480,1	12,2	12,7	12,4	0,3	3,6	3,5	3,7
30/05/12	12:20:00	481,1	481,7	480,9	12,1	12,5	12,3	0,3	4,1	4,1	4,3
30/05/12	12:21:00	477,8	478,4	477,4	11,6	11,9	11,8	0,1	3,3	3,2	3,4
30/05/12	12:22:00	482,5	483,1	482,2	12,1	12,5	12,2	0,3	4,6	4,4	4,8
30/05/12	12:23:00	481,2	481,9	481,1	11,7	12,0	11,9	0,1	3,1	3,3	3,4
30/05/12	12:24:00	483,1	483,4	482,7	12,1	12,5	12,2	0,3	4,1	4,0	4,3
30/05/12	12:25:00	484,0	484,4	483,5	12,3	12,7	12,5	0,3	3,5	3,5	3,7

Table 7 - Energy Consumption in ER28 in a Week

ENERGY CONSUMED	
EA+..:	"329.602 kWh"
EA-..:	"-66.951 kWh"
ER+..:	"1390.836 kVArh"
ER-..:	"-0.004 VArh"

VI. Result Analysis

Parts of spreadsheets developed from measurements are presented below in Tables 8 and 9 and Graphics 1 and 2. These tables and graphics show mean values and standard deviations of various electrical parameters measurements, observing for example: Power Factor PF medium found for ER22 was 0.56 and 0.18 for ER28; the observed average Active Power for ER22 was 6.8 KW and the ER28 1.8 KW.

Table 8 - Average Values of Electrical Parameters of ER22

Statistical Calculations	Apparent Power (S) Trif. in KVA	PF Trif. average per 15 min block	Active Power (P) Trif. in Watts (kW)	Demand Active Power (P) Trif. Measured in KW per 15 min block.	Active Energy (P) Trif. Measured in kWh	THD VOLTS U1 em %	THD VOLTS U2 em %	THD VOLTS U3 em %	Medium Voltage between Phases in Volt	Average current between phases in Amper
Average value of measures in one minute intervals	11,6	0,56	6,8	8,9	1,7	4,0	4,2	4,0	474,0	14,1
Maximum value of measures in one minute intervals	17,6	0,80	14,2	26,8	3,4	10,3	10,5	10,7	485,4	21,6
Minimum of measures in one minute intervals	8,9	-0,03	2,2	2,9	0,2	1,6	1,5	1,4	455,3	11,0
Standard	2,2	0,1	3,2	3,2	0,7	1,4	1,4	1,5	4,9	2,8

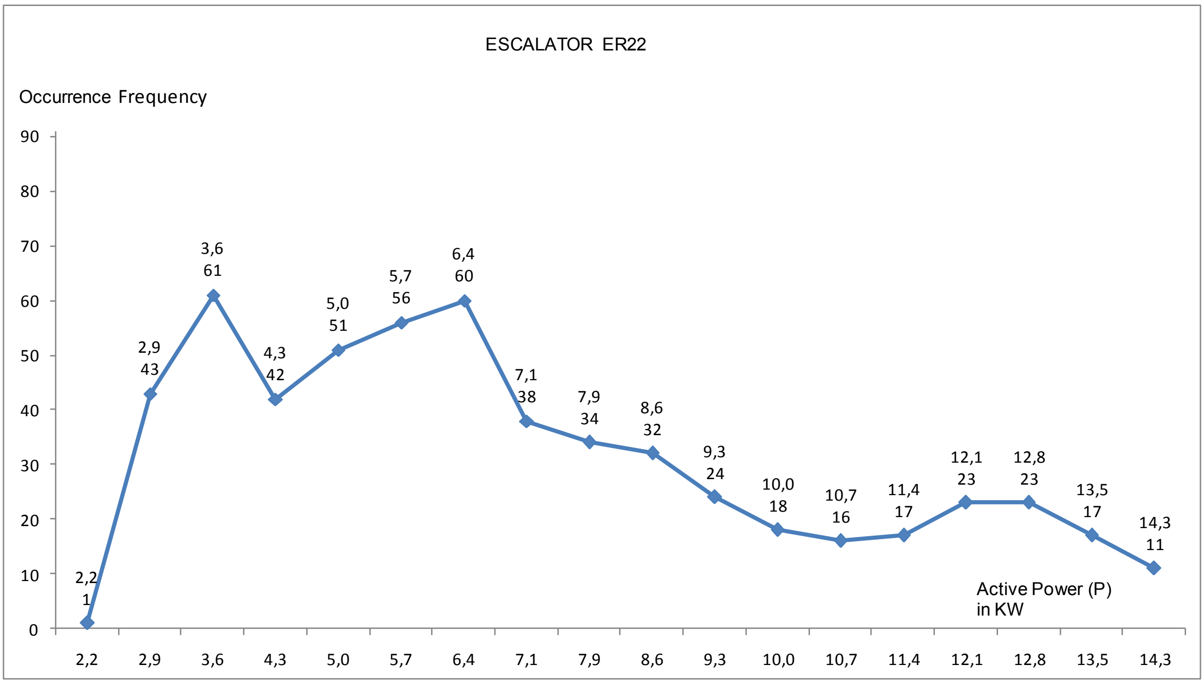
Table 9 - Average Values of Electrical Parameters of ER28

Statistical Calculations	Apparent Power (S) Trif. in KVA	PF Trif. average per 15 min block	Active Power (P) Trif. in Watts (kW)	Demand Active Power (P) Trif. Measured in KW per 15 min block.	Active Energy (P) Trif. Measured in kWh	THD VOLTS U1 em %	THD VOLTS U2 em %	THD VOLTS U3 em %	Medium Voltage between Phases in Volt	Average current between phases in Amper
Average value of measures in one minute intervals	10,0	0,18	1,8	3,4	0,5	3,9	4,0	3,8	474,2	12,1
Maximum value of measures in one minute intervals	11,7	0,35	3,8	10,3	0,9	11,2	10,1	10,6	484,7	14,0
Minimum of measures in one minute intervals	8,7	-0,57	-5,3	2,5	-0,2	1,4	1,5	1,4	453,1	10,9
Standard Deviation	0,4	0,1	2,2	0,3	0,2	1,6	1,4	1,5	4,6	0,4

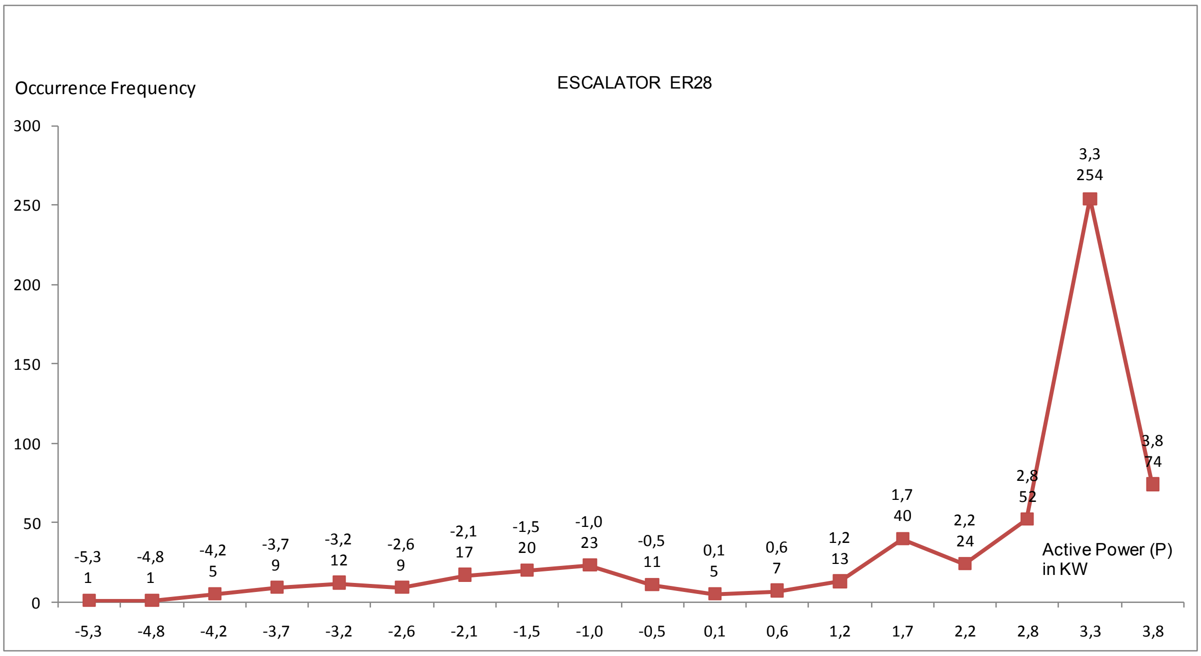
These various values of active power and frequencies contained in the graphics 1 and 2 have a positive correlation with user flow at the station. So the higher the flow of users on the treadmill higher your energy consumption.

The incidence of negative values in the active power contained in graphic 2 are related to the moments that the escalator was too full of users and working to descend. These values indicate that the engine was regenerating energy to the low voltage system.

Graphic 1 - Histogram of Active Power (P) of ER22



Graphic 2 - Histogram of Active Power (P) of ER28



VII. Energy Estimates and Financial Indicators

The active power installed for this set of motor was calculated to be 7.1 Mega Watt. If modernization is performed in 385 escalators, the estimated reduction in energy consumption of 788 MWh / year and a consequent reduction of CO2 emissions estimated at three hundred ninety-seven tons per year (397 Ton. CO2/year). Used as reference to calculate the reduction of the CO2 value of 504 kg CO2 per 1,000 kWh consumed, as defined by IEA - International Energy Agency.

It is noticed that with the calculations performed in Table 10, the scaling motor is possible in all 385 escalators installed motor with more than 20 years and has already surpassed its useful life. It was considered for calculation of the average energy consumed measured in escalators Itaquera 22 and 28, the gaps and the induction of these same values for all the stairs through the scope of proportionality energy consumption with their respective gaps.

Table 10 - Estimates of Energy and Power Motors

CURRENT DATA						ESTIMATED DATA				
Motor Capacity	ELEVATION [m]	Number of Motors	Nominal Power KW Installed in Motor Current	Average Value Pot. KW	Average Value of Total Power in KW	Estimated Total Saved Energy in kWh / year	Estimated Reduction in CO2 Emissions in Ton / year	Capacity in CV for New Motor	Capacity in KW for New Motor	Future Nominal Power in KW for New Motor
15 CV	3,36	3	33,12	2,1	6,3	9922,5	5	10	7,36	22,08
15 CV	3,68	6	66,24	2,3	13,8	10867,6	5,5	10	7,36	44,16
15 CV	3,84	5	55,2	2,4	12	11340,1	5,7	10	7,36	36,8
15 CV	4	20	220,8	2,5	50	11812,6	6	10	7,36	147,2
15 CV	4,16	13	143,52	2,6	33,8	12285,1	6,2	10	7,36	95,68
15 CV	4,32	7	77,28	2,7	18,9	12757,6	6,4	10	7,36	51,52
15 CV	4,48	5	55,2	2,8	14	13230,1	6,7	12,5	9,2	46
15 CV	4,64	17	187,68	2,9	49,3	13702,6	6,9	12,5	9,2	156,4
15 CV	4,8	12	132,48	3	36	14175,1	7,1	12,5	9,2	110,4
20 CV	4,48	5	73,6	2,8	14	13230,1	6,7	12,5	9,2	46
25 CV	4,96	2	36,8	3,1	6,2	14647,6	7,4	12,5	9,2	18,4
25 CV	5,12	33	607,2	3,2	105,6	15120,1	7,6	12,5	9,2	303,6
25 CV	5,28	19	349,6	3,3	62,7	15592,6	7,9	12,5	9,2	174,8
25 CV	5,44	16	294,4	3,4	54,4	16065,1	8,1	12,5	9,2	147,2
25 CV	5,6	17	312,8	3,5	59,5	16537,6	8,3	15	11,04	187,68
25 CV	5,76	9	165,6	3,6	32,4	17010,1	8,6	15	11,04	99,36
25 CV	5,92	8	147,2	3,7	29,6	17482,6	8,8	15	11,04	88,32
25 CV	6,24	53	975,2	3,9	206,7	18427,6	9,3	15	11,04	585,12
25 CV	6,4	2	36,8	4	8	18900,1	9,5	15	11,04	22,08
25 CV	6,56	16	294,4	4,1	65,6	19372,6	9,8	15	11,04	176,64
25 CV	6,72	14	257,6	4,2	58,8	19845,1	10	20	14,72	206,08
25 CV	6,88	8	147,2	4,3	34,4	20317,6	10,2	20	14,72	117,76
30 CV	6,56	6	132,48	4,1	24,6	19372,6	9,8	15	11,04	66,24
30 CV	6,72	1	22,08	4,2	4,2	19845,1	10	20	14,72	14,72
30 CV	6,88	15	331,2	4,3	64,5	20317,6	10,2	20	14,72	220,8
30 CV	7,2	23	507,84	4,5	103,5	21262,6	10,7	20	14,72	338,56
40 CV	7,52	4	117,76	4,7	18,8	22207,6	11,2	20	14,72	58,88
40 CV	7,68	1	29,44	4,8	4,8	22680,1	11,4	20	14,72	14,72
40 CV	7,84	4	117,76	4,9	19,6	23152,6	11,7	20	14,72	58,88
40 CV	8	1	29,44	5	5	23625,1	11,9	20	14,72	14,72
40 CV	8,16	4	117,76	5,1	20,4	24097,6	12,1	20	14,72	58,88
40 CV	8,32	1	29,44	5,2	5,2	24570,1	12,4	20	14,72	14,72
40 CV	8,48	4	117,76	5,3	21,2	25042,6	12,6	20	14,72	58,88
40 CV	8,64	2	58,88	5,4	10,8	25515,1	12,9	20	14,72	29,44
40 CV	8,8	5	147,2	5,5	27,5	25987,6	13,1	20	14,72	73,6
40 CV	8,96	3	88,32	5,6	16,8	26460,1	13,3	25	18,4	55,2
40 CV	9,44	6	176,64	5,9	35,4	27877,6	14,1	25	18,4	110,4
40 CV	10,56	3	88,32	6,6	19,8	31185,1	15,7	25	18,4	55,2
40 CV	12	10	294,4	7,5	75	35437,7	17,9	30	22,08	220,8
40 CV	12,48	2	58,88	7,8	15,6	36855,2	18,6	30	22,08	44,16
Total		385	7135,5		1464,7	788133,7	397,2			4392,1

Economic financial indicators allow to verify adherence to this project of energy efficiency and could be presented as a possible project to the Eletrobrás considering the RCB of 0.62 (Figure 4) for the worst scenarium of energy coast.

Eletrobrás is holding of the Brazilian Power System that controls around 60% of the national electricity generation, 60% of the transmission grid and some distribution utilities. This project is "Programa Nacional de Conservação de Energia Elétrica" (National Electricity Conservation Program) PROCEL if the ratio of cost to benefit (RCB) is less than 1 (RCB <1), the project is viable.

Figure 4 - Simulation of the indicator "RCB" in Excel

B17 f_x =(B24 *B26) / (B28 * B30)

	A	B
16		
17	Ratio of Cost to Benefit (RCB) =	0,62
18	$RCB = \frac{CC \times FRC}{Ec \times Tarifa}$	$FRC = \frac{i(1+i)^n}{(1+i)^n - 1}$
19		
20	R$2,39 (Brazil) = $1,00 (USA)	
21		
22	Input data	
23		
24	CC (initial cost for installation of motor, frequency converter and PLC) =	58133,4
25		
26	FRC (capital recovery factor) =	0,10
27		
28	Ec (kWh / year) =	36672,20
29		
30	Rate or "Tarifa" (R$ / kWh) =	R$ 0,25
31		
34	Operating hours per day =	19,6
35		
36	Operating days per year =	365
37		
38	Average energy required in kWh per hour =	9,5
39		
40	Estimated percentage of energy savings =	54,0%
41		
42	Life of the new equipment in years =	20,0
43		
44	Rate of funding per year =	7,4%

In the worst case (Figure 5) the indicator MIRR Payback resulted in approximately 10 years for the return of investment depending on the savings of estimated energy.

Figure 5 - Simulation of the indicator "MIRR Payback" in Excel

B19 f_x =LN(2) / (LN(1 + B15))

	A	B	C
1	Cost of electricity per kWh:	R$ 0,25	
3	Estimated energy savings in kWh per year:	35548	
5	Scenario where the value KWh energy decreases in the annual rate:	0,02	
7	Initial cost for installation of motor, frequency converter and PLC	(R$ 58.133,40)	
9	Financing Rate	7,4%	
11	Reinvestment Rate and Cost of Capital	5,1%	Year 1
13	Cash Flow	(R$ 58.133,40)	R$ 8.709,27
15	MIRR (Modified Internal Rate of Return)	7,3%	
17	MIRR = $\left(\frac{-VPL(taxa\ r, valores[positivos]) * (1 + taxa\ r)^n}{VPL(taxa\ f, valores[negativos]) * (1 + taxa\ f)}\right)^{\frac{1}{n-1}} - 1$		
19	Payback MIRR (year) = LN(2) / (LN(1 + MIRR))	9,8	

The active potency installed in these motors, calculated in 7.1 Mega Watt (Table 10), suggests that the equipment involved is a great option for modernization, as its lifetime is improved and great potential for energy savings.

If modernization is performed in 385 escalators, the estimated reduction in energy consumption of 788 MWh / year (Table 10) and a consequent reduction of CO2 emissions estimated at three hundred ninety-seven tons per year (397 Ton. CO2/year).is expected.

VIII. Conclusions

The analysis of the simulations, figures and statistics on the various factors and proposed scenarios, we can conclude:

This modernization project of the escalators are compatible with the concepts of energetic efficiency, vision and mission of the Companhia Metropolitano de São Paulo and relevant legislations. All these calculations were possible due to the advanced technology of these equipment's, associated with affordable coast.

In this case study we conclude that the variable-input users on the station has direct relationship with the variables related to variable consumption of energy, load and power of the motors.

It can be concluded that the escalator ER22 station Corinthians Itaquera (which is in the right direction, i.e. in the same direction as the flow of incoming passengers at this station) has very good correlation with the variable power with input users at the station, Amps current in the motor load at the tip of the motor shaft.

The estimates of energy savings (Table 10) over the costs of financial investment (Figures 4 and 5) for this modernization project indicate that the project has great feasibility. This takes into account the possibility that even in the worst scenario the cost of energy supply financial returns before the half lifetime of the equipment that were planned for this modernization.

The current state of art of technology combined with high adherence of measurements, analysis and simulations indicates (Figures 4 and 5) great potential of feasibility. In calculating the RCB value was used for 20 years to the life of the set of new equipment.

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Global Warming Potential propels NEMA motor section actions

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Background

The National Electrical Manufacturers Association (NEMA) Board of Governors annually looks at key issues that bear potential to impact the electroindustry. A key requirement is that the issues that are examined have not been previously addressed by NEMA in the context of either as a threat and/or opportunity to NEMA member manufacturers. If those requirements are met, then that issue will be considered to be designated as a NEMA Strategic Initiative (NSI). It is confirmed as a NSI after determination and evaluation of the resources needed to secure a good outcome of the NSI. Each NSI is evaluated and audited on an annual basis to determine if goals have been met, and whether the NSI has been completed or needs to be dropped or continued.

The NEMA Board of Governors evaluated a carbon footprint study as both a potential challenge and opportunity for its members.

Abstract

This paper addresses two key areas of climate change concern. First, we document an in-depth carbon footprint study by MIT's Material Systems Laboratory. The study, funded by NEMA, developed a scalable, quantitative methodology to estimate the global warming impact associated with electro-industrial products. Two key metrics to quantify the impact of a product on the environment are energy use and life cycle greenhouse gas (GHG) emissions, the latter often referred to as a product's "carbon footprint." Accurately calculating a product's carbon footprint can be a challenging task due to the complexity inherent in most products. To that end, a methodology, called the Product Attribute to Environmental Impact Algorithm (PAIA), has been developed that relates the intrinsic attributes of electro-products to their GHG emissions. This approach reveals opportunities to reduce the environmental impact of products under review by identifying the key drivers of GHG emissions. The assessment considers emissions throughout a product's overall life cycle including materials acquisition, manufacturing, use, and final disposal.

Next we describe and document the most recent regulatory and advanced product development initiatives being taken by the members of the NEMA Motor Generator section to address the MIT report's findings. By teaming together, the overall impact being made by NEMA has been calculated to reduce annual energy requirements by over 4 Twh, while maintaining the necessary product utility of industrial and commercial polyphase motors in the USA required to deliver performance and fit to motor users and OEMs.

Introduction

Characterizing the GHG emissions or "carbon footprint" of a product generally requires a comprehensive life cycle analysis (LCA), proceeding from raw material extraction and transportation to manufacturing, distribution, consumer use, and end-of-life disposal. Such efforts are resource-intensive, complex, and fraught with uncertainty due to the dynamics of supply chains, multitude of parts within a product, and lack of comprehensive life cycle inventory data. An alternate approach is to identify the principal "drivers" of carbon impact within a product and characterize how changes in those drivers impact the total footprint.

There is presently no broadly applicable standard methodology for the electro-industry to determine this impact. An approach that maps the intrinsic attributes of electro-products to GHG emissions can reveal opportunities to reduce the carbon impact of electrical products. This has potential implications not only for sustainability, but also for marketing strategies and profitability. The work presented here covers the impact of motor products and similar work has also been conducted for light bulbs, ballasts and connectors.

Motor products

Electric motors are responsible for 40% of global electricity usage, most significantly driving pumps, fans, compressors, and many other mechanical traction equipments. The International Energy Agency (IEA) estimates 7% of global electricity demand could be saved through the use of higher energy efficiency motors (IEA, 2006[1]). Very limited research has been reported on the carbon footprint quantification and methodology development for motor products. The company ABB has launched an online calculator that will help users minimize the carbon footprint of industry's largest user of electricity, the electric motor (ABB, 2011[2]), however, this method is tailored to ABB's own products. A more recent study (Torrent et al., 2012[3]) reports using the Methodology for the Ecodesign of Energy Using Products to assess the influence of certain design parameters in the environmental impact of three-phase induction motors.

The NEMA members of the Motor & Generator Section (1MG) took part in this MIT study to better understand and evaluate the electric motor's carbon footprint. The study's determination that electric motors have a 99.8% of their GHG impact in the use stage, confirmed the need for NEMA to continue programs supporting the application, design and selection of motors and motor driven systems as a leading method of reducing GHG in the industrial and commercial market segments.

Methodology

The focus of this project is to provide a high-level guideline for use by the electro-product industry in identifying the "hotspots" for carbon impact along product supply chains. The Product Attribute to Impact Algorithm (PAIA) method has been developed for this purpose. This procedure could also help a company identify the impact of potential mitigation strategies and prioritize supplier data collection efforts. There are three core steps involved in the methodology including a high level triage assessment, attribute investigation and finally, PAIA model development and application.

High level triage assessment

First, a high level triage assessment is performed using data from publicly available literature and data sets. We identified and aggregated several sources of data by reviewing the academic literature concerning LCA of related or similar products, commercial life cycle inventory databases, existing industry analyses of components or products of interest, and some limited primary data collection activities. These data were carefully examined and comparably evaluated, with the aim of creating the best possible preliminary estimate through the use of existing data. Where data are lacking, we developed engineering process models or data collection procedures with the participating NEMA member companies. The analysis pays particular attention to quantifying the uncertainty associated with the data as a function of the age, source and appropriateness of the data.

Using the preliminary or high level model, we performed Monte Carlo statistical simulations for uncertainty and sensitivity analysis. The objectives of this step were to prioritize further data collection efforts and potentially minimize uncertainty in the footprint result. Understanding uncertainty helps to improve confidence in footprint comparisons as well as any decisions that might be made based on the footprint. It also is a good way to decide whether to emphasize primary or secondary activity data for a particular process/emission source (BSI, 2008[4]).

A contribution analysis was undertaken to sort the impacts of components within the product to determine the subset of phases, components or materials that make up the majority of the GHG impact. In addition, the contribution analysis allows us to identify which activities contribute most to the variance of the result to understand which activities can be targeted to lower the overall uncertainty in the result.

Attribute investigation

The goal of attribute investigation is to identify important attributes or characteristics of the product under evaluation based on the high impact activities identified in the previous step. First, a list of candidate attributes is compiled and then narrowed through discussions with experts in the industry and review of publicly available data. This step aims to enable scaling across the set of products within a product class, so that individual assessments for every product can be avoided. This step may also eventually improve design efficiency by assessing impact from high-level product information based on common product attributes.

PAIA-based model development and application

In the final step, the areas that contribute to a significant level of the total impact are mapped to relevant product attributes to form the algorithms that underlie the PAIA model. As an example of this last activity, we have worked to find relationships between certain product attributes and the general bill of activities for the AC motor product. For the motor, we have data on the products' attributes (horsepower, poles, enclosure, efficiency class, etc.), as well as the corresponding total mass and use efficiency (activities). Through statistical regression the mass (by kg, related to the materials, manufacturing and distribution phases) and efficiency (by %, related to use stage) could be related to carbon impact for any a particular AC motor product, accompanied by the attendant uncertainty.

System Boundaries

The analysis encompassed raw materials extraction, transportation, conversion processes, assembly and manufacturing, use and end-of-life disposal activities (see Figure 1). The life cycle inventory for a product combines information regarding the product's bill of materials (BOM) with supply chain data on energy use, emissions in manufacturing, transportation and use known as the bill of activities (BOA).

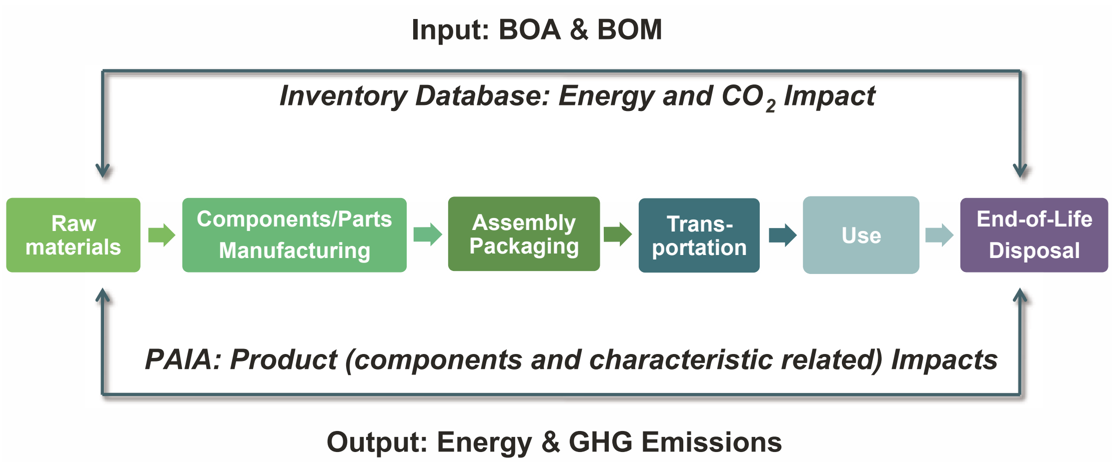

Figure 1 Overall system boundary for life cycle impact calculation

Product description

For this study, small/medium-sized polyphase AC motors, which constitute the most prevalent motor types by market share, were chosen as the focus of this analysis. The materials within this product category include steel of various grades (including electrical grade), cast iron, aluminum, copper, electronics, plastics, and packaging and insulation material. The analysis also includes the wiring necessary to connect a motor to an electric supply as well as the internal cabling.

The use phase for the AC motor was given particular emphasis in the analysis, focusing on intensive use scenarios. The functional unit will be framed in terms of the output power and speed of the motor. The use phase assessment will also reflect the change in efficiency over the lifetime of the motor to develop common load profiles for these products that may be transferable to multiple product categories.

Calculating impact

As mentioned above, the BOA is a list of product activities, such as masses of materials, content of components, energy use parameters as well as transportation distances and modes. This information is combined with the GHG emissions data related to materials extraction, manufacturing activities, fuel consumption and electricity production, available from commercial and public databases or literature. These include the CO_2-equivalent emissions value per activity, which is a list of supply chain emissions describing quantities of greenhouse gas emissions associated with delivering a unit of activity (e.g., CO_2 emitted per kilogram of aluminum). To determine the overall impact the BOA is multiplied by the relevant emissions factors and combined with the uncertainty ranges as described above.

Data limitations

The reliability of the results and the conclusions of the LCA depend in large measure on the quality of the inventory data that is used. Throughout the research process, NEMA and its member companies collaborated to provide the necessary data as quickly and accurately as possible. Bill of materials information is therefore viewed as reliable because it was supplied and vetted carefully by company representatives. However, there are several limitations to the approach used for this study. Primary data on energy consumption during the manufacturing and assembly of the focal products was not available. Primary data on the impacts of end-of-life stage activities are also missing. There is also incomplete information on details concerning transportation (distribution stage), although, as will be shown this is not expected to contribute significantly to the product’s lifecycle emissions.

In addition, there are sources of uncertainty in the life cycle inventory data, such as the assumed emissions factors and data obtained from the ecoinvent database. This uncertainty may arise from measurement error, variation within processes, temporal discrepancies, and geographical distributions. There is also substantial uncertainty within data drawn from the literature due to differential system boundary definition. As mentioned above, the use of Monte Carlo simulations is incorporated into the PAIA-based model to focus the effort used to understand uncertainty around the most sensitive aspects of the results.

Results

Evaluation of the GHG emissions throughout the overall life cycle of the AC motor (25HP, general purpose, 6-pole, cast iron, premium efficiency, and total fan cooled enclosure) is shown in Figures 2 and 3. The study shows that the use phase dominates other phases in terms of energy consumption, comprising more than 99.8% of the impact. Materials and manufacturing combined are responsible for less than 0.5% of total life cycle carbon emissions. The manufacturing burden is a bit lower than the materials burden. However, it is clear that the assumptions for the use phase can influence the overall results quite significantly.

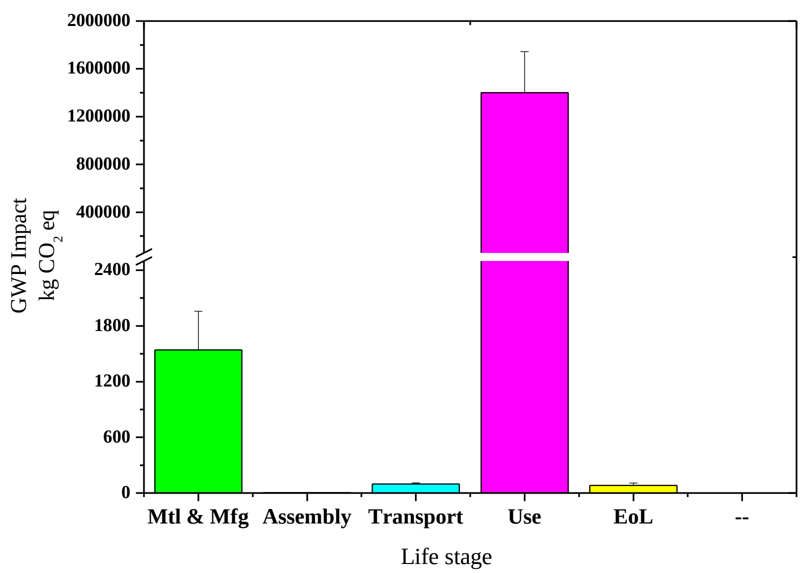

Figure 2 Overall life cycle impact, expressed as global warming potential, of a typical 25 hp NEMA Premium electric motor, operated for 5,000 hours/year over 20-year lifetime powered by an average US electricity grid mix. This is based on a general purpose, 6-pole, cast iron, premium efficiency, and total fan-cooled enclosure.

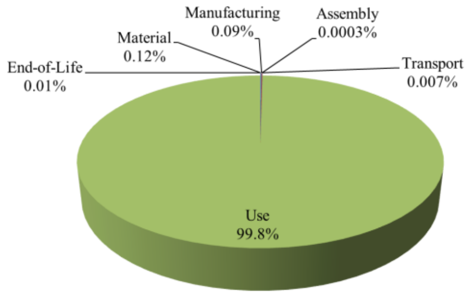

Figure 3 Percentage impact of a typical 25 hp NEMA Premium electric motor, operated for 5,000 hours/year over 20-year lifetime powered by an average US electricity grid mix.

Materials and Manufacturing Impact

When the use stage is excluded, the importance of certain components becomes evident, as shown in Figure 4. A handful of parts dominate the impact caused by parts production. These are, in order of importance: the rotor, the stator, and the frame. Together these constitute almost 90% of the materials and manufacturing footprint.

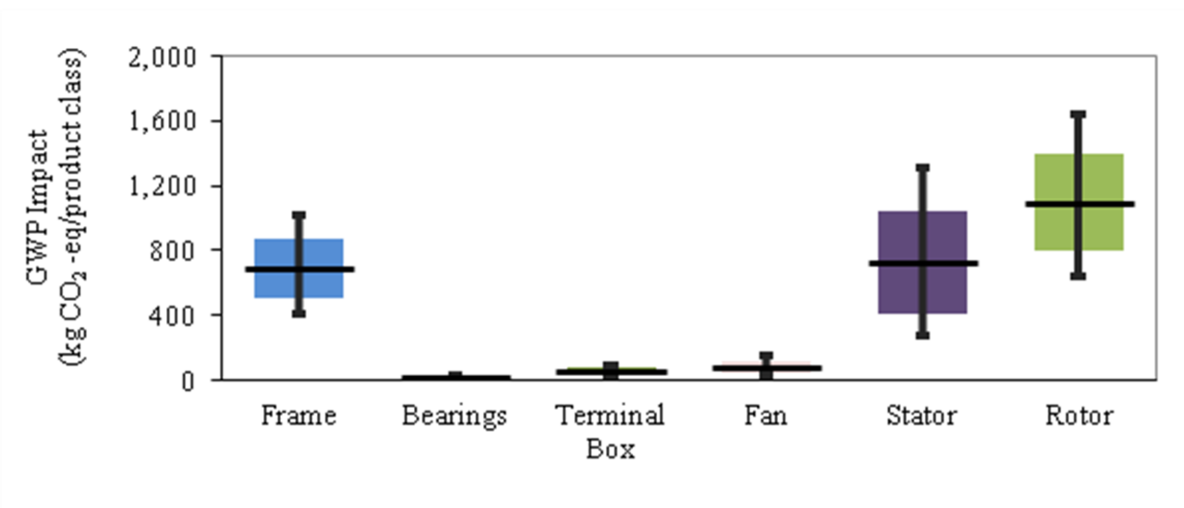

Figure 4 Impact of major components for a 25 HP NEMA premium motor.

We also looked at the impact of a specific motor product broken down by the major materials as sown in Figure 5. Steel makes up more than half of the materials GHG emissions (mean value), followed by cast iron (31%). The main reason for the dominance of these two materials is that they account for 85% of the total motor mass. The AC motor product uses a large amount of ferrous metals.

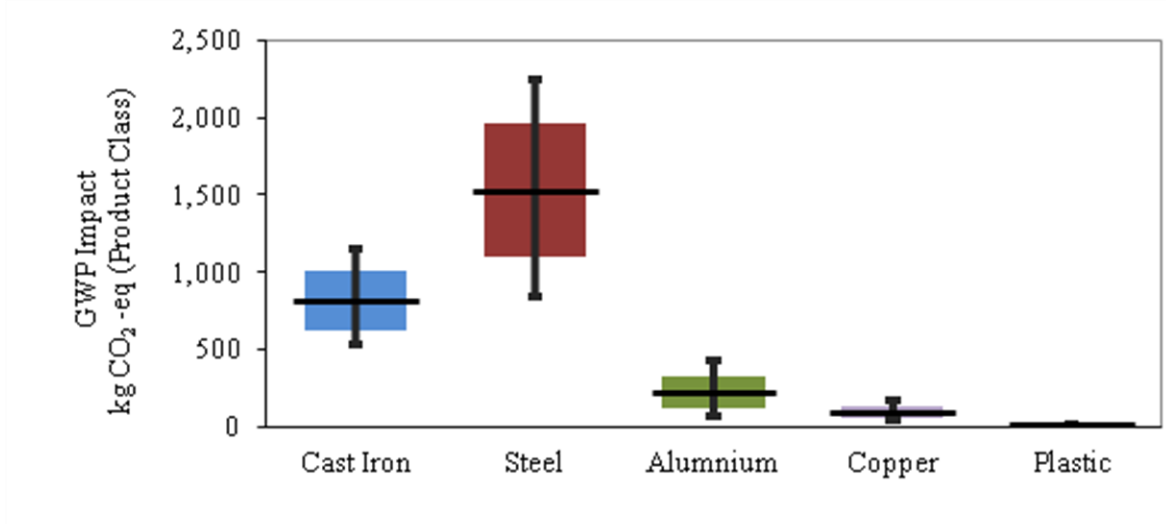

Figure 5 Impact evaluated by materials for 25 HP NEMA premium motor.

Impact of an undefined AC motor

The PAIA-based model is developed to evaluate the GHG for a range of AC motor products based on the attributes identified in the sections above. The role of these analyses is to show the ability to scale impact across a series of products within the same general product category. Therefore, the general impact can be obtained across many products without having to perform a detailed assessment.

Materials and manufacturing impact

Based on the data from NEMA companies, the components list and mass fraction for the three types of AC motors are comparable and quite similar. This means that if we obtain the data for the total mass for a general purpose, three-phase NEMA AC motor, then the components list and mass fractions can be gathered accordingly. The total mass is influenced by the following attributes: construction type (cast iron, rolled steel, or aluminum), frame size (associated with the rated horsepower, speed, and construction type), poles (speed), enclosure type, and efficiency class.

As seen in Figure 6, the total mass for a cast iron AC motor product (general purpose, three-phase NEMA AC motor) is closely related to the frame size. The spread in the data is due to the variation in the number of poles, enclosure type and efficiency class, as well as manufacturer differences.

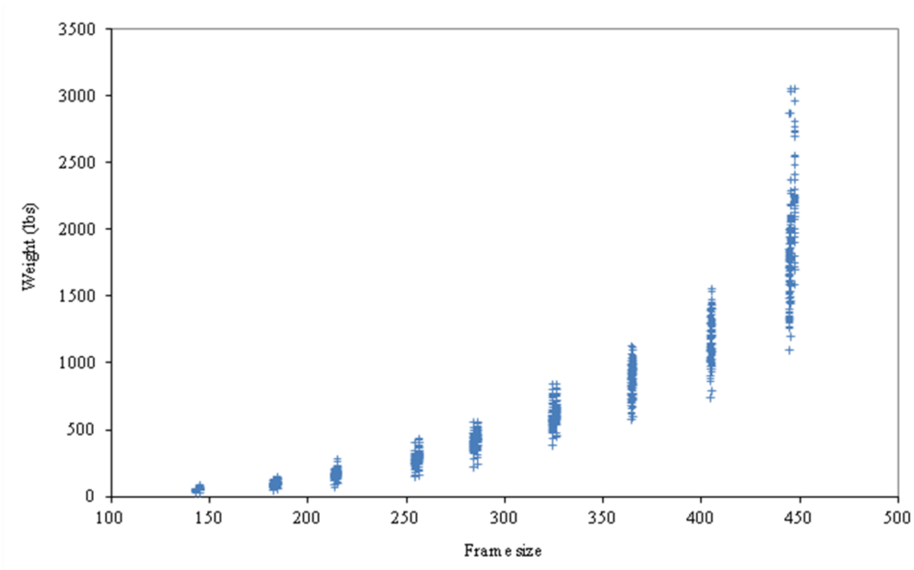

Figure 6 Weight data for AC motors of various frame sizes.

For a motor, the GHG emissions can be quantified in terms of both the attributes and mass information. While there are differences in the mass fraction and materials for each component across a set of motor attributes, we assumed that motors ranging from 1HP to 100HP have the same set of components and mass fraction of these components based on mass fraction data for 5HP, 25HP, and 100HP AC motors provided by NEMA members. As a result, we completed an analysis to quantify the GHG emissions in materials and manufacturing phases for motors ranging from 1HP and 100 HP, shown in Figure 7.

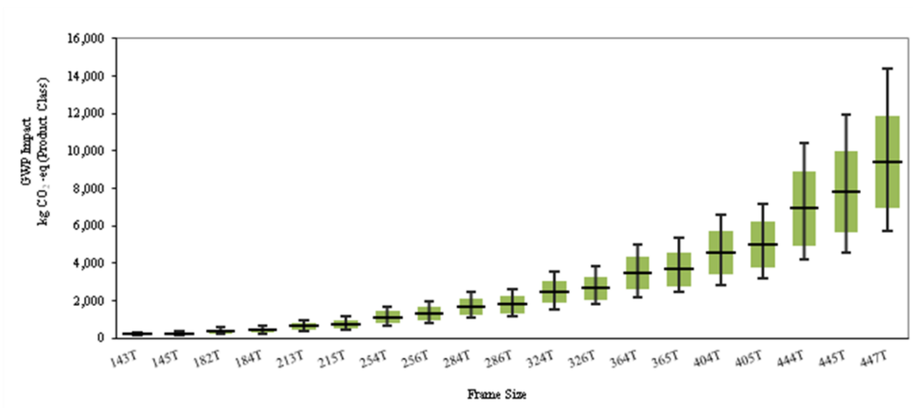

Figure 7 GHG impact for materials and manufacturing of AC motor product associated with frame size

Use phase

The GHG emissions impact during the use stage of a motor is directly influenced by the rated power, life span, service hours per year, and efficiency. An indirect parameter is the grid mix impact factor. Similar to the data gathering activities for the total mass of each AC motor from companies' product catalogues, we also gathered data for efficiency (as a percentage) associated with the horsepower, which is influenced by the frame size, enclosure type, and efficiency class, as well as by manufacturer as shown in Figure 8.

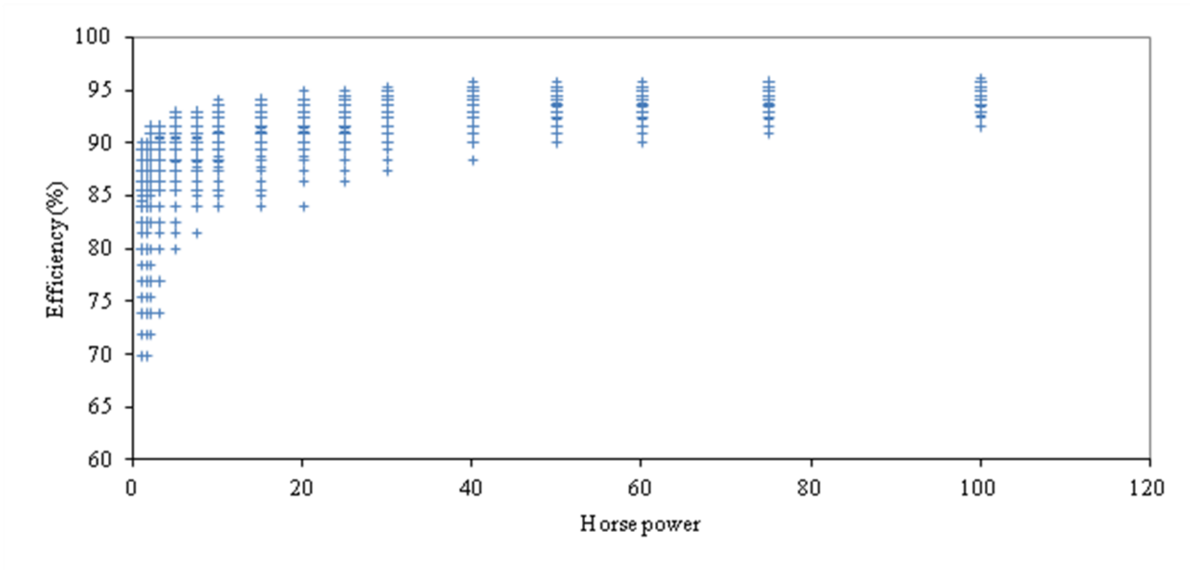

Figure 8 Efficiencies for AC motor products with various horsepower settings

Similarly, we conducted an analysis to quantify the GHG in use stage for any undefined motor based on the efficiency horsepower. Data assumptions include the lifetime of the motor is 20 years, and service time is 5,000 hours per year. The motor product is used in the U.S., thus the U.S. grid mix GWP is used. The resulting GHG impact by horsepower is shown in Figure 9.

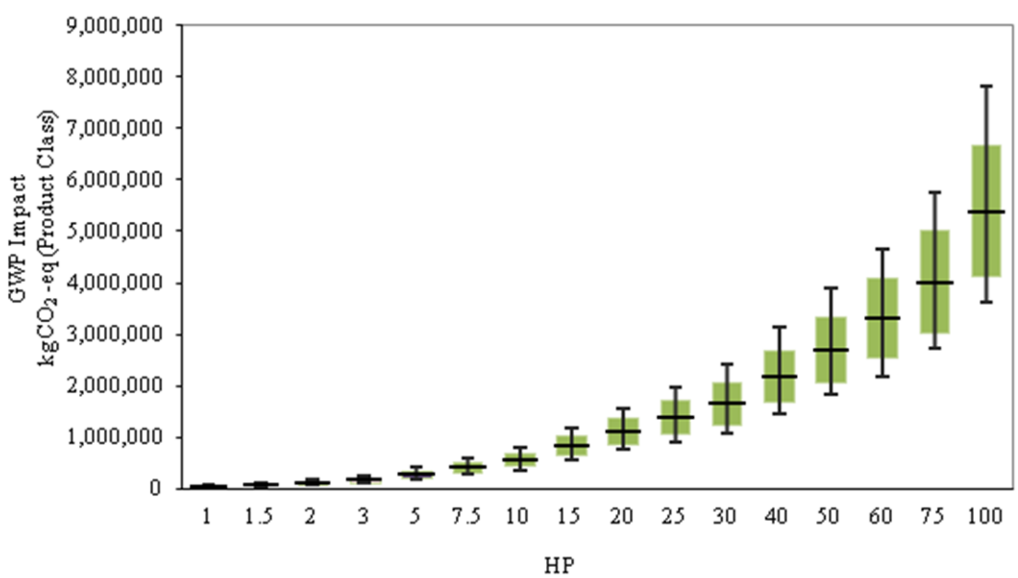

Figure 9 GHG impact for AC motor products (use stage only) associated with horsepower

US Department of Energy Motor Regulation

NEMA 1MG used results of the MIT study to help supplement suppositions of energy savings in a proposal made to the US Department of Energy (DOE) in response to the Department's intended regulatory activity regarding AC induction motors.

The NEMA 1MG introduced NEMA Premium® high performance motor standards in 2001 as a clear way for end users and OEM's to quickly identify polyphase motors having efficiency levels at or above NEMA Standard MG1, Table 12-12 or Table 12-13.

In preparation for a Department of Energy review of the Energy Independence Security Act 2007 (EISA), whose provisions included increased motor efficiency, those provisions also mandated DOE to begin review of motor regulation in 2010. In response 1MG began discussions with leading efficiency advocates. In reacting to potential increased DOE regulation, the NEMA 1MG Section formed a coalition with efficiency advocates. Called the Motor Coalition, the group explored gaps of AC motors not regulated by DOE. The gaps in motors not covered that the Coalition studied, revealed the potential for substantial energy savings. The Motor Coalition developed and studied a plan to expand motor efficiency regulation by broadening the scope of motor types and categories covered by efficiency standards.

The Coalition used existing data from 1MG member manufacturers as well as studies conducted by independent surveys. A picture of the motor market was developed that included reasonably accurate figures for the various horsepower ratings, as well as specific motor categories. The data captured not only the current definitions of covered product in type one and type two, it also added categories for definite, special purpose, partial motors and a host of other lessor categories. Next, the study broke down these categories using standard NEMA reporting power ranges (see Table One). Including a power level that allowed 1MG and advocates to accurately estimate the amount of energy saved per year. Using the MIT carbon footprint study to supplement studies affirming the life cycle value of higher efficiency motors, coupled with energy savings estimated by the Coalition, DOE's own estimates confirmed our supposition.

Of primary concern to manufacturers and OEM users, beyond energy savings, is the ability to maintain a motors necessary performance and utility, assuring interchangeability and retrofit capability for motor users in the USA. The Coalition also maintained a goal of acceleration of the adoption of premium efficiency levels for motors not covered in EISA.

1MG and the Coalition also determined that 56 frame TEFC motors above one HP not currently covered by regulation, should be added to the list of covered products for regulation. The 56 frame product would be required to meet the same efficiency levels as the corresponding 140 frame motors currently or proposed to be covered by regulation. 1MG has estimated over one million 56 motors would be added as a result. The total number of motors in these new categories that will be added to regulation requirements will exceed 4 million. This is significant increase from the present 1.6 million units estimated to be included in the EISA regulation, bringing the new total to 5.6 million motors covered by federal minimum efficiency standards. It was determined that over 66 categories and sub-categories could be added through the evaluation conducted by the Motor Coalition. 1MG members were required to verify that all of these 66 new motor categories could be built to meet the NEMA MG1, 12-12 or 12-13 efficiency levels without compromising form, fit, and function needed by the market and the NFPA National Electric Code. Once the 1MG members completed their review, the 66 categories were finalized in Table 2 below.

Table 0ne

HP Range and Type units	Table 12-12 Efficiency	DOE 1998 Average Installed Efficiency	Efficiency Percent gain	Estimated Kilowatts Saved per Hour	Estimated Kilowatts Hours Saved per year @ 4000 hours of operation
1 to and including 5 HP	89.5%	82.7%	8.2%	379,940	1,519,759,754
>5 to and including 20 HP	91.7%	86.8%	5.6%	417,403	1,669,612,146
>20 to and including 50 HP	94.1%	89.2%	5.5%	276,754	1,107,016,373
>50 to and including 100 HP	95.0%	91.9%	3.4%	144,238	576,950,419
>100 to and including 200 HP	95.4%	92.7%	2.9%	56,690	226,760,701
>200 to and including 500 HP	95.8%	93.4%	2.6%	46,078	184,310,307
Total Units					5,284,409,701

1MG used a conservative 4,000 hour of operation per year to calculate the 5.3 Twh savings. The Department of Energy and Lawrence Berkley National Lab [LBNL] used a more sophisticated model that not only includes the hours of operation, but also includes estimates for partial load and motor applications and captures the energy saved in generation and transmission. The resulting energy savings from LBNL is over 7.5 quads during the estimated life of the products.

Motor Coalition adds nearly 4 million units in four new categories

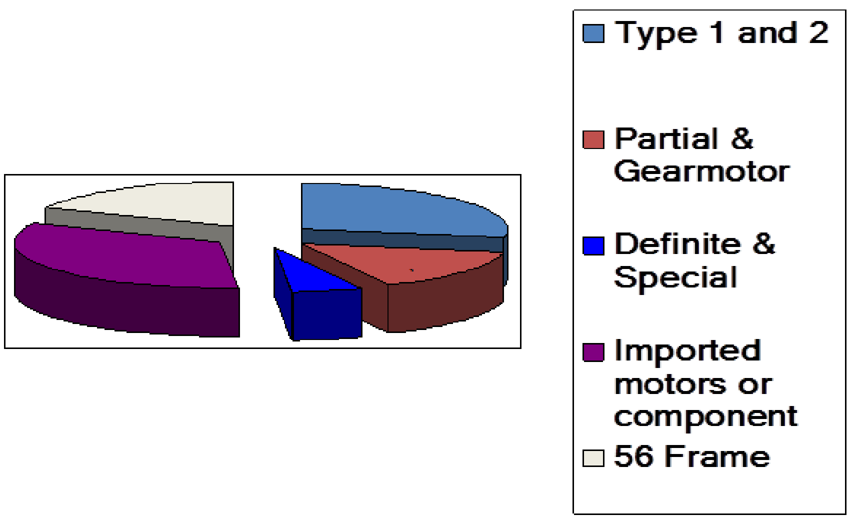

Table two
Motor Coalition Expanded Product Scope

Total 5.6 million units USA per year

After the results in Table 2 were completed the information was reviewed by the 1MG Energy Management Committee and the efficiency advocates to sort out any anomalies. The resulting data verified that by expanding the scope of motors to be covered by regulation the energy saved each year would be nearly 5.3 Twh.

The data, reasoning, and methodology were presented to DOE in a formal petition for a direct final rule in August 2012. Support for the petition has been expressed in letters to DOE written to support the Motor Coalition petition by states and numerous outside groups. DOE has not responded to the petition at this writing.

Conclusion

NEMA and its members consider energy efficiency a key component in its activities as an association. The paper presented offers a prime example of two important initiatives that interrelate to reinforce the NEMA commitment to promote energy efficiency in a smart meaningful way.

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A New Method to improve Installed Motor Efficiency

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Abstract

The paper will introduce a new method to improve installed induction motor efficiency. The method could improve induction motor efficiency from 1 to 2 grades by replacing current aluminum rotors with copper rotors, and not changing the stators. The prototypes have been developed and tested. The test results proved the method is workable. The prototypes test results and the computer simulation results on a series of small motors (< 30KW) were completed. The efficiency improvement potential by this method will be introduced. A pilot project has been established and this work will also be presented. The total energy saving potential and the possibility to develop a new efficiency standard for the rebuilt motor will be discussed.

1. Introduction:

As one of the most important power equipments in the production and daily life, motors play the role of converting electric energy into mechanical energy to drive mechanical equipment. The total electric power consumption in China in 2010 was 4,181.65 TWh. Among them, industrial electric power consumption reached 3,073.6 TWh, accounting for 73.5 percent of the total electric power consumption in the society. According to statistics, the total electric power consumption of motor in China in 2010 was 2,653.02 TWh, accounting for 63 percent of total electric power consumption in the society. Among them, the total electric power consumption of motors in the industrial system was 2307.63 TWh, accounting for 75.1 percent of the total electric power consumption in the industrial system[1].

It is because of the high ratio of motor electric power consumption in the industrial field that the motor energy-efficiency improvement possesses such important significance in promoting energy saving, environmental protection and sustainable development. If the motor efficiency can increase by 1 percent in China, the electric power saving can achieve 26.5 TWh valuing 26.5 billion yuan (US$4.27 billion), equivalent to carbon dioxide emission reduction of 26.5 million tons (1 ton CO2/MWh).

To date, all the major countries in the world have formulated and implemented the minimum energy efficiency standards for motors (MEPS). These standards require that the energy efficiency levels of all the newly-made motors should reach the compulsory minimum energy efficiency standards. The standards' formulation and implementation greatly pushed forward the motor energy-saving promotion work. But the current standards only focus on the newly-made motors, and they have no impact on the motors already installed and in use. Because of the large number of motors already installed and in use, they consume much more electric power than the newly-made motors do. If the efficiency of the motors already installed and in use can be improved, the motor energy-saving work will be effectively promoted.

The mechanisms of encouragement and compulsory eliminations are the dominant measures adopted in China to accelerate the substitution of installed low-efficiency old motors so as to increase the motor efficiency level and reduce motor energy consumption. But these mechanisms mainly depend on the administration order. It is relatively difficult to promote these mechanisms in large scale without the financial subsidy support. In addition, the difficulties to recycle the large quantities of eliminated old motors increase. As a result, the impact on the environment increases.

The International Copper Association (ICA) in cooperation with the Yunnan Copper Die Casting Technology Co., Ltd. (YCD) under the Yunnan Copper Co., Ltd put forward the scheme of using cast copper rotor to renovate low-efficiency motors for motor efficiency improvement for the first time. Beginning from 2010, the two sides jointly carried out research and development work of using copper rotor for in-use motor energy-efficiency improvement. The research results proved that the motor energy efficiency can achieve 1 to 3 percent improvement after the aluminum rotor is replaced by the specially designed copper rotors, improving the motor energy efficiency levels by 1 to 2 grades, namely from energy efficiency grade IE1 to IE2 and even to IE3, so as to achieve the renovation process from low-efficiency to high-efficiency motors.

The research results also proved that this method is simple and feasible. Compared with compulsory replacement of original old motors, this method can effectively reduce resource and energy consumption as well as discharge of the wastes for environmental protection, not only achieving energy saving and emission reduction, but also turning the waste materials into useful ones to prevent energy consumption for the recycling, smelting and processing of the waste materials which complies with the national industrial policies of resources saving and comprehensive application. The cost of using copper rotor is greatly lower than that of using the newly-made motor in replace of the old one, greatly shortening the period of return on investment which no doubt can arouse the end users' enthusiasm and greatly reduce the promotion difficulties in the in-use motor efficiency improvement.

2. Y-series motors in China:

Squirrel cage induction motors are the most used motors at present. Squirrel cage induction motors took a share of over 85% of the total middle and small motors output in 2007 in China[2]. Currently, squirrel cage induction motors are widely applied in industries, agriculture, national defense, commerce, public facilities and transportation, becoming an indispensible motor for all kinds of industries.

In China, the most popularly installed squirrel cage induction motor currently is the Y-series motor which was developed in 1982. The ICA in cooperation with the YCD redesigned the copper rotor of the Y-series motor and carried out relevant prototype motor tests.

The Y-series motor with the final design completed in 1982 as mentioned, which is the general-purpose fully-closed self-cooling squirrel-cage three-phase asynchronous motor, was designed by the relevant institutions organized by the Chinese government in 1979, complying with the power grades and installation dimensions specified in the international IEC standard and adopting the class-B insulation. The Y-series motor possesses following features:

- The Y-series motor's efficiency level is equivalent to IE1;
- The installation dimensions of Y-series motor and power grades fully comply with those specified in the IEC standard;
- The Y-series motor adopts the rated voltage of 380V, rated frequency of 50Hz and the wiring methods of "Y" for motor with rated power of 3 kW and below and "△" for motor with rated power of 4 kW and above.
- The Y-series motor is used for the general mechanical equipment without special requirements including fans, water pumps, machine tools and mixers.

The Y-series three-phase asynchronous motor can be classified into two basic series, namely IP23 (protection-type) and IP44 (closed-type). The features of the two series are briefly introduced as follows:

1. Features of the Y-series (IP23) three-phase asynchronous motor

The Y-series (IP23) motor is a three-phase protection-type cage asynchronous motor. Its protection structure type is different from the Y-series IP44's closed-type structure, but is superior to the general drip-proof type structure. It can prevent a finger from touching the live conductors or the rotating parts inside the motor chassis, avoid small solid foreign objects with diameter larger than 12 millimeters from entering the motor and prevent the falling of water at 60 degree angle or smaller between the water falling and the vertical directions from dripping into the motor. Therefore, the protection grade of the motor chassis of the Y-series (IP23) three-phase asynchronous motor is remarkably improved as compared with the old-type J2-series motor.

As a result, its operation is safer and more reliable. The Y-series (IP23) three-phase asynchronous motor's rated voltage, rated frequency and power range are 280V, 50Hz and 5.5 kW - 132 kW respectively. In addition, it has 14 power grades, 6 motor-base numbers and 45 specifications. The power grade and installation dimension of the whole series of motors comply with the IEC international standard. The motor synchronous rotational speeds include 3,000 rotations/min, 1,500 rotations/min, 1,000 rotations/min, 750 rotations/min and 600 rotations/min. Its coil-windings adopt the class-B insulation materials. All motors of this series adopt the A-type wiring method. Its cooling method is IC01.

2. Features of the Y-series (IP44) three-phase asynchronous motors

The Y-series (IP44) three-phase asynchronous motor is a general-purpose fully-closed fan-cooled cage-type asynchronous motor which is suitable for driving various types of mechanical equipment without special performance requirements including blowers, air compressors, water pumps and metal-cutting machine tools. Its rated voltage, rated frequency and power range are 380V, 50Hz and 0.55 kW - 160 kW respectively. It has 22 power grades. The motor synchronous rotational speeds include 3,000 rotations/min, 1,500 rotations/min, 1,000 rotations/min, 750 rotations/min and 600 rotations/min. Its cooling method is IC0141. Many different types of the derived series and special-use series of motors can be derived from the basic Y-series motors by suitably changing part of the electromagnetic structure design or processing technology.

The Y-series (IP44) three-phase asynchronous motor possesses the following good performance and structural features.

(1) Relatively high efficiency level. The Y-series (IP44) small three-phase asynchronous motor maintains the advantage of the relatively high efficiency level of the J02-series motor. Its weighted average value of efficiency is 0.413 percent higher than that of J02-series motor, achieving the international IE1 standard. The motor efficiency level improvement will bring the large electric power-savings and economic benefit to the society.

(2) Relatively good starting performance. The locked rotor torque value of all the Y-series (IP44) motors is 33 percent higher than the average locked rotor torque value of the J02-series motor. The starting torque achieves the high starting-torque level of the JQ02-series motor. The minimum torque is guaranteed to be 0.8 times higher than the rated torque. In addition, the torque of most of the motors achieves or exceeds one time of the rated torque. Therefore, its starting performance is very good. The starting of motor with load is also very smooth.

(3) Low noise and low vibration. The sound power noise standard is specified for the Y-series (IP44) three-phase asynchronous motors, which are classified into two grades, namely Grade I and Grade II, according to the noise limit values for customer's selection. As the bearings are specially designed for motors used in this series, the running noise is greatly decreased. The actual measured noise is 5 dB - 10 dB below that of J02-series motor. The vibration of the Y-series (IP44) motor is greatly reduced compared to the J02-series motor.

(4) Relatively good protection performance. The structural design of the Y-series (IP44) three-phase asynchronous motor meets the protection requirements against outside solid objects and water splashing, and can effectively prevent the foreign objects from damaging the motor and/or the human body.

(5) Reliable operation and long service life. The coil-winding of the Y-series (IP44) three-phase asynchronous motor adopts class-B insulation materials. When the altitude does not exceed 1,000

meters and the cooling-air temperature does not exceed 40℃, the temperature increase of the motor stator (resistance method) does not exceed 80K. Therefore, all the motors except for a few motor specifications have a temperature increase margin of at least 15K. This relatively big temperature increase margin can prolong the motor service life and improve the motor reliability.

(6) Good appearance. The main structural parts including motor end cover, junction box and fan cover of the Y-series (IP44) three-phase asynchronous motor looks much better than those of the traditional older products. The volume and weight of the whole motor series are on average 15 percent smaller and 12 percent lighter respectively than those of J02-series motor.

3. The prototypes development and performance analysis:

The energy efficiency level of the Y-series motor is equivalent to the IE1 efficiency level. By using the redesigned copper rotor with the original stator, the motor efficiency can be effectively improved while complying with the basic parameters of the original motor standard including the starting torque and starting current.

Through analysis and comparison, we selected two types of motors, namely Y132-4 motor with power of 7.5KW and Y160-4 motor with power of 11KW which are the most widely used and the most representative ones, for the redesign of the copper rotor under the condition of keeping the stator unchanged. Two design schemes were prepared for each motor type.

The YCD has already started commercial copper rotor production on a large scale in China by using the die-casting method[3]. Through the cooperation with them and based on the four different schemes, the corresponding copper rotors are made and installed on the existing Y-series motors with the unchanged stators for relevant tests. The results are shown in the following tables:

Table 1, Comparison of Y-132-4 7.5KW motor before and after rotor changing

	AL rotor	Cu rotor (Design A)	Cu rotor (Design B)
Efficiency	87.90%	89.18%	88.88%
Power factor	0.8623	0.8605	0.8534
Locked rotor current	6.7	7.49	6.29
Locked rotor torque	2.37	2.08	2.27
Maximum torque	2.72	2.76	2.23

Table 2, Comparison of Y-160-4 11KW motor before and after rotor changing

	AL rotor	Cu rotor (Design A)	Cu rotor (Design B)
Efficiency	90.07%	91.12%	91.25%
Power factor	0.8497	0.8492	0.8485
Locked rotor current	5.99	6.83	7.06
Locked rotor torque	2	1.96	2.21
Maximum torque	2.35	2.377	2.23

It is necessary to point out that the efficiency of the original Y-series aluminum rotor motor is the nameplate efficiency which is based on the old measurement method, namely the assumption method of the 0.5 percent of the stray load loss. While the motor efficiency level after using the copper rotor is measured by adopting the stray-loss actual measurement method according to the IEC60034-30 standard. If based on the old measurement method (0.5% stray load loss), the efficiency of 2 prototypes with copper rotors would be 90.42% and 92.22% respectively. That means 2.5% efficiency improved with only a change of the rotor.

According to the IEC600034-30 standard, the two motors with the efficiency level of IE1 achieved the efficiency level of IE3 after their rotors were replaced by the copper rotors.

We also designed copper rotors for the Y-series motor with power of 0.55 KW - 22 KW including 2, 4, 6 pole motors for efficiency improvement. Through computer simulation, all the 66 type motors of the Y-series achieved the efficiency level of IE2 after their rotors were replaced by the redesigned copper rotors. Among the 66 type motors, 80.3 percent, namely 53 type motors, achieved the efficiency level of IE3 after using the copper rotors. The efficiency improvement effect is quite apparent. Figure 1 shows some of the simulation results (The efficiency simulation results here is under 100% load).

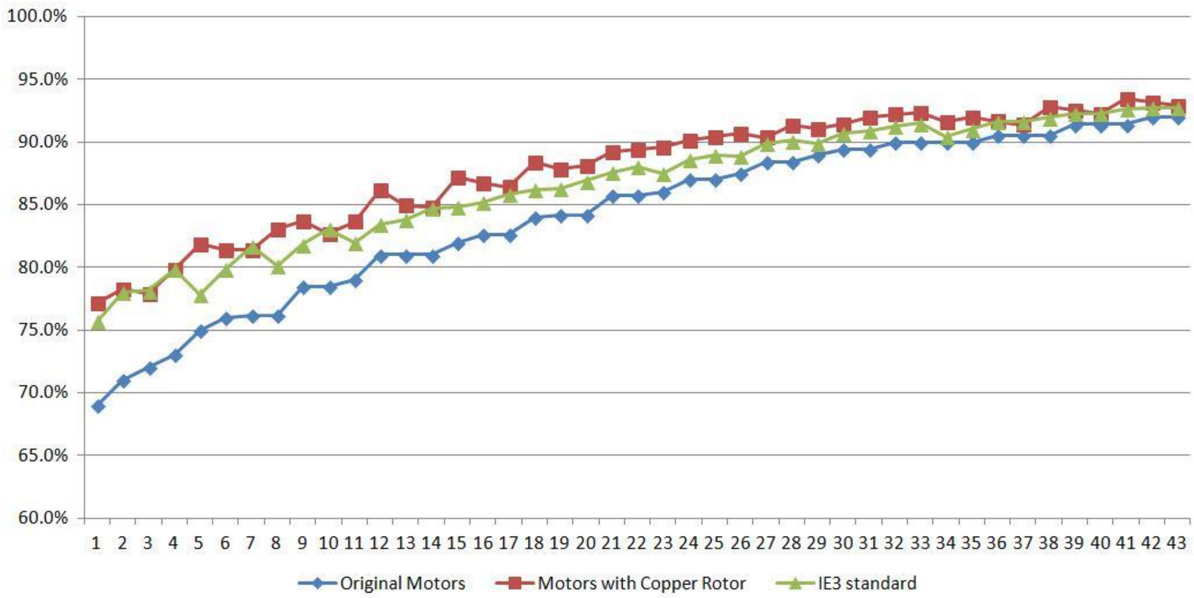

Figure 1, Simulation results of Y-Series motors with Copper Rotor

The results proved that by simply change the AL rotor with a copper rotor without changing the stator, the motor efficiency level could be improved by 1 or 2 grades. The method is very simple and cost efficiency. Besides improving the efficiency on installed motors, the method could be also used by motor manufacturers to produce IE3 motors by using old tooling and stators. It provides a very flexible way for motor manufacturers to design their catalog. For example, they can use the same stators to produce IE2 & IE3 motors, the only difference being the rotor. If a Al rotor is used, the motor is IE2, but if a copper rotor is used, the motor is IE3.

In addition, this method also applies to the motor efficiency improvement for motors in the maintenance and repair process.

In the practical application, most users turn to repairing motors instead of replacing them by new ones when their motors malfunction. According to a survey, 87 percent of malfunctioned motors will be reused after maintenance and repair in China. Only 13 percent of them will be replaced. About 10 percent of the total installed motors will malfunction each year in China. This means about 8.7 percent of the total installed motors will be repaired each year. Therefore, if the motor energy efficiency levels can be improved in the maintenance and repair stage, the overall in-use motor energy efficiency levels can be significantly improved.

A motor was usually repaired several times before its elimination. The life cycle of some motors is even over 40 years. In most situations, the imperfect coil-rewinding process at the motor maintenance and repair stage will cause a negative impact on the motor working efficiency and its energy efficiency performance. As a result, the motor energy efficiency level will be very low after several maintenance and repairs. This means that the motor will consume more electric power than before in order to maintain the same output power.

The motor energy efficiency will reduce by 1 to 2 percent on average after each maintenance and repair. The total electric power consumption of industrial motor in China is 2,653TWh. If we conservatively estimate that the energy efficiency reduction rate is 1 percent after each maintenance and repair, and 8.7 percent of the total in-use motors need maintenance and repair each year, then the overall energy efficiency loss of installed industrial motors in China is 1%*8.7%=0.087% per year.

This means that the electric power loss caused by imperfect coil-rewinding processes at the maintenance and repair stage each year will increase by 2.3 TWh (2,653TWh*0.087%). In fact, these unnecessary electric power losses can be completely avoided by improving the coil-rewinding process at the maintenance and repair stage.

It is necessary for the motor maintenance and repair industry in China to carry out reform in order to reduce the electric power consumption in a large-scale and sustainable way and decrease the greenhouse gas emission at the same time. The motor maintenance and repair operations should guarantee that the energy efficiency performance of the motors after maintenance and repair should achieve the same levels as before. Of course, it is better if the performance can be improved. In addition, these operations are technically and economically feasible.

Currently, two technical solutions for motor efficiency improvement at the motor maintenance and repair stage have been adopted:

(1) Coil-rewinding

(2) changing the stator iron-core laminations.

Currently in China, 95 percent of the motor maintenance and repair adopts the coil-rewinding method, while the method of changing the stator iron-core laminations is not widely adopted. If the coil-rewinding method is correctly adopted, the energy efficiency of the motor after repair can be kept the same as before, or even slightly improved. Changing the stator iron-core laminations can also improve the motor energy efficiency. But the process of this method is relatively complex. Its overall repair and manufacturing cost can exceed that of making a new motor. Therefore, its application is limited because of the economic and technical reasons.

The work done by the ICA and the YCD proved that the efficiency of the motors after maintenance and repair can be effectively improved by adopting the method of changing to a copper rotor at the motor maintenance and repair stage which opens an economical and feasible way to improve the motor efficiency levels at the maintenance and repair stage.

Through the theoretical analysis, the method of using a copper rotor for motor efficiency improvement mainly applies to the current aluminum-rotor motors with power below 30 KW. The number of motors within this scope is very huge.

4. The motor market in China:

The motor ownership in the civil market including residential areas and high-rise buildings is about 120 million KW (120 GW). The ownership of the small and medium-sized motors as well as the high-voltage motors in the industrial system is 688 million KW (688 GW). The total ownership of motor in China exceeds 800 million KW (800 GW).

The total ownership of motor in the industrial system in China in 2010 achieved 688 million KW, or about 84.7 million motors. Among them, high-voltage motors accounted for 118 million KW, or about 2.2 million motors, and small and medium-sized low-voltage motors accounted for 570 million KW, or about 82.5 million motors.

The small and medium-sized low-voltage motors are those used in the largest quantity in the industrial enterprises in China. The ownership of small and medium-sized motors accounts for 82.9 percent of total ownership of the motors in the industrial system in China by power, and accounts for 97.4 percent of the total ownership of the motors by number.

Table 3, Ownerships of various motors in the industrial system in China in 2010

	Power (100 million KW)	**Quantity (10,000 sets)**
Low-voltage motor	5.70	8,250
High-voltage motor	1.18	220
Total	6.88	8,470

Motors used in the industrial system include in-use motors and standby motors. The total power of the in-use motors in the industrial system in China in 2010 was 526 million KW, accounting for 76.6 percent of the total motor ownership. The total power of the standby motors was 162 million KW, accounting for 23.5 percent of the total motor ownership.

Therefore, the market space for the motor efficiency improvement by adopting the rotor-replacement method is very huge.

5. The rotor replacement process:

The rotor-replacement method for motor efficiency-level improvement is a simple operation. The process procedures are briefly described as follows:

- Dismantle the motor according to the regular procedure and remove the original aluminum rotor from the motor.
- Usually there is an interference fit between the rotor iron core and the motor shaft. Remove the shaft from the rotor iron core by adopting the method of rotor heating in order to avoid damaging the shaft and iron core.
- Access the quality of the original shaft. If it can be used, press it into the copper rotor. If it cannot be used, install a new shaft into the copper rotor.
- Test the dynamic balance of the rotor on the dynamic balancing machine after the shaft is inserted and install the bearings on to the rotor by using the bearing heater to heat the new bearings.
- Reuse the parts such as the motor base and end covers after cleaning by using sand-blasting equipment if these parts can meet the requirements after testing. Install new parts with the same specifications if the original parts cannot be reused.
- Use the high-efficiency fan and fan cover as the heat generation of the copper rotor is low.
- Replace the original junction box cover and wiring board with new ones, reuse the junction box seat after cleaning and reinstall the junction box.
- Carry out the ex-factory inspection for the renewed motor according to the method for making new motors after the re-fabrication completion of the stator, rotor, motor base, end cover, fan, fan cover and junction box.

The above procedures mainly aim at using the copper rotor to renovate the in-use motor. For the motor at the maintenance and repair stage, it is necessary to adopt the conventional method to rewind the motor stator coil-winding so as to repair the motor. The other procedures are the same.

6. Conclusion:

It can be concluded that the method of replacing the in-use motor's aluminum rotor with the copper one can effectively improve the efficiency of the in-use motor. This method possesses the superiorities of simple operation, high reliability, low cost and short period of return on investment. It is inevitable that this method will greatly promote the in-use motor's efficiency level improvement, reduce the energy consumption, protect the environment and promote the sustainable development.

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Efficient energy use needs a system approach

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Jussi Manninen, VTT

Jero Ahola, Lappeenranta University of Technology

Abstract

The programme on efficient energy use (EFEU) within the Finnish CLEEN consortium has been running for over two years. The program is geared at providing methods, tools and technologies to enable a gradual increase in energy efficiency beyond what can be achieved by constant improvement and application of Best Available Techniques (BAT).

The generic target of the EFEU research programme is to develop methods and tools to measure, model, analyse and optimise energy efficiency. The basic idea is to use a system level (top-down) approach in different scales instead of optimising individual system components. The main focus of the program is on energy conversion and distribution and process industry.

The industry is the most important individual energy end user in Finland with a share of 47 percent. Also, energy conversion and distribution are seen as a key element in improving energy efficiency. The developed methods, tools and services for improving energy efficiency provide participating companies means to improve both the energy efficiency and the economic efficiency of their products and processes.

Due to losses in the energy conversion chain a saved joule close to the end use location may result to savings of up to ten joules in the primary energy. This means that by improving end use efficiency the amount of delivered energy decreases leading to less capital investments in the energy conversion chain.

The initial findings of this task suggest that while energy efficiency is increased also the system reliability enjoys a boost. An analysis on the efficiency at the system level has also been developed within the programme.

A wider adoption of system thinking necessarily leads to fewer possibilities for sub-optimisation. This can be achieved when systems are more adaptive and widen their optimal operation region.

1. Introduction

Today people and industries are more dependent than ever on a constant supply of electricity. Emerging new technologies to generate electricity are still marginal in comparison to electricity produced by the use of fossil fuels. Despite new findings to utilize reserves in the previously expensive materials, like oil shale or oil sands, the world faces a shortage in its available energy resources.

Thus, saving energy has gained in importance. The EU commission, for instance, has an ambitious goal of saving 20 percent in primary energy use by 2020. The decision has been made mainly to advance the following trends: ensuring the sufficiency of non-renewable resources, slowing of excessive climate warming, ensuring the competitiveness of European industry and reduction of energy dependency.

All of the above trends can be influenced with end-use energy efficiency. For instance, the International Energy Agency, IEA, has estimated that for every dollar invested in improving end-use energy efficiency, investments in the supply side can be decreased by two dollars. [1]

In section 2 we describe a new way of doing research. This kind of work has been pioneered in Finland by a consortium called CLEEN Ltd. CLEEN brings together the minds from different companies and research institutions.

In section 3 we examine closer one of the CLEEN programs: Efficient Energy Use (EFEU). CLEEN uses a system approach to explore energy efficiency. One of the major advantages in a system approach is that the research will be concentrated on generic energy intensive applications instead of industry specific ones.

In section 4 we take a look at some of the preliminary results from the EFEU program. Here we will concentrate on system efficiency where a useful tool has been developed, and measuring energy efficiency. Also some energy efficiency services that have been developed within the program will be dealt with.

2. New of way doing research

The work that is being described in this paper is coordinated by the Finnish company CLEEN Ltd (Cluster for Energy and Environment). The company was established in 2008 and today it has 45 shareholders consisting of major international companies and relevant national research institutes. The companies are global technology and market leaders and have significant energy and environmental related R&D activities in Finland.

The ownership of CLEEN is divided between private companies, research institutes and universities. The funding of its research activities, i.e. research programmes, is provided by the participating companies. Significant contribution comes also from non-shareholders and The Finnish Funding Agency for Technology and Innovation, Tekes.

The objective of CLEEN is to create value to the participants through its operations by offering the most competitive environment for joint knowledge building of the best industrial and academic competences. The national aspect is that the hub and access into the network of world class energy and environmental core competences would be found from Finland. Therefore it is crucial that Finland holds its competitiveness and reputation as a place for trustworthy and flourishing environment for open innovation. [2]

The shareholders define the focus, targets and practices for CLEEN Ltd. Expected benefits are that the development of world leading know-how will be ensured, the best talent will be attracted and the international cooperation will be easier to accomplish. The industry, research institutes and universities working together, the joint project planning and the new joint research programmes will considerably facilitate the development of the whole innovation chain and the development of globally competitive technology and service products. [3]

3. Efficient energy use (EFEU) as a target

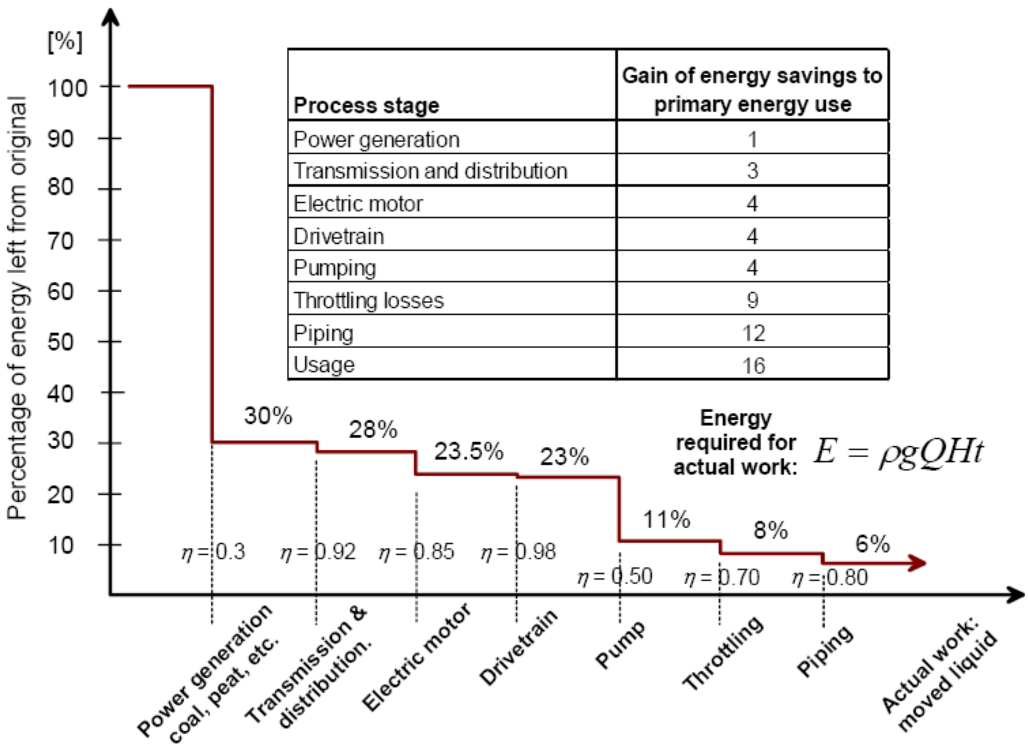
CLEEN uses a system approach to explore energy efficiency. One of the major advantages in a system approach is that the research is concentrated on generic energy intensive applications instead of industry specific ones. A list of the participants in the EFEU program is provided in Appendix 1. The program is scheduled to be fulfilled in five years. Its budget is approximately 12 million Euros.

With this program generic methods and tools to measure, model, analyse and optimize energy efficiency are developed. The basic idea is to utilise system level (top-down) approach instead of optimizing individual system components. A more generic term, “holistic energy approach”, is also sometimes used, but in this paper we use the term “system approach.”

This means that the trend now is geared towards getting to know the whole process that has to do with energy efficiency whereas before the thinking has concentrated more on individual components in saving energy. This approach requires a joint effort where even competitors share information about the efficiency of motors and their control systems. [4]

The work in the EFEU programme has been divided in several tasks. One of these is called energy efficient fluid handling systems. The importance of this line of research is underlined by the fact that some 22 percent of industrial electric energy is used in pumping applications.

The work is based on the finding that power losses through each stage in the power consumption process add up to significant amounts (Figure 3.1). The savings in the energy end use result to more than ten times of savings in primary energy use and also affect to the requirements of the energy transmission chain. If energy can be saved in some stages of the process, the gains in primary energy savings can be significant. [5]



Process stage	Gain of energy savings to primary energy use
Power generation	1
Transmission and distribution	3
Electric motor	4
Drivetrain	4
Pumping	4
Throttling losses	9
Piping	12
Usage	16

Figure 3.1. Energy flow from the primary energy to the actual use in a pumping process. The savings in the energy end use result more than ten times of savings in primary energy use

To define energy efficiency is rendered more difficult if not solely the efficiency of conversion is analysed but instead the whole service or added value is looked upon. This means, with the pumping system as an example, that the purpose of the whole exercise is not to run a pump but to move fluid from point A to point B. This leads to including downstream processes, tank locations, piping, etc., which make defining the metrics of measuring energy efficiency crucially important. Other questions of interest are the maximum technically and economically achievable energy efficiency for the selected system and finding the savings potential in systems with complex interactions such as industrial processes and regional energy systems. [6]

The main focus of the program is on energy-intensive process industry end use, regional energy systems and energy chains because, firstly, the industry is the most significant individual energy end user in Finland with a share of 47 %. Secondly, energy conversion and distribution is from EU and larger perspective seen as a major contributor in improving energy efficiency, and new fuels and concepts are emerging.

Improving energy efficiency provides participating companies means to improve both the energy efficiency and the economic efficiency of their and their customers' products and processes. In EFEU the research topics are selected in such a way that they are generic energy intensive applications instead of being industry specific. For example, some of the research topics include future industrial separation, low temperature heat recovery and pumping, ventilation and mixing systems. The aspects of education and services help in disseminating the message of improving energy efficiency in existing systems. In EFEU this will be accomplished by promoting the research results in M.Sc. and Ph.D. studies at technical universities and also in adult education. The intermediate goals of the EFEU program are illustrated in Figure 3.2. [7]

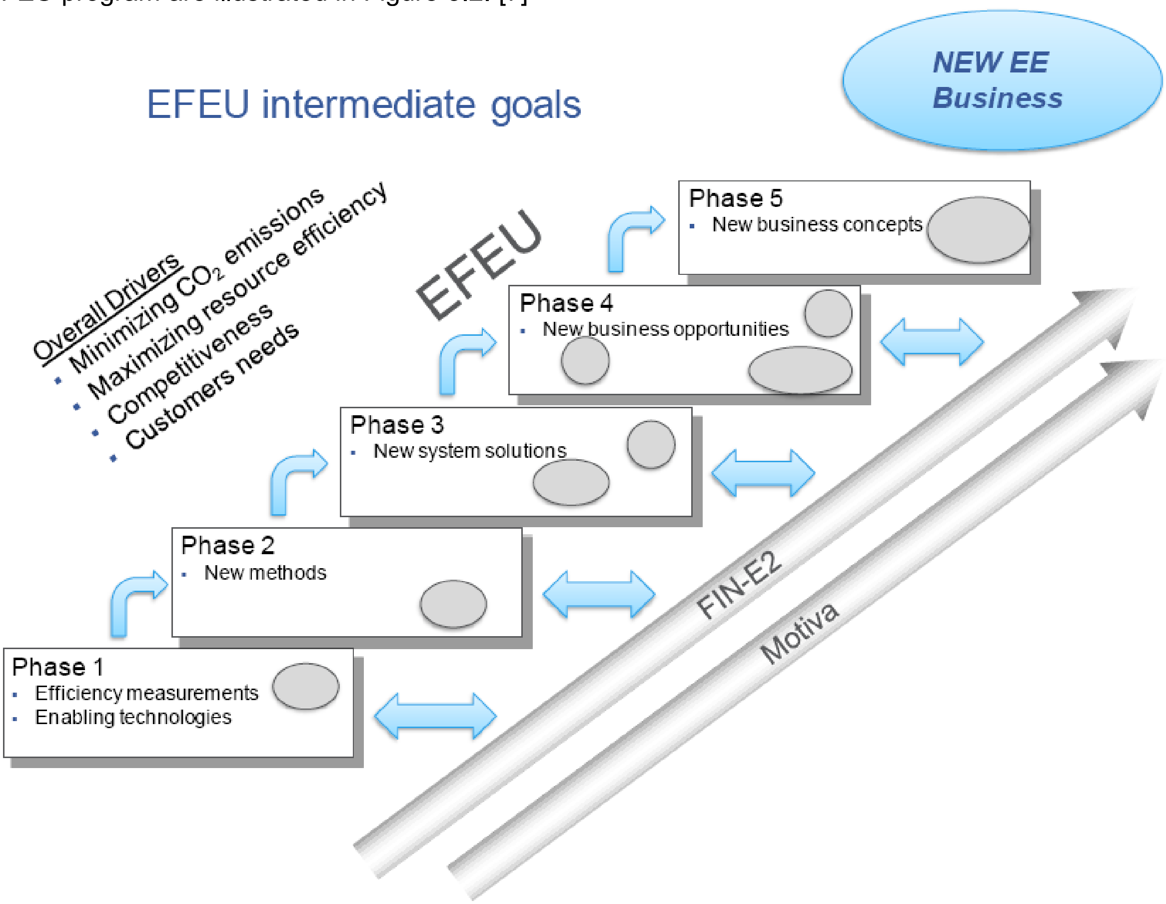


Figure 3.2. EFEU goals

4. Results are beginning to take form

The EFEU program has been running since 2012 and some preliminary results can already be distinguished. As described before, system efficiency, measuring energy efficiency and energy efficiency services belong to the core research areas of the program. Thus they represent such areas where some of the earliest results come from.

4.1. System efficiency

Here the main goal of research has been to develop methods, tools, and understanding of how the energy efficiency of pump, fan and mixer systems can be radically improved from current values. Some of the fundamental research questions have been at the systems level: how the systems should be optimally designed and selected so that the life cycle costs of the whole system will be optimised? Also the question of the surrounding process is scrutinised as it has a major effect on the optimum level of selected criteria.

It is also considered how uncertainties in the system requirements can be taken into account and tolerated without losses in the system performance. As a result of the above considerations the requirements to the design of individual components, such as pump, electric motor and frequency converter, are dealt with.

The research is also extended to the sub-system level where new methods and tools to designing and optimising energy efficient pumps, fans and mixers are developed. Here research is carried out on new software and model based algorithms that allow frequency converters to be used in real-time cost optimisation.

Main results last year include practical test cases for the further study of design, selection and control of pump systems. Also a simulation tool to study the system wide energy efficiency effect of different pumping system components has been developed. This tool (later PSOT) can also be used to select the best possible device combination for an existing process.

This year the program will look among other things into these matters:

1. Simulating the energy efficiency improvement potential in existing systems with the replacement of pump, motor and frequency converter.
2. Developing a simulation tool to study the effect of different variable-speed control methods on the system life-cycle costs. Systems level comparison on the benefits of improving components vs. improving the control method.
3. Background study and development of a low specific speed pump technology able to fulfill current efficiency requirements

The research approach here is top-down, from system level to component level. An important part of the research is how systems level optimisation and design should be taken into account in the design and optimisation of individual system components. [8]

4.1.1. Pumping system optimisation tool

Pumps driven by electric motors are important devices in many industrial applications, and they account for over 20% of all the electricity consumption in European industry. Traditionally, both pumps and motors were often oversized during design phase to provide margin for some unknown future needs or increased reliability. Therefore the machines are in many cases driven outside their optimal operating region, leading to lower efficiency and increased operation and maintenance costs.

Because of the increasing energy costs and environmental awareness, energy effectiveness has become an important matter when designing industrial facilities. According to recent studies, the total energy consumption of pumping systems could be lowered by up to 30% with better design and choosing of pumps. Pumping System Optimization Tool (PSOT) aims to help choosing the right combination based on the data of the target process. It also allows the comparison of different devices and their effect on the life cycle costs for known operating conditions. [9]

Pumping system optimization tool has been realized with the Matlab programming system at the Lappeenranta Technical University. Matlab (matrix laboratory) is a widely used numerical computing environment for matrix manipulations, plotting of functions and data, and implanting of algorithms.

Figures drawn from induction motor and frequency converter optimizations are efficiency maps. An example is shown in Figure 4.1. Here frequency converter plot has frequency [Hz] and output current [A] as axes, and data from the motor part is drawn in the figure as red crosses. The nominal operating point of the machine is drawn in black circles. With the program also pie charts can be drawn to highlight the division of life cycle costs between, investment, energy and maintenance. Hence the choice of equipment can be visualised and it can be established whether the above mentioned figure of up to30% can be reached within the whole operating range. This is in contrast to many tools that only estimate the choice of equipment using the operating point instead of the whole range. This also exemplifies the system approach in practice.

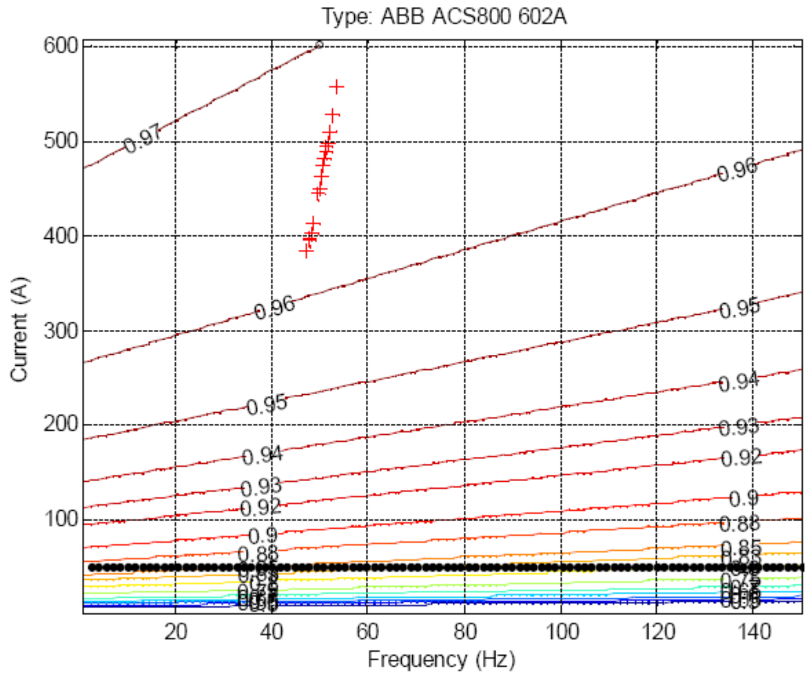


Figure 4.1. An example of frequency converter efficiency map plotted by PSOT

4.2 Measuring energy efficiency

The program aims to, on the basis of the research that has already been carried out at the Aalto University (see below), to gain a more thorough understanding of the benefits and limitations of existing efficiency analysis methods. Also a many faceted system level method will be developed. The main objective is to create a new efficiency analysis method called PEXE (Primary Energy Efficiency).

The PEXE method can be seen as an energy-focused simplification of life-cycle assessment, where the primary energy factors are based on exergy, not energy, factors. This provides the possibility to use known exergy efficiency factors for large portions of a studied system and to concentrate the efficiency improvement effort in to areas of most importance or interest but still being able to analyse the overall system efficiency. Exergy efficiency indicates also how far from ideal the system is and what the quality of the energy and energy losses is.

At the system level the main research question is how to balance between multiple metrics e.g. energy efficiency, cost efficiency and CO2-efficiency,- and boundaries – what are the conflicts between them and under which circumstances they are appropriate indicators and how these conflicting indicators can be handled in existing and new analysis tools.[10]

4.2.1 Energy efficiency and CO_2 *assessment*

In an energy efficiency and CO_2 emission assessment of Bio-SNG production different methods for assessing the energy efficiency were compared.

There are different methods used to evaluate the energy efficiency of the production system having a slightly different scope. The thermodynamic efficiency is the ratio of work output to heat-energy input in a heat-engine cycle. Exergy, by definition, is the maximum useful work that can be obtained from a system at a given state in a given environment. In other words, it is the most work one can get out of a system. Energy conversion systems (like a boiler) are usually evaluated on the basis of their conversion efficiencies.

The assessment looked into the energy efficiency and CO2 emissions of Bio-SNG production by applying three different efficiency analysis methods: thermodynamic efficiency or a “general” engineering approach, exergy analysis and primary energy analysis as suggested in the EPBD (Energy Performance of Buildings Directive - 2010/31/EU, implemented by European standard EN 15603).

Exergy analysis is a technology based on the second law of thermodynamics. Exergy is a combination property of a system and its environment, because unlike energy it depends on the state of both, the system and the environment. Exergy is a state property for a fixed environment and the exergy of a system in equilibrium with the environment is zero. Exergy analysis is used to compare, improve and optimize processes. It provides efficiencies that measure how far the process studied is from ideal and in which parts of the process exergy losses occur. The method cannot directly recommend how the process could be improved, but if changes to the process are made, it shows whether or not the changes were thermodynamically beneficial. [11]

4.3. Energy efficiency services

Energy efficiency services play an important role in spreading the message of energy efficiency. The services are addressed in the EFEU program. Here the following research questions are dealt with. What kinds of capabilities are needed in the process of co-creating energy efficiency solutions at the regional level? What kind of collaboration models can be used to facilitate the development of energy efficiency solutions between the service supplier and the customer? What kind of energy service business models can be developed by redesigning regional energy systems?

Also of importance is the potential market success of the new services. Here the research question is how the commercialisation cycle of energy efficiency solutions can be accelerated.

These research questions are approached through a set of case studies in selected regions. The pilot case study is Lohja region. Based on the pilot case, the development of an approach for regional energy systems will be started. The approach for regional energy systems will be tested with Lappeenranta case study. Besides the business model within the region, Lappeenranta case study is linked to marketing of energy efficiency services to Russian markets. After this a planned series of context dependent analyses, refining and generalisation of the approach will continue. [12]

4.3.1. Case studies on regional energy efficiency

In the EFEU program the region of Lohja was chosen for closer scrutiny. Lohja is a city of 47 000 inhabitants in southern Finland. In the case study the following things were looked at. What is energy efficiency in Lohja comprised of? What are the major challenges with an optimal energy solution? How can the development be advanced? And also what kind services may the process inspire?

The case study also included comparisons to the Austrian city of Güssing and the Swedish City of Stenungssund. From these examples we learned that the work can be initiated through a crisis (as in Güssing) or through strategic company partnerships (as in Stenungssund). The funding at the start can stem from the EU (Güssing) or also from private companies and the state and the EU (Stenungssund).

In Lohja some of the major challenges with the optimal energy solution were found to be energy audits, sensible investments (decentralised energy production), compressing the community structures for energy efficiency and utilising the city’s woods for energy production.

This year the research programme will be continued to Lappeenranta and St. Petersburg. Lappeenranta is a city of 72 000 inhabitants in south-eastern Finland. Here a Lappeenranta energy showroom will be developed. The experiences made in Lohja and Lappeenranta will serve as a basis to improving the energy and environment efficiency in St. Petersburg. District heat plays an important role both in Lappeenranta and St. Petersburg. Russia has the biggest district heat market in the world with a total capacity of 230 GW (Finland: 15 GW). [13]

5. Conclusions

We set out with the argument that in a world of diminishing energy reserves it is of utmost importance to conserve energy which also includes more energy efficient use (EFEU). The EFEU program has as its goal to advance new ways of energy efficient technologies. The research has been of pre-commercial nature which means that the participating companies can make further R & D investments. This also implies that the scope has been generic so that the results can be applied to all industries. Thus no figures of potential savings are given as they can vary greatly from industry to industry.

In the paper we scrutinise the inner workings of the CLEEN consortium and take a close look at its EFEU program. One of the guiding principles of EFEU is the finding that power losses through each stage in the power consumption process add up to significant amounts. When these losses can be addressed, energy can be saved remarkably.

One practical tool that has been developed in the program is introduced. With the pump system optimisation tool (PSOT) different kinds of set-ups can be studied prior to purchasing the real equipment. This way the optimal operating region can be found and the unnecessary purchase of oversized equipment (as a precaution) can be avoided. This is also the key to lower maintenance costs besides lower operation costs.

Measuring energy efficiency is important in getting the right feedback for further development of the systems. Here a new analysis method focusing on Primary Energy Efficiency is being developed.

A way of achieving the goal of efficient energy use is to unite already existing energy networks in a new optimal way. This is being done in the international co-operation between Lappeenranta in Finland and St. Petersburg in Russia.

The dissemination of energy efficiency services is of decisive importance in getting to results. Services can be based locally and the experiences from one place can be applied in other places. This approach was used here in the Lohja case and further developed in Lappeenranta and St. Petersburg.

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Figure source

3.1. Efficient Energy Use (EFEU) program plan 2012 – 2016, page 11

3.2. Energy Use (EFEU) program plan 2012 – 2016, page 14

4.1. Petteri Mustonen, Tero Ahonen and Antti Kosonen: Pumping system optimization tool. Lappeenranta Technical University 2012

Appendix 1

Participants in the EFEU program

ABB Oy

Andritz Oy

Empower IM Oy

Fortu Oyj

Fortum Power and Heat Oy

Gasum Oy

Helen Oy

Kumera Oy

Metso Oyj

Sulzer Pumps Finland Oy

Wellquip Oy

Aalto University

Lappeenranta University of Technology

Tampere University of Technology

VTT Technical Research Centre of Finland

Åbo Akademi University

"Easy" program for electric motor systems efficiency in Switzerland

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Swiss Agency for Efficient Energy Use

Abstract

Industrial electric motor systems represent by far the largest share of industrial electricity use. The equipment is in general too old, inefficient, oversized and not adapted to load. Industrial firms often do not have the capacity and the in-house knowledge for a systematic improvement of the energy efficiency of their rolling stock. In order to lower the barrier of time- and cost-intensive preliminary analyses preceding the retrofit of motor systems a subsidy program was developed. The incentive program is based on earlier developments of an audit method for companies with many hundreds and thousands of rotating machines. The primary goal of the method is to identify effectively the potentially most cost-efficient energy savings.

The Swiss financial incentive program Easy (Efficiency for Electric Motor Systems www.topmotors.ch/easy) was launched on 1 November 2010 by the Swiss Agency for Efficient Energy Use (S.A.F.E.). The goal of the program is retrofitting existing motor systems in mid-size industrial and infrastructure plants and large buildings with an annual electricity consumption between 10 and 50 GWh. The program has a budget of CHF 1 million from public funding and runs until 31 October 2014.

So far 4142 electric motors have been assessed in detail and 104 motors have been measured on site. Some efficiency measures (motor / pump replacement through more efficient and / or smaller equipment, installing frequency converter, better transmission, better control system for compressors, etc.) have already been implemented, with more expected to be carried out by 31 October 2014.

The results show, that from the 4142 motors 56% are already older than their operating life expectancy. The oldest motor has been running for 64 years. The median of motors' output power is 5 kW (half of the motor population is below 5 kW output power). Only 20% of motors are equipped with a frequency converter.

For the 104 motors measured, median output power is 24 kW and the median load factor is 61%.

Lessons learned confirm on the one hand, that the process with the necessary preliminary assessments is long and tiresome. It requires human and financial resources and know-how, which are often lacking in the factories. On the other hand, the approval of the management and committed energy managers are a must for a successful implementation.

The way forward foresees a continued implementation of the program beyond 2014, complemented by an education and training program for energy managers and technicians.

Introduction

S.A.F.E. made an analysis involving 25 Swiss industrial plants which shows that motor systems are responsible for 87.8% of total electricity consumption. The analysis made it clear that programs focusing on industrial motor systems are necessary.

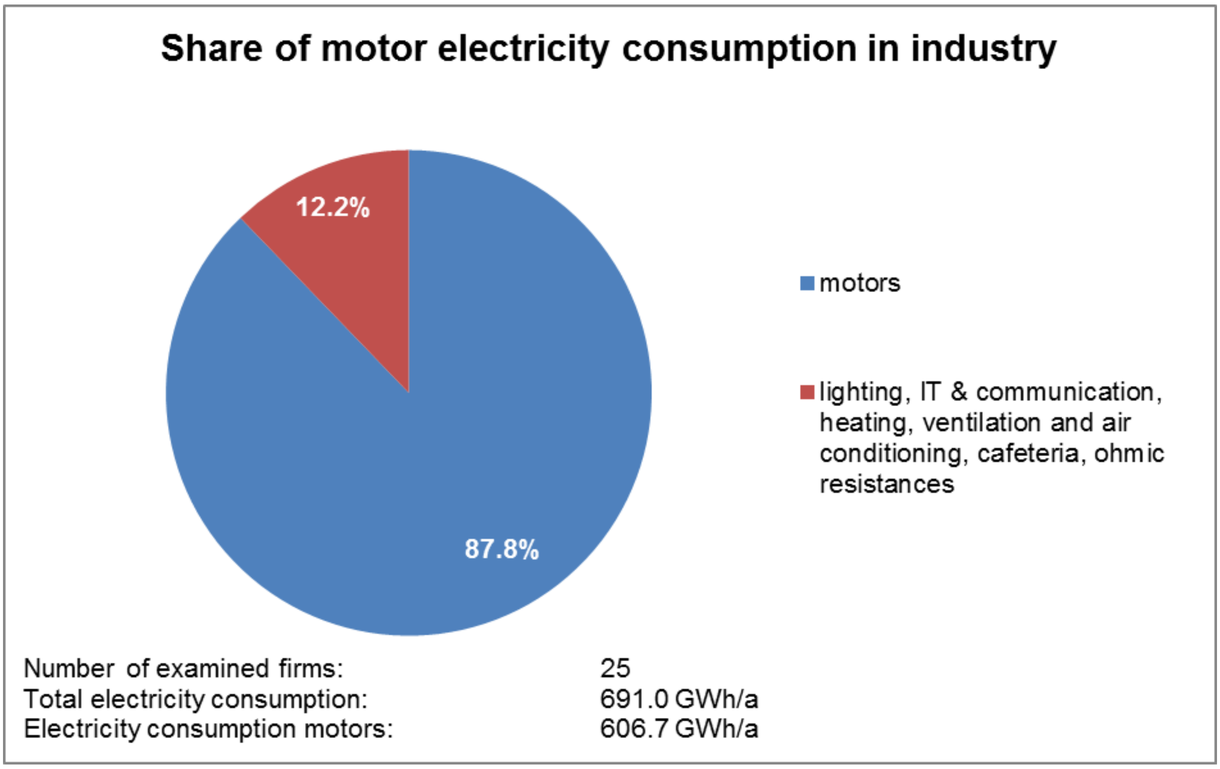

Figure 1 **Motor systems are responsible for 87.8% of industrial electricity consumption**

S.A.F.E. 2013

Overview of the program

Easy was launched by S.A.F.E. on 1 November 2010 and will end on 31 October 2014. The program has a total budget of 1 million CHF which S.A.F.E. won through a public tender. The tender is held annually, supervised by the Swiss Federal Office of Energy (Swiss government) [1]. The financing is secured through an additional fee on the tariff for the transport of electricity through the transmission grid.

Scope, goal

The scope of the program is retrofitting existing motor systems in industrial plants, infrastructure systems and large buildings, consuming more than 10 GWh/a of electricity. Since there is a minimum management cost associated with each participating factory and the possible savings are dependent on the total electricity consumption of participating factories, S.A.F.E. decided that participants should consume at least 10 GWh/a so that the program management costs would not be higher than the possible savings.

Four steps

Firms entering the program go through a standardized four-step audit process (Motor-Check), with the first three steps being preliminary analyses and the last being the implementation of efficiency measures.

For each step, a tool was developed by S.A.F.E. to help find the motor systems promising the highest savings in a systematic manner. (Reference to these tools is made in the section "Case study: meat processing plant"[1].)

Subsidy

The subsidy is based on the total costs of each step. A subsidy is given for all four steps, with a higher percentage for the preliminary analyses. The rationale behind this is that these analyses are

[1] Further reading: [2]

necessary to be able to retrofit motor systems and since they are time-consuming and cost-intensive, they constitute the main barrier for efficiency improvements. The goal of the program is to help firms overcome this barrier.

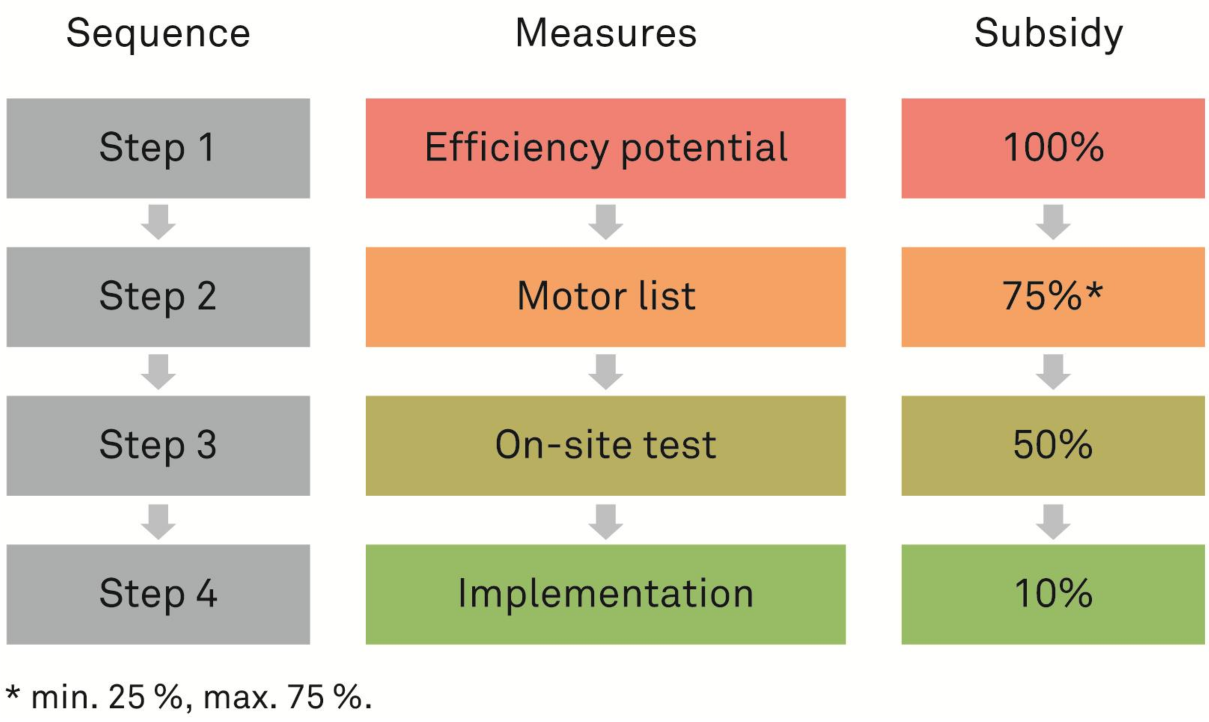

Figure 2 Easy four-step process and respective share of subsidy

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For steps 1 - 3, the costs for both internal work (e.g. the necessary time for putting together the motor list) and external services (e.g. on-site tests by consulting engineers) borne by the firms are taken into account. For step 4, the subsidy is given for all types of measures and their attributed costs aimed at improving the complete motor system efficiency (e.g. improved operation and part load control, improved transmission and gears, advanced driven application, planning, installation) - thus not only for motor replacement.

Results

In the following sections, the results of analyzing 4142 motors from the motor lists of 18 industrial plants and infrastructure systems are shown.

S.A.F.E. together with its partners carried out pilot projects for motor systems retrofits in industrial firms before the start of the Easy program in the framework of the program "Topmotors". The results presented in this section of the paper take into account the analyses made under both programs (10 firms under Easy and 8 firms under Topmotors).

Table 1 gives a summary on the assessed firms with details to the number of motors on their motor lists and the motors tested on site.

Table 1 Assessed firms, number of motors on motor list and tested on site

No.	Core business	Electricity consumption	Motors on motor list	Motors tested on-site
		[GWh/a]	[no.]	[no.]
1	Dairy	40.2	294	23
2	Energy solutions	38.4	652	33
3	Waste incineration	38.2	277	14
4	Chocolate	35.4	540	25
5	Dairy	19.7	223	-
6	Chemical industry	16.9	96	-
7	Water supply	15.3	163	-
8	Industrial adhesives	12.4	381	-
9	Plastic material	11.9	10	-
10	Medical products	11.8	186	-
11	Rolled aluminum	11.4	108	-
12	Chalk production	10.0	74	-
13	Bioorganic products	7.8	381	-
14	Meat processing	5.9	42	9
15	Vegetable oils	4.9	208	-
16	Chocolate	3.5	325	-
17	Confectionary	2.8	42	-
18	Yeast production	2.3	140	-
Total		**288.8**	**4142**	**104**

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Some firms have not yet finished all steps of the program, therefore their data is not yet available.

The main criteria for taking motors onto the motor list are output power, age and operating hours per year. The eighteen factories for which a motor list is available have a total electricity consumption of 289 GWh per year, their 4142 motors on the motor list consume 196 GWh electricity per year. Thus, motors on the motor list are responsible for about 70% of the total motor systems electricity consumption within a factory.

Table 2 gives an overview on the different characteristics of the 4142 motors assessed.

Table 2 Analysis of 4142 motors, from the motor lists of eighteen firms

Application	Number		Energy consumption		Rated power per motor		Age	Operation	Equipped with VSD	
			total	per motor*	average	maximum	per motor*	per motor*		
	[no.]	[%]	[GWh/a]	[MWh/a]	[kW]	[kW]	[a]	[h/a]	[no.]	[%]
Fans	1044	25%	65.5	63	18	1000	16	5455	311	38%
Pumps	1590	38%	43.2	27	13	315	16	4275	279	34%
Rotating machines	672	16%	29.9	44	35	4050	22	2883	63	8%
Cooling compressors	124	3%	21.5	174	64	450	17	4283	17	2%
Air compressors	109	3%	22.0	202	74	315	15	4064	25	3%
Other	251	6%	8.4	33	25	2870	18	4491	60	7%
Conveyors	352	8%	5.4	15	6	160	19	4232	66	8%
All motors	**4142**	**100%**	**195.9**	**47**	**21**	**4050**	**17**	**4351**	**821**	**20%**

*average

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Note: results are shown by application, in descending order according to total energy consumption

The most numerous applications are pumps and fans. Fans are responsible for the highest share within the total energy consumption of all applications. Figure 3 below shows the share of energy consumption for each application.

The energy consumption of compressors per unit (one cooling compressor, one air compressor) is significantly higher than that of other applications.

Annual operation is on average 4351 hours per year.

20% of motors are equipped with variable speed drives (VSDs). The VSDs are mostly used in fan and pump applications because of their "square torque to frequency"[2] characteristics. The average age of motors equipped with a variable speed drive is 11 years, thus lower than the average age of all motors. This suggests that motors which have more recently been put into operation are more likely to be equipped with a VSD.

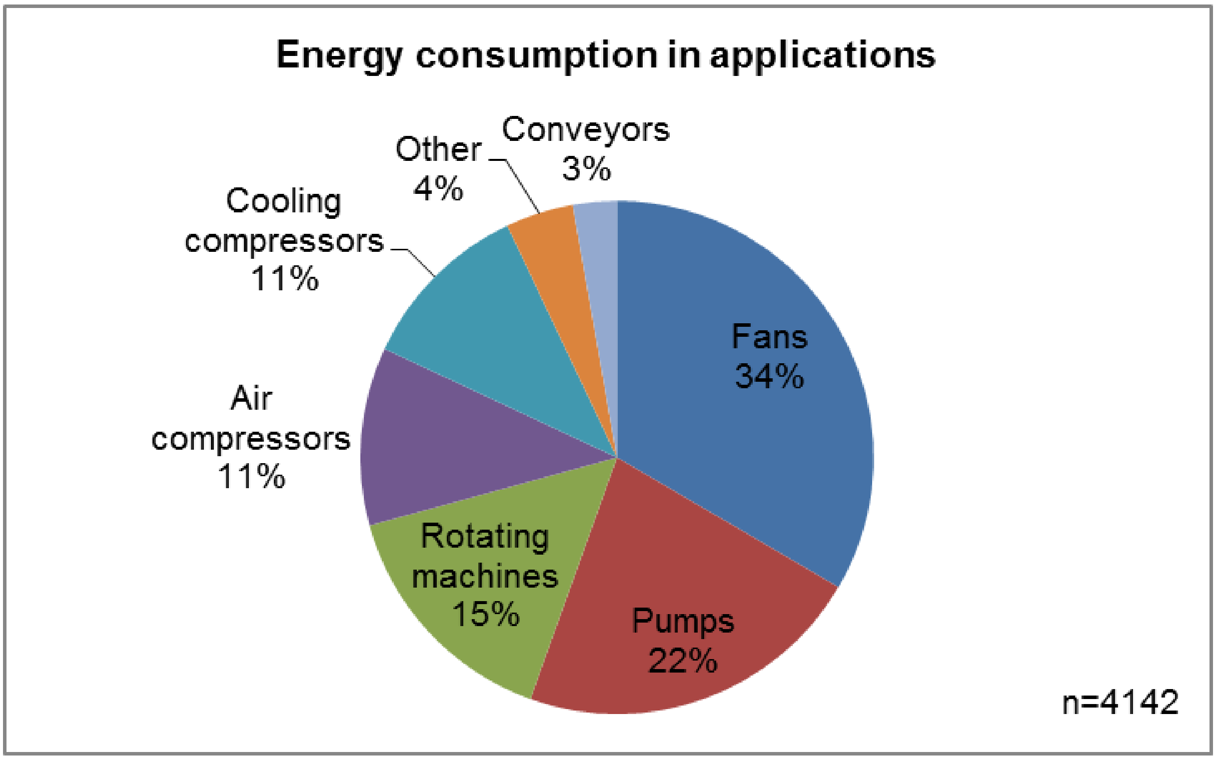

Figure 3 **Share of energy consumption according to application**
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[2] In the context of variable frequency drives there are two general types of machines: i.e. conveyors have a constant torque while reducing the frequency; pumps and fans have a square relationship between frequency and torque. This makes the latter applications profit much more from a VFD.

Motors are too old

56% of motors in operation are too old and shown above the red line in Figure 4. These motors are on average 99% too old which means that most motors have been running almost twice as long as their expected lifetime. The oldest motor found has been running since 64 years.

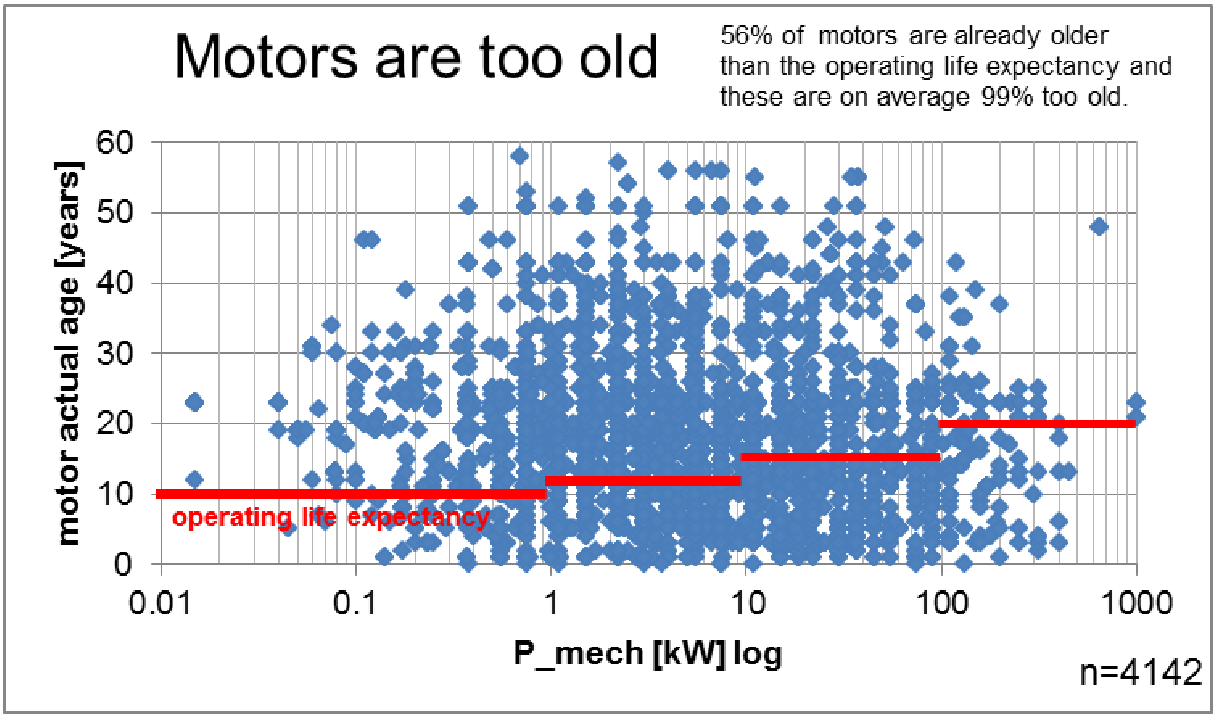

Figure 4 **Motor age and expected lifetime**

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Table 3 **Expected motor lifetime**

Output power	Expected lifetime (years)
below 1 kW	10
1 kW - 10 kW	12
10 kW - 100 kW	15
100 kW - 1000 kW	20

Source: [3]

Output power

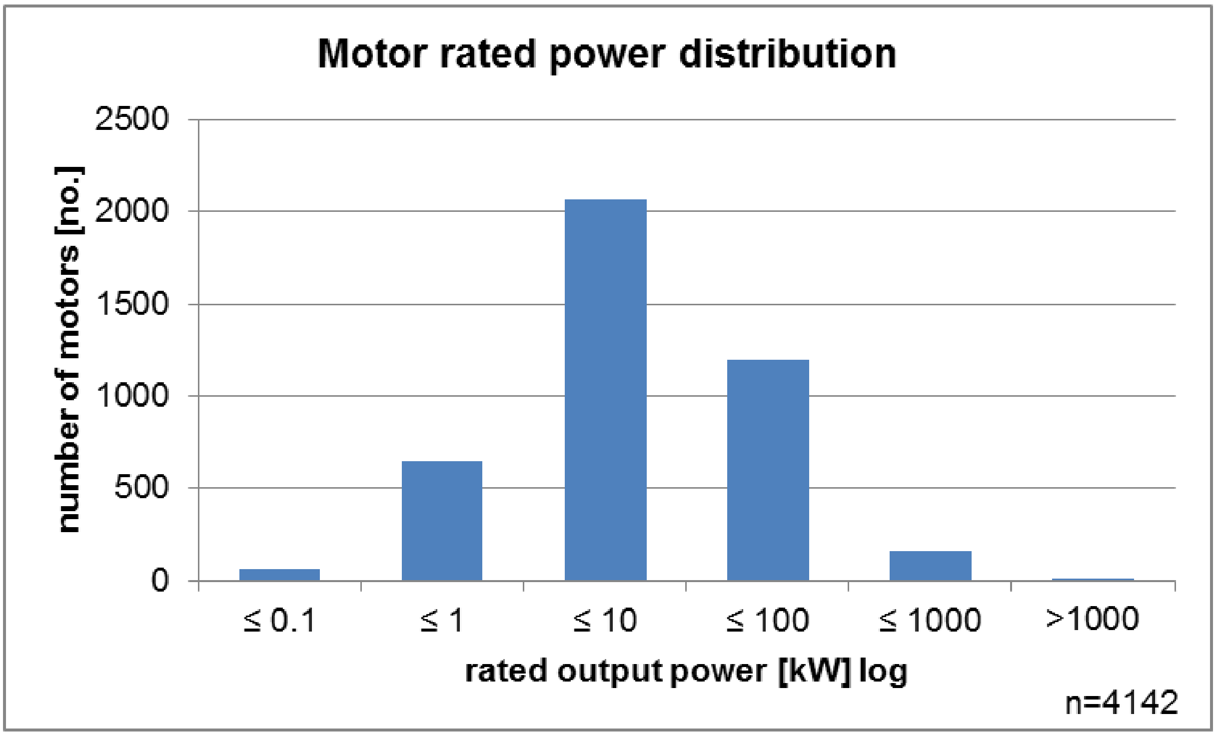

Figure 5 **Motor output power**

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67% of motors have an output power below 10 kW. The median is 5 kW which means that half of the motors assessed have an output power below 5 kW, and half above. The average output power of motors is 21 kW.

S.A.F.E. observed in these industrial applications that conveyors, pumps and fans tend to have smaller output power (on average below 20 kW), while compressors (for cooling and compressed air) have a larger output power (on average above 60 kW). The high number of fans and pumps affects the average output power of all motors.

The application with the highest output power is a 4050 kW motor used in a turbine test facility.

Load factor

This section presents the results of 104 on-site measurements.

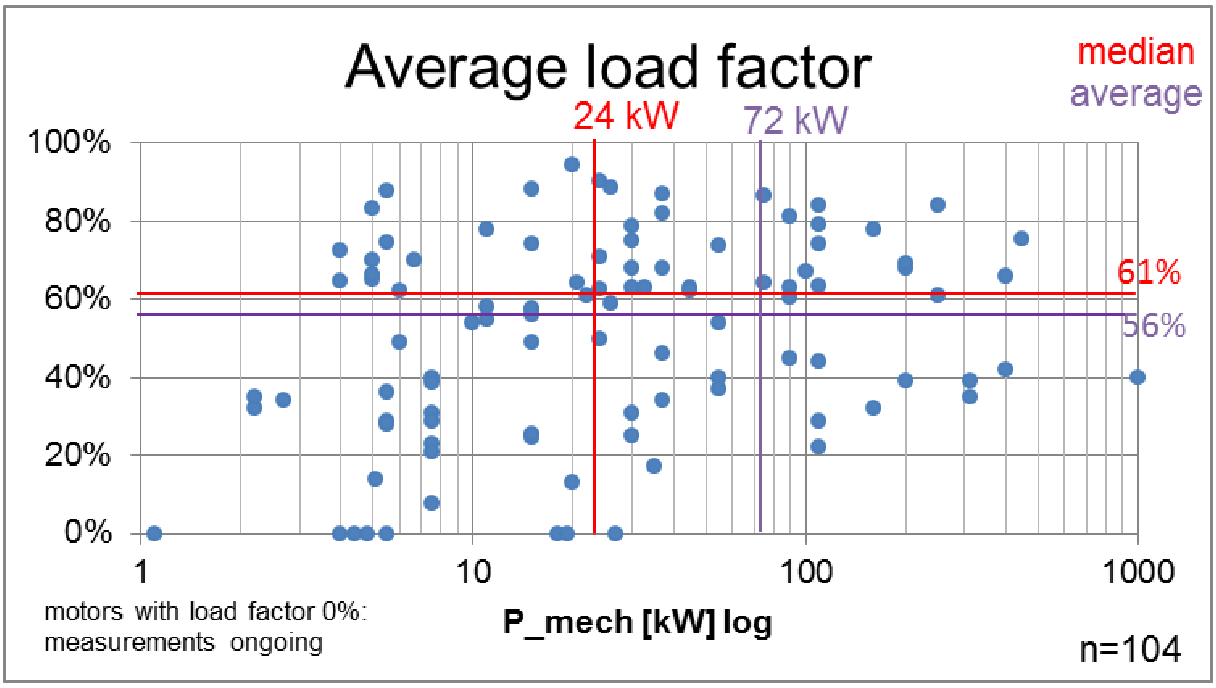

Figure 6 **Load factor of motors measured**

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Note: The load factor of motors currently being measured (8 motors) is shown at 0% and not taken into consideration for the calculation of median and average load factors.

The electric input of motors is measured on site in order to observe their starting condition, continuous operation and - if necessary - changing load situations. Figure 6 shows that the average size of motors chosen for measurements is 72 kW while the median is 24 kW (half of the motors tested have an output power below 24 kW). These measurements are a prerequisite to analyze the necessary output size of the motor and to calculate the average load factor. The annual load factor is calculated from the electricity used, the output power of the motor and the measured load factor. The median annual load factor of the motors is 61%. This means that half of these motors have an annual load factor below 61%. 39 motors have an annual load factor below 50% which suggests that they are heavily oversized.

Figure 7 shows an example of an on-site input measurement of a 55 kW motor with 90% efficiency (at full load) driving a blower during start and nominal operation. The results show an average electric input of 22.5 kW (corresponding to a load factor of 38.5%) with a partial load efficiency of 88%. It also shows that the machine has no higher load requirement during the starting phase and runs fairly constantly during operation. The analysis suggests that an IE3 motor of 30 kW output with 93.6% efficiency would be sufficient. Together with other mechanical improvements (lower air volume and speed, better transmission with synchronous belt) a 15 kW motor with a 2 year payback is recommended as a replacement.

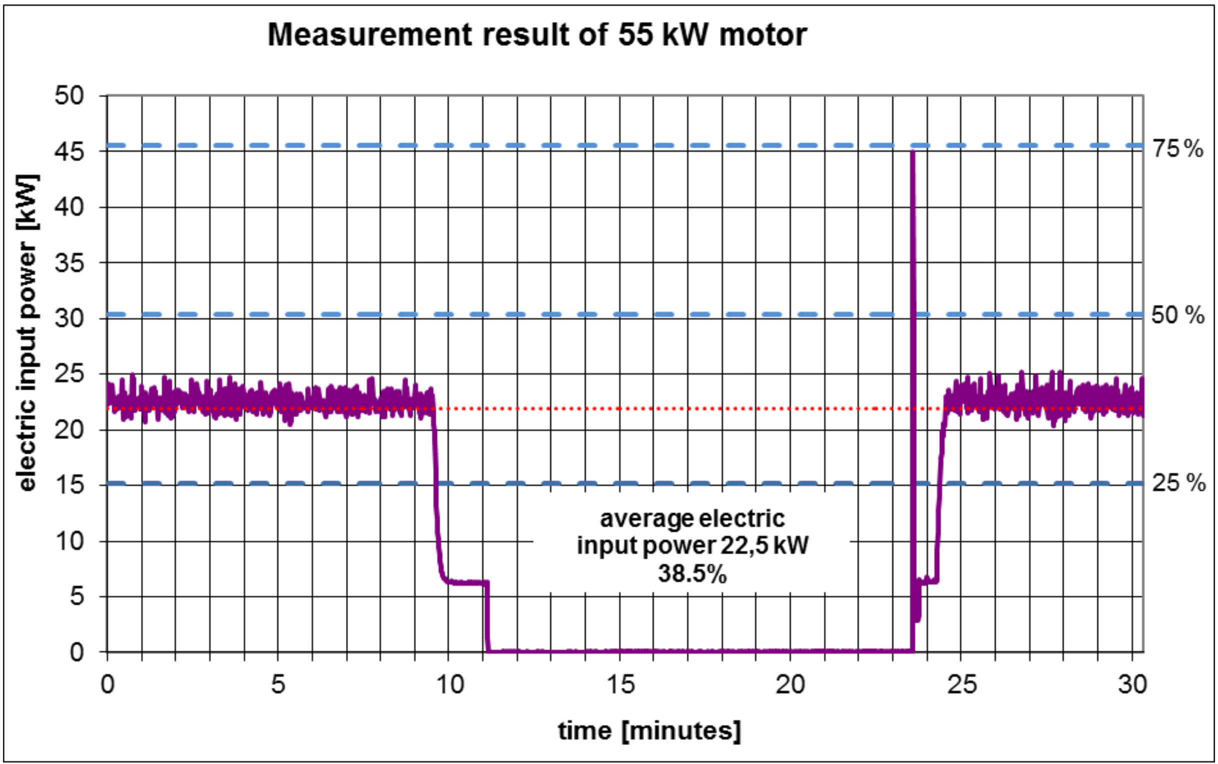

Figure 7 On-site measurement of the electric input (55 kW output)

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Typical efficiency improvement measures

Typical efficiency measures which have been implemented at participating firms are:

- Higher-level control system for compressed air and cooling systems
- Reduction of volume, nominal pressure and speed in air ducts and water pipes
- Downsizing of motors based on actual measured requirements
- Improve starting conditions to reduce maximum required torque
- Replacement of old motors with new (down-sized) IE3 motors
- Installation of variable speed drives in motors with variable load conditions
- New, smaller components (e.g. pumps, fans, compressors) for an optimized system
- Better transmission (synchronous belts) or direct drive
- Optimization of operating hours depending on production requirements (e.g. necessary operation during the night, weekend, etc.).

Case study: meat processing plant

A plant producing fresh meat and meat products for Switzerland and the European Union is participating in the Easy program, optimizing its existing motor systems. The company employs 210 people, has an annual sales volume of CHF 150 million and an electrical energy consumption of nearly 6 GWh per year.

Like all the companies taking part in Easy, the plant went through the four-step Motor-Check audit. In a first step, the efficiency potential was estimated with the help of the software tool for efficient motor systems (SOTEA) [4]. It showed a modest 7.2% electricity savings potential, if 44% of motors were to be replaced with more efficient ones. This relatively low potential is due to the fact that most motors were relatively young (compared to the average age of motors found in other plants), being in operation only since 12 years. The second step was building a motor list using the software tool Intelligent Motor List (ILI+) [5]. The motor list contained about 40 motors. In a third step, 13 motors from the motor list were measured on site, efficiency improvements were elaborated, the expected savings were calculated and the best solution was recommended. Now the company is in the process of implementing these recommendations, taking a stepwise approach.

First, a higher-level intelligent control system was installed for the air compressors. In addition, an air-pressure reduction of the entire network was possible once the new control system was in place. The actual pressure reduction exceeded all expectations (from the original 8.3 bar down to 7 bar) and doubled the expected electricity savings. The evaluation of the optimized operation showed total savings of 35 MWh/a. The current energy consumption is 16% lower compared to the original condition.

Figure 8 One air compressor (left) and display of new, higher-level control system (right)

Second, the ventilation system was optimized by installing new IE3 motors controlled by frequency converters.

Third, an intelligent control system is planned to be installed for the cooling compressors. The standstill of the cooling system has an enormous impact on the production and therefore must be carefully planned. Negotiations regarding the implementation of this measure are ongoing between the company and the supplier.

Table 4 summarizes the planned and already implemented measures. The individual measures have different payback times ranging from 1.5 to 7.3 years, while the payback of the total package is only 2.4 years.

Table 4 Summary of optimization measures at meet processing plant

No.	Optimization of	Investment	Savings		Payback
		[k CHF]	[MWh/a]	[k CHF/a]	[a]
1	Air compressors	8	35	5	1.5
2	Ventilation system	53	56	7	7.3
3	Cooling compressors	65	308	39	1.7
Total		**126**	**399**	**52**	**2.4**

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Lessons learned

Throughout the management and implementation of Easy, S.A.F.E. learned a number of lessons which can be summarized as follow:

1. Plant managers lack resources, meaning both necessary time and engineering know-how to design and optimize electric motor systems in an energy efficient manner.
2. Motor manufacturers and service companies are not pursuing the sale of efficient motors or components. Partly, because this requires changes in their business model (and they have not yet recognized their potential gains in selling energy efficiency) and partly because they lack the necessary knowledge for optimizing systems. The supply of IE3 motors proved to be a challenge, often accompanied with long waiting periods and discouraging comments from the suppliers.
3. Machine builders threaten with early termination of warranty in case they are asked to change one or more components for more efficient ones (instead of the client ordering a whole new machine).
4. The implementation of efficiency measures for motor systems which are involved in the core production process are hindered by fears of a possible production standstill.
5. The costs of on-site measurements and related efficiency improvement engineering and recommendations were on average 1000 - 1500 EUR per motor system in the Easy program. This was higher than anticipated and is independent of motor size, but can be higher for complex systems. This means that only larger machines or machines with many identical small motors can be improved in a cost-effective manner.
6. Some industrial plants participating in the program decided to mandate external engineers to help them order new equipment and negotiate with manufacturers and OEMs for more energy efficient solutions. External efficiency advice is very costly but sometimes necessary.
7. Investments for motor systems as part of a systematic improvement process quickly add up to a few hundred thousand EUR - an investment decision to be taken to the top management level due to its scale. Plant managers do not have a direct contact or any influence on top management, therefore they cannot argue in favor of a positive decision on proposed energy efficiency measures.
8. The economic assessment of investments in industry and the subsequent investment decisions are essentially based on short pay-back periods (below 3 years) instead of life-cycle costs. This means that even if the purchase price of a motor represents only a few percent from its total life cycle cost and the electricity costs during its life cycle make up more than 90% of the life cycle cost (see Figure 9), the purchase price remains the decisive criteria in the investment decision.
9. A "champion" is necessary in all firms to make the retrofit project reality and is willing to make the implementation successful.
10. The time period between the initial contact to a firm and the efficiency measures implemented at the firm is one to three years, thus relatively long.
11. The first positive results of implemented efficiency measures stimulate the implementation of further measures.
12. The fact that 56% of motors run almost twice as long as their expected lifetime points at the lack of a continuous improvement process within the factories.
13. The subsidy helps to open doors but does not bring a remedy to all problems. A subsidy of 10% for the improvement measures in the implementation phase proved to be too low to be able to effectively influence the investment decision of certain firms for more energy efficient solutions.
14. All these factors doubled the costs of the program management (to date), for providing the necessary system optimization know-how to the firms, for the negotiations with manufacturers, machine builders and service companies and for keeping the motivation of the project "champions" in the firms high towards realizing the efficiency measures.

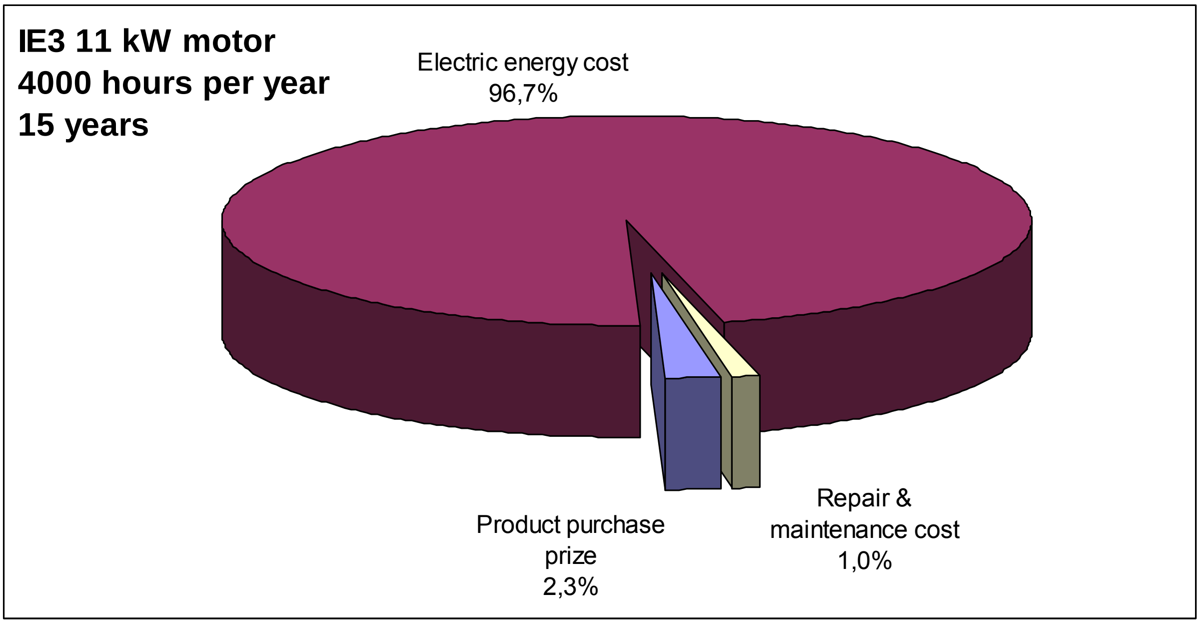

Figure 9 **Life cycle cost of a 11 kW IE3 motor.**

Source: [6]

Way forward

Through the implementation of Easy, S.A.F.E. realized that it is not enough to bring external know-how to the factories and enterprises, but the know-how needs to be present in-house. Certain structural changes in the hierarchy of the industrial enterprises must support a continuous efficiency improvement process. S.A.F.E. is convinced that these changes could be achieved through the introduction and support of energy management systems and through adequate training.

The Swiss parliament has decided to introduce a voluntary agreement scheme for energy-intensive companies. Companies with an electricity cost share of more than 5% within total costs could enter into efficiency target agreements and have their feed-in tariff payments refunded.

In January 2013, a first continued education program for energy management (Certificate of Advanced Studies) was launched at the University of Geneva. The course received very positive feedbacks and generated much attention. S.A.F.E. is now working in cooperation with the University of Geneva to build up the course in the whole country, targeting plant managers, representatives of manufacturers, importers, OEMs, service companies, consulting engineers and costumer consultants in utilities. The joint program foresees two focus areas: energy management and energy technology. In the latter, a great emphasis will be put on motor systems optimization.

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Barriers to ESCOs' Projects Relating to Motor Systems and Recommendations on how to Overcome them

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Abstract

ESCOs are a well known delivery mechanism to implement energy savings technologies, in particular in companies and organizations which do not have the time, the expertise or the financial means to implement the efficiency solutions. The concept is particularly attractive because it normally provides performance guarantees and thus takes away some of the risk element from the end use organization. ESCOs are now operating in many different countries, under different business models and contract implementation routes. ESCOs are mainly active in the non-residential building sector and to a somewhat lesser extent in the industrial sector. ESCOs have not so far implemented many projects in motor systems (motors, pumps, compressors, fans, conveyors, etc.), even though these types of projects often yield large energy savings and short payback times (i.e. very profitable projects). They should thus be very attractive for implementation under the ESCO concept. This paper firstly gives an overview of the ESCO concept, and goes on to investigate why not many projects are undertaken for motor systems. The paper finally draws some conclusions and gives recommendations on how to further enlarge this important market.

1. Different types of energy service

The term “Energy Services” is often used by various organisations and it encompass the provision of different services. It is therefore important to clarify the different type of services and companies providing these services.

Companies providing energy services to final energy users, including the supply and installations of energy-efficient equipment (including motor systems), and/or the building/plant refurbishment, maintenance and operation, facility management, and the supply of energy (gas, electricity, oil, heat, etc.), are defined as ***Energy Service Provider Companies (ESPCs)*****.**

Typically ***ESPCs*** may be consulting engineers specialising in energy efficiency improvements, equipment manufacturers, energy suppliers or utilities. ESPCs provide a service for a fixed fee or as added value to the supply of equipment or energy. ESPC may have some incentive to reduce end-user consumption, but this is not their core business or is not as clear as in the ESCO approach (see below). Often the full cost of energy services is recovered in the fee, so the ESPC does not assume any risk in case of energy underperformance. ESPCs are paid a fee for their advice/service rather than being paid based on the results of their recommendations.

In Europe many ESPCs have offered energy services for a number of years. ESPCs became active either :
(1) Through regulation, in particular for the provision of heating in public buildings (e.g. in Italy or France), or
(2) With the gradual restructuring of electricity and gas utilities (e.g. in Germany, where several municipal utilities were initially forced to offer energy services, and later developed this as a business activity) and energy suppliers obligations and white certificates, or
3) Via business ventures by large building control and equipment manufacturers.

Some ESPCs have also been active in the industrial sector. A sub-type of the service provided by ESPCs to industrial facilities are energy audits and monitoring & targeting. In some European countries (e.g. France, Finland), audits have been subsidised by the government. ESPCs have also been active in motor systems, and in particular in compressed air systems.

Energy Service Companies (ESCOs) may offer several of the ESPC services but go further in many important aspects. ESCOs are fundamentally different from ESPCs and the ESCO activities can be distinguished from ESPCs' activities in the following ways:

1. ESCOs guarantee the customer that it will receive the same level of energy services at a lower cost, or reduced energy consumption by implementing an energy efficiency project. It therefore offers performance guarantees which can take several forms. It can revolve around the actual flow of energy savings from a project, can stipulate that the energy savings will be sufficient to repay monthly debt service costs for an efficiency project, or that the same level of energy service will be provided for less money.
2. The remuneration of ESCOs is directly tied to the energy savings achieved.
3. ESCOs may finance, or assist in arranging financing for the installation of an energy project they implement by providing a savings guarantee.
4. ESCOs can retain an on-going operational role in measuring and verifying the savings over the financing term.

The ESCO experience is valuable to facility owners specially to those who do not:

- understand their energy bills,
- believe they have any energy inefficiencies and wastage,
- understand where savings opportunities may lie or how to implement measures to achieve them.
- know how to raise finance to implement energy efficiency, or
- appreciate the value of operational monitoring in controlling energy costs.

ESCOs provide a valuable service for facility owners by finding and implementing self-financed energy savings opportunities which cut energy waste and emissions. An ESCO is a company that provides integrated energy services to their customers, which may include implementing energy-efficiency projects (and also renewable energy projects), frequently on a turn-key basis.

The typical ESCO projects may include the following elements:

- Investment Grade Energy Audit[1];
- Identification of possible energy savings and efficiency improving actions;
- Comprehensive engineering and project design and specifications;
- Guarantee of the results by proper contract clauses (e.g. setting baselines)
- Code compliance verification and guarantee;
- Procurement and installation of equipment;
- Project management and commissioning;
- Facility and equipment operation & maintenance for the contract period;
- Purchase of fuel & electricity (to provide heat, comfort, light, etc.);
- Monitoring and verifications of the savings results;
- Project financing.

Although the ESCOs ensures that the above actions are undertaken, the ESCO however, may not by itself undertake all of them and may sub contract some of them out. While some activities may be subcontracted out, the ESCO remains responsible for delivering the final result and the overall success of the project.

[1] The Investment Grade Audit (IGA) deserves special attention. The traditional energy audit does not sufficiently consider how implemented measures will behave over time. Because auditors must consider the conditions under which measures will function during the life of the project, an IGA builds on the conventional energy audit. Unlike the traditional energy audit, which assumes that all conditions (related to system, payback, people) remain the same over time, IGA attempts to more accurately predict a building's *future* energy use by adding the dimension of a 'risk assessment component' which evaluates conditions in a specific plant. Aspect of the IGA include risk management, the "people" factor, measurement and verification, financing issues, report presentation guidelines, and master planning strategies (see Hansen and Brown 2003).

Energy Performance Contracting **(EPC)** is a fundamental concept embedded in the ESCO service and is a form of 'creative financing' for capital improvement which allows funding of energy efficiency upgrades through energy cost reductions. The approach is based on the transfer of technical risks from the client to the ESCO based on performance guarantees given by the ESCO. In EPC, ESCO's remuneration is based on demonstrated performance; a measure of performance is the level of energy or cost savings or the level of energy service. EPC is a means to deliver infrastructure improvements to facilities that lack energy engineering skills, manpower or management time, capital funding, understanding of risk, or technology information. Cash-constrain (especially for non-core investments such as energy efficiency), yet creditworthy, customers are therefore good potential clients for EPC. EPC is risk management and effective ESCOs have learned to use project financial structure to help manage the risks.

The financing of the project is ensured through two main types of contracts: ***Shared Savings*** **and** ***Guaranteed Savings*****.**

In the ***Shared Saving*** contract, the ESCO assumes both forms of risks i.e. the technical and credit risk. The ESCO either provides capital from its own resources or is itself the borrower of the capital from the bank/financial institution.

In the ***Guaranteed Savings*** contract, the client assumes the credit risk, while the ESCO only assumes the risk for achieving the savings (technical risk). This format suits small and/or under-capitalised ESCOs which cannot borrow significant amounts of money from the financial markets, and prefer not to finance the energy efficiency investments. Instead, these ESCOs prefer a scheme where the customers are financed directly by banks or by a financing institutions and where the ESCO is only a technical engineering/risk management company that guarantees energy savings which are sufficient to meet the repayments to the investing bank. This scheme is likely to function properly only in countries where there is a well established banking structure and sufficient technical expertise within the banking sector to understand energy-efficiency projects and the ESCO concept (e.g. the US, UK, Austria, and more recently, Hungary).

EPC should be clearly distinguished from energy *supply contracting* (delivery contracting) that is focused on the supply of a set of energy source (e.g. steam, electricity, hot water, etc.), and on the efficiency of the primary conversion system, mainly via outsourcing the energy supply (fuel purchase and generation set/boiler). "Chauffage" (French term for heating) is a refined form of supply contracting, where also the demand side is optimized and the ESCO sells conditioned space per square meter. In contrast EPC targets savings in energy demand.

The three broad options for financing energy efficiency improvements can be summarized as follows:
(a) ESCO Financing - refers to financing with internal funds of the ESCO and may involve use of its own capital or funding through other debt or lease instruments;
(b) Self Financing - customer financing usually involves financing with internal funds of the user/customer backed by an energy savings guarantee provided by the ESCO; and
(c) Third-party financing (TPF) - project financing comes from a third party, e.g. a finance institution, and not from internal funds of the ESCO or of the customer.

Leasing can be another attractive alternative to borrowing because the lease payments tend to be lower than the loan payments; it is commonly used for industrial equipment. The client (lessee) makes payments of principal and interest; the frequency of payments depends on the contract. The stream of income from the cost savings can in most cases cover the lease payment. The ESCO can arrange an equipment lease-purchase agreement with a financing institution..[2]

[2] There are two types of leasing. **Capital leases** are installment purchases of equipment. In a capital lease, the lessee owns and depreciates the equipment and may benefit from associated tax benefits. A capital asset and associated liability appears on the balance sheet. In **operating lease** the owner of the asset (lessor – the ESCO) owns the equipment and essentially rents it to the lessee for a fixed monthly fee; this is off-balance sheet financing source. It shifts the risk from the lessee to the lessor, but tends to be more expensive to the lessor. Unlike in capital lease, the lessor claims any tax benefits associated with the depreciation of the equipment. The non-appropriation clause means that the financing is not seen as debt. The operating lease is a kind of rental in which the period of contract is less than the life of the equipment and the lessor pays all maintenance and servicing costs.

An ESCO is a service company and *not* a bank or a leasing company. The primary reason that ESCOs do not and "should not" provide project financing with internal funds is that it makes their balance sheet look like a bank and not a service company. Local practices, the inability of customers to meet financiers' creditworthiness criteria and costs of equity financing are some of the factors that determine whether ESCOs will provide financing (debt or equity) (Hansen 2004). Small and/or under-capitalised ESCOs which cannot borrow significant amounts of money from the financial markets prefer their role not to be to finance energy efficiency investment.

The approach to financing is just one factor that shapes the structure of an EPC; other factors relevant for the type of financing arrangements and repayments structure include the allocation of risks, the services contracted, and the length of the contract. *Shared Savings* is also distinguished from *Guaranteed Savings* by the basis of the guarantee. Shared Savings guarantees reduced energy costs while Guaranteed Savings focuses on reduced energy consumption. When energy prices are volatile, Shared Savings seriously increases the ESCOs' risks

Typical projects that have been implemented by ESCOs in the US and Europe include the following:

- Operation and refurbishment of buildings (HVAC, lighting);
- Installation and operation of combined heat and power plants;
- Industrial facility refurbishment and operation;
- Public lighting refurbishment and operation.

ESCOs have mainly installed the following technologies: lighting, heating, ventilation, and air-conditioning, energy management systems, variable speed drives, CHP plants.

2. ESCO projects size and types

The classic ESCO service is usually provided to large energy users, those spending at least US$ 100,000/year on energy. Only such large energy users can have energy retrofit projects large enough to easily absorb the ESCO's administrative costs of developing a custom relationship and contract with a new customer.

The most common projects have been in buildings, as buildings tend to have more predictable energy consumption patterns (the main variables being occupancy and external temperature). Typical projects in buildings cover lighting, heating, ventilation, and air-conditioning (HVAC), and energy management systems. The recent energy industry restructuring has stimulated projects in CHP for large commercial centres, hospitals, and in industrial facilities. Boiler house improvements (and the provision of "heat service" or "Energy Supply Contracting ") have also featured significantly in many ESCO contracts, particularly in the public sector.

ESCOs are more reluctant to undertake projects in the industrial sector, where there is a higher degree of perceived risk especially at the process end. This is due to variations in business cycles (expansion or contraction of production), changes in product mix etc.

A common ESCO project type in the industrial sector and large commercial buildings is CHP. In these projects the ESCO may sets up a special purpose entity to Build, Operate and Own (BOO) the CHP plant. From this, the ESCO sells electricity and heat produced offering at lower cost to the industrial user. The ESCO is able to sell any surplus electricity to the grid. After the completion of the contract term the ESCO may transfer the CHP plant ownership to the client.

Recently ESCO specialized in specific technologies, e.g. lighting retrofits have emerged. These ESCOs would implement highly standardized projects at low transaction costs and thus allowing them to implement them in smaller clients.

A limited number of highly specialized ESCOs are undertaking projects in the thermal process in industry, and in particular on heat recovery (Siitonen). Projects relating to Motor and Motor Systems are not very often covered by ESCOs even though these types of projects offer large energy savings, and short payback times. This is due to a number of barriers which are discussed below.

3. General barriers to ESCO projects

The main barriers that inhibit the wider deployment and development of ESCOs are summarized below (These are discussed in more detail in: Bertoldi et al 2006, Hansen 2004).

Low awareness, lack of information and skepticism at the client side of the market for energy services.
The reasons for this are:

(a) energy savings are "not seen" and there is lack of information and understanding of the opportunities that energy efficiency offers and especially of how EPC works;
(b) high technical perceived risk and concerns over the safety and reliability of equipment;
(c) fear of job losses by energy/maintenance managers;
(d) limited understanding of energy use patterns and load profiles, as well as unavailability of such data;
(e) lack of culture for project financing'
(f) limited confidence in ESCOs due to short track record or poor performance; and
(g) end-user not understanding the ESCO contract

Poor understanding of energy efficiency by financial institutions.
The lack of commercially viable and sustainable project financing is largely due to conservative lending practices within the majority of financing institutions. The problem is further aggravated by the limited knowledge of energy efficiency project financing – especially through ESCOs – within the banking sector. As a result, energy efficiency projects are perceived to be more risky, hence higher interest rates are attached to them and lending terms are kept short. The real problem however is not the lack of funds, but rather the "disconnect", or gap, between established methods of traditional 'asset based' lending and the special financing intricacies of energy efficiency projects requiring 'cash-flow based' lending. Energy efficiency projects are often non-asset based and hence insistence on collateral by financing institutions becomes a great barrier. Once the financing institutions begin to accept the energy saving stream as an asset, this barrier will be eliminated

Small size of projects: many energy efficiency projects are too small to attract the attention of large financial institutions. This creates a perceived "small market size" by the banking industry and lack of interest on their part to invest the time and resources to finance small energy efficiency projects.

Legal and Regulatory Frameworks in many countries are not conducive to energy efficiency investments, particularly EPC.

Insufficient Understanding of Measurement and Verification Protocols. These are vital to demonstrate the achievement of savings to investors. Unfortunately, these are not fully known and/or understood either by the borrowers or the lenders.

Administrative hurdles
Complicated procurement procedures for the public sector are unsupportive of the ESCO concept. (e.g. often separate calls for tenders required for project design and for project implementation). Other hurdles are high transaction costs, spilt incentives (different responsibility for investment and operation) in organisations, and unwillingness to allow and involve outsiders in facility operation.

Lack of motivation: For most organizations, energy costs are usually a small fraction of total costs and hence a low priority. In addition, energy efficiency projects usually are not prioroty when they compete for limited in house capital with core business or more 'traditional' and 'visible' investments. Management fails to see energy efficiency as an investment and, therefore, tends to compare energy efficiency projects with other facility expenses. Management also fails to discern the difference between the self-funding nature of energy efficiency and other projects which require new budget allocations.

4. Specific barriers in the industrial sector and motor systems

The following are typical barriers that ESCOs face in the industrial sector. These are based on the

Difficulty to predict energy consumption and assess the project risk. In the industrial sectors there are large variable operating conditions, e.g. variation in production (quantity and type of production) and therefore it is more complex to establish the baseline compared to other project e.g. in the building sector. In addition, there is a lack of sub-metering for sub-systems and equipment (e.g. compressors, pumps, etc.) and measurement techniques could be complex or expensive (e.g. ultrasonic flow measurement). In addition there is a lack of M&V protocols to monitor and report the energy savings, partly due to the difficulty to establish baselines. As examples while for building retrofits there are common deemed saving calculation methods in white certificates schemes, these are very limited or not existing for industrial projects, including motor systems.

High transaction costs. In industry there are specific processes and technologies, especially for the core process. ESCO would need to acquire and manage all the specific technological expertise (some ESCO in fact operates only in specific sectors, e.g. pulp and paper, steel, or food and beverages industries), but then in some countries this would be applicable to only a limited number of industrial clients, thus resulting on very high transaction costs. Many industrial equipment (including motor system), plants and processes are very specific to the industrial plant and production, especially when relating to the core process. ESCO tends to have more specific knowledge on energy management, then on specific building technologies.
In addition, the ESCO would need to carefully asses financial stability and continuity of operations of the potential industrial client. ESCO contract have a medium time span duration (e.g. 3 to 5 years, but could be longer), and industrial plants may be close or changed during this period due to relocation or going out of business. Many motor projects too small (e.g. compared to CHP) to be attractive to ESCOs and therefore should be combined with other energy efficiency improvements such as lighting, ventilation, etc.

High technical risk perceived and concerns over the safety and reliability of equipment. In the industrial sector what matters most is the production and product quality. There is the fear in production manager to disruption production with energy efficiency retrofits, especially for core systems. Usually the production plants are based on tried and tested equipment with established reliability and which has earned the confidence of the production manager over time. When any piece of equipment needs replacing (as part of either routine or breakdown maintenance) it is usually replaced with the same exact type of equipment unless a different type offers significant improvement in the process output quality and speed. Energy savings alone are not considered as a valid reason for changing the proven old machinery, even if the energy savings of the new type will payback the investment rapidly. As an example, in the blow molding machinery, very sturdy, reliable and old models (more than 20 years) of machinery are still used and individual parts are changed if any failure happens. Recently however, very efficient machinery has been placed on the market which although yields little improvement in the production output, but offers considerable energy reduction per unit of production and which would certainly justify the change for the new machinery. As another confirmation of this we have seen that many industrial companies implement measures to save electricity in the lighting and ventilation systems, and sometime in the compress air house (which do not interfere with the production process) but less in the motor systems, especially if linked to the core processes, even though much larger savings are potentially possible with the latter.

Fear of job losses. Traditionally in medium and large sized companies there is a maintenance engineer or an energy engineer responsible for the energy optimization of the plant. Usually these employees are fully aware of the technical possibilities of improving energy efficiency. However they are very often unable to influence the equipment purchasing decisions, often taken by the procurement department (which very often still uses the lowest first cost, as its guiding principle).

When an ESCO is contracted to optimize the energy systems, the energy engineer very often feels his job threatened or at the least sees the ESCO as a competitor. The Energy Manager can thus be hostile to have an ESCO working on the site. The ESCO on its part needs the full support of the energy manager, who is familiar with the systems and the technical details. Very often the process is very specific and the energy manager has a much better understanding and capacity to master the applications than any external ESCO. It is important for the success of the project that the ESCO and the energy/maintenance manager create a strategic alliance. It is also worth mentioning that some large companies may have an extremely competent energy department. In this case the energy department could act as an internal ESCO, assuming the technical risk of the project. This is known as "Internal Performance Contracting". In such circumstances, it becomes a strategic decision by the company whether to outsource the risk management to an external ESCO or allow the internal energy department to take on this function. The latter route of course enables the company to retain the whole benefit of the energy efficiency investment. In some cases the "conflict" between the energy manager and the ESCO resulted in the ESCO audit recommendations being implement by the company own staff and thus the ESCO did concluded a contract with the company. In some other case industrial companies are reluctant to hire an ESCO for fear that some sensible information on production technologies and costs are disclosed to competitors by the ESCO.

Energy savings are "not tangible". Energy costs are considered like any other production related cost, and the only way to influence the energy costs are thought to be getting the best electricity and gas tariffs. Such cost savings are immediately tangible and clearly visible. Companies make efforts negotiating tariffs, including power demand, reactive power limits. By investigating efficiency opportunities, companies could potentially achieve large cost savings and at the same time hedge against raising utilities tariffs. This is a specific barrier which results from limited understanding of energy use patterns and load profiles, as well as unavailability of specific data (see also the barriers on the difficulty to predict energy consumption). There is often a severe lack of sub-metering facilities and a poor understanding of the breakdown of individual processes and equipment where energy savings may be achieved. In particular motor and motor systems are considered as energy overhead, and their energy consumption is often buried under the general electricity consumption, and gets lumped with electricity costs of lighting, office equipment, HVAC, etc.

Lack of trust in ESCOs. A barrier frequently quoted by a number of ESCOs who try to do business with the industrial sector is that industrial clients are not keen on having an outside company learning the details of their production processes, plants and energy consuming equipment which may be commercially confidential. There is also a general diffidence on an ESCO offer which proposes to give "free" savings and capital investment. Very often clients see a catch in the offer, industrial companies do not realize the funding comes from existing utility costs; so that new budget allocations are not required. In addition, industrial companies have a very short time vision and often do not have a clear idea of where their business will be in two or three years in terms of size, location, product mix, etc.. The lack of trust is not just in ESCOs but also shown by the ESCO in the industrial sector clients. ESCOs may hedge themselves against the higher risk associated with industrial sites (bankruptcy, re-location, change in product mix), and thus may request higher share of the cost saving in their contract offers.

SMEs & ESCOs

A large amount of industrial companies are small and medium sized enterprises (SMEs), which are unable to benefit from ESCOs because of the minimum size criteria. SMEs usually do little or no energy saving upgrades and oblivious to their opportunities. They have neither the internal expertise nor the financing capability to identify and implement energy efficiency measures. SMEs account for a significant part of energy expenditure of most industrialised nations and therefore have an important potential for savings at a national level. As the SMEs have only a limited ability to exploit these opportunities. A possible way to bringing energy efficiency to the many SMEs is by diffusing the ESCO concepts amongst all existing small contractors serving the SME sector. Most SMEs already have trusted mechanical/electrical service contractors who know their facilities well. These firms provide preventive maintenance, breakdown repairs and sometimes small capital upgrades. Though these contractors are usually small, they can become "mini-ESCOs" for the SME sector. There is already an ongoing working relationship between small contractors and their SME customers. As a result the small contractors do not incur any costs to build credibility with their client. They do not have to provide formal savings guarantees to convince customers of their capabilities or willingness to stand behind their services. Both, the contractors and SMEs know well that their ongoing relationships could easily be damaged if the contractor fails to deliver its promised services. Small contractors are particularly sensitive to maintaining good customer relations. Therefore complex contracts are not needed to cover contingencies of savings being less than a guaranteed level. The ongoing SME/small contractor relationship for other services can be the foundation for an "ESCO-type" sale of incremental energy efficiency products and services, without the overhead of building a new relationship with a new ESCO.

5. ESCO projects in Motor Systems

There are already some ESCO projects in motor systems. These upgrades include the replacement of the motors (with high efficiency motors), the installation of Adjustable Speeds Drives (ADSs), which save energy in fluid application with variable flow, but only rarely the improvement/replacement of the end-use device such as fans and pumps, with some ESCO projects in compress air systems. The fluid distribution system (piping, ducts, and compress air system distribution network) are usually not part of the ESCO projects, though these could also be optimized and could result in large savings. .As already indicated motor systems may be a relative small component of total energy consumption especially in energy intensive companies (e.g. cement or chemical companies). For this reason, motor systems usually do not justify an ESCO project covering only the motor system 9but we see lighting only projects in industrial buildings, see below). There is however no reason why motor systems may not form part of an overall larger ESCO project.
According to the European Motor Challenge program (www.motor-challenge.eu), non-energy intensive sectors (such as diaries, textile, mechanical sector, etc.) have the potential to achieve large and substantial energy saving in motor systems These savings could be of the order of 500 MWh or more per year, i.e. approximately 50000 Euro saving per year (representing from 10 to 30% of total electricity costs). Yet most of these projects are not undertaken by ESCOs, rather by the companies themselves using external consultants and equipment manufacturers. According to the European GreenLight program, (www.eu-greenlight.org), there are many projects of small saving size (from about 3000 to 15000 Euro per year) undertaken by ESCOs but only doing lighting refurbishments in industrial buildings (this type of projects are often called "relighting"). This confirms that additional difficulties and barriers do exist in ESCOs implementing projects in motor systems in the industrial sector.
To add to the barriers already listed, motors are often embedded in other equipment (pumps, blow mounding machine, compressors, etc.) and it is almost impossible for the ESCO to "get inside" the equipment and change the motors or add the ASD. In this case ESCOs need to develop the solution with the OEMs. There are also concerns about losing the guarantee issues by manufacturers for modified equipment. An "easier" sector to implement motor systems projects is the retail sector, where a number of ESCOs have optimized the electricity consumption of refrigeration systems in supermarkets, often by installing an ASD. However these projects fall more into buildings and commercial sector rather than in industry and the process sector.
In the industrial sector the supply of compressed air is sometimes contracted. This is quite close to the concept of the energy performance contracting. In this type of contract the ESCO may invest in a new compressor with improved efficiency performance and the payment of the service is made through the compressed air unit price, which includes the cost of electric consumption. The ESCO therefore has an economic interest to optimise the compressed air production). In principle, this is not dissimilar to the boiler upgrade in pure "energy contracting" contract types. The price charged to the customer for the service i.e. compressed air (or heat in the case of Chauffage,) is at the point of generation. In the case of compress air distribution systems, large savings are usually available downstream (e.g. by reducing the leakages). It would be more interesting to see contracts where the cost of the supplied air is charged at the point of use. The ESCO in that case would have a strong motivation in optimising also the distribution system.

More recently we are beginning to see an increasing interest by ASD manufacturers to install this energy saving technology in the industrial sector using an ESCO delivery model. In some cases the ASD manufacturers have teamed up with an existing ESCO serving the industrial sector. The ESCO has provided that audit, arranged the financing, provided the technical guarantees and monitored the savings. An example is the Kemira GrowHow fertilisers plant ventilation system upgrade by a Finnish

ESCO together with a large equipment manufacturers, which resulted in savings of 4000 MWh per year (Savolainen 2007). Another interesting area of increasing interest for ESCO projects is the water supply and waste water treatment where large pumps are employed. Here the application of ASDs could save large amount of energy.

6. Conclusions and the Way Forward

Due to a number of existing barriers not many ESCOs are active in the industrial sector and in particular in projects inclusing motor systems. This is surprising since large energy savings are available in motor systems with short payback periods. This paper has discussed the main barriers and below it makes some suggestions on how to increase the number of ESCOs projects in this sector. The following recommendations are proposed to further promote the ESCO concept in industrial projects:

Increase Dissemination of ESCO Services and Projects

The first task is to raise awareness by demonstrating the ESCO role and process, and the resulting advantages for the industrial company. There are already a number of governmental programmes to accelerate the diffusion of the ESCO concept. However the programmes require customised attention for each industrial sector. There are some common themes that may be addressed centrally, such as the co-ordination of banks and public bodies in the development of pre-approved energy efficiency loans or access to credit for efficiency projects. However, the industrial sector has different needs and different problems compared with the building sectors (where most of the ESCO projects take place). Therefore various governmental programmes to promote the ESCO concept must be tailor-made for the industrial sector, and wherever possible use the industrial trade associations as partners to promote the ESCO concept. It is also important to educate the consumer as well, through consultation and training to improve customers' solicitation, evaluation and selection of ESCOs.

Launch an accreditation system for ESCOs

Since many organisations are eager to call themselves ESCOs, without having proper qualifications and experience, the next important action is to ensure that all those wishing to work as ESCOs achieve and demonstrate set of minimum prescribed standards.

In the United States, an ESCO accreditation system has been implemented by the National Association of Energy Service Companies (NAESCO). In Europe, an effort is underway to define the minimum set of qualifications for ESCOs, together with a system to assure the quality of service. While a temporary voluntary solution can be valid in the short term, a long-term solution could be found in a mandatory European standard.[3]

Increased cooperation between ESCOs and vendors/OEMs

Before designing a program to support ESCO in the industrial sector, there must be good understanding of sector size, energy intensities, skills within the sector, needs and concerns. Co-operation with relevant individual trade associations, OEMs and wholesalers will be vital for designing an appropriate support package for each type of industry. Governments, utilities, and/or broad based trade associations are well placed to provide the co-ordinated effort to needed to accelerate the diffusion of ESCO concepts throughout the industry.

OEMs need to recognise that there is an opportunity for increased profits by increasing product sales or services to their existing clients. OEMs will normally prefer to apply their own successful business model, even though they may be aware of other savings opportunities within customer facilities.

[3] This is proposed by the Energy Services Directive, which says that energy services shall be provided (art. 7) by "*qualified*" ESCOs, installers and energy advisors and consultants. Art. 8 of the Directive asks for "*appropriate qualification, accreditation and certification schemes"* for such energy services providers, "*with a view of maintaining a high level of technical competencies of personnel and the quality and reliability of energy services offered"*.

The pursuit of the opportunity to expand their business will require OEMs:
a) Learn to explore a new business opportunities, and
b) Learn how to base their sales on energy efficiency measures.

ESCOs could be excellent strategic partners of OEMs in selling energy efficiency measures, and to set up a turn-key project based on performance contracting.

Turning small contractor into a special bread of ESCOs

The energy efficiency focus and services which ESCOs provide to large energy users can also be delivered by small contractors to SMEs. These small contractors have the advantage of an ongoing relationship of trust from their current customers, eliminating the typical ESCO's need to sell and prove itself to customers. However small contractors need to "wake up" to this opportunity of expanding their businesses. They will need energy efficiency training and support services presented in their language. Specialist training and support is needed in the areas of selling, financing, predicting and demonstrating and proving of energy savings, The diffusion of ESCO type services to small contractors can be accelerated with the co-ordination of a national body such as government, utility or broad trade association.

Develop Funding Sources

ESCOs need working capital for marketing and project preparation and development. Sources of debt and equity financing need to be located. Several possible funding sources should be investigated: commercial banks and lending institutions; venture capital firms; equity funds; strategic partnerships (e.g., utilities and engineering firms); leasing companies; and equipment manufacturers

Governmental incentives and grants for audits, tradable energy saving certificates (e.g. France, Italy) and CDMs can make an additional contribution. ESCOs must be aware of these support schemes and should use these to offer shorter contract duration, or a higher share of the resulting cost savings to their clients.

Standardise Contracts and M&V

An important action in the way forward is to standardise Measurement and Verification (M&V) procedures. This will give enhanced confidence and build trust with end-users and above all with the financial community. With greater confidence in the results, the financial community will have a better understand of EPC. This in turn should facilitate the release of capital funds by financing institutions without unreasonable terms attached to cover their risks .

The development of standard EPC contracts has been an elusive task as various companies consider their contract approaches unique and proprietary. European banks however, should fund only those EPC projects with contracts that at least have M&V protocols specified. The International Performance Measurement and Verification Protocol (IPMVP) is a good first step. M&V protocols should pay more attention to the industrial projects and to the industrial specific situations. Evaluation protocols are also needed for tradable energy saving certificates, and CDMs projects.

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EMSA- Policy Guidelines for Electric Motor Systems

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Abstract

An important insight into energy efficiency policy around the globe is that there is no single instrument that is able to bring alone energy savings swiftly. Also, the most cost efficient solution will not automatically be adopted in the industrial context because other elements influence decision making like risks and value attributed to energy efficiency. Therefore a mix of policy instruments is needed to overcome the barriers for energy efficiency.

Within the IEA 4E Project Electric Motor Systems Annex the EMSA Task “Motor Policy” will design and propose a global policy guideline for exploiting efficiency potentials in motor driven systems - consisting of mandatory, voluntary and financial measures as well as procedures for monitoring and compliance. The publication targets policy makers both in industrialized and in developing countries.

Examples of mandatory policies and related issues are international energy efficiency standardization, testing procedures and based on that mandatory national minimum energy performance standards, product certification and registration programs and compliance aspects.

Examples of voluntary measures are labeling programs, voluntary agreement schemes, energy management and energy audit programs, several awareness raising instruments (incl. training, guides, tools, benchmarking, etc.).

Financial instruments are for example tax allowances, grants and rebates, soft loans, guarantees for credits, contracting, etc.

International exchange is another important issue, therefore conferences, events and international initiatives will be described.

This paper presents an overview of the content of the publication (now in draft stage) and shows a few examples of mandatory and voluntary policies to give a current insight.

Introduction

The IEA Implementing Agreement "Efficient Electrical End-Use Equipment" (4E) is driving governments and industry to higher concerns for energy to be saved. Within 4E the "Electric Motor Systems Annex" (EMSA) steers the motor technology world towards the necessary knowledge and empowerment to reap the fruits of energy savings promised by new technology and better design and the economy of higher fuel and electricity prices.

EMSA has been engaged in motor policy since its outset in 2008. A first analysis was published in 2009 as "Motor MEPS Guide" [1] profiting mainly from the US experience in setting mandatory standards. In 2011 a second volume followed: "Motor Policy Guide, Part 1: Assessment of Existing Policies" [2] analyzing motor policy instruments in nine countries/regions. Now the "Policy Guidelines for Electric Motor Systems" is proposed that summarizes the experience in various countries with mandatory and voluntary schemes, with or without financial incentives and a multitude of information elements.

The goal of the planned Policy Guidelines for Electric Motor Systems is to propose guidelines for policy makers both in industrialized and in developing countries on which policy instruments shall be applied to reach market transformation of motor systems (a sort of "cook book") and what needs to be taken into account when implementing such policy instruments. The publication will show successful examples deemed worthwhile to follow.

The Policy Guidelines for Electric Motor Systems shall be ready as a complete draft by the end of 2013, to be reviewed and edited for publication by mid-2014. The report will be published online (www.motorsystems.org) and will be announced to an interested larger audience through EMSA newsletters and at international conferences (eceee Industrial Summer Study, Motor Summit, etc.).

Switzerland (represented by A+B International) and Austria (represented by the Austrian Energy Agency) are responsible for the first drafts. During 2013 more international experience and expertise will be invited to contribute substantially to this document. The following text shows an overview and some examples of the current status (May 2013) of the document.

Overview of contents

In the Policy Guidelines for Electric Motor Systems policy instruments are grouped into three main categories of policy measures (mandatory, voluntary and financial measures) and international exchange is handled in an own chapter (see table below).

Overview of the table of contents of the Policy Guidelines for Electric Motor Systems

Chapter no.	Main chapters
1	**Executive summary**
2	**Introduction**
3	**Organisational structure of national motor policy implementation**
4	**Mandatory measures**
4.1.	International standards for efficiency testing and efficiency classes for motors and systems
4.2.	Build-up of necessary testing capacity and quality (training, accreditation, round robin)
4.3.	Mandatory national efficiency requirements
4.4.	Product certification
4.5.	Product registration
4.6.	Compliance (monitoring, verification & enforcement)
4.7.	Mandatory audit programs
5	**Voluntary measures**
5.1.	Labelling
5.2.	Product certification (IECEE)
5.3.	Voluntary agreements with industry
5.4.	Awareness raising
5.5.	Company motor policy
6	**Financial incentives**
6.1.	Potential sources of funding programs
6.2.	Tax allowances for energy-efficiency investments
6.3.	Grants for optimization of old and new systems
6.4.	Soft loans
6.5.	Guarantees for credits
6.6.	Contracting
6.7.	Electricity tariff benefits for energy-efficiency-investment
7	**International exchange**
7.1.	Initiatives
7.2.	Institutions, organizations
7.3.	Events
8	**Conclusions and recommendations**
9	**List of abbreviations**
10	**References**

Examples of Mandatory Measures

Under this heading mainly Minimum Energy Performance Standards (MEPS) are described in this paper, in the Policy Guidelines for Electric Motor Systems other instruments as international standards for electric motor system, testing procedures and based on that mandatory national minimum energy performance standards, product certification and registration programs and compliance aspects will be included.

Minimum Energy Performance Standards

The concept of mandatory minimum energy performance standards (MEPS) is based on the experience that industry will rarely adopt new and higher efficiency technology if it involves higher purchase costs. Even if mainstream economic theory and industry itself suggests that cost-effective decisions and investments are made, the reality in many industry projects shows that the barrier for a life cycle cost based investment plan is too high and the concern for wasted energy is too low.

The USA National Electrical Manufacturers Association (NEMA)/American Council for an Energy-Efficient Economy (ACEEE) approach in setting up mandatory MEPS has proven this point and has shown a successful market transformation.

The policy approach for mandatory MEPS is manifold. It consists of a sequence of steps that are described in the table below:

Steps for introduction and renewal of MEPS

Step	Measure	Level
1	Set internationally harmonized standards for motor efficiency testing and efficiency classes.	International
2	Raise national awareness for importance of energy efficiency, electricity use in industry with electric motor systems.	National
3	Initiate legal process of having the authority to issue market transparency (energy labels) and market transformation (MEPS).	National
4	Assign authority to entity responsible for setting targets, issuing MEPS, define testing procedures, accredit testing laboratories, develop product registration and define sanctions for violating products and industry.	National
5	Set-up research team for market data and technology development, for research of environmental effects of more efficient products, on impact on market structure and burden for investments in industry.	National
6	Stake holder process to define time line for targeted values.	National
7	Issue legal document (national law) for setting the MEPS.	National
8	Start monitoring & verification program with check-testing of compliance. Publish annual report on process and progress.	National
9	Define update cycles of MEPS.	National

Minimum energy performance standards are set by national authority through national laws. The law requires usually a defined list of products, a methodology to set MEPS and a government entity charged with this procedure. Many countries with MEPS for electric motors have detailed legal procedures on negotiating with stakeholder groups and universities to agree on a precise level of MEPS plus a subsequent introduction and development plan to later increase the MEPS in a predefined sequence.

Industry is usually invited to collaborate with the responsible government agency and is then involved in the stakeholder consultation through their industry associations and some key manufacturers. In the European process also NGOs were invited for this stakeholder dialogue. This helps to formulate targets in a triangular configuration involving three major groups of stakeholders:

- Government, interested in a balanced approach to MEPS that can be successfully brought into law respecting parliamentary majorities and procedures. Governments do not want to privilege certain industries or "punish" other industries with severe burdens that they cannot carry easily. Governments want to have a positive impact of MEPS on the national employment situation and on international competitiveness of the domestic industry.

- Industry, interested in low interference into free markets and low responsibility of added mandatory restrictions for energy efficiency. Industry is afraid of low quality and cheap import products that take market shares away from national manufacturers. This is a strong argument for MEPS. Usually some of the leading industry will take the front runner approach and make energy efficiency its business model and its brand. Thus some leading manufacturers can influence the development in a positive way.

- NGOs, interested in long-term development, CO2 mitigation and energy savings. They can coordinate different NGOs and gain technical and policy know-how to influence the decision making process.

Based on sufficient technical evidence from independent research sources, mid- and long-range performance targets can be set. It is best if the methodology for setting targets and deciding on MEPS is transparent with a well-defined timeline and the research is based on national market surveys and recent technical developments.

The procedure for setting MEPS takes several years, allowing industry to prepare new product lines with high efficient products and to abandon older inefficient products from their production.

Examples of Voluntary Measures

Before choosing the right policy instrument out of a broad branch of possibilities careful analysis is needed, which should include the identification of the market forces (all actors in the market chain to implement energy efficiency measures) that have to be strengthened.

Differentiated policy strategies are needed to provide incentives as well as support both in the long-term and the short term perspective. Existence of and possible interaction with other energy/CO2 related policy instruments should be evaluated. “Normally a policy instrument will need to be part of a package of instruments in order to increase the combined efficiency and effectiveness and overcome all market barriers” [3, p. 18]

Therefore the first step is to involve relevant stakeholder and market actors in the design and the construction of the policy instrument. Usually these are: industrial associations, chambers of commerce, ministries for environment, relevant regional and local partners (e.g. energy agencies), and financial institutions (banks, e.g. for subsidies).

A difficult step is the estimation of the expected impact and cost-efficiency of the policy instruments. Usually studies on this issue are done before implementing the policy package.

Another part is the definition of the target of the instrument. It should be: specified (concrete as possible: what is aimed for, who is targeted), measureable (measureable objectives), ambitious (targets should go beyond business as usual), realistic (with respect to desired effect, available budget and timeframe), time framed (when should results be achieved). [3, p 19]. Also, already in the planning status monitoring activities have to be considered.

Under the heading voluntary measures mainly labeling, energy audit and energy management program and tools are described in this paper, in the “Policy Guidelines for Electric Motor Systems” other instruments as voluntary agreement schemes, benchmarking, guides, databases, trainings and companies motor policy will be included.

Labeling

Energy efficiency labels are well known internationally to show energy efficient products to end consumers. They exist in different shapes and classifications within various national programs for a multitude of products: electric appliances, electronics, electric motors, pumps, cars, etc.

An energy label for electric motors must be based on two basic pre-requisites:

- An international (or national) testing standard for the energy efficiency of a product.
- A national labeling directive that sets the thresholds between each label class; IEC 60034-30-1 for electric motors defines these thresholds already and gives an indication for the information on the motor rating plate.

National legislation is necessary to implement mandatory labelling for a given product with a precise scope, to define whether the label is to be displayed at the place of sales (or permanently to be displayed on the product) and to give the authority to laboratories in industry or third-parties to assign a label to a product.

Energy Audit Programs

Energy audit programs are a very cost efficient way to reach national targets on greenhouse gas reduction or increase in energy efficiency.

An audit program is not a single instrument but a policy package consisting usually of:

- an informative instrument (recommending energy saving measures through audits)
- a financial instrument (subsidy to companies in the industry and service sectors).

From the energy audits, saving potentials and saving measures are identified. The companies and organisations then decide whether to carry out saving measures or not. [3]

From the policy design point of view, an energy audit program usually consists of several elements:

- The implementing instruments: like the legislative framework, the subsidy/financial scheme and other incentives/promotion and marketing activities.
- The administration of the program with the interaction of the key players (the administrator, very often government level body, the operating agent (e.g. an energy agency), the auditors, and the participating organizations); the development of the energy audit models and the monitoring system.
- Quality assurance: comprises the training and/or the authorisation of the auditors and the quality control (checking of the reports).
- In addition different audit tools (excel sheets, report templates) are made available.

Energy audits are a quite unique instrument to tackle the real efficiency of already installed motor systems. They can give insight to the inter-correlations between the motor and the driven systems and the actual need of the process and therefore also consider sizing aspects and the running time of a particular motor and possibilities to switch it off.

For all steps/elements of energy audit programs energy efficiency in motor systems has to be considered. The main areas are:

- Definition of motor systems as specific area to be considered within energy audits
- Motor systems specific targets within the program (e.g. number of motor systems audited within one year)
- Training and qualification of energy auditors in this area (e.g. by training workshops on the different types of motor systems (motors and frequency drives, chillers, compressed air, fans and pumps).
- Development of tools specifically for energy audits for motor driven systems (e.g. energy audit guidelines, energy consumption calculation for specific systems, saving calculation methods for energy saving measures; energy audit reporting guidelines for different motor systems).

Example Austria energieeffiziente betriebe program as energy audit program

In Austria the voluntary program energy efficient companies focuses on Small and Medium Enterprises. The content of the program includes technological focus on motor driven systems (pumps, fans, compressed air and cooling systems), that are technologies used in very different sectors. The first two years (2005-2007) were used to build up the program and discuss details with the Environmental Ministry of Austria (BMLFUW) and the regional programs.

In Austria the energy audits are financially subsidized by national and regional sources. Regional program managers are in close contact with the auditors and the companies. They are responsible for the authorization of the energy auditors based on professional experience, technical education and further trainings.

Results of energy audits together with saving potentials are reported to the regional program managers responsible for quality assurance of the reports. In addition consultants in the regions document the implemented and planned measures in a partly public database, including the name of the company, the name of the consultant and details on activities as well as energy- and cost savings. This data is summarized and evaluated on regional level, incl. measures suggested and implemented. Furthermore, within the program all forms of national and regional activities for awareness raising are implemented. Motor systems aspects are integrated by a technological focus incl. trainings, tools (audit guides) and the build-up of an expert network.

Energy Management Programs

In many companies there is no structured approach to improve the energy performance. Although the possibilities to improve the energy performance may be known either identified within an energy audit or by internal staff, the measures are not implemented. This is due to several reasons, one being that the top-management or other key stakeholders oppose such measures or prefer other measures. In case the measures are implemented, often the energy consumption starts to rise again after a certain time because there are no responsible persons for maintaining the optimized systems.

Therefore a systematic approach is needed. First of all, energy must be a key topic in the company, from top-management down to all employees all relevant persons shall be engaged in saving energy. Clear target setting and the follow-up of saving measures ensure that energy efficiency steadily rises. Systematic energy management as systematic tracking, analysis and planning of energy use is one of the most effective approaches to improve energy efficiency in industries [4, p.5].

Energy management programs are policies and initiatives that encourage companies to adopt energy management. [4, p 10].

Recommendations for the integration of motor systems aspects in energy management programs are for example:

- Policy makers should build on the energy management standard ISO 50001 and develop programs to set incentives to encourage industrial and service sector companies to use this powerful tool.

- The implementation of energy management systems should be assisted by qualified consultants and tools. Examples of useful tools are e.g. for identifying the main users (energy balance, purchasing recommendations, etc.).

- A reference document (motor systems guide) for "motor policy" on company level should be developed. This document should show how motor efficiency is to be considered within an energy management system. This comprises the definition of purchasing criteria, motor inventory list, guidelines for replacement, requirement for installation or acceptance tests, requirements for repair.

- Energy management auditors (external, internal) and energy managers should be trained for the use of such a document.

- Purchasing recommendations should be published (cooperation with producer is needed); industrial associations should promote these recommendations (members should refer to these recommendations during sales process).

Tools

The term tools in this paper describes web- or Excel-based or other software applications which are intended to facilitate the estimation and quantification of energy saving possibilities in motor driven systems. The use of recommended calculation tools can help to standardize energy audit processes and enables energy efficiency programme managers to promote a uniform product. Usually motor system tools are designed to very specific purposes.

Examples of specific functions are:

- Calculation of energy savings when replacing an AC-motor with a higher efficiency one (therefore those tools have sometimes a database with new motors behind them)

- Installing a Variable Speed Drive on a pump or fan application

- Estimating heat recovery by a heat recovery system for an air compressor

Some examples of such tools are MotorMaster+International, EMSA Motor Systems Tool www.motorsystems.org, Airmaster, Fan and Pump System Assessment Tool.

Excel-based tools are also used to estimate the energy demand of electric motor systems in companies or generally for all electric users in a company and to identify the most relevant motors. Those tools work usually without metering of specific motors and need only estimations on running time and nameplate data of the motors installed within a company.

Example Switzerland Excel-based software tools alongside the motor efficiency decision process

In Switzerland, S.A.F.E. developed Excel-based software tools to help industrial users assess the savings potential of their existing motor systems:

1. SOTEA (Software Tool für effiziente Antriebe - software tool for efficient drives) is used to assess the efficiency potential of motor systems in one plant. The goal is to give the industrial user a rough number of possible savings which largely depends on the age of the installed motor stock.
2. ILI$^+$ (Intelligente Liste - intelligent list) is used to compile a list of motors, from which motors with the highest savings potential can be chosen for retrofit. The Decision Maker of the tool helps users identify a relatively small number of motors representing a relatively large share of total possible savings.
3. The standardized template for a motor testing protocol helps to summarize motor test results and proposed motor systems efficiency measures together with the expected costs and savings.

These tools are directly linked to and applied as part of the Motor-Check (a motor systems energy audit methodology).

Potential of reduction according to criteria

Criteria		Default values	My values	Number of motors		Potential of reduction of energy		Potential of reduction of costs	
				absolute	in %	[kWh/a]	[kWh/LC]	[CHF/a]	[CHF/LC]
(1) Rate of realisation of the maximal saving potential in %		50	70	145	22%	480'838	7'341'977	60'105	917'747
(2) Age, older than x years		15	13	396	61%	599'043	8'450'073	74'880	1'056'259
(3) Operating hours per year > x Stunden		3000	5000	334	51%	468'685	5'726'851	58'586	715'856
(4) Dimension of motors > x kW		10	8	151	23%	443'558	6'980'616	55'445	872'577
(5) Motors without FC (frequency converter)		yes	yes	606	93%	701'838	9'273'035	87'730	1'159'129
(6) Application	Pump	yes	yes	0	0%	0	0	0	0
	Ventilator	yes	yes	144	22%	135'617	1'545'474	16'952	193'184
	Compressor air compr.	yes	yes	0	0%	0	0	0	0
	Compressor cold	yes	yes	0	0%	0	0	0	0
	Mechanical conveyor	yes	yes	0	0%	0	0	0	0
	Others	yes	yes	508	78%	645'643	8'924'267	80'705	1'115'533

ILI⁺ Decision Maker, www.topmotors.ch (Source: S.A.F.E., 2013)

Conclusions

An important insight into the best practices in energy efficiency policy around the globe is that there is no single instrument that is able to bring alone energy savings swiftly. Also, the most cost efficient solution will not automatically be adopted in the industrial context because other elements influence investment decision making like risks, costs and value attributed to energy efficiency.

The policy needs a mix of several ingredients, in four main areas:

1. Mandatory performance standards are necessary because international experience shows that the life cycle cost approach is not generally used and that industry still will buy the cheapest (least efficient) product for a certain task. Mandatory Minimum Energy Performance Standards on the other hand - based on national law - keep cheap inefficient products from the market which can be reinforced through a rigorous compliance regime.

2. Voluntary measures include labeling, voluntary agreements and awareness raising. Qualified and focused information is necessary for motor manufacturers and motor users, training is also important for engineers who need also testing equipment for analyzing running stock and tools for the optimal design of new equipment.

3. Financial incentives help especially in industry to raise awareness for energy efficiency, to open the factory gates for expertise that will look at hidden improvement potentials and to convince management eventually to invest in regular efficiency improvements that keep the entire rolling stock up to date with modern efficiency technology.

4. International exchange is the most effective way for the design and implementation of successful policy instruments. Learning from the experience of other countries reduces the costs and risks of the envisaged policy instruments to the possible minimum.

EMSA has been engaged in motor policy since its outset in 2008. The "Policy Guidelines for Electric Motor Systems" will summarize the experience in various countries with mandatory and voluntary schemes and will therefore help policy makers to design efficiency policy instruments according to international standards.

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Dutch Program 'Green Deal efficient electric motor systems' and Energy efficiency programs as implementing forces

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Frank Hartkamp, Ronald Vermeeren, NL Agency Energy and Climate

Abstract

The paper will present and document the combined efforts of producers and installers of efficient motor systems in the Netherlands and the Dutch government in developing a program for implementation of efficient motor systems.

The Dutch government has initiated a Green Deal program in order to accelerate the implementation of green climate-effective and innovative projects in the Netherlands. Core characteristics of these projects are concrete green benefits of the project, in a relative short period of time (2-3 years), and the need for removing barriers in the market (by government assistance).

Research and pilots show that optimization of electric motor systems and application of the best available technology can deliver reductions of 20 - 30% of the electricity use in industrial production systems and in cooling, ventilation and heating systems. Combined effort of industry, government and research companies is initiated to overcome these barriers the coming years.

A consortium of manufacturers and installers of efficient motor systems in industry has started the Green Deal Efficient Electric Motor systems in cooperation with the Dutch ministry of Economic Affairs. The project focusses on developing pilots and projects on motor systems based on systematic analysis applying best available technologies and life cycle costing principles. And on the potentials of financial services for investing and operating motor systems. Practices will be made available aiming at raising awareness and capacity building within the sector and transfer towards OEM and industrial end-users.

A close cooperation is established with the implementation practices of Energy management systems in industry. NL Agency facilitates this process with the large industrial companies in their work on increasing their energy efficiency (in voluntary agreements (VA's)). The Green Deal project profits also from the close operation with the Dutch 'Knowledge Network EMS' in order to reach the industrial end users. And from the participation in the Electric Motor Systems Annex (EMSA) for technical guidance, capacity building and knowledge on performance and IEC/ISO systems standards.

Introduction

Electric motor systems (EMS) use up to 69% of electricity in Dutch industry. Research and projects show that system optimization and best available drive technology can deliver reductions of 20 - 30% in pumps, fans and compressors in heating, cooling and ventilation systems, and industrial handling, processing and production systems. Thus lowering the national electricity bill by 5 to 8%. Obstacles in the marketplace and a low awareness of best practice and technology hamper market penetration.

Complexity of the issue, unfamiliarity with best practices and the BAT (best available technology), the limited use of life cycle cost principles and the lack of funding make that possible savings are implemented only partially or in the long term.

For industrial users optimizing motor systems means a direct cost savings and the ability of using the resulting funds in an other way. This translates into a 1 on 1 enhance competitiveness. In addition, the focus on efficient drive systems offers the companies / equipment builders commercial opportunities as well as opportunities to (internationally) distinguish themselves.

Since June 16, 2011 the European Directive (2005/32/EC) came into force with requirements on the minimum efficiency of electric motors. This Directive, further explained in the Regulation EC 640/2009 dated July 22, 2009, offers an excellent opportunity to apply the effective system approach directly and optimize the motor systems.

Government and the Dutch motor systems industry have started the Green Deal Efficient Electric Motor Systems to accelerate the market penetration, in alignment with other initiatives like the transition within industry towards the energy management system standard ISO50001.

Instrument of Green Deals

Remove bottlenecks in sustainable initiatives

In the development of sustainable initiatives, companies, civil society organizations and other governments face barriers. For example, if they want to run project to generate energy or to use less water. The barriers can have various causes. Sometimes the laws and regulations are causing delays. Another time the initiators have trouble finding suitable cooperation partners. And sometimes

Figure 1 From Applicant via Government to Result (See for translation the text box on the next page)

Translation from Dutch text in figure 1:

Title: 'How does the Green Deal work?'

Text box: 'Result': With these green deals we (Government and Dutch society) are taking concrete steps towards a sustainable society. With economical viable projects. This is the beginning. The coming period the government will continue in closing deals with Dutch society.

they're not succeeding in getting enough money together. In those cases, the Dutch national government can help through a Green Deal. Figure 1 shows an simple scheme with the parties involved: applicant ('Indiener' in Dutch) and government ('Overheid' in Dutch), and the green result ('Resultaat' in Dutch).

Green Deals ensure sustainable economic growth

The Netherlands want to move towards an economy where sustainability and economic growth go hand in hand. Growth is not at the expense of the environment, but takes into account the environment and the needs of future generations. The Green Deals fit within it. They provide short-term outcome for all. This effect is even greater, as other parties will follow the Green Deal. [1]

Green Deal Efficient Motor Systems

Bottlenecks on the implementation of Efficient Motor systems (EMS) by industrial end-users

(Inter) national studies, projects and practical experiences confirm the bottleneck associated with market players, such as the manufacturers / suppliers of electric systems, installers and maintenance providers, equipment manufacturers (OEM) and end-use industries (manufacturing).

Analysis of the market of electric motors supply and maintenance in the Netherlands, and the practices of the OEM's and industrial end-users shows that for a successful acceptance of efficient motor systems all market parties have to get involved.

Figure 2 shows these barriers for each party involved, starting with suppliers and – through installers and OEMs ending with the end-users. Some main barriers are the focus on lowest investment cost, focus on motors only, instead of system benefits, low knowledge of opportunities for system efficiencies and the split in allocation of investment and operational cost with the end user.

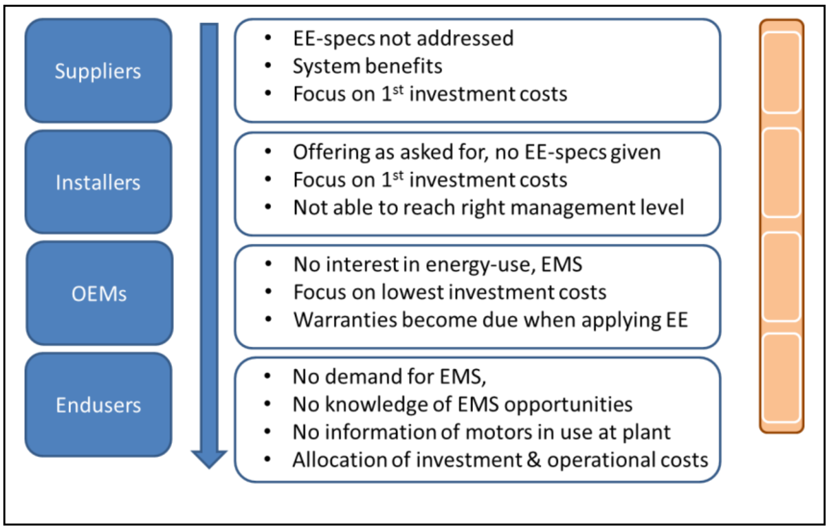

Figure 2 Obstacles in marketplace for Efficient Motor Systems

Initiative Green Deal Efficient Motor Systems

The initiators of this specific Green Deal Efficient Motor Systems are the FEDA and the Uneto-VNI. FEDA is the Federation of suppliers of Electric Motors, Drives and Automation Engineering, and Uneto-VNI is the trade association of installation and electromechanical maintenance companies.

The two organizations together with their member-companies want to encourage a wider application of efficient electric motor systems by reducing some of the above mentioned issues. And so assisting the users of the motor systems in achieving direct energy savings, and strengthening their competitiveness by developing innovative products and services, as well as developing more activities by the energy suppliers and service providers. Which translates into growth in sales and employment.

FEDA and Uneto-VNI and twenty-six member-companies from FEDA and Uneto-VNI have joined the Green Deal and are participant in the project. As well as two main pump suppliers. The project will be carried out by the 28 participants. The program management is done by TPA consultants, in cooperation with FEDA and Uneto-VNI. The government is involved via NL Agency as secretary of the project group and directly via the Ministry of Economic Affairs in a steering committee.

The project (Green Deal) consists of three components that aim at reducing some of the issues raised in the market, improving the conditions in the supply chain, and the realization of a number (example) projects by end users by which direct energy savings are realized, and following the examples is further stimulated in the market. The project duration is 2,5 up to 3 years.

The project has the following project-activities: A1 & A2. Preparation, training and performing pilots; followed by execution of projects; B. Finance Scheme(s); C. Knowledge transfer. In this paper we will focus on A1/A2 [3]. In figure 3 the project scheme is presented together with the main steps for each project or business case.

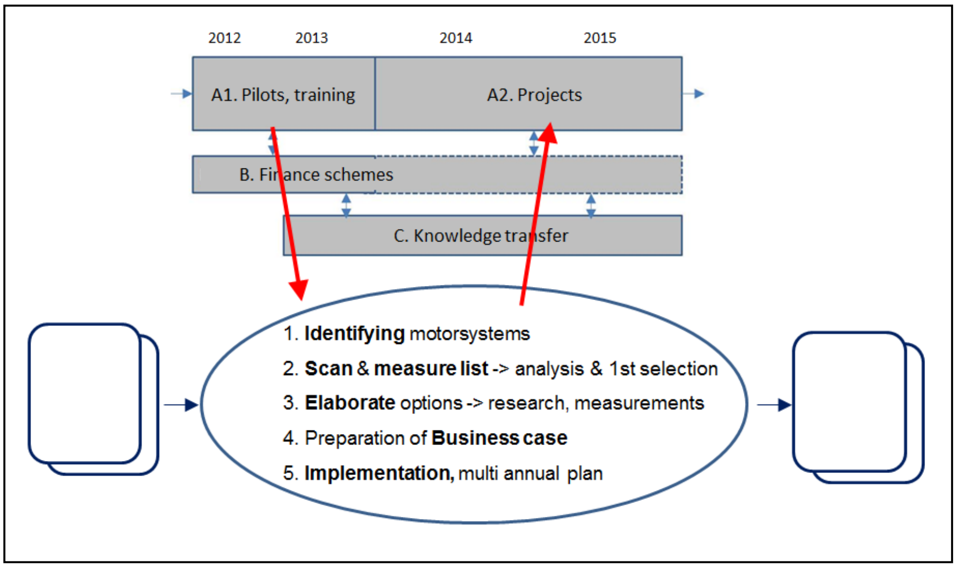

Figure 3 Project scheme with step 1 up to 5 towards implementing the business case

In cooperation with the partners of the Green Deal Efficient Motor Systems and the (some of the) end-users of motor systems a standard approach or working method is developed for analyzing and optimizing a specific motor system. The five basic steps are shown in figure 3. The format of the businesscase will defined by the partners, with a number of objective criteria. Depending on the specific expertise and interest of the partners and the end-users, and on the available data at start as well as the ambition (or desired scope) of the end-user these five steps will be customized in every single project [4].

Several tools are available to calculate and present energy efficient motor systems, life cycle cost, and type of drive and control component. Via the participation of the Dutch knowledge network efficient motor systems in EMSA the Motor Systems Tool became available for analyzing and calculating the motor systems of the end user. The tool is unique in its 'system approach' and is brand independent. See www.motorsystems.org for more information and download area. The Life Cycle Cost method is aimed at the end users' management and procurement department.

Five pilot projects will be started to make GD-partners more familiar with the standard approach, and to get some good business cases for promotion and publicity. In the same period focus will also be on identifying any specific problems in the application of this approach and in the realization of these business cases. For example the requirements by procurement and or plant management sets, the connection to internal organization and maintenance, and investment planning, etc.

Systems approach

The maximum savings potential of efficient motor systems can only be realized by following the so called systems approach. This is a term which hints at a systematic analyses of a motor system starting with the process or the drive-load.

Applying a state of the art efficient electric motor can bring efficiency improvements of 0,1% up to 10% compared to the minimum standards in place. See the green dot-line in figure 4 below. Looking at improvements at the 'core motor system' (the blue dot-line in the figure) increases the savings potential considerately. Now also the control, the transmission and the component like a pump or compressor is part of the analyses for an optimal motor system. Potential savings are now increased up to 20-30%. The best approach however in terms of efficiency improvements is at making an analyses of the complete total motor system, i.e. including also the ducting and the process (conditions) itself, see the red dot-line in figure 4 [5].

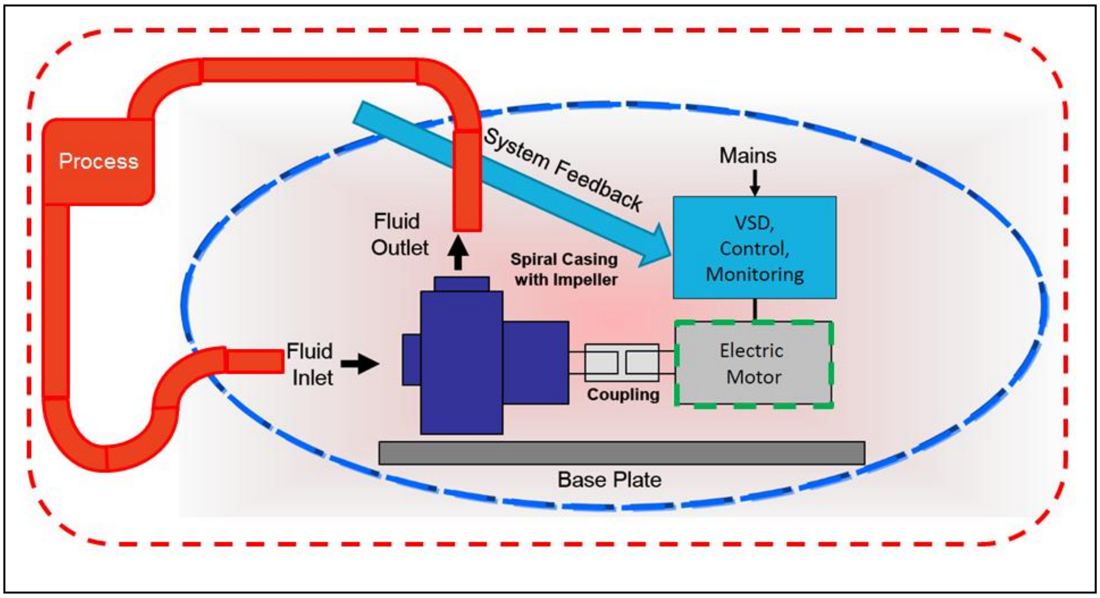

Figure 4 Systems approach for efficient motor systems

First pilots started

In the first quarter of 2013 five pilots are being started, in different industrial sectors: the dairy sector, the wastewater treatment sector, paper industry and the drinking water sector. Much focus is on pump systems, and the first analyses come to a short list of potentially promising systems.

Within one pilot the first challenge is to make the analysis of the installed base in cooperation with the personnel on the work floor (maintenance). One objective of this particular project is to make a coupling with the maintenance and investment program for the short and midterm.

In another project the analyses will target at an integrated analysis of the process itself, i.e. analyzing the aeration process (process control for oxygen demand in the waste water), and the efficiency of motor, the drive, transmission and the design of the aerator itself. This will be done in cooperation with the OEM, supplier, installer and engineers.

Alignment with energy efficiency programs

A close cooperation is established with the implementation practices of Energy management systems in industry. NL Agency facilitates this process with the large industrial companies in their work on increasing their energy efficiency (in voluntary agreements (VA's)).

The long lasting experience on energy management implementation was shared by the Netherlands, represented by NL Agency, respectively in the CEN project team for development of EN 16001 and in the ISO TC 242 that developed ISO 50001. These experiences formed a strong base for the development of ISO 50001. Therefore a transition from the Netherlands practice of energy management to ISO 50001 seems a logical one.

The quality of implementation of the energy management systems in place with the VA participants is monitored every year by NL Agency. Opportunities are identified to improve the system and its effectiveness. The systems are based on (elements of) the standard ISO14001 and some participants have started already a transition towards ISO50001.

In the 2012 monitoring of the energy management systems special attention has been given towards the opportunities for efficient motor systems (EMS). The areas which offer the best opportunities are Energy Planning; Implementation, operation and monitoring; Maintenance and repair of EMS; and Procurement and Design (see also paper 041).

And the Green Deal project profits also from the close operation with the 'Knowledge Network EMS' in order to reach the industrial end users. As well as from the participation in the Electric Motor Systems Annex (EMSA) for technical guidance, capacity building and knowledge on performance and IEC/ISO systems standards.

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Figure source

Figure 1 From Applicant via Government to Result

Figure 2 Obstacles in marketplace for efficient motor systems

Figure 3 Project scheme with step 1 up to 5 towards implementing the business case

Figure 4 Systems approach for efficient motor systems

Market Transformation Program for Electric Motor Systems - Global progress report and outlook

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Abstract

The market transformation towards highly efficient, integrated electric motor systems is making slow progress. The basic development of market transparency with agreed harmonized international efficiency measurement standards and efficiency classes has made progress for fixed speed electric motors. The expansion of the scope of engineering practice to also include new motor technologies run on variable speed and towards more complex systems applications of motors with pumps, fans, compressors and mechanical movement machines is recognized but so far almost non-existent in the market place.

The introduction of mandatory minimum requirements for the sale of fixed speed electric motors that started in 1997 will reach a first plateau in 2015 for the USA, Canada, Mexico, Australia and New Zealand. The European Union, Switzerland and China have also adopted mandatory minimum requirements, though they are not yet fully aligned with the premium efficiency level IE3 defined in IEC 60034-30. Today 69% of motor electricity is used in countries with Minimum Energy Performance Standards (MEPS) for motors. Most of these countries have not yet implemented the necessary compliance measures. A global energy efficiency certification system to give industrial buyers the confidence of a superior product was launched at the end of 2012 by the IEC System for Conformity testing and Certification of Electrotechnical Equipment and Components (IECEE).

Very few MEPS for motor systems exist, among them are the new European Ecodesign requirements for small integrated circulators and larger non-integrated pumps and ventilation fans. The complexity of these MEPS for motor-plus-application has led to additional efforts in persuading the European Commission and extra time to secure industry's acceptance. Also similar requirements for pumps and fans are started in Australia, China, Mexico, Vietnam and other countries

A report on international activities of the International Energy Agency's Implementing Agreement 4E Electric Motor Systems Annex (EMSA) is presented here. The goal of EMSA is to improve energy efficiency of electric motor systems through information dissemination, capacity building, training, experience exchange and other activities.

1. Facts and figures of the global motor market

Based on the energy data base of the IEA [1], the global annual electricity production in 2009 was 20 100 PWh and the respective final consumption was 16 800 PWh. According to A+B International's recent update of the Global Motor Energy Data Base [2] the rolling stock of electric motor systems of all types and sizes account for 45% of the electricity consumption in rotating machines totaling 7 600 PWh[1]. With 60% of the total, industry applications of motors are still by far the largest share (see Figure 1). Thus they are responsible for some 5 100 Gt of CO_2 emission from fossil power plants. Motors in the six largest electricity consuming countries/regions (USA, China, EU-27, Japan, India and Russia) already account for 70% of the global electricity demand and 75% of global CO_2 emissions. China, South Africa and Russia have an especially high share of industry use of electricity and therefore have an overall larger share of motor electricity than the global average. China alone is responsible for 22% of motor electricity and 30% of motor CO_2 emissions. Some of these large countries have extremely high CO_2 emission factors because the electricity is generated almost exclusively from coal, oil and gas: South Africa, Australia, Saudi Arabia, China, India and Indonesia are in the highest consuming group. The annual electricity cost at 0.1 € per kWh for motors amount to some 760 billion € per year.

[1] Physicists emphasize that an electric motor does not "use" electricity, but it drives a machine and thus delivers work. The motor itself is responsible for some 10% losses, plus the additional losses in the VFD, the gear, the transmission and the driven equipment. Systems efficiency values are often below 50%.

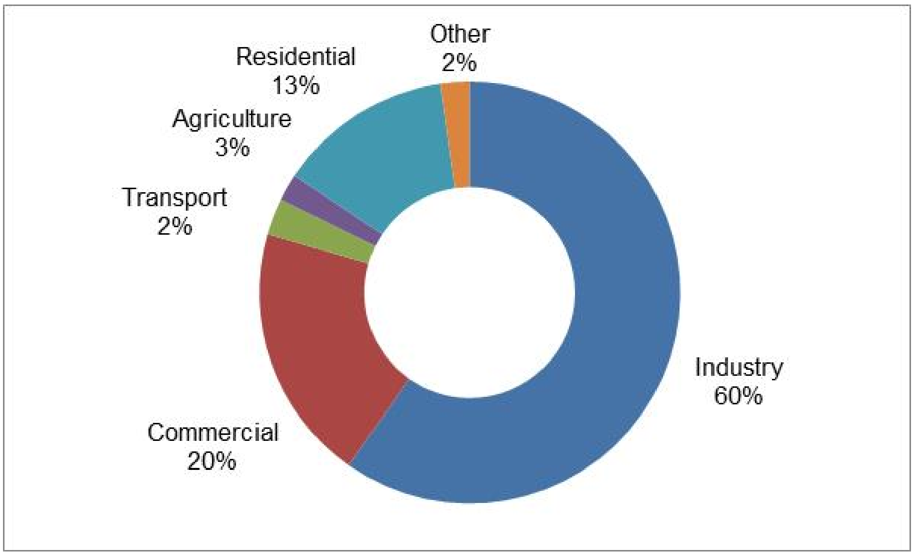


Figure 1 **Global electricity demand for electric motor systems: Share of sectors (Source: A+B International: Global Motor Data Model, 2013, based on IEA energy statistics 2009)**

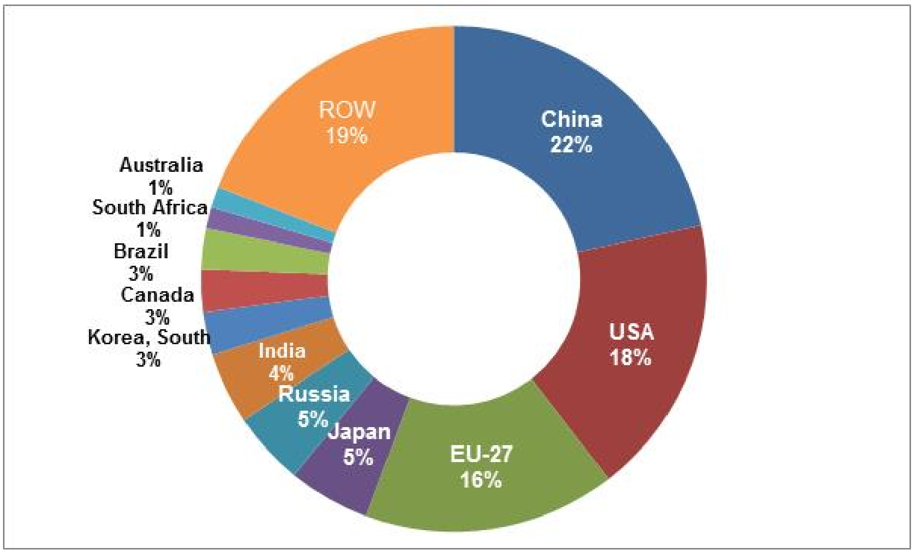


Figure 2 **Global electricity demand for electric motor systems: Share of countries (Source: A+B International: Global Motor Data Model, 2013, based on IEA energy statistics 2009), ROW: rest of the world**

The total electricity demand for motors systems has a tendency to increase substantially due to economic expansion, especially in the five large BRICS[2] countries (see Figure 2). The energy savings potential for electric motor systems presented in [3] has still not been challenged by a more comprehensive and updated global study. A policy path towards sustainable development can within 20 years indeed deliver 20% electricity and cost savings compared to Business-as-Usual - a period within which all motors need be replaced anyhow at the end of their technical lifetime. This would at least keep the electricity consumption almost constant after 2015: the efficiency gain can compensate the additional demand of BRICS countries.

2. Market transformation: wish and reality

The global motor and drive systems market is expanding especially in the five rapidly growing BRICS countries. Based on 2006 data from [3], the global increase of electricity demand for motor systems between 2006 and 2030 in a "Business-as-Usual" (Baud) scenario reaches 2.5% p.a. The estimated

[2] BRICS: Brazil, Russia, India, China, and South Africa

annual sales volume of 30 million medium size motor published in [4] is outdated by today's data. More recent and more comprehensive market research by Chausovsky from IMS [5] published at the Motor Summit in Zurich in 2012 has added specifics to the data on global market development. The development from traditional "electro-mechanical" motor manufacturers to new "integrated automation" producers with electronic controls (variable frequency drives (VFD), and factory automation systems) has changed the industry. Fewer and bigger global players are in the process of leading the market with international take-overs of complimentary products and smaller manufacturers. This development towards big conglomerates has changed both the regional market access of big players and their portfolio of different types of systems and components they deliver. In 2011, according to market research by IMS [5], 49 million low voltage motors with a revenue value of 15.0 billion USD and 21 million VFDs with a value of 12.6 billion USD were globally shipped (sold to end-users). The respective average product value is thus 305 USD per motor and 601 USD per VFD. This means that the total sales volume in USD of VFDs is rapidly catching up with that of motors, and the average VFD product price is almost double the price of a motor. This is certainly enough reason to restructure the manufacturing industry.

Nevertheless, the transition towards more energy efficient electric motor systems is slow; the large potential energy savings are not yet being harvested. IMS [5] estimates the share of the revenue from motor sales for IE3 and higher efficiencies to go from some meager 4% in 2010 to a proud 25% in 2015. This will in turn move the entire rolling stock of motors in 2015 according to [4] slowly only to some 11% market share for IE3. The development is on one hand driven by countries with MEPS for new installations and on the other hand it is slowed down by the lack of investment in the renewal of old inefficient equipment and the lack of knowledge for regular inspection and systematic systems integration.

The first indicator of inefficient motor systems in the rolling stock is motor age. The running stock of electrical motors is aged (see Figure 3) and lacking regular renewal and technical enhancement. The recent analysis in 17 industrial parks in Switzerland with 3 979 electric motor systems listed in the context of the Easy financial incentive program [7] and [8] shows that 58.4% of the motors are already older than the operating life expectancy (10 to 20 years depending on size) and these motors are on average 99.3% too old. The assumption is, that - if in a highly developed economy the motors in use are way too old - in a global perspective the problem could potentially be much more severe. Industry is losing money with old, inefficient and frequently oversized motors, and manufacturers are not marketing their products sufficiently to convince industry to buy their modern highly efficient new equipment and systems.

The second indicator of inefficient motor systems is oversizing. Motors too large for their required duty run on low efficiencies in partial load. Often 100% or 200% oversized machines can be seen in operation. The past fears of overheating or of not being able to deliver the necessary starting torque are in many cases unfounded. So, when a motor needs to be changed, its required output size needs to be thoroughly reassessed. An easy measurement of the input electricity during start and normal operation can provide the answer. A smaller motor as the replacement is generally much cheaper and most of the time more efficient. The introduction of variable frequency drives is, in this context, a dangerous measure. Only when the new motor requires a VFD based on its variable load profile and is then correctly sized the introduction of a variable frequency drive can help to improve the efficiency under variable load. A VFD should not be used as a means to keep a system oversized because they have low efficiencies in partial load.

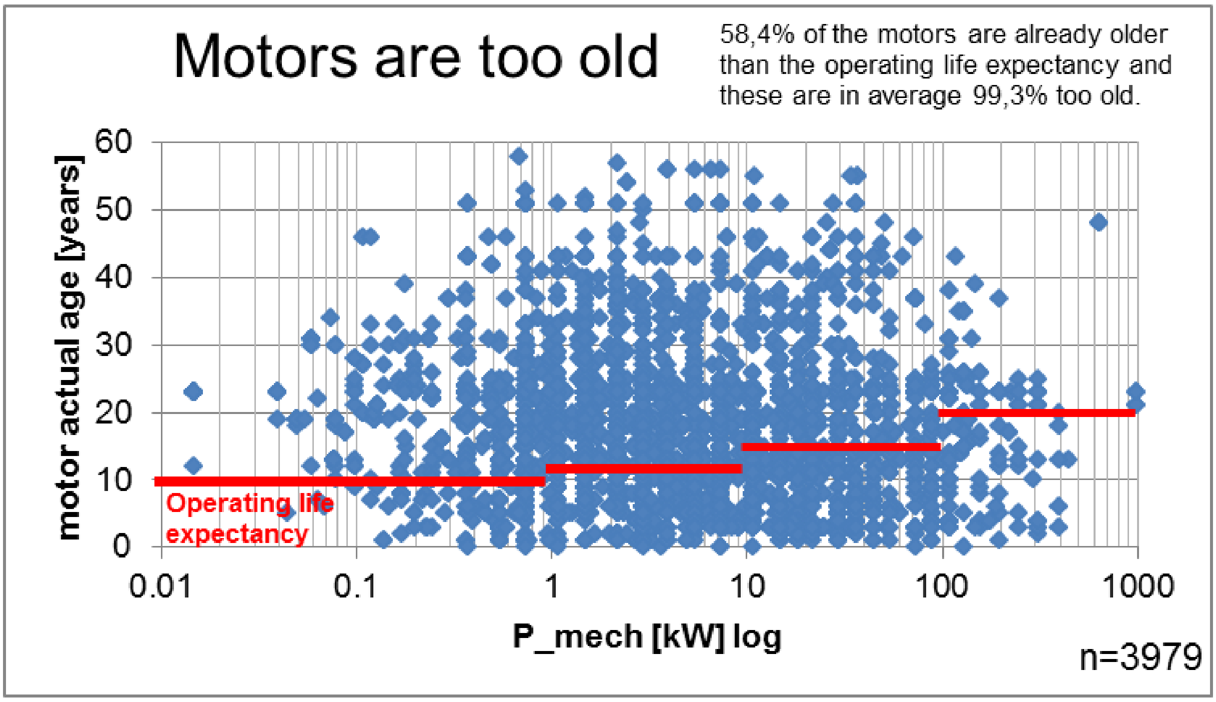


Figure 3 Motor age compared to nominal operating life expectancy in industrial plants in Switzerland (Source: Easy 2013)

3. Economic downturn slows development

The economic downturn in 2007 has reduced industry output and this reduces in turn electricity consumption, but it also diminishes the investment capacity of industrial plants to renew and improve their old equipment. The downturn and later stagnation is concentrated in the industrial and developed economies (USA, Europe), and not in the developing economies (China, India, Brazil, etc.) where steep growth is still visible (see Figure 4).

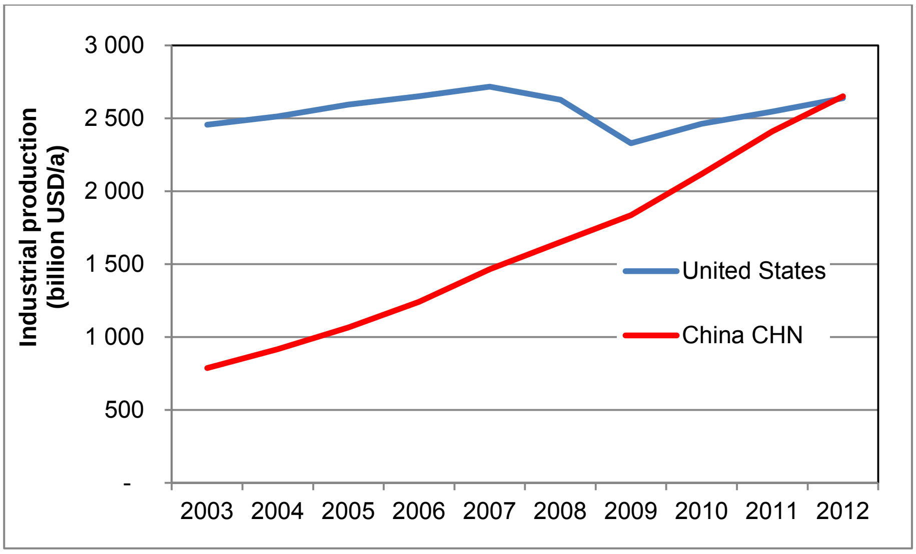


Figure 4 Industrial production in constant USD, seasonally adjusted (Source: Worldbank Global Economic Monitor, 2013)

The development of energy efficient electric motor systems depends on a number of key parameters:

- Industrial demand. If demand is expanding (see Figure 4) it creates increasing volumes of motor sales for new installations and replacement; this increases competition and can lower product prices.

- Energy and electricity price (see Figure 5). Rising energy prices create higher demand for reduced operating costs with savings from energy efficiency; thus it can stimulate investment in energy efficiency improvement and replacement of old running stock.
- Price of base materials for motors, namely copper, aluminum (see Figures 6 and 7), electric steel and rare earth materials. If prices of a specific material are rising, tendency grows to avoid or reduce the use of the specific materials. Within certain limits the substitution of several materials and respective technologies is possible. This can endanger certain technologies that heavily depend on one material: copper rotor, permanent magnet motors, etc.
- Price of labor: The share of work cost is not high in electric motors. Still the gross hourly wage and the number of hours needed per piece on average are a substantial element of optimization of product cost.
- Lately energy efficiency measures are under competition from lower renewable energy prices. When wind and solar energy (see Figures 8 and 9) can more often produce large quantities of electricity at specific times at grid parity (cost equal to conventional electricity production) then efficiency measures need to become also more cost effective.
- The competition for electro-mechanical equipment (motors and generators) especially in small sizes is intense. Only clear efficiency certificates can remove cheap, inefficient and low quality products from the market.
- For manufacturers the VFD is the more profitable piece of equipment with a higher margin of profit and more rapid return on investment in new product lines. Few motor manufacturers are also strong VFD manufacturers.
- Many specialists in combined products (motor plus VFD plus pump or fan or compressor) are increasingly becoming independent of motor manufacturers and start to design, measure, build and market tailor-made motors for their packaged and well integrated application.

The economic downturn in 2007 has reduced industry output and this reduces in turn electricity consumption and price, but it also diminishes the investment capacity of industrial plants to renew and improve their old equipment. Electricity prices for industry are increasing only slowly, still either cross-subsidized from high household tariffs or by artificially low fuel prices. And - of course - no external costs both from fossil and nuclear production are reflected in the end-user prices. In Europe electricity prices for industrial consumers have stagnated since 2008 (see Figure 5).

The electricity prices in Europe have more recently been lower due to the growing share of wind and solar power production (see Figures 8 and 9). Presently, the production from solar (daytime, good weather) plus wind (bad weather, 24 hours) is delivering more stable and more predictable capacities. The renewable electric energy production cuts the required peak production from conventional fuels every day between 9 and 17 hours and reduces the conventional production to a constant band load. The result is lower sales price for conventional power production. No external costs both from fossil and nuclear production are reflected in the end-user prices. This considerable change in the production park has caused severe headaches in the power industry which has benefited for decades from trading and pumping low to peak power. Power control has become more difficult: user side power management with factory automation has become more advantageous and is already in part reflected in good pricing schemes.

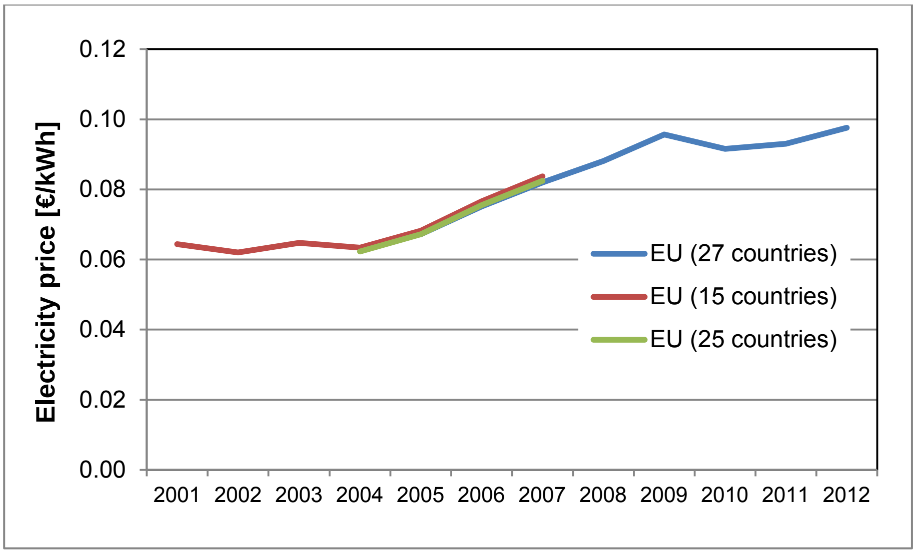


Figure 5 **Development of average nominal electricity price for industrial consumers in Europe (Source: Eurostat database, 2013)**

The price of copper has two well-known tendencies: First the price is highly volatile and depending on world (and regional) copper demand which in turn depends on industry development. Second, it has on the long run rising price levels because all known reserves have the tendency to only be able to deliver high quality copper at increasing cost. The variation reaches a factor of 4 between maximum and minimum prices paid in the last 5 years.

Also, aluminum prices are highly volatile and follow overall industry development. However, there was only a variation of a factor of 2 between maximum and minimum prices paid in the last 5 years, much lower than in copper.

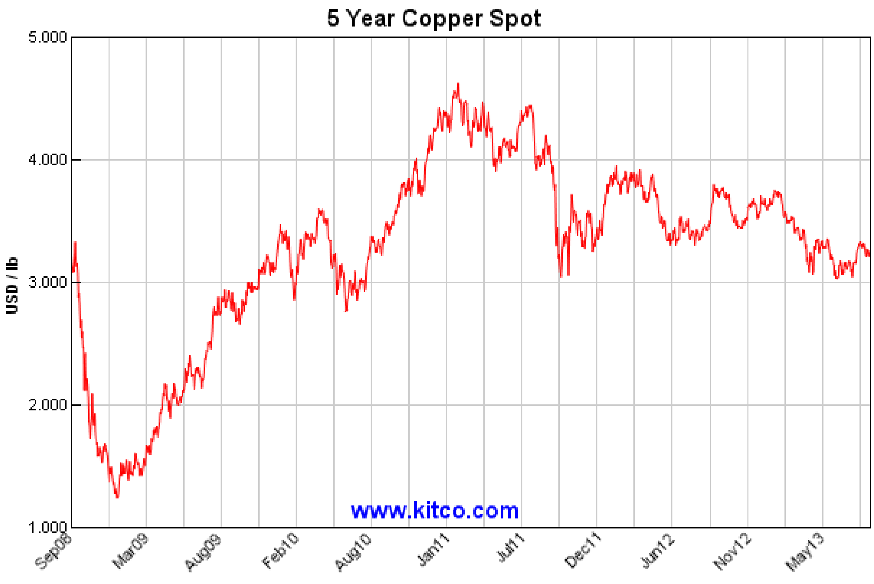


Figure 6 **Copper price 2008 - 2013 (Source: London Metal Exchange, Kitco)**

Figure 7 **Aluminum price 2008 - 2013 (Source: London Metal Exchange, Kitco)**

Solar and wind energy production in Germany and Austria has reached a level where renewable production capacity cuts the daily peak from 8 am to 6 pm to an entirely flat level (see Figures 8 and 9). This has large impact on the power pricing during the daytime and during sunny and/or windy situations. Many conventional power suppliers with large and continuous band production profiles (fossil or large hydro and especially nuclear) suffer heavily from the decay of their revenue. This can in turn reduce total electricity prices for large industrial users and disturbs and can stall investment in energy efficiency measures.

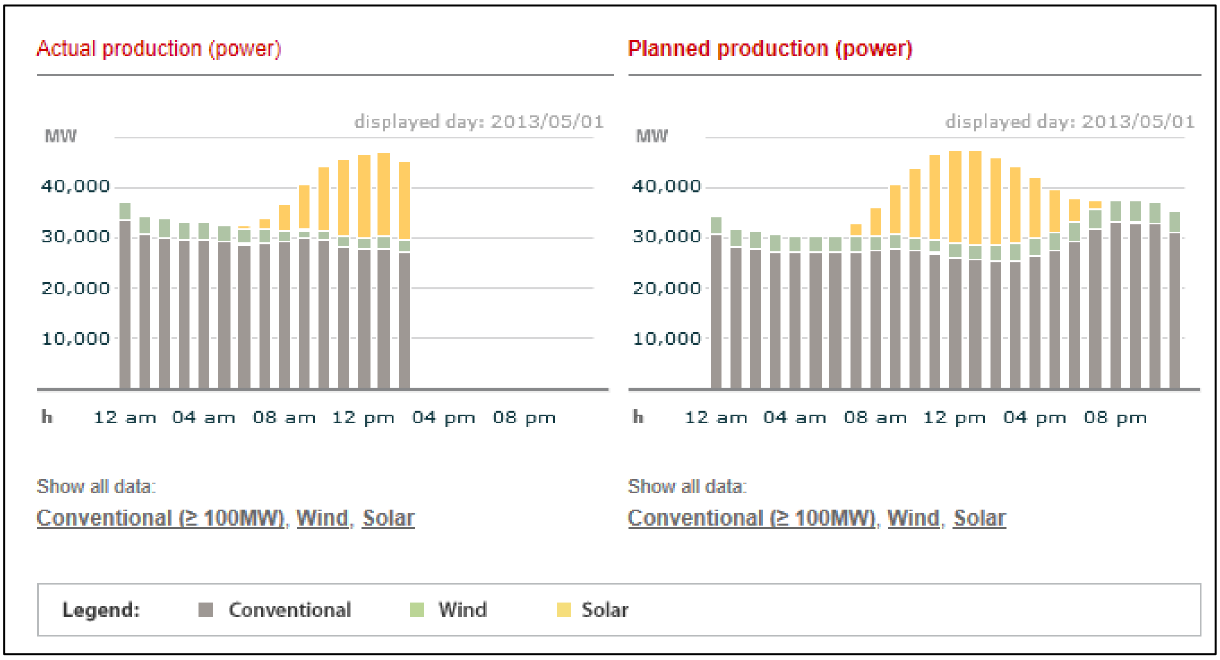


Figure 8 **Conventional, solar and wind production Germany/Austria, actual and planned, peak demand 47 000 MW, sunny day on 1 May 2013 (Source: Transparency Platform EEX, 1 May 2013, www.transparency.eex.com/en/)**

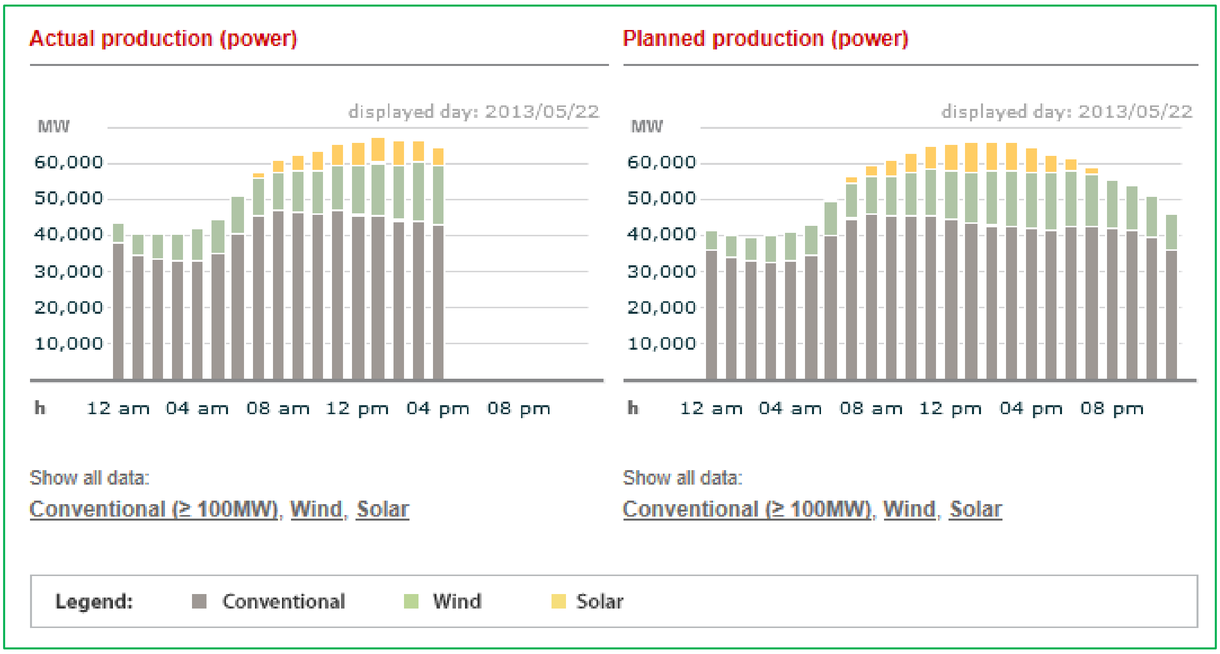


Figure 9 **Conventional, solar and wind production Germany/Austria, actual and planned, peak demand 65 000 MW, 8 000 MW solar and 16 000 MW wind power on rainy day on 22 May 2013**
(Source: Transparency Platform EEX, 22 May 2013, www.transparency.eex.com/en/)

4. Standards for efficiency measurement and efficiency classification

Accurate efficiency measurement is still the first step

Global standards are slowly making a dent in the wilderness of nationally controlled motor markets with diverging frequencies, voltage, frame sizes, and efficiency definitions and standards. Imports are subject to high certification barriers, renewed testing and tariffs. Harmonization is still far away, more developed by now in fixed speed standard induction motors than in all other components. Neither VFDs, nor pumps, fans, compressors or transmissions and gears have any kind of standardized international method to measure energy performance.

The International Electrotechnical Commission (IEC) has developed in the past decade a comprehensive set of industry standards for electric motors that are slowly replacing older national standards with agreed measurement standards that allow verification at the manufacturing plant, in the government check-testing lab or on the users' site. Thus the accuracy and repeatability can be secured. So lower quality and inefficient products can be identified and with nationally issued legal measures kept from the market. The product definition for electric motors, scope, general performance, environmental conditions, tolerance and rating plate requirements are laid out in IEC 60034-1:2010 which defines basic use conditions and states the required information on the rating plate (see Figure 10). Proposals are ready to introduce a chip for radio frequency identification (RFID) onto the rating plate to make the motor data and their rating much easier to be identified and checked by both the user and the compliance authorities, especially if the motor is embedded into a machine.

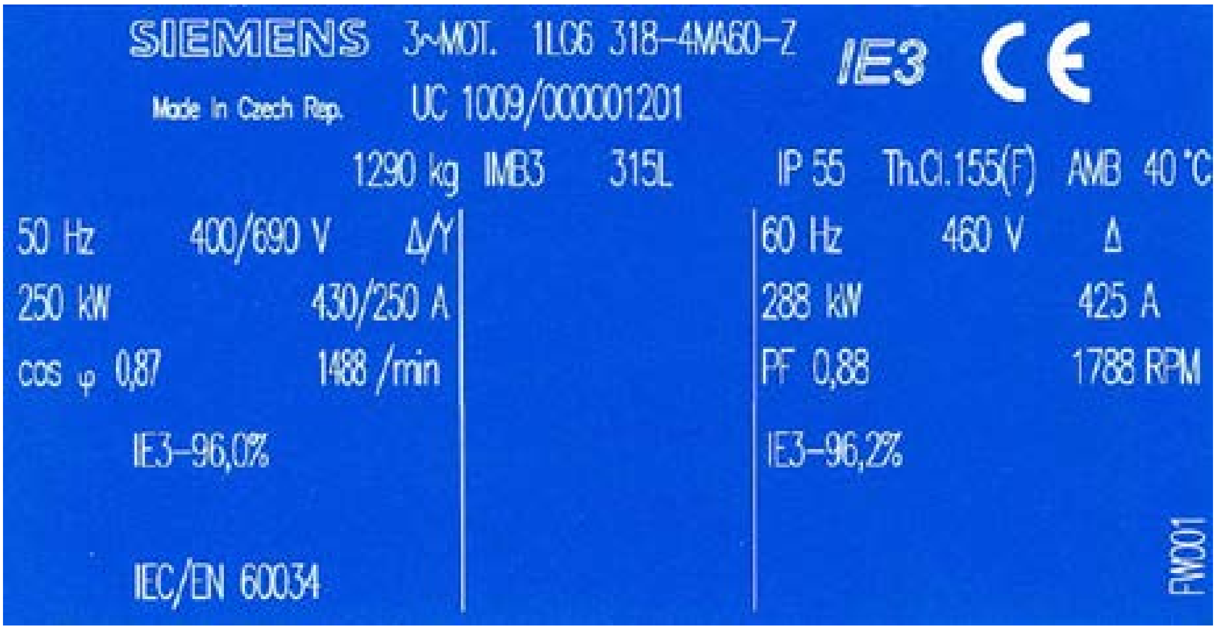


Figure 10 **Rating plate according to IEC 60034-1 for 3-phase 4-pole IE3 motor: at 50 Hz with 250 kW and 96.0% efficiency (1488 rpm), cos φ 0.87;400 V, 430 A; at 60 Hz with 288 kW and 96.2% efficiency (1788 rpm). power factor 0.88 460 V, 425 A; (Source: Siemens online catalogue 2013)**

The next important element is the efficiency measurement now defined in IEC 60034-2-1:2007 for general induction motors with continuous updates available in 2014. Now the efficiency measurement is also defined with two additional standards: IEC 60034-2-2:2010 for special motors and coming up in IEC TS 60034-2-3:2014 for converter fed motors.

The new frontier for industrial users is on electric motors that accommodate variable loads by controlling rotating speed and torque according to the momentary needs. These motors are driven by VFDs together with conventional asynchronous induction technology or use state of the art technology with permanent magnet, switched reluctance or synchronous reluctance. Because of harmonics from the VFD the performance of the motor is changed and its efficiency lowered. The respective standards for efficiency measurement (IEC/TS 60034-2-3:2014) and efficiency classes (IEC 60034-30-2:2015) for VFD fed motors are available in draft status and will be published shortly.

A number of research projects with round robin tests and other in-house measurement series have been made to improve the accuracy and repeatability of motor efficiency measurements. The available findings from Australia, Canada and Europe are now included in the revised IEC 60034-2-1 and include a more precise definition of the necessary sequence of the measurements, the required instrumentation uncertainty, ambient and product temperature control and measurement during the test, etc. The efficiency measurement methods for induction motors fed by converters are now well established (see Figures 10 to 12) and routinely available at a number of independent and industry laboratories around the world for small and larger motor sizes. These findings are integrated into the new IEC/TS 60034-2-3 for converter-fed motors.

Figure 11 Measurement set-up for measurement of motors with variable frequency drives at the Hydro Quebec motor testing laboratory, near Montreal, motor under test is to the right, the torque and speed meter in the middle (under yellow cover), the load machine is to the left, the VFD is placed outside the picture (Source: Pierre Angers 2013)

Figure 12 Yokogawa WT 3000 Precision Power Analyzer in a variable frequency efficiency measurement of the set-up in Figure 11 at the motor testing laboratory of Hydro Quebec near Montreal (Source: Pierre Angers 2013)

New data acquisition systems have been developed in several testing laboratories. Their advantage is that the entire measurement program can be programmed and driven by remote control; the data acquisition is done automatically (see Figure 13). Many earlier human errors (including wrong copying, rounding, etc.) are eliminated.

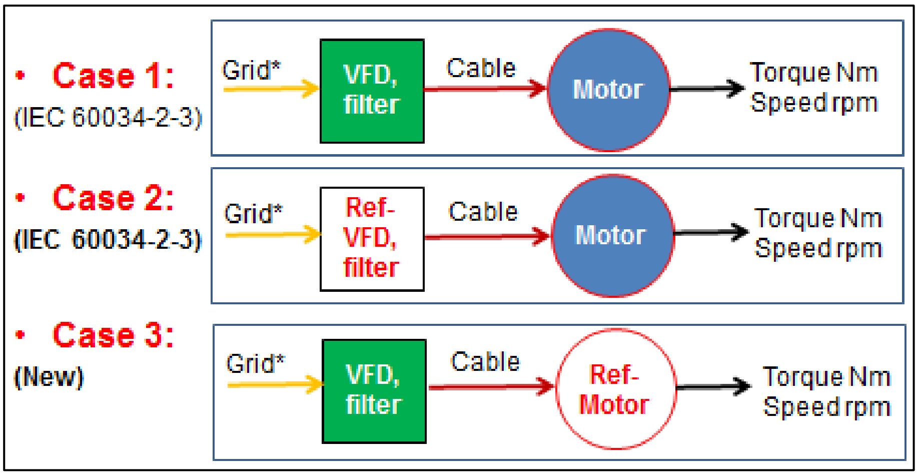
Figure 13 **Programmed testing sequence and automatic data acquisition. Measurement of 315 kW 4-pole IE2 motor with variable torque. (Source: Gamak Motors, Istanbul, 2013)**

Efficiency classification is the second step

The next crucial element is the standard for efficiency classification based on these internationally harmonized IEC measurement standards. IEC 60034-30:2008 has caused a big market jump in 2008 by presenting a common language for IE1-Standard Efficiency, IE2-High Efficiency and IE3-Premium Efficiency motors. The scope was only for 2-, 4- and 6-poles, with a frequency of 50 and/or 60 Hz, and with output sizes from 0.75 and 375 kW. The now completed revision in IEC 60034-30-1:2014 is expanding the scope also to 8 pole motors and the output size from 0.12 kW up to 1000 kW. The introduction of IE4-Superpremium Efficiency is the logical consequence of the ongoing rapid technology development plus the fact that the USA, Canada and Mexico already have a Minimum Energy Performance Standard (MEPS) on IE3 in place since 2012.

Systems efficiency measurements are step number three

The evidence shows in all energy efficiency programs for motors that large savings can only be achieved through system optimization. This includes the electrical side (transformer, uninterruptable power supply, power factor correction, variable frequency drive and motor) as well as the mechanical side (transmission, gear, brake, clutch, the driven equipment) and its operation condition (no idle time, no standby, no operation without use, no unnecessary high loads, high speeds and pressures in ducts and pipes). In order to avoid a mismatch between two or more components new kinds of software tools are necessary. The Motor Systems Tool MST [6], developed in the context of EMSA by S.B. Nielsen (Denmark), is an excellent example for that.



In Case 1 a VFD and a motor is available and they can be tested together.

In Case 2 only the motor is available, the VFD has to be replaced by a reference converter.

In Case 3 only the VFD is available, the motor has to be replaced by a reference load machine.

Figure 14 **IEC 61800-9 Efficiency classes and efficiency measurement of motor plus VFD (Source: SC22G AG15, 2013)**

The next step is towards systems optimization. This takes into account the combined efficiency from an electric motor and a variable frequency drive. A series of measurements have been made in 2012 by Canadian, Australian and European laboratories to secure the methodology of measurement of additional harmonic losses. Now the standard for the efficiency measurement and efficiency classification of the combined operation of a VFD and a motor IEC 61800-9 will be developed and shall be published by 2016. It will account for the three different situations, shown in Figure 14. This schematic is based on the fact that often motors and VFDs are manufactured separately by different manufacturers. The two products meet for the first time in a factory, ready to be mounted into a large machine. If a motor with its VFD has to be measured the procedure is clear and simple. A combined efficiency can be established with only output and input measurements, thus avoiding the complex measurements of the harmonics in the feeder of the motor. To secure the measurement of a motor alone in IEC 60034-2-3 a reference converter is used (case 2). The most challenging situation for measurement is the given VFD without a motor (case 3). A reference load has to be designed in order to have the VFD measured and the results are reproducible in other test labs.

The efficiency measurement set-up is complex because also the electrical power (voltage and current, power factor, and harmonics) between VFD and motor in point needs to be measured accurately. These measurements require advanced instrumentation technology to return accurate results for the harmonic content.

5. Certification

The recently launched project by IECEE[3] together with NEMA wants to go one step further. It will introduce a globally harmonized certification and label system for motors that is secured by the international IECEE logo. This will then include transparent and accurate efficiency ratings, coming from measurement results by qualified (i.e. regularly calibrated instruments, trained staff), independent and government accredited testing laboratories. They will need trained personnel to perform measurements according to precise efficiency measurement standards and procedures. This kind of network with accredited complex of motor testing laboratories exists so far only on a limited scale (NIST NVLAB[4]), mainly in the USA. Also national governments need to acknowledge this certification and product registration in their legal framework.

6. Policy trendsetters for MEPS

National policies have made large inroads for market transformation by setting MEPS. Notably Europe has reached the same level of advancement as the US, Australia and Canada who have been world leaders for a many years. The Ecodesign Framework Directive from 2005 [9] has sparked a number of

[3] IECEE: Worldwide System for Conformity Testing and Certification of Electrotechnical Equipment and Components, www.iecee.org
[4] NIST: National Institute of Standards and Technology; NVLAB: National Voluntary Laboratory Accreditation Program, www.nist.gov/nvlap/

systematic technology assessments, ecological research on fabrication, use and decommissioning of product technologies, economic studies, and market impact analysis based on a common method. The Ecodesign technical analysis under Lot 11, led by Anibal de Almeida, has covered motors as well as circulators, pumps and fans [10]. Subsequently all these products have received European mandatory requirements with MEPS; motor MEPS are in force since 2011 and will be gradually upgraded to IE3 (see Figure 15).

Lately, Turkey joined the ranks of MEPS countries implementing IE2. Preparatory work is under way to bring also Japan into the rank of MEPS countries while India remains on a voluntary national scheme only. Many countries are planning to move their MEPS level to IE3 in 2015. 69% of global electricity consumption of motors is by 2013 used in countries implementing MEPS on motors.

Efficiency Levels 3-phase induction motors	**Efficiency Classes** **IEC 60034-30-1** **Global classes IE-Code 2008; rev. 2013 ***	**Testing Standard** **IEC 60034-2-1** **incl. stray load losses 2007; rev. 2013 ****	**Performance Standard** **Mandatory MEPS ****** **National Policy Goal**
Super Premium Efficiency	**IE4**	**Preferred Method**	
Premium Efficiency	**IE3**		**Canada** **Mexico** **USA** South Korea 2015 Switzerland 2015 EU*** 2015 / 2017
High Efficiency	**IE2**	**Summation of losses with load test:** P_{LL} **determined from residual loss**	**Australia** **Brazil** **China** **Europe** **South Korea** **New Zealand** **Switzerland** **Turkey**
Standard Efficiency	**IE1**		**Costa Rica** **Israel** **Taiwan**

bold means in effect

22 May 2013, CUB
A+B International
EMSA/MEPS table May 2013

*) Output power: 0.12 kW - 1000 kW,
50 and 60 Hz, line operated
2-, 4-, 6- and 8-poles

**) for 3-phase machines,
rated output power < 1000 kW

****) Minimum Energy Performance Standard

***) European Union (2015: below 7.5 kW),
2017: IE3 or IE2 + Variable Speed Drive

Figure 15 MEPS and IEC standards, status May 2013, Turkey and South Korea joined in 2012 (Source: A+B International, 2013)

In 2013 the European Commission mandated Anibal de Almeida to update the 2008 technical preparatory study and to recommend MEPS for a larger scope of electric motors from 0.12 kW up to 1000 kW, including 8-poles, in line with the revised efficiency classification in IEC 60034-30-1. The goal of the European Commission is to secure the next step in legislation beyond IE3 once the technology is mature and the respective global standards are available. At the same time studies are well under way to also include new motor technologies (permanent magnet motors, switched reluctance motors, etc.) into the scope of the new MEPS.

The US policy discussion between industry and NGOs on the renewal of the current DOE requirement for IE3 Premium Efficiency motors is going into a different direction. In order to avoid the logical next efficiency step to move the current MEPS to a more costly IE4 Superpremium Efficiency level, the wide expansion of the current motor scope for mandatory requirements of IE3 is developed in order to include a number of motor types that were not included before because of their more complex design features.

7. The 4E EMSA program

The IEA implementing Agreement "Efficient Electrical End-Use Equipment (4E) focuses on several important products like solid state lighting, standby, and motors (www.iea-4E.org). The "Electric Motor Systems Annex" (EMSA) concentrates on the market transformation towards more energy efficient electric motor systems in industry, infrastructure and large buildings (www.motorsystems.org). EMSA exists since 2008 and is now a cooperation of Australia, Austria, Denmark, the Netherlands, Switzerland and the USA.

The main goal of EMSA is to speed up the global market transformation towards efficient motor systems through bringing relevant technical and management know-how to the policy leaders as well as to the technical officers in factories and thus help to make better use of the knowledge on how to save energy. EMSA has recognized that for a successful global market transformation it needs to work on different levels, targeting different groups of stakeholders (see Figure 16):

Figure 16 EMSA works on different levels

- On the global level, with international standards development organizations to help develop global standards,
- On the national level with policy makers, to help governments develop and implement policies ranging from MEPS through information & education programs to financial incentives,
- On the company level with industrial users, thus factories to support them in the implementation of energy management,
- On the personal level with individuals, to provide them with necessary information and tools to apply the energy efficiency knowledge for motor systems.

In particular, EMSA provides the following services:

Testing centers	Network of testing engineers to learn how to choose and operate equipment and measurement instrumentation, train staff on calibration procedures and run efficiency measurements.
Motor Systems Tool	Motor Systems Tool for optimization of motor, gears, transmission, variable frequency drive depending on variable load. See EEMODS'13 presentation by Sandie B. Nielsen, Denmark.
International standards	Program to bring national standards in harmony with both IEC standards on motors and systems as well as ISO standards on applications like pumps and fans.
Energy management	Support to the introduction of ISO 50001 and its application to use electrical energy for motor systems in industry efficiently.
Policy Guidelines	Update on best practices for governments interested to launch a comprehensive efficiency policy including industrial motor systems. See EEMODS'13 presentation by Konstantin Kulterer, Austria.
Outreach	Web and periodic newsletter in 5 languages (English, Chinese, Japanese, Russian, German) to over 3 200 interested contacts in 72 countries.

Some other global organizations and initiatives operate in the field of electric motor systems in industry besides EMSA:

Acronym	Institution	Web
IIP	Institute for Industrial Productivity	www.iipnetwork.org
CLASP	The Collaborative Labeling & Appliance Standards Program	www.clasponline.org
SEAD	Super-Efficient Equipment and Appliance Deployment Initiative; SEAD Global Efficiency Medal Competition for Electric Motors	www.superefficient.org
IEA	International Energy Agency energy efficiency department at IEA headquarters in Paris France	www.iea.org/efficiency/index.asp
IEA Industry	Implementing Agreement on Industrial Energy-related Technologies and Systems (IETS).	www.iea-industry.org

Table 1 Global motor systems efficiency programs

In addition, many programs are available as part of national energy efficiency campaigns. EMSA tries to cooperate with the international organizations and initiatives and keep contacts to some of the national activities and report on new events, standards and findings in its newsletter. It has supported the design of the Global Efficiency Medal Competition for Electric Motors with technical advice.

8. The way forward

A number of key barriers have to be overcome for a more rapid market transformation towards energy efficient electric motor systems both in existing and new machines in industry, infrastructure and buildings by the relevant groups of stakeholders:

INDUSTRIAL USERS Slow industrial development, lack of technical and management know-how, shortage of resources and investment capital. *> Initiatives to support efficiency measures for industrial users, better know-how transfer, training and new financing instruments.*
MANUFACTURERS, WHOLESALERS and OEMs Reluctance to upgrade standard products to more efficient ones. *> Training for efficiency know-how, attractive business model for higher quality products.*
POLICY MAKERS (national governments) Incomplete understanding of the impact of legal measures and their economic and ecological benefits. Fragmented efficiency policy with limited means for financial incentives. *> Learning from best practice in a number of frontrunner countries. Support energy management capacity build-up in industry combined with mandatory audits.*
POWER PRODUCTION INDUSTRY Understand potential optimization of production, transmission and transformation capacity with energy efficiency measures and factory automation systems. *> Proactive involvement and industry efficiency subsidy programs.*
ENGINEERING COMMUNITY Work is often fragmented between mechanical and electrical engineers, know how is scarce and not systems oriented. *> Use interdisciplinary approach for systems optimization.*
STANDARD MAKERS IEC (TC2, SC22G) and ISO Coordinated and up-to-date standards for product definition, efficiency measurements and efficiency classes covering all current and recent technology development. *> Rally for regional and national standards to adopt global standards.*
NGOs (environmental protection agencies) Often only fragmented and contradictory arguments are presented for energy efficiency, the focus is mainly on additional power production with renewable energy and environmental protection. *> Concerted efforts to national policy makers and industrial leaders to adopt rapid measures: MEPS, financial incentives, compliance programs with check-testing. Efficiency measures cause no environmental damage.*

Table 2 Barriers and possible actions by stakeholders to overcome the barriers (Source: A+B International, 2013)

The earlier calculated potential energy savings of electric motor systems in [3] are today neither wrong nor outdated, but the envisaged 20% to even 30% savings compared with a Business-as-Usual scenario by 2030 still lay deep-frozen in the industrial refrigerator, waiting to be melted and cooked into concrete action and implementation plans. These actions will lower operating cost for industry, create profitable additional jobs for manufacturers and help the environment.

Acknowledgements

The authors want to thank the members of the 4E EMSA group (Australia, Austria, Denmark, the Netherlands, Switzerland and USA) for their know-how and insights into market transformation in industrial motor systems.

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Selecting the most efficient motor control system for a given application: the Extended Product Approach in prEN 50598 series of standards

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Abstract

The EN 50598 standard project (prEN) is a response to the European Commission (EC) regulation regarding ecodesign requirements for electric motors. The standard specifies a system-level methodology called the *Extended Product Approach* (EPA). The EPA allows determining the energy efficiency of motor systems, considering both the efficiency of the equipment and the requirements of the application.

This paper presents an overview of prEN 50598 and clarifies the major stakeholders and the work flow between them. It also presents an example of Extended Product Approach to highlight best practice regarding the design of motor-based applications: match the application requirements and avoid oversizing.

1. The European Regulation 640/2009 (Ecodesign of electric motors)

The European Commission (EC) regulation No. 640/2009, *Ecodesign requirements for electric motors*, is following the worldwide trend of implementing regulations for more efficient motors in industrial applications. There are three major deadlines associated with specific requirements:

1. **From June 16, 2011:** Motors shall not be less efficient than the IE2 efficiency level defined in IEC 60034-30 [1].
2. **From January 1st, 2015:** Motors with a rated output power between 7.5 and 375 kW shall not be less efficient than the IE3 efficiency level, or meet the IE2 efficiency level and be used with a Variable Speed Drive (VSD)
3. **From January 1st, 2017:** Same requirements as point 2 above for motors of rated output power between 0.75 and 7.5 kW.

In contrast to other regulations worldwide, the European Regulation allows the option of using a Variable Speed Drive (VSD) in conjunction with an IE2 (less efficient) motor as an alternative to an IE3 motor. This option can lead to the belief that both solutions (IE3 motor alone or IE2 motor with a VSD) are equivalent in terms of energy efficiency in any application and form interchangeable motor control solutions, which is far from reality.

It is unquestionable that using a VSD allows to design great energy-efficient solutions for suitable applications. However, it is also unquestionable that when a VSD is improperly used in an application, the resulting overall energy consumption can be significantly higher, which is against the energy reduction objective of the European Regulation!

Up to now, the Regulation only considers the products (motor, control system, load machine) individually. While it is of course worthwhile to always choose the most efficient components, **it is only by considering the entire application and performing system-level optimization that significant energy savings can be achieved**.

Consequently, the upcoming EN50598 series of standards (*Ecodesign for Power drive systems, Motor starters, Power electronics & their driven applications*) aim to provide:

- A generic methodology (known as the "Extended Product Approach" or EPA), guidelines and calculation methods to compute the Energy Efficiency Index of extended products (motor system + mechanical load) for any application,

- Requirements regarding the environmental impacts of motor systems and associated product declaration.

2. Overview and usage of the prEN 50598 series of standards

2.1. Description of the three parts of prEN 50598

The prEN 50598 standard comes in three parts as described in Table 1.

Table 1 – Overview of prEN 50598 series of standards

Part	Title	Content
1	*General requirements for setting energy efficiency standards for power driven equipment using the extended product approach (EPA), and semi analytic model (SAM)* [2]	This part describes the general methodology (referred to as the *Extended Product Approach*) to derive the energy consumption (or equivalent indicator) of a motor system within an application. It also specifies the responsibilities of the difference stakeholders (manufacturers, technical committees…). Key concepts such as "Semi-Analytical Model", "application duty profile", "extended product" and others are introduced in this part.
2	*Energy efficiency indicators for power drive systems and motor starters* [3]	This part supports part 1 and focuses on determining the power losses (and hence the efficiency and the energy consumption) of any motor system, i.e. a motor + its control system, be it a VSD or a starter.
3	*Quantitative eco design approach through life cycle assessment including product category rules and the content of environmental declarations* [4]	This part deals with the environmental aspects of ecodesign (CO2 balance …). It is not detailed in this paper.

2.2. Scope, stakeholders and usage of prEN 50598-1

Part 1 of the standard is necessary to understand the generic methodology to be used to assess the energy consumption of any application embedding a motor system, as well as key concepts and definitions:

- The motor and its associated *Motor Control System* (based on a VSD or a motor starter) form the ***Motor System***. VSD-based motor systems are called *Power Drive Systems* (PDS).

- The *Motor System* and its driven mechanical equipment (pump module, fan…) form the ***Extended Product*** **(EP)** (e.g. complete pump, fan system…). The Extended Product is used in certain operating conditions.

- The operating conditions are defined notably by the ***Duty Profile*** of the application (how much time is spent at different load levels) and the associated ***Operating Points*** of the equipment (generally defined by torque and speed). At these operating points, the losses of the motor system can be computed using the model and process specified in Part 2.

- By combining the losses of the motor system and the losses of the load machine at these torque-speed operating points, it is possible to derive an ***Energy Efficiency Index (EEI)*** of the application. It is the responsibility of the Extended Product technical committee to specify standard procedures for doing this. This approach of computing an EEI considering the motor system within its application is called the ***Extended Product Approach (EPA)***.

- Note that the same process can be conducted for several possible control systems, allowing selecting the most energy-efficient control system for a given specific application (see example in section 4).

The Extended Product and its components are illustrated in figure 1 (extract from the prEN 50598-1).

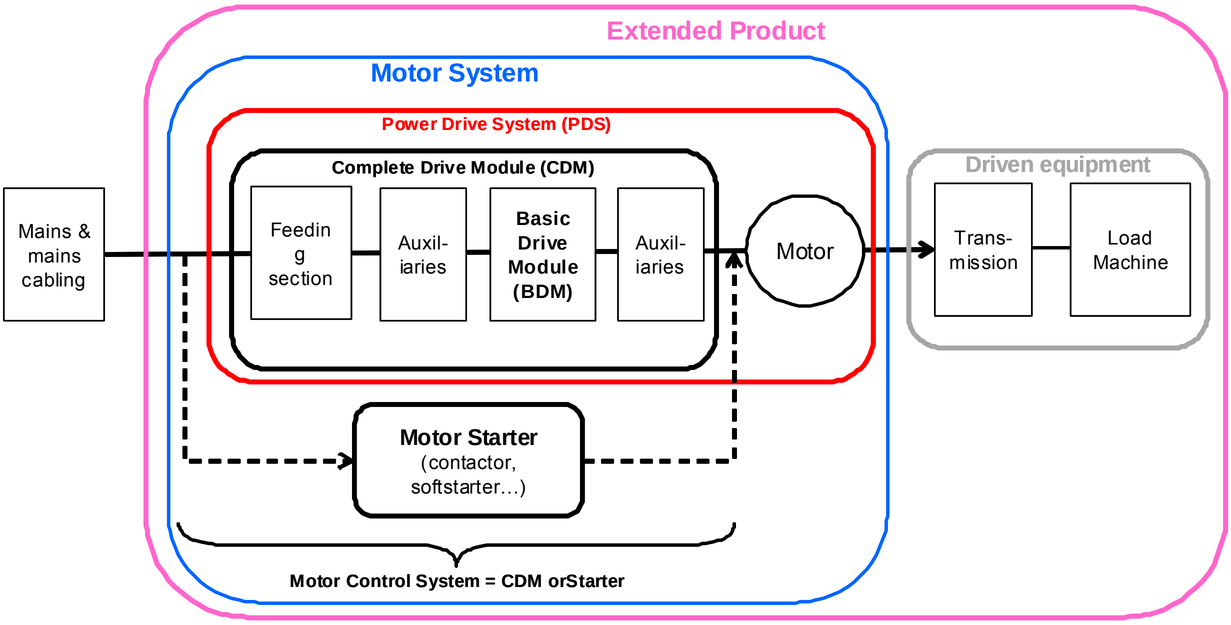

Figure 1 – Extended Product (e.g. a complete pump system) and its components

Basically, prEN 50598-1 provides a procedure to compute an *Energy Efficiency Index (EEI)* for a motor system performing an application, from the detailed characteristics of the motor, its control system, the mechanical load connected to it, and the operating conditions of the application. This is illustrated in figure 2. This procedure is called the *Extended Product Approach* and uses a mixture of required measurements and mathematical models for each component of the extended product.

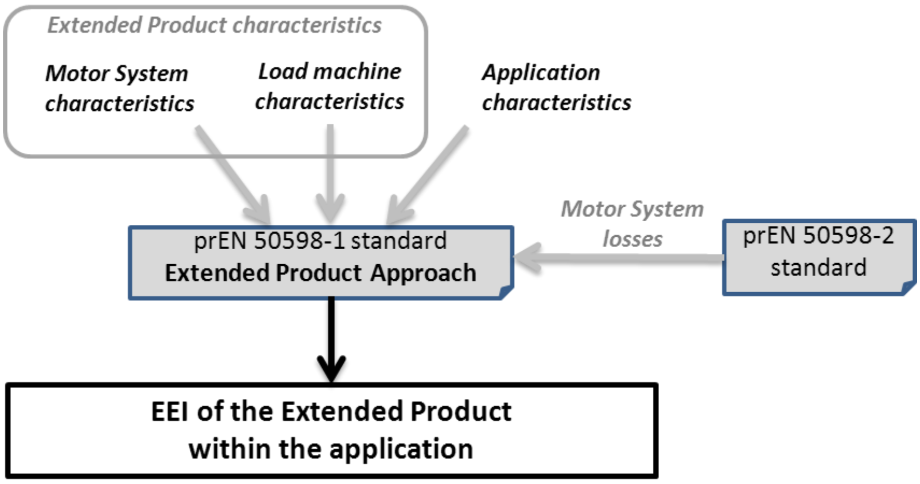

Figure 2 – Inputs and output of prEN 50598-1 standard

This part of the standard is primarily intended to be used by Extended Product committees (e.g. pump and fan committees) to establish their own standards regarding the energy efficiency of the extended products under their responsibility.

From the generic *Extended Product Approach* specified in prEN 50598-1, specific equivalent approaches customized for a given type of Extended Product can be derived. The customization process carried out by the Extended Product standards committee notably includes the definition of standardized types of applications of the extended product, standardized operating points for the equipment, and adaptation of the terminology and required data. The specific extended product standard will be typically based on this Part 1.

This dedicated standard can in turn be used by extended product manufacturers (e.g. pump system manufacturers) to compute the Energy Efficiency Index (EEI) of their products.

This project is strongly supported by CEN TC 197 Pumps, currently preparing a dedicated EPA standard, and is also considered by other CEN committees such as TC 156 Ventilation for buildings and TC 113 Heat pumps and air conditioning units.

Manufacturers of motors, drives and motor systems will be required to provide the necessary data, essentially consisting in losses or efficiency values at a maximum of eight standardized torque-speed operating points. These data will need to be determined and produced according to the specifications of prEN 50598 (see figure 3).

In case a specific application considered does not fit into the standardized applications defined by the extended product standards committees, the Extended Product Approach specified in EN 50598-1 can also be used directly by the application designer to compute the Energy Efficiency Index of that specific application.

2.3. Scope, stakeholders and usage of prEN 50598-2

Part 2 of the standard supports Part 1 by providing methods to compute or measure the losses of the Motor System, or its individual components, at specific torque-speed operating points:

- If the motor system is based on a motor starter (contactor, soft starter…), then the losses associated to the switchgear is simply computed as 0.1% of the motor's rated output power, regardless of the operating point.
- If the motor system is based on a VSD, then the specified mathematical models or measurement processes shall be used to estimate the losses of the motor system at each operating point.

Part 2 of the standard is essentially intended to be used by motor, drives and motor system manufacturers to deliver data (losses, efficiencies…) at several standardized operating points.

2.4. Conclusion on the usage of upcoming EN 50598 standard

prEN 50598 provides calculation methods, measurement specifications and guidelines allowing computing the Energy Efficiency Index (EEI) of a motor system (motor + control + load) performing some application.

The process, known as the Extended Product Approach (EPA) uses data from both the equipment (motor losses, drive or starter losses, …) and the application (duty profile), because what matters for energy efficiency is how well the equipment suits the requirements of the application.

Figure 3 sums up the different major stakeholders and how they will be required to deliver or use data.

2.4. Example from Europump

Europump, the European association of pump manufacturers, has published a guide to present the Extended Product Approach for pumps. The guide [5] describes how to adapt the EPA for pump applications. It defines 3 types of typical applications (closed-loop variable flow, open-loop variable flow, constant flow) with associated duty profiles, and details on how to compute the Energy Efficiency Index of pumps systems. It also provides guidelines on which types on pumps are most suitable for each type of application.

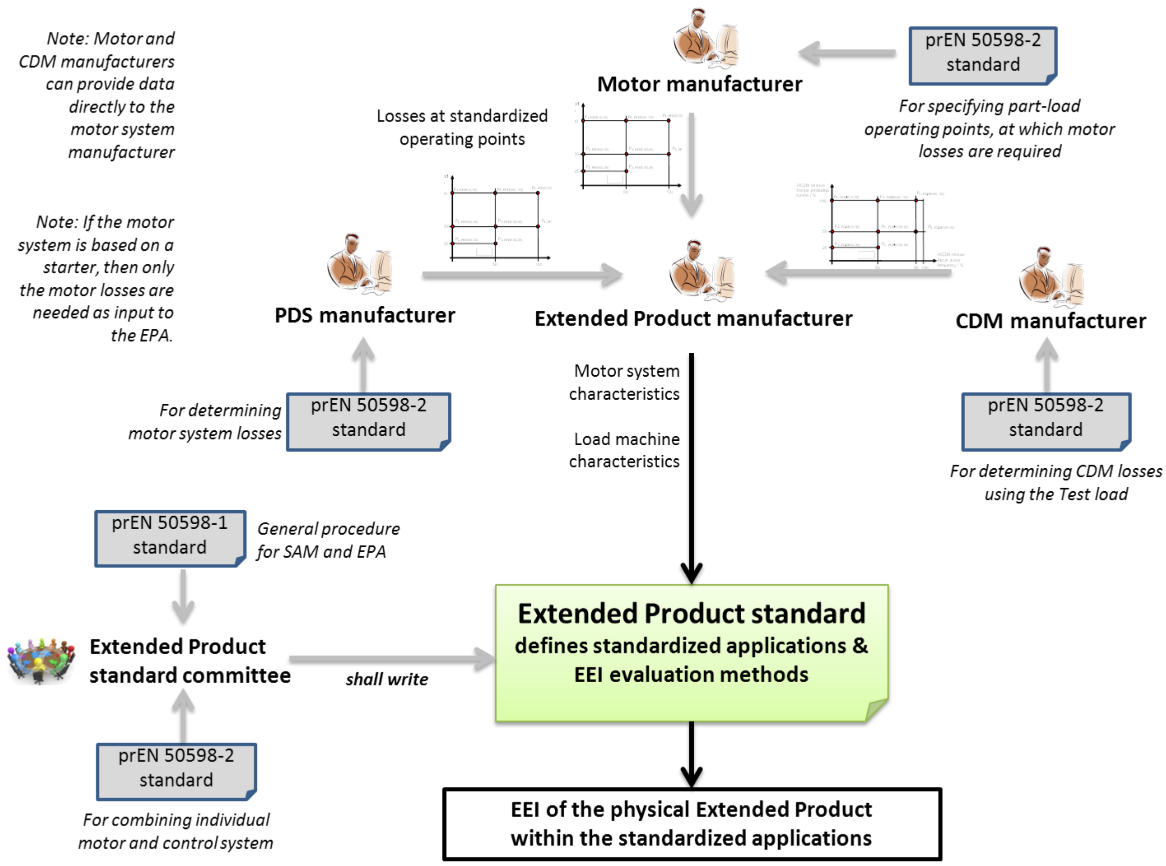

Figure 3 – Stakeholders and data flow for establishing and using extended product standards derived from EN 50598-1.

3. Elements for choosing the right control strategy for an application

3.1. Importance of adopting a system-level approach

The Extended product Approach in prEN 50598-1 is really a system-level approach: it considers not only the intrinsic energetic performance of the devices (motor, control system and load) composing the Extended Product, but also, and essentially, how efficiently these devices are used within the application. Furthermore the energy consumption of necessary auxiliaries, like filters or cooling system will be considered too.

Indeed, only a system-level approach is likely to lead to significant energy savings:

- The incremental progress in terms of energy efficiency of individual devices is fairly modest. For example, the difference in rated efficiency between a larger IE2 motor and an IE3 motor is about 2 points only.
- This incremental progress can be totally ruined if the highly-efficient product is used in poor operating conditions; the overall energy efficiency of the application can be extremely poor. Even the most efficient device of the world would waste a lot of energy when improperly used within an application.

- Therefore, it is essential to pay attention to using the most appropriate devices in the most appropriate manner for a given application. For example it is important to avoid much changing load conditions or to avoid over-sizing. Here all components / processes of your application have to be considered, especially the load machine. This is the only way to achieve significant energy savings, and this is what a system approach is all about.

3.2. Application requirements to consider, other than energy efficiency

Several points of attention other than energy efficiency need to be considered before deciding which solution is best suited to an application:

- Costs: purchasing, installation, operation, maintenance
- Implementation: easiness of installation, operation and maintenance, cooling requirement, power supply requirement
- Robustness: safety, Electro-Magnetic Compatibility, availability…

These elements need to be considered in the process of choosing the most appropriate control strategy overall (see [6] for details).

3.3. Criteria for choosing the most energy-efficient control strategy for an application

3.3.1. Don’t confuse speed and load

As far as energy efficiency is concerned, the most important task is to define the requirements of the application in terms of motor speed control, in order to choose the most appropriate control strategy (contactor, soft starter, or variable speed drive).

It is worth noting that speed is often confused with load. The load of a motor is actually characterized by two separate quantities:

- the speed of the motor’s shaft, and
- the torque applied by the motor to the mechanical load as required by the work to be done.

A motor is able to deal with the load changes required by the application by self-adjusting its torque. It is only when the application requires varying the speed independently of the torque that a VSD has to be used.

3.3.2. Match the equipment to the requirements of the application – Avoid oversizing

As mentioned above, significant energy savings can only be achieved when the equipment used to implement the application matches the actual requirements of the application. Examples of bad application / equipment matches likely to lead to a significant waste of electrical energy are:

- Using a throttle to control the flow of a liquid in an application where the per-unit flow is often small.
- Using a variable speed drive in an application where it would be sufficient to let the motor adjust the load by changing the torque and not the speed.
- Using a variable speed drive to merely control the starting phase of the motor until it reaches rated speed (it would be better to use a soft starter).

- Over-sizing the motor or any component of the extended product. A line-start motor system has near-nominal efficiency between 30% and 100% of load and allows overload for short periods of time with the same efficiency. For other arrangements (e.g. motor controlled by a VSD), the near-nominal efficiency range can be narrower and overload is not possible (see figure 4).

  In any case, it is crucial to size the equipment to make sure the motor, its control system and the load all operate most of the time at operating points where their efficiency is optimal.

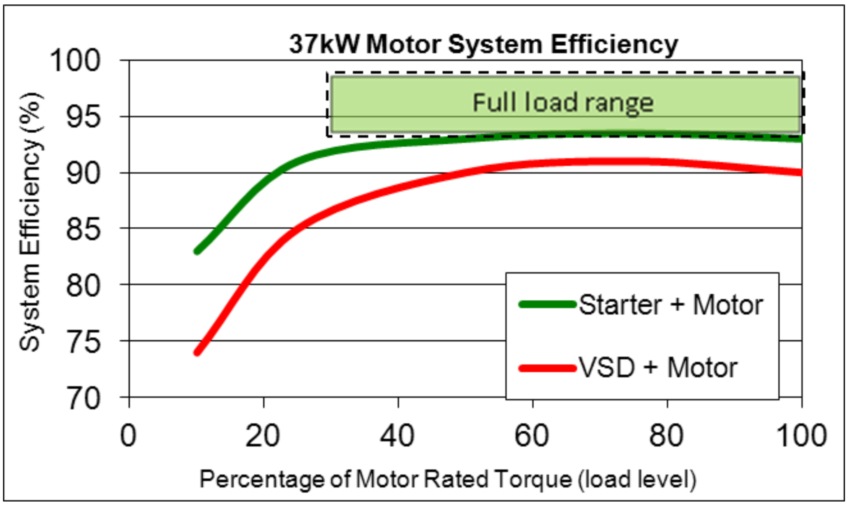

Figure 4 – Motor system efficiency as a function of load level (source: [7])

3.3.3. Use the duty profile of the application

The duty profile of an application is a graph or a table describing how much time (or fraction of time) the application needs to spend at the different load levels. The definition of the load and the appropriate values typically depend on the application: it can be a power, a flow, etc. Examples of duty profiles are shown in figure 5.

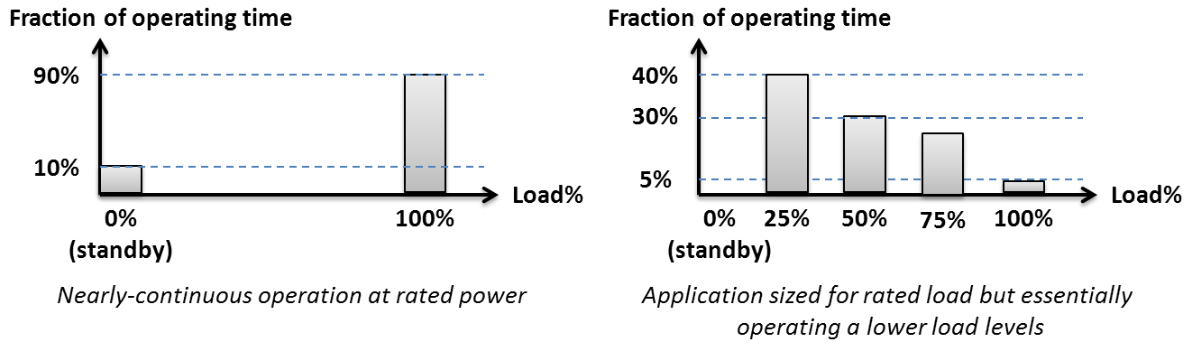

Figure 5 – Examples of application duty profiles

Note: This duty profile is sometimes called a load profile. In the context of EN 50598, the load profile is a graph describing the torque vs. speed relationship of a rotating machine (motor, pump…), while the above figures are called duty profiles.

The duty profile shows the requirements of the application. Each load level is associated to an operating point for the equipment, defined for example by torque and speed values. The duty profile is important because it shows how much time needs to be spent at smaller load levels. This is crucial for choosing the most appropriate solution for the application, because over-sizing shall be avoided if one wants to obtain significant energy savings.

In some cases for examples, it is much more energy efficient to install several smaller, simpler extended products working in parallel in their optimal efficiency zone, and switch them on/off as required by the application, than to install a bigger extended product working at fractional load most of the time.

3.3.4. Use the Extended Product Approach specified in prEN 50598-1

The duty profile can be used to derive the operating points of the equipment considered for the application. Following the Extended Product Approach, the losses of the parts can be determined from these operating points, and the overall energetic performance of the solution considered can be assessed.

Several technical solutions in response to the application requirements can be compared in order to select the most energy-efficient one. That is, the technical solution that answers the requirements of the application in the most energy efficient manner (see example in section 4).

3.3.5. General principles for choosing the motor control solution

The selection of the most energy-efficient motor control solution for an application shall always result from a system-level Extended Product Approach as specified in prEN 50598-1. It is possible to give general principles and guidelines for best practice (see figure 6).

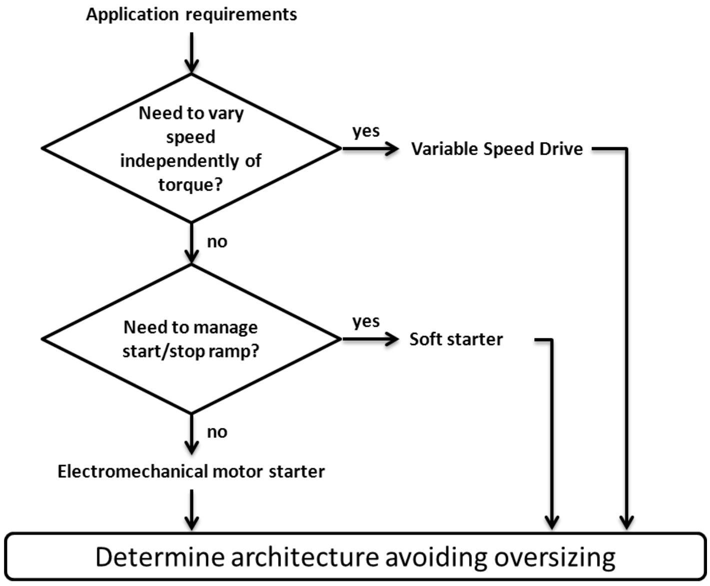

Figure 6 – Procedure for choosing a motor control solution based on energy efficiency considerations

- **Consider the requirements of the application:** What work needs to be done? What is the rated power of the equipment to use in order to avoid over-sizing? What is the duty profile of the application? Does the application need to vary the speed of the motor independently of the torque?

- **Define candidate control solution:** If it is not required to vary the speed of the motor independently of the torque, then a motor starter (contactor or soft starter) is the most energy-efficient solution because it brings the lowest extra losses.

  - If it is necessary to manage the starting ramp of the motor (e.g. in presence of high-inertia mechanical load), a soft starter shall be used for starting and bypassed once the steady state conditions have been reached.

- Otherwise, an electromechanical motor starter (contactor and motor protection) makes a simple, robust and efficient control solution.

If it is required to actually vary the speed of the motor independently of the torque down to a fraction of the rated speed, then a VSD shall be considered, since it is typically more efficient than mechanical means of drastically reducing the speed. A VSD causes significant extra losses, but these are compensated by overall energy savings provided the drive is used in suitable applications.

- **Evaluate energy efficiency:** What would be the operating point(s) of each device at the load level(s) defined in the duty profile? Is it more efficient to have several units in parallel or a single larger unit? The Extended Product Approach can be used to compute the Energy Efficiency Index of the solutions considered.

4. Example of Extended Product Approach (EPA)

This section gives an example of how the Extended Product Approach can be used to compare technical solutions for an application.

4.1. Weighted electrical power as an energy efficiency indicator

The energy efficiency indicator chosen for this example is the weighted electrical power of the application.

The duty profile specifies which fraction of time is spent at the different load levels. Considering a candidate Extended Product (motor system and load) for the application, these loads levels are translated into operating points OP_i. At each operating point, the power consumption P_i can be computed as specified in EN 50598 and related Extended Product standards.

The weighted power $P_{Electrical}$ is the sum of the total electrical power P_i (therefore including losses) required at each point OP_i, weighted by the corresponding time fraction, as shown in figure 7.

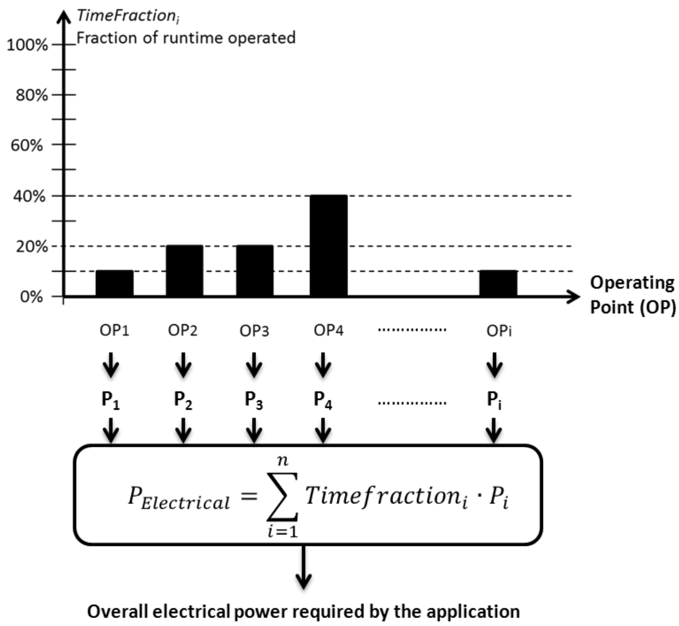

Figure 7 – Procedure for determining the weighted electrical power consumption from the operating points of the Extended Product

4.2. Comparison of two Extended Products for two example duty profiles

In this example we consider two reference 30kW pumping applications:

- **Duty profile 1:** Application essentially requiring operation at maximum load most of the time,
- **Duty profile 2:** Application that needs to be sized for a certain maximum load, but is operated at half load most of the time.

For each of these applications we consider two possible Extended Products inspired by the requirements of the European Regulation (IE2 motor + VSD / IE3 motor):

1. **Extended Product #1:** Contactor + IE3 motor + pump + throttling valve
2. **Extended Product #2:** Variable Speed Drive + IE2 motor + pump

For these two duty profiles and these two candidate Extended Products, we develop the Extended Product Approach using the weighted power as an energy efficiency indicator according to the prEN 50598 standard:

1. Define the operating points based on the duty profile
2. Compute the efficiency for each part of the Extended Product at each operating point
3. Combine the efficiencies to obtain the power drawn by the Extended Product at each operating point
4. Compute the weighted power

Note that:

- For this example we use typical efficiency values provided by manufacturers or application engineers.
- In the context of prEN 50598, manufacturers will be required to provide loss-related data at certain standardized operating points, in order to allow conducting the Extended Product Approach.
- If an operating point of the equipment differs from these provided standardized operating points, an interpolation formula needs to be used to compute the losses at this intermediate operating point. These interpolation formulas will be provided in EN 50598 or in Extended Product standards.

The main data and results are shown in figure 8.

Duty profile time fractions

Load (flow) level	100%	50%	0% (standby)
DUTY PROFILE 1 "nearly full load"	85%	5%	10%
DUTY PROFILE 2 "half load"	20%	70%	10%

EXTENDED PRODUCT #1: Contactor + fixed-speed IE3 motor + pump + throttling valve

Load (flow) level	100%	50%	0% (standby)
Operating point	100% flow	50% flow	0% flow
Pump & throttle efficiency	82.0%	61.5%	-
Motor efficiency	93.5%	93.0%	-
Contactor efficiency	99.9%	99.9%	0.00
Total power consumption at load point [kW]	**39.17**	**26.25**	**0.00**

Weighted electrical power, duty profile 1 [KW]	**34.61kW**	4.4% savings
Weighted electrical power, duty profile 2 [KW]	**26.21kW**	

EXTENDED PRODUCT #2: VSD + IE2 motor + pump

Load (flow) level	100%	50%	0% (standby)
Operating point	100% speed 100% torque	50% speed 25% torque	0% flow
Pump efficiency	82.0%	82.0%	-
VSD-driven IE2 motor efficiency	91.5%	91.0%	-
VSD efficiency (or power losses at standby)	97.0%	92.0%	0.06 kW
Total losses at load point	**41.22**	**21.85**	**0.06**

Weighted electrical power, duty profile 1 [KW]	**36.14kW**	
Weighted electrical power, duty profile 2 [KW]	**23.55kW**	10% savings

Figure 8 – Example of comparison of two different Extended Products for two different duty profiles, using the weighted power as an energy efficiency indicator

In this example, the Extended Product #1 (simple fixed speed EP) requires 4.4% less power than the VSD-based EP #2 for duty profile number 1. The contactor-based Extended Product #1 is thus the best match when the application is operated near full load most of the time.

Conversely, the Extended Product #2, based on a VSD, is a better match when the application is operated at part-load most of the time since it allows saving about 10% of power. In this type of part-load application however, one should also investigate solutions based on smaller units installed in parallel, working in their optimal efficiency range near full load, and switched on/off as required by the application.

This simplified example is for educational purposes and uses simple duty profiles. In reality, the duty profiles can be more complex. Nevertheless, it clearly shows that:

- Depending on the duty profile of the application, a same Extended Product can save or waste energy. It is therefore essential to always conduct a full Extended Product Approach, considering both the products and the application, in order to choose the solution that best saves energy.

- Avoiding over-sizing is essential because pieces of equipment operating at fractional loads are typically much less efficient.

5. Conclusion: Use the Extended Product Approach!

The upcoming EN 50598 standard provides the Extended Product technical committees and manufacturers with a methodology (the *Extended Product Approach* or EPA) that allows assessing the energy efficiency of applications implementing electrical motors. The EPA considers both the intrinsic efficiency of the equipment (power losses at the operating points) and the requirements of the application (its duty profile).

EN 50598 shall be used:

- by Extended Product committees (pump, fan, compressor committees …) to establish their own standards regarding the energy efficiency of the products under their responsibility,
- by manufacturers of motors, drives, motor systems and extended products to estimate the energy efficiency of their products and provide standardized data (efficiencies or losses at standardized operating points) to other stakeholders,
- by application designers to estimate the energy efficiency of candidate Extended Products for any application, in order to always choose the most efficient Extended Product.

The overall energy efficiency of an Extended Product used within an application depends much more on how efficiently its operating points match the requirements of the application, than on the intrinsic efficiency of the equipment. A system-level approach such as the *Extended Product Approach* is therefore necessary to always select the most energy-effective solution to an application.

There is no “one size fits all” solution for motorized applications, as far as energy efficiency is concerned.

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A Framework to Survey the Energy Efficiency of Installed Motor Systems

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Abstract

While motors are ubiquitous throughout the globe, there is insufficient data to properly assess their level of energy efficiency across regional boundaries. Furthermore, many of the existing data sets focus on motor efficiency and neglect the connected drive and system. Without a comprehensive survey of the installed motor system base, a baseline energy efficiency of a country or region's motor systems cannot be developed. The lack of data impedes government agencies, utilities, manufacturers, distributers, and energy managers when identifying where to invest resources to capture potential energy savings, creating programs aimed at reducing electrical energy consumption, or quantifying the impacts of such programs.

This paper will outline a data collection framework for use when conducting a survey under a variety of execution models to characterize motor system energy efficiency within a country or region. The framework is intended to standardize the data collected ensuring consistency across independently conducted surveys. Consistency allows for the surveys to be leveraged against each other enabling comparisons to motor system energy efficiencies from other regions. In creating the framework, an analysis of various motor driven systems, including compressed air, pumping, and fan systems, was conducted and relevant parameters characterizing the efficiency of these systems were identified.

A database using the framework will enable policymakers and industry to better assess the improvement potential of their installed motor system base particularly with respect to other regions, assisting in efforts to promote improvements to the energy efficiency of motor driven systems.

Introduction

Motor systems account for approximately 64% of manufacturing electricity use and are ubiquitous in industrial facilities worldwide [9]. Motor systems, such as compressed air, pumping, and fan systems, represent a largely untapped, cost-effective source for industrial energy efficiency savings that could be realized with existing technologies and best practices [2, 3, 5, 7, 9]. Although motor systems have the potential to contribute substantial energy savings, on the order of 2.58 EJ in final energy use, this potential is largely unrealized [3].

A major barrier to effective decision making to capture the energy savings potential, and to more global acceptance of the energy efficiency potential of motor systems, is the lack of sufficient data to assess the energy efficiency of motor systems across regional boundaries and to document the magnitude and cost-effectiveness of energy savings by country and by region [6].

This paper outlines a data collection framework for use when conducting a survey to determine the energy efficiency of the installed motor system base of a given country or region. Particular focus is paid to pumping, compressed air, and fan systems as these represent a large portion of the energy consumption attributable to motor systems.

The framework is created in the form of a series of tables that identify the information needed to better understand the design, operations, use, and maintenance of the installed motor system base in a given country or region. With this information, the energy efficiency of a particular installed motor system base can be assessed. This framework is intended to standardize the data collected ensuring consistency across various surveys, thus allowing for broader applicability of the survey results. The data collected can serve many purposes. One such purpose may be to develop regional indicators for the energy efficiency of a country or region's motor systems against which to measure energy efficiency improvement.

The framework was informed by several previous studies. Using a combination of experts' opinion and available data, McKane and Hasanbeigi developed an innovative approach to characterize the energy efficiency of motor systems in the United States, Canada, the European Union, Thailand, Vietnam, and Brazil. This approach used bottom-up energy efficiency supply curve models to estimate the cost-effective electricity efficiency potentials and CO_2 emission reduction for three types of industrial motor systems (compressed air, pumping, and fan) for the selected countries/region. The motor system data collection framework proposed in this paper has extensively benefited from the approach developed by McKane and Hasanbeigi [4]. Additional work used to inform the development of the framework includes a comprehensive assessment of U.S. industrial motor systems conducted by the U.S. Department of Energy (US DOE) and an extensive assessment of industrial motor systems and their energy efficiency potential in the EU conducted be de Almeida [8, 1].

The framework described in this paper is meant to be a beginning. The authors seek to initiate an international dialogue with other interested researchers to further refine the proposed framework and to develop ideas on how to get it utilized by government as well as non-government programs addressing motor system energy efficiency.

Purpose and implementation of motor system evaluation

The series of tables developed for this paper are intended to serve as a framework for designing surveys to assess motor system energy efficiency. Before designing the framework, its eventual use, including its purpose and implementation, needs to be understood. By considering aspects of the survey implementation such as the intended user, the larger process for assessing motor system energy efficiency potential into which the survey fits, and the execution model for collecting data, a framework can be devised that best meets the needs of future motor system surveys.

Intended User

A survey of the installed motor system base in a region can be useful to many entities. Government agencies at all levels may be interested in a survey of the installed motor system base to help guide policy towards reducing electric energy consumption within their purview. Utilities may be interested in a motor system survey to better estimate the savings associated with rebate and incentive programs directed towards improving motor system energy efficiency and reducing electricity consumption. Providers of motor system equipment and services may use the information gained from a motor system survey to develop and market products that address energy saving opportunities within the installed motor system base. Energy managers may use the results of the surveys to compare the performance of their motor systems to their peers and identify potential energy saving opportunities. By focusing on the data requirements for characterizing motor system energy efficiency, the framework can be adapted for a range of applications by those seeking to better understand the energy efficiency of an installed motor system base.

The use of data collection framework in energy efficiency policies and programs:

Ultimately, the framework developed here can fit into a larger goal of developing policies that encourage the adoption of technologies, processes, and best practices for improving installed motor system energy efficiency. One example of the steps to achieve this larger goal is provided in the textbox. These steps fall into two phases: baseline current energy efficiency (Steps 1 – 3) and assess energy efficiency potential (Steps 4 – 6). The framework presented here develops Step 2.

Step 1: Collect identifying information on installed motor system(s) base
Step 2: Collect data on the energy efficiency of installed motor system(s) base
Step 3: Using the data collected in Step 2, develop indicators to profile motor system(s) energy efficiency and allow for comparison to similar systems across regional boundaries
Step 4: Enumerate technologies, processes, and best practices for improving motor system(s) efficiency
Step 5: Assess technical potential and economic feasibility of energy efficiency improvement from implementation of identified technologies, processes, and best practices
Step 6: Identify potential policies and programs to assist industry in achieving those energy efficiency improvements that are technically and economically feasible

The framework presented assumes Step 1 has been completed. Step 1 provides basic information regarding the installed motor system equipment and estimated total energy consumption. Sample information for Step 1 can be found in Figure 1. Step 2 uses data collection samples to gather further information on system design, operating characteristics, use, maintenance, and other indicators for assessing energy efficiency.

Sample Information to determine for Step 1		
Electricity Consumption	Motor system type	Motor type
Motor count	Pumping	AC
Motor size	Compressed Air	DC
Operating hours	Fan	Electricity Costs
Power factor	Materials handling	Usage cost
Nameplate efficiency	Materials processing	Demand charge

Figure 1: Sample information of installed motor system base to collect for Step 1

Survey Execution Method

There are many considerations for the execution of a survey of the energy efficiency of an installed motor system base. In addition to determining the data to be collected, some of the considerations that the designers of the survey need to take into account include identifying the sources for the data and establishing the method for implementing the data collection instrument. For example, the data can be collected at the end-user facility or indirectly through surveying providers of motor system equipment and services, experts in the field, and many other channels. The data collection instrument can be implemented through analysis of existing data sources, remotely through questionnaires, on-site surveys at a facility, or through some combination of all three. The selection of the survey execution method will be based on factors included but not limited to current data availability, desired level of detail and comprehensiveness of the survey, and the availability of time, human, and financial resources for survey implementation. It is anticipated that a field sampling model would need to be developed to obtain credible results with a limited amount of resources

In all likelihood, it would not be feasible to survey all motor systems of interest in a given country or region. A more likely execution model would leverage existing data sources for the installed motor system of interest combined with site surveys and remote data gathering (questionnaires). A representative sample of the facilities in the study region would need to be surveyed based on motor system and facility characteristics within the region of study. Further, decisions will need to be made concerning the relative importance of systems to be surveyed. For example, smaller motor systems (i.e., < 15 kW) or motors that operate very infrequently (i.e. < 2000 hours) can likely be excluded from the survey with minimal loss of accuracy in the analysis for Step 3.

The framework presented here seeks to inform the development of a motor system data collection survey instrument under multiple execution methods:

- Where facilities would be surveyed, either onsite or remotely, the framework will guide the development of the questions and measurements to be made at the facility. Information would be gathered with the assistance of energy managers or operators of the motor driven systems

- Where existing data is leveraged to better understand the energy efficiency of the installed motor systems, the framework is intended to guide database querying and analysis by providing the information to be determined from the data sources.

In all cases, the information identified within the framework is to be collected at the facility level for use in a bottom-up analysis of the regional level of motor system energy efficiency. To support the bottom-up analysis and enable efficient data processing, data should be gathered and/or stored electronically. When applied, the information identified within the tables will need to be tailored depending on the availability of resources to conduct the survey, the relevant existing data, and the overall purpose of the survey.

Tables for Motor System Survey Framework

The developed framework for surveying the energy efficiency of an installed motor system base is presented as a series of tables. Directions for using the series of tables are provided below.

Structure of data collection framework

The categories for the questions within the tables have been developed as part of the work undertaken by McKane and Hasanbeigi [5] to characterize the motor system energy efficiency baseline of several countries/region. For their study, the information needed to define pumping, compressed air, and fan system energy efficiency in several countries/region was developed in consultation with industry experts. The information collected took the form of energy efficiency practices that indicate the energy efficiency of each system.

The tables are organized into five columns as follows:

Characteristics: Lists general characteristics of motor systems with respect to assessing their energy efficiency. These characteristics include system sizing, operations, design, use, and maintenance.

Information Needed: Identifies information regarding energy efficient practices for each *Characteristic*

Purpose: Provides a brief explanation of how the energy efficient practice identified in the *Information Needed* column can help to assess overall system efficiency

Sample questions: Provides sample questions for identifying the pertinent information to assess the level of adoption of the energy efficient practice identified in the *Information Needed* column.

Sample Measurements: Provides sample measurements for collecting the necessary information to answer the respective *Sample Question*. "Qualitative" is used to indicate data that can be collected through interviews of facility personnel.

Use of the survey tables

The framework developed intends to be applicable to a wide variety of execution models and abilities of the survey responders. As such, it recognizes the varying degree of time and resources that can be afforded to collecting data by either the surveyor or the person responding to the survey. Multiple tables are developed each balancing the representativeness of the information collected for assessing motor system energy efficiency and the level of effort necessary to collect the data. Practically, not every question will be answered for each facility. The selection of tables for use by the survey executors will depend on the availability of resources and the goals of the ensuing analysis.

Three series of data tables are constructed:

Table 1: The first table is intended to capture the basic information necessary to assess the general motor system efficiency of a facility. The information collected using Table 1 provides a high level understanding of the motor system energy efficiency of a facility. The data identified in this table can be collected without taking measurements within the facility. Questions in Table 1 are applicable to all motor systems including pumping, compressed air, and fan systems. Table 1 should be used if the time allowed for collecting data for any one facility is less than a half-day.

Table 2 Series: Table 2 Series consists of four separate tables that are intended to be used after gathering the information from Table 1. In addition to better characterizing the general energy efficiency of the motor systems, Table 2 Series begins to assess the energy efficiency of specific motor systems, namely pumping, compressed air, and fans by collecting information on energy efficient practices specific to the system. Table 2 delves deeper into the general motor system characteristics whiles Tables 2a-c provide a framework for better characterizing pumping, compressed air, and fan systems respectively. Table 2 series should be used if the burden associated with completing the survey is less than 1 day.

Table 3 Series: While much of the information in the Table 3 Series can be quite indicative of a motor system's energy efficiency, the questions less critical to assessing energy efficiency as is the information collected in the other tables. In some cases, sample questions from Table 3 may be used as substitute data points for the questions developed in Tables 1 and 2 Series.

Table 1: Basic information to assess general motor system efficiencies of a facility

Characteristic	Information Needed	Purpose	Sample questions	Sample measurements
Sizing	Determine if motor system was sized with energy efficiency as a priority	Motor systems may be sized using priorities other than energy efficient operations and as a result they might be oversized resulting in low energy efficiency	• Was the energy efficiency at typical loads a consideration when sizing the motor system?	• Qualitative
Operations	Frequency of motor system energy efficiency assessments and measures taken as a result of assessment findings	Performing frequent motor system energy efficiency assessments helps to ensure that the system is continually reviewed for energy efficiency opportunities	• Has an energy efficiency assessment of the motor system been conducted?	• Qualitative
			• How frequently are energy efficiency assessments performed on the motor systems?	• Qualitative
			• Have projects identified through assessments been implemented?	• Qualitative
			• Is there a business process (including but not limited to an energy management system) for determining when to re-asses the efficiency of a motor system?	• Qualitative
	Rewind policy	An established policy dictating when to replace a motor rather than rewind it can ensure that motor systems operate efficiently in a cost effective manner	• When motors fail, are they replaced or rewound?	• Qualitative
			• Are there qualifications guiding the decision to replace or rewind (i.e. minimum motor size)?	• Qualitative
			• If replaced, are motors replaced with the most energy efficient available motor in the motor class (i.e. Premium Efficiency in the US, IE3 in the EU)?	• Qualitative
			• If replaced with a spare motor, is the spare motor capacity typically matched to the system demand needs?	• Qualitative
Design	Use of energy efficient motors in all systems	Using the most efficient motor for a purpose will help achieve maximum possible motor system efficiency	• Is energy efficiency rating a top priority when purchasing motors for the facility?	• Qualitative
			• What percentage of motors are the most energy efficient available for their class and purpose (i.e.	• Qualitative

			NEMA Premium Efficiency, IEC IE3)	
	Determine the age of the motor driven system	Older motor systems may not take advantage of new technologies. Wear and tear on older motor systems may lower efficiency. Older systems may no longer match current process needs.	• When was the current motor system designed and installed?	• Qualitative
	Determine if the facility has designed their motor system to operate efficiently if frequently operating at low partial loads	Motor systems operate inefficiently under partial loads. For motor systems operating below a certain load factor, system efficiencies can begin to decline	• When/where applicable, are VSD technologies employed to meet partial loads?	• Qualitative
			• Are multi-sized motor systems used to meet operations with highly variable system demands?	• Qualitative
	Determine if motor shaft work is being efficiently transmitted throughout the motor system	While the motor may operate efficiently, losses can occur during the transmission of the motor shaft work to the system. These losses can be lessened through proper selection and maintenance of transmissions.	• What type of power transmission system is used in the motor system?	• Qualitative
Maintenance	Frequency and elements of maintenance program	Performing regular maintenance is essential to maintaining the energy efficiency of a motor system. A predictive maintenance program can increase system life and sustain energy efficient performance	• Is there a regular predictive maintenance program or is maintenance reactive to problems and breakdowns?	• Qualitative
			• How often are motor systems inspected?	• Qualitative
			• What aspects (e.g., belts, bearings, shaft alignment, lubrication, cleanliness, etc.) of the motor system are focused on during regular maintenance? Does the maintenance program extend beyond the motor to include the system as well?	• Qualitative
			• Are transmission systems maintained periodically (belt tightening, alignment, lubrication, etc.)?	• Qualitative

Table 2: Assessing specific motor system efficiencies in a facility – general questions

Characteristic	Information needed	Purpose	Sample questions	Sample measurements
Operations	Load profile	Motor systems operating at low part loads will operate inefficiently. Frequent operation at low part loads, as indicated by measuring the load profile, is an indicator of low system efficiency.	• What is the process and equipment load profile (i.e., profile of operating hours at various percent of full load power)?	See tables 2a - 2c *Note: Single day measurements of loads may not result in understanding typical load profiles. For a single day survey, measurements should be combined with qualitative questions to better develop an accurate load profile*
Design	Use of multiple motor systems to meet process needs	There are many advantages to using multiple motor systems to meet process needs including greater opportunity to meet process loads while running equipment at full load, but if not appropriately coordinated and used multiple motor systems can operate inefficiently	• Are motor driven equipment sequenced to ensure efficient operations across all loads while also meeting process demands?	• Qualitative • Slip or kWh measurement to determine load
			• Are trim/back-up motor driven equipment fitted with VSDs if applicable?	• Qualitative
			• How often and at what load are trim/back-up motor driven equipment used?	• On/off meters to determine operating hours of motor systems • Slip or kWh measurement to determine load

Table 2a: Assessing specific motor system efficiencies in a facility – pumping systems

Characteristic	Information needed	Purpose	Sample questions	Sample measurements
Sizing	Current pumping system size	Improperly sized pumping systems can often operate inefficiently	• Is the current pumping system sized to the current system demand?	• Qualitative • Pump curve • System curve
			• What are the load requirements for the process?	• Qualitative
			• What is the pump size?	• Qualitative • From nameplate
Operations	Load profile	Pumping systems operating at low part loads will operate	• What are the equipment load profiles, including those of back-up equipment?	• Continuous kWh measurement to determine pump power consumption

		inefficiently. Frequent operation at low part loads is an indicator of low system efficiency.		• Qualitative
	Determine if appropriate pump type is selected for the application	Positive displacement and centrifugal pumps are better suited for certain applications than others. Improper pump selection can lead to poor system performance	• Is the appropriate pump (positive displacement or centrifugal) selected for the current application	• Qualitative

Table 2b: Assessing specific motor system efficiencies in a facility – compressed air systems

Characteristic	Information needed	Purpose	Sample questions	Sample measurements
Sizing	Current compressed air system size	Improperly sized compressed air systems can often operate inefficiently	• Do compressors frequently operate in part-load, unloaded (standby), or blow-off mode?	• Qualitative
Operations	Load profile	Several compressors operating at part loads wastes energy; Frequent operation at low part loads is an indicator of low system efficiency	• What are the equipment load profiles, including those of back-up equipment?	• Continuous kWh measurement to determine pump power consumption • System pressure • Qualitative
	Determine if air is properly filtered and dried before use	Neglected maintenance of dryers and filters, can lead to early failure of a system as well as reduced efficiency	• Are filters cleaned and replaced as recommended by the manufacturer? • Are dryers adequately maintained to ensure air is dried to required pressure dew point?	• Qualitative • Pressure dew point
Maintenance	Determine if the facility has a compressed air leak maintenance program	Compressed air leaks can represent a significant system loss	• How are leaks identified within the facility?	• Qualitative • Ultrasonic leak detection instruments • System leak test
Compressed air use	Determine if compressed	Often cost effective alternatives to using	• Can a blower be used for any of the current	• Qualitative

	air is the best choice for meeting a particular need	compressed air are available, such as blowers, fans, or mechanical devices	compressed air applications? • Is compressed air used for personal cooling? • Is oil-free air used in applications that do not require oil-free air?	
	Compressed air system efficiency is optimized across all process demand loads	For processes that require variations in process demand either over time or across different applications occurring concurrently, a system should be designed to best meet all process loads as efficiently as possible	• Can the system respond efficiently to variable loads (e.g., use of VSDs, sequencing) • Are receiving tanks used? • Are compressors left on idle?	• Qualitative • On/off meters to determine operating hours of compressors • kWh to determine compressor power consumption • System pressure

Table 2c: Assessing efficiency of specific motor system efficiencies in a facility – fan systems

Characteristic	Information needed	Purpose	Sample questions	Sample measurements
Sizing	Current motor system size	Improperly sized motor driven systems can often operate inefficiently	• Is the current motor system sized to the current process?	• Qualitative • Fan curve • System curve
			• What are the load requirements for the process?	• Qualitative
			• What is the fan system size?	• Qualitative
Operations	Determine if the fan systems operates in an appropriate environment	Particular fans are better suited for a particular application. Matching fan type and location can increase fan system life and efficiency	• Is the appropriate fan selected (i.e. radial for high particulate applications) for the appropriate use?	• Qualitative
	Load profile	Fan systems operating at low part loads will operate inefficiently. Frequent operation at low part loads is an indicator of low system efficiency.	• What are equipment load profiles, including those of back-up equipment?	• Continuous kWh measure-ment to determine fan power consumption • Qualitative
Maintenance	Determine if leaks are present in ducting	Losses in the ducting system can add avoidable loads on the fan system	• Are ducts tested for leaks? • Are leaks remedied upon discovery?	• Qualitative

Table 3: Additional assessment of specific motor system efficiencies in a facility – general questions

Characteristic	Information needed	Purpose	Sample questions	Sample measurements
Design	Use of multiple motor systems to meet process needs	There are many advantages to using multiple motor systems including greater opportunity to meet process loads while running equipment at full load, but if not appropriately coordinated and used one motor system may experience unequal wear and tear.	• Are measures taken to ensure even usage on similar size and purpose (i.e. periodic rotating of lead and lag pumps/ lag compressors)?	• Qualitative

Table 3a: Additional assessment of specific motor system efficiencies in a facility – pumping systems

Characteristic	Information needed	Purpose	Sample questions	Sample measurements
Design	Current pump system size	Operating at the Best Efficiency Point as frequently as possible optimizes pump system efficiency	• Was the pump selected to operate at the Best Efficiency Point during typical usage?	• Pump curve • System Curve • Qualitative
	Use of bypasses	Bypasses are the least efficient method of reducing flow	• How often are bypasses used to handle excess flow?	• Qualitative
	Use of throttles	While more efficient than bypasses, throttling pumps does not take advantage of the natural reduction in power consumption per the affinity laws	• How often are throttles used in periods of excess flow? • Are throttles preferred over bypasses?	• Qualitative
	Use of mechanical couples	Mechanical couples can offer more energy costs savings compared to throttles, but less than achievable with VSDs.	• Are mechanical couples used for flow control?	• Qualitative
	Use of booster pumps	Booster pumps can meet high loads, allowing for main pump system size to be reduced and operated at full load more frequently	• Are booster pumps used for high demand equipment/ processes?	• Qualitative

Table 3b: Additional assessment of specific motor system efficiencies in a facility – compressed air systems

Characteristic	Information needed	Purpose	Sample questions	Sample measurements
Design	Use of dedicated compressors	Dedicated compressors for processes that require higher pressures than the balance of facility	• Are dedicated compressors used for meeting isolated high pressure loads?	• Qualitative

		operations can lower overall energy consumption for compressed air systems		
Compressed air operating condition	Compressed air system efficiency is optimized across all process demand loads	For processes that require variations in process demand across different applications occurring concurrently, a system should be designed to best meet all process loads as efficiently as possible	• Are start/stop controls used? • Are engineered nozzles used? • Are there many pressure-reducing-valves onsite? If so, what is the pressure drop across the PRVs?	• Qualitative • On/off meters to determine operating hours of compressors • kWh to determine compressor power consumption • System pressure

Table 3c: Additional assessment of specific motor system efficiencies in a facility – fan systems

Characteristic	Information needed	Purpose	Sample questions	Sample measurements
Operations	Determine if fan system is operated efficiently across all loads	While fan systems are generally sized to a particular load, measures can be taken to ensure high efficiency across varying loads	• If axial fan, are controllable pitch fans used to meet variable air flow requirements?	• Qualitative
	Use of dampers and bypasses	Extensive use of dampers and bypasses can be indicators of poor fan system efficiency. More efficient options may exist for meeting variable loads.	• Are dampers or bypasses used? • If so, to what extent?	• Qualitative
	Fan inlet	Ensuring uniformity of air flow prior to the inlet can increase fan efficiency	• Is there sufficient spacing or are airflow straighteners used to correct flow at inlet?	• Distance between fan and inlet
Design	Current fan system size	Operating at the Best Efficiency Point as frequently as possible optimizes fan system efficiency	• Was the fan selected to operate at the Best Efficiency Point during typical usage?	• Fan curve • System Curve • Qualitative
	Use of multiple fans to meet process needs	There are many advantages to using multiple fans including greater opportunity to meet process loads while running equipment at full load	• Are loads met by multiple fans? If not, can multiple smaller fans meet the loads satisfied by a large fan?	• On/off meters to determine operating hours of fans • kWh or slip to determine load

Conclusion

The common framework presented in this paper supports an assessment of the motor system efficiency in a given region. It provides a building block for developing a survey that collects the necessary data to characterize motor system efficiency, particularly for pumping, compressed air, and fan systems, under a variety of execution models. Using the data from the survey, bottom-up assessment models of the energy efficiency of a region's motor systems can be created. Such detailed assessments can inform policy makers on the energy saving potentials, the measures and technologies that can be adopted in their region, and the cost of their adoption. This will foster the design of more effective and cost-efficient programs for improving motor system efficiencies.

The framework presented can serve to initiate a dialogue regarding the appropriate data to collect when scoping the energy efficiency of an installed motor system base. By reaching a consensus among motor system experts on the framework, surveys conducted independent of each other can be analyzed together to build a more accurate profile of global motor system efficiency.

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IS IE3 Efficiency Class: A Feasible Next Step for Industrial Motor's MEPS in Brazil?

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Abstract

The Brazilian Labeling Program - PBE in industrial induction motors started in 1992. The energy seal for the most efficient products was established around 1996 by The National Program of Energy Conservation - PROCEL. The Presidential Decree no. 4.508 on December 11th, 2002 imposed two tables of minimum efficiency levels for those motors, one for standard and other for high efficiency motors and blocked the manufacture, commercialization and importation of motors which efficiencies were below those levels. In December of 2005, a governmental directive was enacted establishing that in four years there would be only one minimum efficiency levels table and this would be the current high efficiency one. Now only high efficiency motors are manufactured, commercialized or imported in Brazil, the market accommodated the new prices and the difficulties for running all aspects of regulation are being solved.

The international natural next step is to raise the mandatory efficiency levels for those as established for IE3 efficiency class. The market signals indicated that the Brazilian OEMs are suffering with the global competition and any increase of cost is not welcome. This paper presents the studies and activities are taking place in order to implement a new table of mandatory efficiency levels for induction motors as well as the related difficulties.

1-Introduction

Brazil has a huge industrial motor market. There are two causes impelling this fact. The first is Brazil is one of the tenth biggest economies with a strong industrial sector and the other is the well-established machine manufacturer sector. Figure 1 shows the participation of motor electric energy consumption in the industrial electric energy consumption. The last national production estimation was about 1.8 millions of units per year.

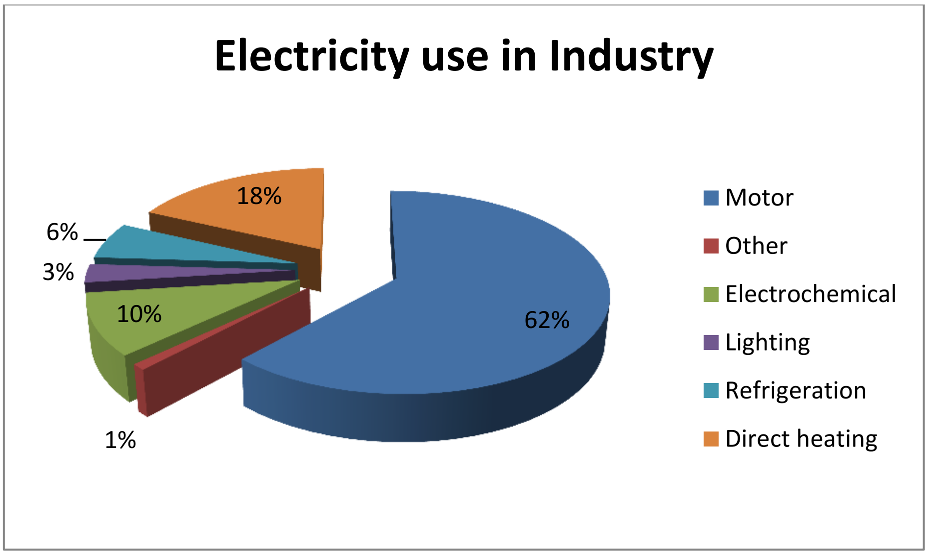


Figure 1: Consumption of electric energy by end-use in the Brazilian industrial sector.

This importance led the Brazilian government to promote energy efficiency in this equipment since 1986 [6, 7]. In terms of minimum efficiency levels the first tables were proposed in voluntary basis in 1998 coming from the efforts of PBE, coordinated by the Instituto de Metrologia Nacional - INMETRO (Brazilian regulatory institute for weights and measures) and PROCEL run by Centrais Elétricas Brasileiras - ELETROBRAS. During the 2001 energy crisis, the Act 10295 of October 2001 made the Executive Power responsible for implementing specific requirements regarding maximum levels of energy consumption or minimum levels of energy efficiency for equipment. This regulation for all energy consuming equipment was established by the Executive Order 4059 of December 2001, which instituted the Comitê Gestor de Indicadores e Níveis de Eficiência Energética – CGIEE (governmental energy efficiency indicators regulation and management office), who is responsible for designing specific regulations for specific types of equipment through technical committees.

In 2002, CGIEE selected industrial induction motor to be the first equipment to have mandatory efficiency level. The Specific Motors Regulation became a reality through Presidential Order (PO) 4508 of December 11, 2002.

That regulation included three-phase induction motors from 1 to 250 hp, 2, 4, 6 and 8 poles, continuous operation, 600 V maximum, establishing two minimum efficiency levels, one for standard motors (similar to IE1 values) and other for high efficiency motors (similar to IE2 values), separated or as part of end-use machinery, imported or manufactured in the country. The wide scope of this regulation encompassed approximately 70% of the market, and also the innovative aspect of setting up the Target Program that shall indicate the next step of minimum energy efficiency levels evolution so it became a process of efficiency improvement.

The Target Program focused to eliminate the table for standard motors and the new minimum efficiency level table was that one of the high efficiency motors. After studies and surveys, the Target Program became real through the Joint Ministerial Order 553 of December 8, 2005, executed by the Minister of Mines and Energy; the Minister of Science and Technology; and the Minister of Development, Industry, and Foreign Trade. This ordinance confirmed the proposed table and established 4 years to enter in force for separated motors and an additional 6 months for the inventory to be sold and 4 years in a half for end-use machine and an additional 6 months for the inventory of these machines to be sold.

INMETRO published the order 243/2009 and 488/2010 which made mandatory the labeling program for motors and extend the labeling program for open drip proof motor in order to complete the legal infrastructure of regulation. Responding the demand from the OEM sector, INMETRO postponed the regulation for more 6 months for motors inside the machines.

Since December of 2009 for separated motors and December of 2010 for motor parts of other machines, the regulation is in place. After some years running these efficiency levels is time to analyze the next step. This paper presents the status of MEPS implementation in Brazil and the studies and activities are taking place in order to implement an IE3 efficiency class table as minimum mandatory efficiency levels for induction motors.

2 – Status of Motor Regulation

The analysis of the implementation of the regulation can be categorized into motors and end-user machines, imported and domestic. In terms of domestic manufacturing motors, the manufacturer's participation in PBE is mandatory so all motors meet the MEPS. In the same way, motors for domestic OEM also meet the MEPS when they are bought from domestic manufacturers.

Import requests are performed through product codes in a Government software system. In the case of an isolated motor, regulatory requirements are implemented when two related codes are requested. Thereafter the procedure is different depending on whether the importer is a foreign motor manufacturer or a tradesman. In the first case, it is required the manufacturer enter in PBE, their product lines attend the labeling requirements and their laboratories accredited by INMETRO. In the second case, the importer has to send to the accredited laboratory, a sample of the batch that was imported, following the quantity specified by a national sample standard, to an accredited laboratory. After the test of compliance with minimum efficiency levels, if approved, every batch is released; otherwise unapproved importer takes care of sending the whole batch back to the country of origin.

The biggest problem lies in imported end user machines. There are about 100 codes related to import machinery and the regulatory requirements are implemented in the top 15.

There are reports that there are motors and machines being imported through product codes in which the regulatory requirements are not implemented. The Brazilian government is aware and complaints are being investigated.

To strength the inspection structure, INMETRO promotes periodically training programs to continuously qualify the inspectors in the compliance rules for end use machinery and motors.

3- Brazilian Premium Efficiency Class for induction motor – IR3

As Brazilian MEPS for industrial motors is quite similar to IE2 Efficiency Class, the next step in terms of MEPS is to follow the nominal rated efficiency values of IE3 Premium Efficiency class defined by IEC 60034-30 (2008). The standard committee discussed and studied for more than a year to create a minimum efficiency level table that follow IEC one but also respect the strong Brazil OEM market. It includes values for 8 poles and lower level for 0, 75 kW 2 poles. The other values are the same although it permits seven different values for motor manufactured in smaller frames. Table 1 shows the efficiency table defining our Efficiency Premium Class – IR3. The Brazilian Technical Standard Association – ABNT will publish it in the end of 2013.

Table1. Minimum rated efficiency for Premium Efficiency Class

Power		**Pole**			
kW	**cv/hp**	**2**	**4**	**6**	**8**
		rated efficiency			
0,75	1	77,0	83,5[1]	82,5	75,5
1,1	1,5	84,0	86,5[2]	87,5[3]	78,5
1,5	2	85,5	86,5	88,5[4]	84,0
2,2	3	86,5	89,5[5]	89,5[6]	85,5
3	4	88,5	89,5	89,5	86,5
3,7	5	88,5	89,5	89,5	86,5
4,4	6	88,5	89,5	89,5	86,5
5,5	7,5	89,5	91,7[7]	91,0	86,5
7,5	10	90,2	91,7	91,0	89,5
9,2	12,5	91,0	92,4	91,7	89,5
11	15	91,0	92,4	91,7	89,5
15	20	91,0	93,0	91,7	90,2
18,5	25	91,7	93,6	93,0	90,2
22	30	91,7	93,6	93,0	91,7
30	40	92,4	94,1	94,1	91,7
37	50	93,0	94,5	94,1	92,4
45	60	93,6	95,0	94,5	92,4
55	75	93,6	95,4	94,5	93,6
75	100	94,1	95,4	95,0	93,6
90	125	95,0	95,4	95,0	94,1
110	150	95,0	95,8	95,8	94,1
130	175	95,4	96,2	95,8	94,5
150	200	95,4	96,2	95,8	94,5
185	250	95,8	96,2	95,8	95,0

220	300	95,8	96,2	95,8	95,0
260	350	95,8	96,2	95,8	95,0
300	400	95,8	96,2	95,8	95,0
330	450	95,8	96,2	95,8	95,0
370	500	95,8	96,2	95,8	95,0

[1] For motors produced in frame size 80, the minimum efficiency value is 83%.

[2] For motors produced in frame size 80, the minimum efficiency value is 84%. [3] For motors produced in frame size 80, the minimum efficiency value is 85.5%

[4] For motors produced in frame size 100, the minimum efficiency value is 86.5%.

[5] For motors produced in frame size 90, the minimum efficiency value is 87.5%.

[6] For motors produced in frame size 100, the minimum efficiency value is 87%.

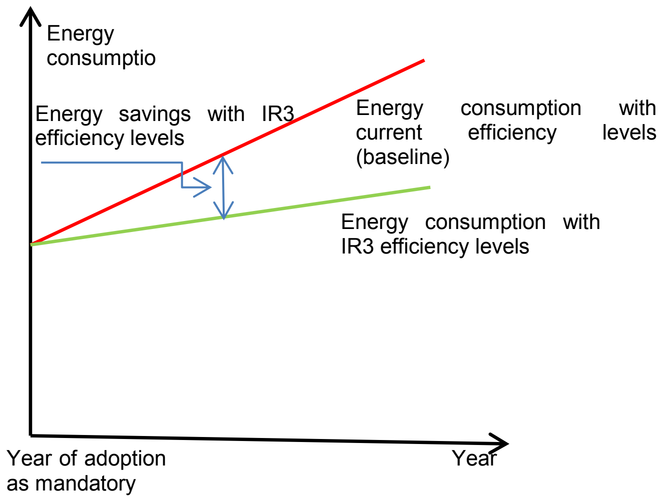
[7] For motors produced in frame size 112, the minimum efficiency value is 91%.

The test methodology for efficiency determination is similar to IEEE 112 – B.

4- Estimated Energy Savings by the Adoption of Class IR3 as MEPS

To estimate the energy savings of the adoption of efficiency values of table 1 as the mandatory minimum efficiency values we consider the period starting from the year of the adoption (2017) to the reference year for the National Energy Plan 2030 – PNE (2030) [3]. The methodology used was developed by Eletrobras Procel, in partnership with Universidade Federal de Itajubá (Unifei), for the evaluation of the results of the Eletrobras Procel Seal for Three-Phase Induction Motors [1]

This methodology takes into account as baseline the consumption of the total installed motors with current efficiency levels and compares it with the replacement for the new levels, as shown in Figure 2.



.Figure 2 – Evolution of energy consumption curves of the motors installed.

Source: Eletrobras Procel, 2009 (adapted).

The equivalent consumption according to the power ranges and annual sales were used to calculate the consumption of the total installed motors for baseline or for IR3 levels, This calculation took into account the average efficiency, annual depreciation of efficiency and expected lifetime for each range, according to the Eletrobras Procel methodology[1]. These premises are in agreement with the

International Performance Measurement and verification Protocol – IPMVP [5] so as to provide greater reliability to the estimate figures.

Moreover, the operating hours, load factor and average efficiency per range were also considered, as stated by Eletrobras Procel[1]. An efficiency factor is included to simulate the variation of the rated efficiency with the load. Table 2 presents some of these data used for the estimates.

Table 2 – Data used for the estimated energy results with the use of IR3 standards.

Poles	**Power Range**	**Representative Power (Power/hp)**	**Operating Hours (T/h)**	**Average Load-Factor (LF)**	**Efficiency Factor (EF)**
2	1 a 10	5	800	55%	98.2%
	>10 a 40	25	1000	61%	99.2%
	>40 a 100	70	1200	70%	99.8%
	>100 a 250	175	2000	74%	99.9%
4	1 a 10	5	800	55%	98.2%
	>10 a 40	25	1000	61%	99.2%
	>40 a 100	70	1200	70%	99.8%
	>100 a 250	175	2000	74%	99.9%
6	1 a 10	5	800	55%	98.2%
	>10 a 40	25	1000	61%	99.2%
	>40 a 100	70	1200	70%	99.8%
	>100 a 250	175	2000	74%	99.9%
8	1 a 10	5	800	55%	98.2%
	>10 a 40	25	1000	61%	99.2%
	>40 a 100	70	1200	70%	99.8%
	>100 a 250	175	2000	74%	99.9%

Source: Eletrobras Procel (2009)

The average efficiency per power range was calculated according to the tables of the Brazilian Labeling Program – PBE and Classes IR3 which are presented in Table 3.

Table 3 – Current average (η_a) and IE3 (η_{IR3}) performances

Poles	Power Range	Current Average Performance (η_a)	Average Performance IR3 (η_{IR3})
2	1 a 10	85.9%	86.5%
	>10 a 40	91.2%	91.5%
	>40 a 100	93.6%	93.6%
	>100 a 250	95.1%	95.3%
4	1 a 10	86.6%	88.7%
	>10 a 40	92.2%	93.2%
	>40 a 100	94.1%	95.1%
	>100 a 250	95.2%	96.0%
6	1 a 10	85.0%	88.7%
	>10 a 40	91.6%	92.5%
	>40 a 100	93.9%	94.5%
	>100 a 250	95.1%	96.5%
8	1 a 10	83.8%	84.3%
	>10 a 40	91.2%	90.5%
	>40 a 100	93.3%	93.0%
	>100 a 250	94.4%	94.4%

Source: Authors' own table based on IR3 table and the PBE table.

In addition to these data, the lifetimes of 13, 20, 25 and 29 years were used, respectively in relation to power ranges of 1 to 10 hp, between 10 and 40 hp, between 100 and 250 hp, since for all of them there is a motor efficiency loss of 2% during its life cycle.

The following equation was used to calculate the consumption of all motors installed:

$$CP_k = \sum_{j=1}^{m} \sum_{i=1}^{n} Ce_{ji} \,.\, V_{ji} \qquad (1)$$

Where:

- Ce_{ji} is the equivalent consumption of power range "j" in year "I";
- V_{ji} is the sales of equipment with power range "j" in year "i";
- "k" is the index that shows the number of class IR3 motors or with current efficiency;
- "j" is the index that shows power range as established previously;
- "i" is the index that varies from the year of purchase until the year of the end of its lifetime.

To calculate Ce_{ij} the following equation is used:

$$Ce_{ji} = \frac{0{,}735.Pot_j.T_j.FD_{ji}.FC_j}{\eta_j.FR_j} \qquad (2)$$

Whereas:

- Pot is the representative power range "j";
- T is the operating hours of range "j";
- FD is the depreciation factor of range "j" in year "i";

- FC is the load factor of range “j”;
- η is the efficiency of range “j”;
- FR is the efficiency factor[1].

Considering the average sales growth of motors of 4.1% per year that is based on the most likely estimate of electric energy consumption increase in the country by EPE[3][2] and the entry into effect of class IR3 motors as MEPS in Brazil by 2017, we have come to the results shown in Table 4 by the application of the mentioned methodology.

Table 4 – Energy savings results with the adoption of class IE3 for motors marketed in Brazil.

Year	Energy Saving (GWh)
2017	127
2030	2,297

Source: the authors based on the methodology and related assumptions.

According to PNE 2030 [3], the Brazilian electric energy saving target resulting from induced actions is 53,000 GWh by 2030. So, the adoption of class IR3 can account for a contribution of 4.33% for this target.

The energy savings by 2030 is equivalent to that generated by a 551 MW hydropower plant if a typical utilization factor of 56% and losses of 15% in the electric system power are considered.

If the same annual growth is considered for electric energy consumption of 4.1% per year, the average consumption of electric energy per residence in Brazil will be 328 kWh/month in 2030, whereas it was 159 kwh/month in 2012 (EPE, 2013). Therefore, the electric energy to be saved by 2030 could be used to supply 580 thousand residences for a year or for a city with 2 million dwellers.

The energy saved between 2017 and 2030 is estimated to be 16,053 GWh.

5- Next steps for the implementation of the New MEPS

The estimated savings that can be obtained by the adoption of class IR3 and its compliance with PNE 2030 have motivated experts, manufacturers and consumers to introduce this efficiency class in the Brazilian motor specification standard. This has been in progress since 2012 by ABNT, where this motor class is known as “Efficiency Premium Class – IR3”. As said, it is expected its publication by the end of 2013. The introduction of this efficiency class within this standard will indicate to the market the possibility to purchase motors with higher performance levels than the ones currently available as it was done in the past when standard and high efficient motors classes coexisted.

Once this induction motor class is defined, the next step is to promote incentives so that the market shall consider the possibility of purchasing these “new” types of motors, since its adoption, although with higher prices than the current models, will mean lower operational costs with appropriate less time for return on investment considering the regular operation time in industrial processes.

Such incentives must involve various stakeholders. Manufacturers can use promotional motor replacement programs with discounted rates. Governmental programs, such as Procel, can develop

[1] The FR factor was estimated by Unifei and indicates a variation of the performance shown in the tables (PBE and IE3) in relation to the load of the motor.

[2] This relation is supported by the fact that nearly 25% of the electric energy consumption of the country is related to industrial electric motors and an increase in sales has a direct impact on the overall consumption of this equipment.

technical guides, software and instructional materials to enlighten the benefits of using Premium motor and other issues as purchase and operation guidelines. Procel Seal may be granted to Premium motors. Banks can promote by including them as mandatory in the project financing if appropriated.

Arising the market penetration of premium motors, the following and immediate step is the inclusion of class IR3 in PBE, which will permit the evaluation of efficiency conformity. The, manufacturers will declare and prove the efficiencies of current motors (IE2-related efficiency) and the new Premium motors (IE3-related).

At the same time, the Government, by CGIEE, shall conduct actions to subsidize the proposition of a new target program. This new target program intends to adopt as minimum efficiency level for motors manufactured, imported or commercialized in Brazil the level expressed in table 1 in 4 years after the publication of the associated ordinance. In doing this, current IE2 motors will no longer be marketed and Brazil will enter in a very restricted group of countries that adopt IE3 level as MEPS.

Previously, however, the CGIEE shall require a detailed study of the market impacts, to be conducted by INMETRO, where assessments must be made addressing the reflexes on the steel industry with regards to the production of steel for Premium Motors, as well as the increasing motor prices related to these developments and productions. These impacts will be studied for motor and end use machines sectors.

The motor technical committee does not expect difficulties in the steel industry to attend the future demand and it also expect the motor market for customers that run motor will absorb the prices rises as they will have operational cost reductions. The critical point is the impact of these prices elevations on the OEM sector. This sector is suffering global changes with the concentration of world production in few countries that can cause de-industrialization in other countries.

6 – Conclusions

The savings obtained by the introduction of a new class of Premium Motors are significant and can account for about 4% of the energy saving target for 2030. It is preliminarily estimated that the impacts on the steel market and on motor prices for motor users shall not pose constraints since the industry is prepared to meet the future demand of silicon steels and the motor users will have economic benefits from the higher efficiencies. Even though, these issues will be object of a detailed analysis. The crucial question is related to the OEM sector in which motors are part of other machines and the price rises reflect directly on prices of these machines. This sector is highly sensitive to foreign competition, both due to imported equipment and the importation of finished products. Some experts connect the activity level of this sector with the industrialization level of a country. The final conclusion is that even with all mentioned difficulties we do believed IE3 Class as MEPS in Brazil is feasible.

7- Referencies

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The Status Quo of Electric Motor Energy Standard Setting and “Top Runner” Experience in Japan

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Abstract

Energy performance standard setting activities for electric motor in Japan has been lagging behind the foreign countries such as the U.S. and European nations. However, the committee for “Top Runner” energy performance standard setting for three-phase electric induction motor was established in December 2011 and the requirements such as product coverage, standard and target year have been specified in January 2013. The draft standard scheme is scheduled to be finalized within FY 2013. The standard was set at the level equal to IE3 standard, and manufacturers and importers are required that sales-weighted average efficiency of their products in each category should exceed the standard by the target fiscal year 2015. By implementing the standards, the sales weighted average efficiency is expected to be improved from 81.1% in 2010 to 87.1% in 2015. According to the bottom-up analysis developed in this study, 43TWh of electricity can be saved in 2035, which accounts for 4% of the nationwide total electricity consumption. Implementation of the standard can greatly contribute to energy savings.

Meanwhile, Japan has already realized substantial energy efficiency gain in equipment and appliance equipped with smaller electric motor like air conditioner, refrigerator and vehicles by means of Top runner scheme. In addition, Japan has strongly promoted VVVF (Variable Voltage Variable Frequency) technology that plays important role in contributing to energy efficiency. These Japanese experiences would be an implication for the nations aiming to further improve energy efficiency of the equipments and appliances. This paper also addresses how Top Runner scheme has ever contributed to energy efficiency improvement. Implementation of the Top Runner standards on the three-phase induction motor that can greatly contribute to energy saving is expected to supplement these past activities in Japan.

First, this study will present the motor market situation in Japan and the draft energy performance standards for three-phase motor established for the first time in Japan. Second, the expected energy savings by implementing the standards will be analyzed. Finally, based on the Japanese experiences, contribution of Top Runner scheme to the motor energy performance improvement will be discussed.

1. Background

1.1 Motor Market in Japan

Figure 1.1 shows annual production volumes and the total output capacity of motor in Japan. The production volumes have been decreasing over the last two decades due majorly to reduction in AC single-phase motor and stays at the level of less than 10 million for the past few years. The total output capacity has been decreasing at a rate lower than production volumes, as the output capacity per unit of AC single-phase motor is much smaller than AC three-phase motor. The total output capacity stays at about 20 million kW.

Since irregularity in data of production volumes and the total output capacity is observed between 2008 and 2009, the breakdown into motor technologies using the 2008 data is shown in Figure 1.2. Though AC three-phase induction motor accounts for 44% of the productions volumes, its share in total output capacity is as much as 85%, as the unit capacity of three-phase induction motor is much greater than single-phase motor.

Major usage of three-phase motors are represented by pumps, compressors, blowers, conveyers, and manufacturing machineries.

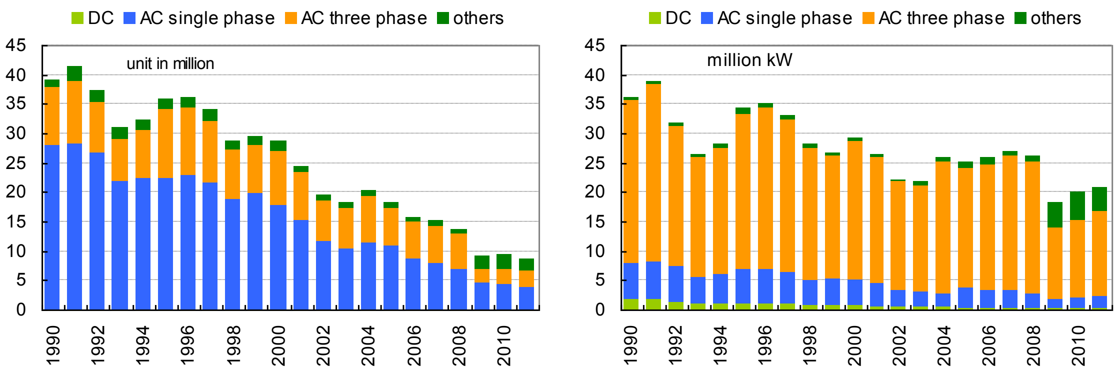

Figure 1.1 Production Volumes and Total Output Capacity of Motor

Source: Yearbook of Machinery Statistics, Ministry of Economy, Trade and Industry, Japan

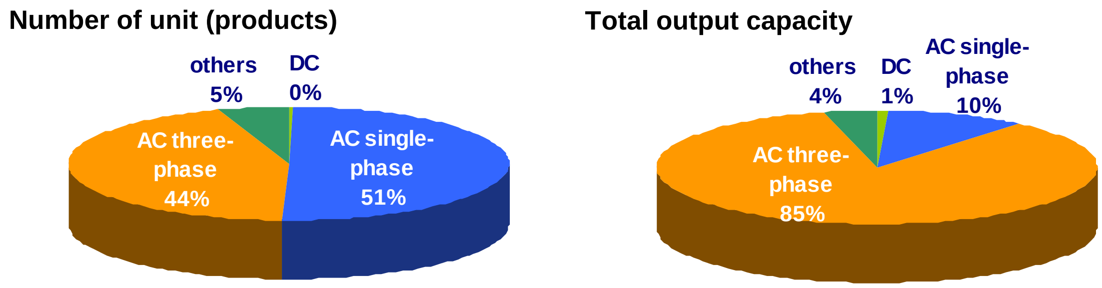

Figure 1.2 Sales Volume Breakdown into Motor Technologies (2008)

Source: Yearbook of Machinery Statistics, Ministry of Economy, Trade and Industry, Japan

1.2 Electricity Consumption of Three-phase Induction Motor

The number of three-phase induction motor owned is estimated to be 97 million, of which 74 million are newly targeted by the Top Runner standard [1]. The rest is majorly represented by compressors used in freezing and refrigeration that are already targeted by existing Top Runner standard. Annual electricity consumption of newly targeted three-phase induction motor is estimated to be 434TWh (43% of the national total electricity consumption) out of 543TWh (54%) of the total three-phase induction motor (Figure 1.3). The fact that significant amount of electricity is consumed by three-phase induction motor is one of the key factors encouraging the government to add three-phase induction motor into the Top Runner standard scheme.

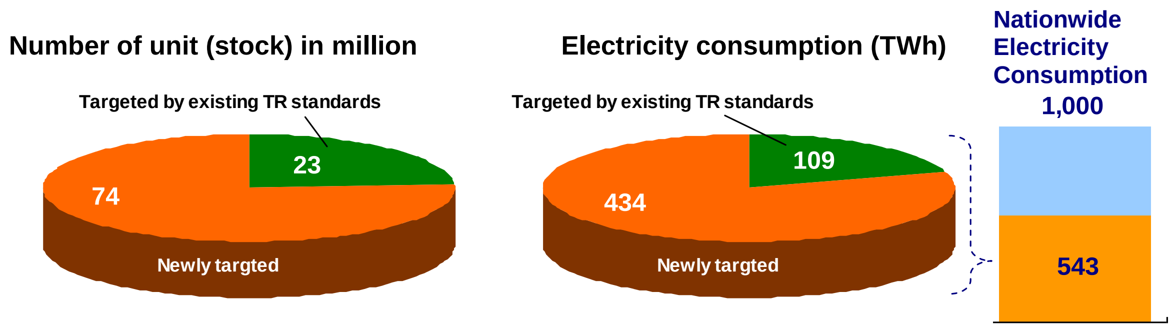

Figure 1.3 Number of unit owned and Electricity Consumption of Three-phase Motor

Source: Estimated from "Survey on Energy Consuming Equipments", The Institute of Applied Energy, 2009

1.3 Current Situation of Energy Efficiency of Three-phase Induction Motor in Japan

Figure 1.4 compares the current standards in Japan (JIS: Japanese Industrial Standards) and international standards specified in IEC (International Electrotechnical Commission). The standard of regular type lies roughly at the same level as IE1 and the high efficient type is at IE2. According to the survey [1], it is estimated that 97% of motors sold in Japan is categorized in IE1 level. The Japanese market is dominated much largely by lower efficient motors, comparing to the market in the U.S. where the total of IE2 and IE3 represents 70% and the market in Europe where IE2 accounts for 12%. This market situation is also one of the key drivers for standard setting for three-phase induction motors.

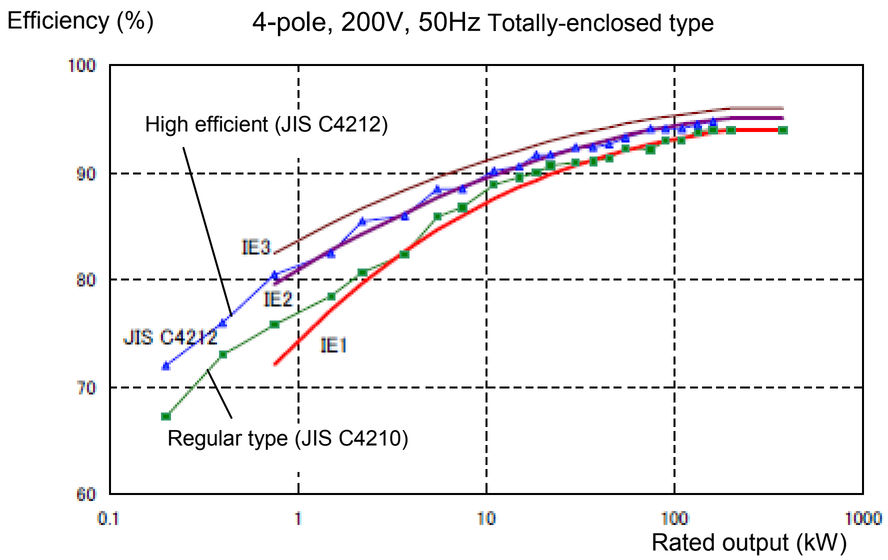

Figure 1.4 Comparison of Motor Efficiency

Source: "Survey on Energy Consuming Equipments", The Institute of Applied Energy, 2009

2. Top Runner Standard for Three-phase Induction Motor

2.1 Energy Efficiency Standards Subcommittee

A committee for energy performance standard setting for three-phase electric induction motor (Three-phase Induction Motor Evaluation Standards Subcommittee) was held twice on the 13th December 2011 and 28th January 2013 since its establishment under the Energy Efficiency Standards Subcommittee of the Advisory Committee for Natural Resources and Energy Ministry of Economy, Trade and Industry in December 2011. The subcommittee discussed implementation of the standard imposed on manufacturers and importers of three-phase induction motors with a view to improving the energy performance of the products. The draft standards went through public comment process till 22nd March 2013 and are scheduled to be reported to the WTO/TBT (World Trade Organization; Agreement on Technical Barriers to Trade) to avoid trade barriers to imported products, then to be published within the FY2013 (till the end of March 2014). The draft results [2] of the discussions including the scope of target product, target year, standards of three-phase induction motors are presented below.

2.2 Scope of Target Product

Three-phase induction motors included are those which meet all of the conditions presented in Table 2.1, based on the scope of three-phase induction motors specified in Japanese Industrial Standards JIS C 4034-30 "Rotating electrical machines - Part 30: Efficiency classes of single-speed, three-phase, cage-induction motors (IE code)". Motors that are used for special purpose, such as under high temperature, for vessels or ocean structures, for submerged pumps, for disaster preventive pumps, for dust collectors used in sewage treatment plants, in explosive atmosphere, under cryogenic temperature, are excluded from the scope. The excluded motors account for no more than 3% and 7% of the sales volume in 2008 and 2009, respectively. In addition, motors that are completely integrated into machines such as pumps, fans, compressors and cannot be tested separately from the machines and motors that are manufactured solely for VVVF driving (inverter) are excluded (note that inverter driven motors with base frequency is 50 Hz ±5% or 60 Hz ±5% are included).

Table 2.1 Conditions for Scope of Target Products

item	conditions
Rated frequency or base frequency	50 Hz ± 5% or 60 Hz ± 5% or products compatible with both 50 Hz ±5% and 60 Hz ±5%
Speed	Single speed
Rated voltage	No higher than 1,000 V
Rated output	No lower than 0.75 kW, nor higher than 375 kW
Number of pole	2 poles, 4 poles or 6 poles
Type of use	- Continuous operation at a constant load for sufficient time to allow the motor to reach thermal equilibrium - Repeated use as a cyclic start and stop at a certain load level for a duration shorter than the time in which the motor reaches the thermal equilibrium. The rated cyclic duration factor is to be no lower than 80%.
Power source	Utility power supply (which means "not VVVF driven")

Source: "Interim Report by Three-phase Induction Motor Evaluation Standards Subcommittee, Energy Efficiency Standards Subcommittee of the Advisory Committee for Natural Resources and Energy (Draft)", January 28, 2013, Ministry of Economy, Trade and Industry, Japan

2.3 Standard Setting by Top Runner Approach

The standard of motor is established in the framework of "Top Runner" approach, where the standard is set at the level of the highest efficiency currently existing on the market, adding a certain level by considering potential technological improvements. The average efficiency weighted by sales volume is verified whether it meet the standard at the target year, which allows each manufacturer and importer to select the level of efficiency for each model so that the overall average is achieved. The more details are described in chapter 4.

2.4 Standards and Target Year

The target year was set at FY2015, taking into account the time needed for elementary technologies development, product design and development and product penetration into the market. The target year is harmonized with the trend in Europe where the MEPS (Minimum Energy Performance Standard) on three-phase induction motors is scheduled to be upgraded to IE3 (premium performance specified in IEC) from IE2 (high performance) in 2015. In addition, the IEC standards are widely used in many countries. This timeline helps Japanese manufacturers to effectively draw up strategies for investment in production process with a view to increasing the international market share.

Figure 2.1 and Figure 2.2 show the standards for 50Hz and 60Hz, respectively. Since Japan is divided into two geographical areas depending on the frequency of power supplied by utilities, 50Hz and 60Hz, the standards are established individually for each frequency. The standards are categorized based on motor rated output; 13 categories for 60Hz and 23 categories for 50Hz. The highest efficiency currently on the Japanese market in the each category is expressed by dot. The Top Runner standards are set at the level equal to the IE3 standards.

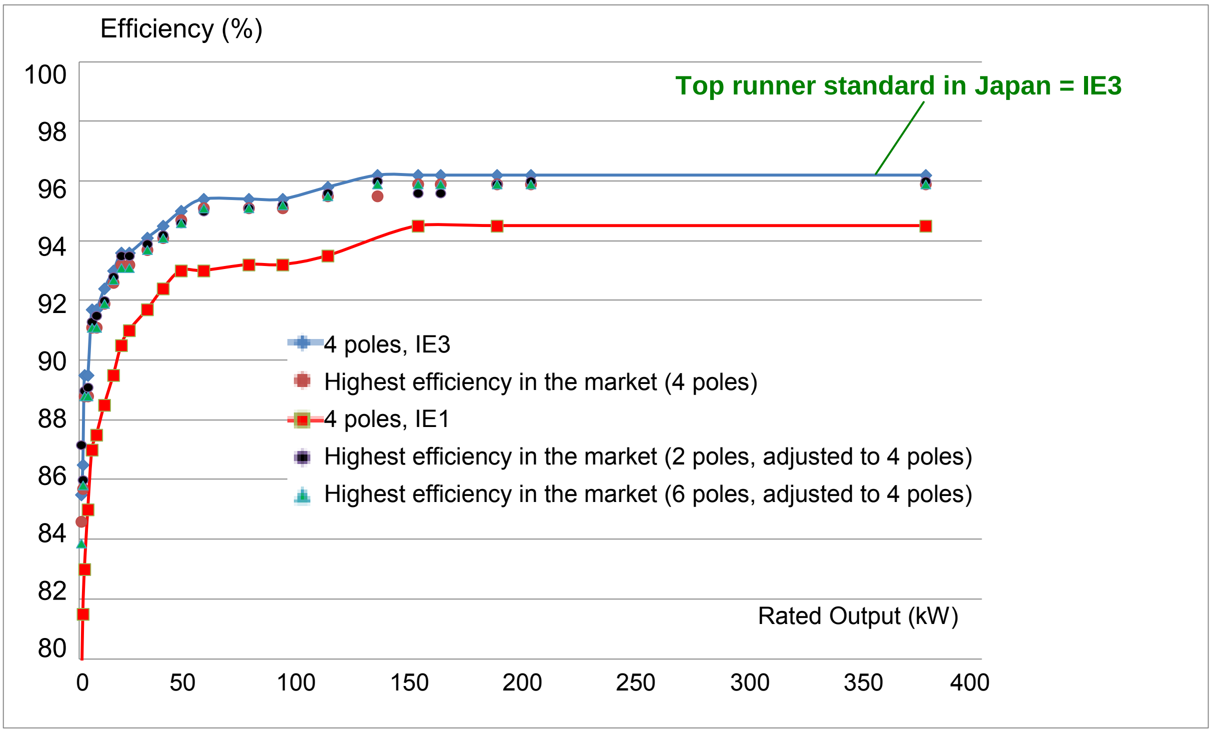

Figure 2.1 Energy Consumption Efficiency at Rated Output of 60 Hz

Source: "Interim Report by Three-phase Induction Motor Evaluation Standards Subcommittee, Energy Efficiency Standards Subcommittee of the Advisory Committee for Natural Resources and Energy (Draft)", January 28, 2013, Ministry of Economy, Trade and Industry, Japan

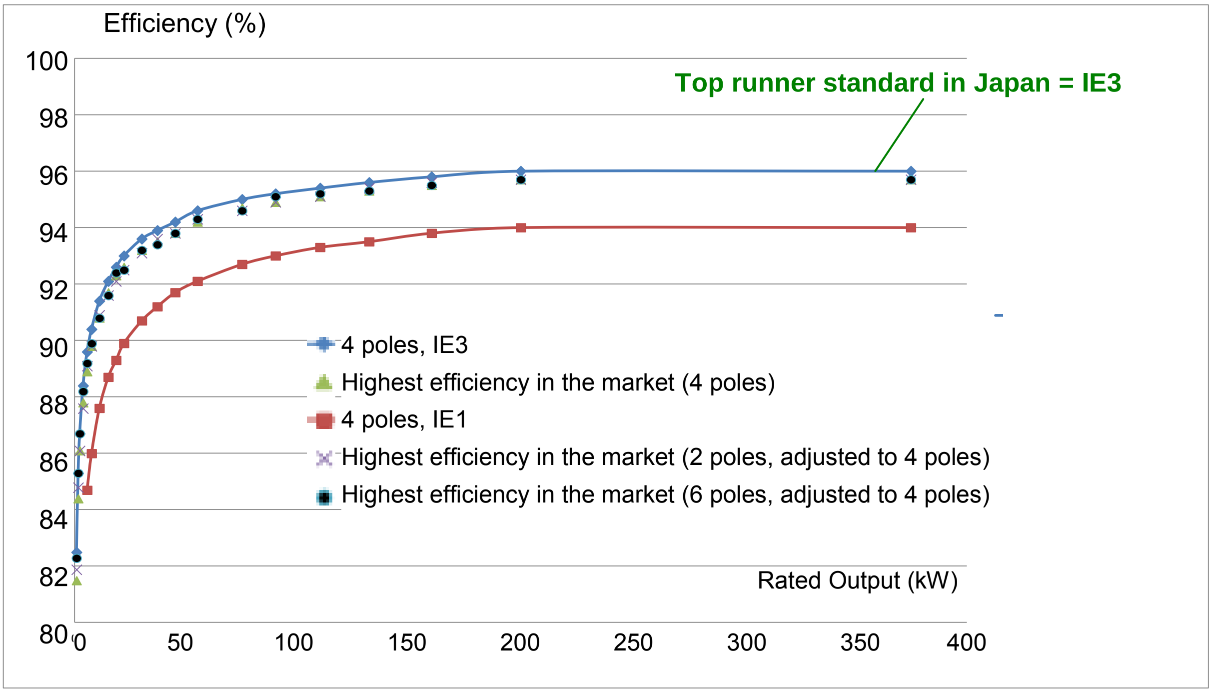

Figure 2.2 Energy Consumption Efficiency at Rated Output of 50 Hz

Source: "Interim Report by Three-phase Induction Motor Evaluation Standards Subcommittee, Energy Efficiency Standards Subcommittee of the Advisory Committee for Natural Resources and Energy (Draft)", January 28, 2013, Ministry of Economy, Trade and Industry, Japan

2.5 Expected Efficiency Gain at Target year

By introducing the Top Runner standards, the improvement ratio of sales-weighted average efficiency is expected to be 0.6% compared to the highest efficiency currently on the market for 60Hz (6.2% compared to IE1 standard) and 0.8% for 50Hz (8.8% compared to IE1 standard). The overall sales-weighted average efficiency is estimated to be improved from 81.1% in 2010 to 87.1% in 2015 (improvement ratio is ((87.1%-81.1%)/81.1%=7.4%), under the assumption that the share of sales volume of each category does not change.

3. Expected Energy Savings

In order to figure out energy saving by efficiency gain in three-phase induction motor, bottom-up stock accounting approach based on flow-stock model was developed. Only the motors newly included in the Top Runner Standards are analyzed. As the annual sales volume is set at 2008 level of 4 million (two thirds of the production volume [1]) through 2035, the number of motor owned is estimated to be decreasing from 74 million in 2010 to the constant level of 59 million from 2020. The sales (flow) average is set at 81.1% in 2010 and 87.1% in 2015 as estimated above, and then assumed to reach 96% in 2035 (Efficiency improved case), while the efficiency is set constant in Efficiency fixed case (Table 3.1).

Table 3.1 Major Assumptions

		2010	2015	2035
Sales volumes		4million/year(1)	←	←
Sales average efficiency	Efficiency fixed case	81.1%(2)	←	←
	Efficiency improved case	81.1%(2)	87.1%(2)	96.0%(3)

(1): The third of the sales volumes of three-phase induction motor of 6million is estimated to be exported in [1]. (2): See 2.5. (3): Assumption

In the Efficiency fixed case, electricity consumption of the three-phase induction motors will decrease from 434TWh in 2010 to 345TWh in 2035, while decreases up to 300TWh in the Efficiency improved case (Figure 3.1). The expected energy savings is 5TWh in 2015 (target year) and 43TWh in 2035, which equal 4% of the nationwide total electricity consumption.

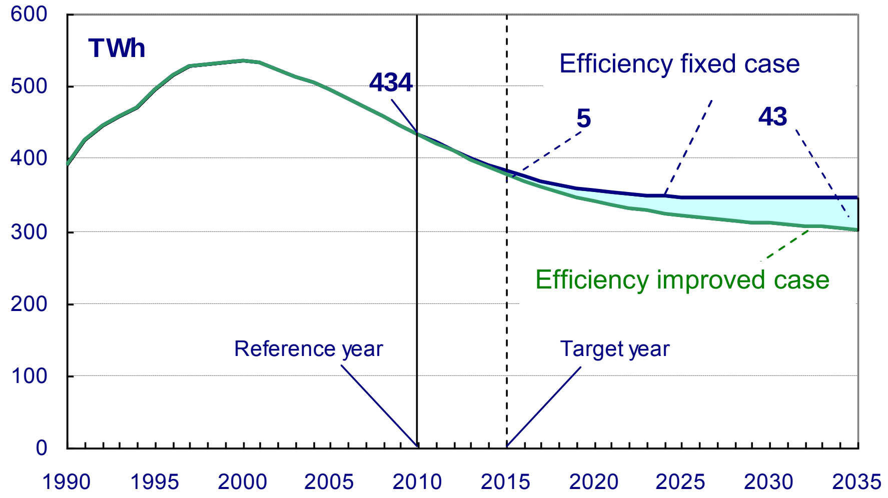

Figure 3.1 Energy Saving by Efficiency Improvement in Three-phase Induction Motor

4. Contribution of Top Runner Scheme to Energy Efficiency Improvement

As stated above, establishment of standard for motor in Japan is arriving late at major international stage. However, Top Runner standards have ever realized considerable energy efficiency gain in a variety of equipments and appliances. This chapter describes how Top Runner scheme has ever well functioned in Japan.

4.1 Features of Top Runner Scheme

There are two major types of energy efficiency standard, one of which is minimum energy performance standard (MEPS) and the other is class-average standards (CAS). The MEPS requires manufacturers to achieve prescribed minimum efficiencies in each and every product. The products that do not meet the standards are prohibited to be sold. The MEPS is the standard that is most widely introduced in the world. On the other hand, the CAS specifies the average efficiency of a manufactured product, allowing each manufacturer to select the level of efficiency for each model so that the overall average is achieved.

In Japan, a CAS scheme was introduced for refrigerator, air conditioner and passenger vehicle by the Energy Conservation Act enacted 1979. The standards were set at the level achievable by the feasible technology development aiming at enhancement of voluntary effort by manufactures and importers. At the time of revision of standard, it was often observed that the energy efficiency of many products had already exceeded the new standard. This achievement by manufacturers more than expected had led to the idea that the highest efficiency in the market should be targeted and created the concept of “Top Runner”. Although there was protest from manufacturers, the adoption of the Kyoto protocol in 1997 pushed forward legislating the Top Runner scheme and the Revised Energy Conservation Act in 1999 introduced the Top Runner scheme. The covered items include household appliances, OA equipments, boilers, vehicles, transformers and vending machines, totaling 23 items as of March 2011. Since then, commercial refrigerators and heat pump water heaters were added and are currently going through finalization process for implementation of standards.

The most remarkable feature of Top Runner of Japan is that the standard is set at the level of the most efficient product that exists in the market at the time of standard setting. This standard is presumably the most stringent in the world. However, Top Runner as applying CAS allows manufactures to meet the standard by the sales-weighted average energy efficiency, which brings the benefit that manufacturers can provide a variety of product lineup to meet the consumers’ needs (both low-efficient and high-efficient), while guaranteeing the total energy efficiency of the market. In order to keep the inefficient and inexpensive products in the market to meet the consumers’ needs, more efficient products should be put in the market. Consequently, this enhances technology development for energy efficiency. Summarizing the advantages in Top Runner scheme;

- Significant improvement in energy efficiency in shorter time.
- Responsive to consumer needs: “High-efficient & expensive”, “inefficient & inexpensive” and “inefficient & expensive” can co-exist in the market, which meets the consumers need.
- Incentive for manufacturers to develop more efficient product: Along with higher standard than MEPS, in order to keep the inefficient products in the market to meet the consumers’ needs, more efficient products should be put in the market. Consequently, enhances technology development for energy efficiency.

4.2 Significant Efficiency Gain by Top Runner Approach

The sales-weighted average energy efficiency was greatly improved by Top Runner Approach as shown in Table 4.1. Energy efficiency improvement achieved of many of the items is greater than the expected improvement. Motors with lower output capacity are already regulated by Top Runner scheme, integrated in appliances and vehicles.

Table 4.1 Improvement in Energy Efficiency By Top Runner Approach

Item	Improvement in energy efficiency (achieved)	Improvement in energy efficiency (expected)
TV set (CRT)	25.7% (1997➔ 2003)	16.4 %
VCR	73.6 % (1997➔ 2003)	58.7 %
DVD	45.2%(2006➔2010)	20.5 %
Room air conditioner	67.8 % (1997➔ 2004) 15.6%~16.3% (2005~2006➔ 2010)	66.1 % (1997➔ 2004) 17.8%~22.4% (2005~2006➔ 2010)
Refrigerator	55.2 % (1998➔ 2004) 43.0% (2005➔2010)	30.5 % (1998➔ 2004) 21.0% (2005➔2010)
Freezer	29.6 % (1998➔ 2004) 24.9% (2005➔ 2010)	22.9 % (1998➔ 2004) 12.7% (2005➔ 2010)
Light duty vehicle (gasoline)	48.8 % (1995➔ 2010)	22.8 % (1995➔ 2010)
Freight vehicle (diesel)	21.7 % (1995➔ 2005)	6.5 %
Vending machine	37.3 % (2000➔ 2005)	33.9 %
Fluorescent lump	35.7 % (1997➔ 2005)	16.6 %
Copy machine	72.5 % (1997➔ 2006)	30.8 %
Computer	80.8 % (2001➔ 2007)	69.2 %
Magnetic disc	85.7 % (2001➔ 2007)	71.4 %
Rooter	40.9% (2006➔ 2010)	16.3%
Washlet (*)	14.6 % (2000➔ 2006)	10.0 %

*: "Washlet" is a toilet with electric-heated-seat and with bidet function.

Source: METI

4.3 Success Factors and Lessons Learnt in Top Runner Scheme

The Top Runner scheme has realized significant improvement in energy efficiency of equipments. In general, one of the fundamental factors that energy efficiency policies can perform well is that the energy prices are high. The purchasing power of consumer that can afford high-efficient products which are often expensive is also another important factor. Besides these general factors, there are mainly four success factors inherent in the Top Runner scheme, which are shown below.

- <u>Cooperation among stakeholders</u>: The government and manufacturers have worked together closely on figuring out the trend of market and technology and also formulating the standards. In the standard setting process, openness and transparency were guaranteed.
- <u>Culture of Japanese companies</u>: Obtaining "Energy efficiency No.1" is the most major priority for the Japanese manufacturers, which matches with the concept of Top Runner.
- <u>Stage of market development and industrial structure</u>: The number of the major active manufacturers in Japan is less than 10 and they have matured technologies which are about equal among manufacturers. This background could promote competition in energy efficiency improvement.
- <u>Pressure from consumer</u>: The market has an unformed framework (unwritten rule) that ensures compliance by manufacturers, with the fact that the damage on the company image caused by non-compliance badly affects business performance.

On the other hand, there are lessons learnt. Top Runner standards tend to be set higher than the MEPS. It is indeed true that excessive high standard could deteriorate business performance of manufacturers, since retail prices are in many cases determined by retailer and manufacturers can not pass the incremental cost incurred by energy efficiency improvement to the retail price.

- <u>Strains on manufacturers</u>: Retail prices are in many cases determined by retailer, so can not pass the incremental cost incurred by energy efficiency improvement to the retail price. This affects revenue. Besides, manufacturers that can not meet the standards withdraw from certain categories or stop manufacturing. (e.g.: gas/oil boiler, smaller-size refrigerator)

- Sacrifice on functions/features of appliances: Excess focus on energy efficiency sacrifices functions/features of appliance (e.g.: growth in size of room air conditioner, short life-span of gas boiler by corrosion caused by condensation by lowering exhaust gas temperature).
- Technological ceiling: The energy efficiency of appliances might be reaching a limit identified by their specific technologies after several times of revision of standards (Figure 4.1). Efficiency improvement of room air conditioner and refrigerator slows down, which might mean approaching to the limit of the conventional technology. On the other hand, fuel economy of vehicle accelerated, due to contribution of new technology, such as hybrid car.

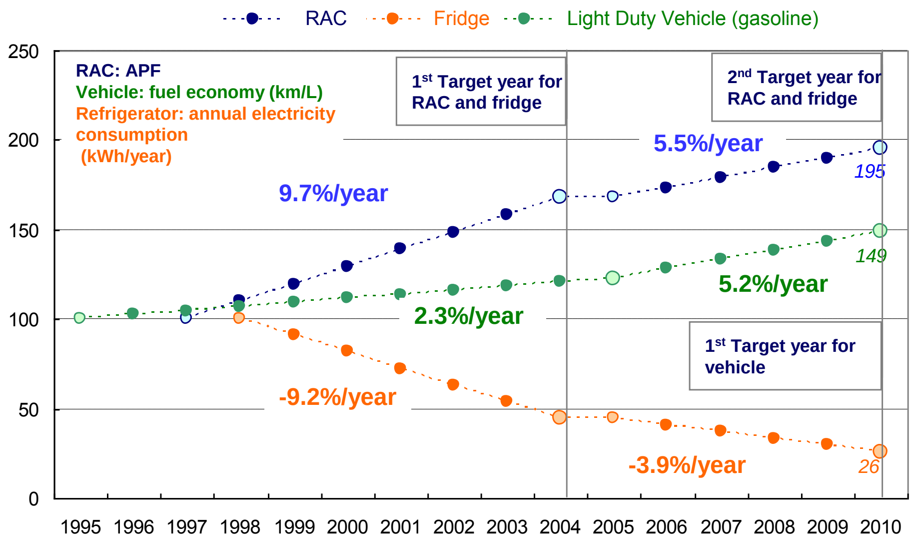

Figure 4.1 Efficiency Gain by Top Runner

In Japan, the government and manufacturers worked closely together to set the feasible targets and realized achievement of efficiency gain. Top Runner success can be indeed greatly attributable to the unique market and culture of manufacturers. However, the concept of Top Runner is recently diffusing in the world; the HEPS (higher energy performance standard) in Thailand gives certificate to the only higher efficient products, the program "Top-10" (http://www.guide-topten.com/) in Europe showcases Top 10 efficient products and encourages consumers to purchase them. Internationally, the SEAD (Super-Efficient Equipment and Appliance Deployment) as one of the CEM (Clean Energy Ministerial) initiatives are carrying out activities to raise the efficiency ceiling by pulling super-efficient appliances into the market, along with activities to raise the efficiency floor level and to strengthen the efficiency foundation by technical support. More recently, the Chinese government announced in the 12th 5-year National Plan to introduce Top Runner scheme in the near future and research institutes and standard organizations are starting discussion on framework of the standard, target products and timelines, etc.

Figure 4.2 shows the total electricity consumption breakdown by equipments estimated based on existing survey [3] and documents from the subcommittees for standard setting in METI. Household appliances and commercial equipments have accounted for 23% of the electricity consumed in Japan. Implementation of Top Runner scheme to three-phase induction motors would expand the share of equipments covered by Top Runner to 66%.

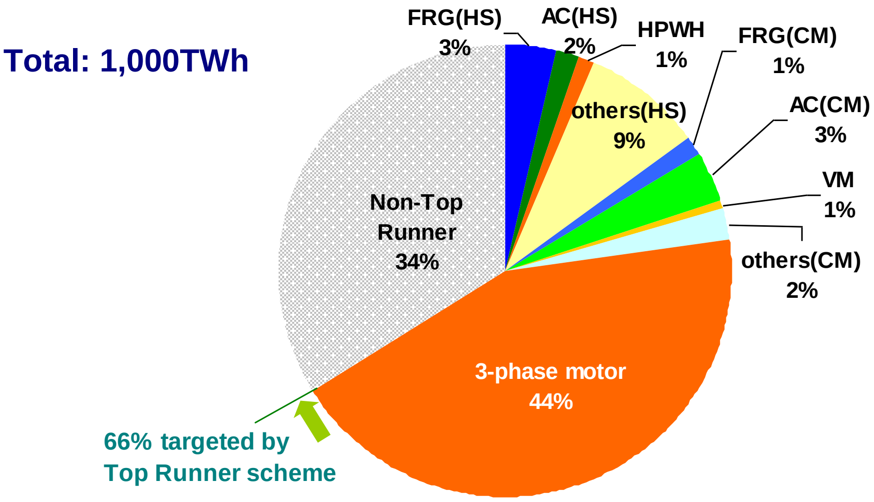

Figure 4.2 Top Runner Share in the Total Electricity Consumption in Japan

Note: FRG means refrigerator, AC conditioner, HPWH heat pump water heater, VM vending machine, HS household and CM commercial.

Concluding Remarks

Although Japan has been lagging behind the countries in setting standard for motor, the standards based on the Top Runner scheme are scheduled to be implemented no later than the end of FY2013. The Top Runner standards for three-phase induction motors have features that harmonize with international trends. The standard was set at the identical level of IE3 that is widely used in the world. The target year was set at 2015 when European MEPS on three-phase induction motors is scheduled to be upgraded to IE3. By implementing Top Runner scheme to three-phase induction motors, the share of the equipments covered by Top Runner in the total electricity consumed in Japan will expand to 66% from 23%.

As Top Runner scheme has ever realized greater efficiency improvement in a variety of appliances and equipments, such as refrigerators and air conditioners and vehicles since its implementation in 1999, substantial energy saving in three-phase motor can also be highly expected. According to the analysis result from this study, electricity consumed by motors will be reduced by 43TWh in 2035, which accounts for 4% of the nationwide electricity consumption.

Acknowledgement

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Standard Format for IEC Standards -

Learning from motor standards for other electric equipment

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Abstract

IEC standards perform a very important role in enabling international trade of electric equipment. Ideally, they can be used to facilitate compliance with national energy efficiency regulations. Yet many IEC standards do not clearly include previsions for a well-defined scope or standard operating conditions. Neither do they include energy efficiency classifications that could also be used for mandatory requirements such as Energy Labels and Minimum Energy Performance Standards (MEPS).

The experience with updating the IEC 60034 standard series include efficiency classes as well as standard operating conditions for electric motors (IEC 60034-30-1) shows that an entire market has the opportunity to adopt the same efficiency measurement standard and classification scheme. The example also demonstrates that within five years such international standardization is possible. It has significant impact for the market transparency of quality products to be produced in one country and shipped across the globe for another country. It is essential for a successful market transformation towards higher energy efficient products.

It also shows that the user end of the supply chain of motors will ask for certification of the applicable products through existing schemes like IECEE[2], i.e. established requirements for the quality of the testing lab enabling the credible display of the measurement result on the rating plate.

The IEC Strategic Group (SG1) has agreed to support the implementation of the motor standardization experience to other mass produced electrical equipment like TVs, refrigerators, air conditioners, washing machines, lamps, etc. This is important because experience with CFL and LED lamps clearly shows that the difficulty in prescribing internationally coordinated efficiency levels has hindered harmonization and global market transformation.

However, it will be necessary to clarify (and maybe re-define) the role of international standard makers vis-à-vis national governments and their authority for energy efficiency requirements.

1. Why is a standard energy efficiency format needed for IEC standards?

Energy efficiency has changed the way we look at mass produced equipment and industry standards. It is no longer enough to just standardize safety issues or dimensional properties and other functional performance elements as the energy efficiency rating of a product has now moved to the foreground. The agreement between industry, governments and NGOs has grown strongly over the last decade that internationally compatible standards are necessary for all products that can easily be shipped and traded.

The standard - in the case of electrical equipment the IEC standard - has become the reference point for many governments to issue energy labels and minimum energy performance standards and to check their compliance. In order to facilitate the issue of labels and MEPS in national legislation a

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[1] 4E is the Implementing Agreement of the International Energy Agency IEA on "Efficient Electrical End-Use Equipment" www.iea-4e.org. EMSA is its "Electric Motor Systems Annex" www.motorsystems.org .

[2] IECEE: Worldwide System for Conformity Testing and Certification of Electrotechnical Equipment and Components, www.iecee.org

common understanding is necessary of what type of information should be available for all mass produced pieces of equipment.

Valuable experience has grown from the past decade of evolution in electric motor standards. The challenge that has emerged is:

- What are the key ingredients of a set of product standards to allow the goal of rapid adoption in national legislation?
- What kind of products lends themselves to such a standard format?

2. Who is IEC and what is its role?

The International Electrotechnical Commission IEC [1] today is the leading standard making organization in the field of all electrical, electronic and related technologies with some 10'000 technical experts contributing voluntarily world-wide. IEC gets its income form membership fees and the sale of standards. IEC works in parallel with the International Organization for Standardization (ISO [2]) that is responsible for almost 20'000 standards for manufacturing and technology, ranging from food safety to computers, and agriculture to healthcare. IEC and ISO cooperate together closely and coordinate their work in many general and organizational fields.

IECs goal are improved conditions for fair trade and transparent markets through global harmonization. To achieve this goal standards help to create a level playing field for industry and other stakeholders.

The IEC was founded as non-governmental and not-for-profit organization in 1906 in London, since 1948 it has its seat in Geneva Switzerland. Currently 82 countries are members and another 82 countries take part in an affiliate country program. An IEC member country (i.e. a National Committee, NC) signs a contract with IEC when becoming a member which obligates it to adopt International Standards "to the greatest extent possible" in its country. The scope of IEC work developed historically: it started with the most obvious coordination tasks: Terminology (TC1). Later individual products and other topics of general concern for industry followed: Rotating Machines (TC2) was the first group of equipment, then a group of standards to align engineering work procedures followed: Information structures, documentation and graphical symbols (TC3), Graphical symbols for use on equipment (TC4). Only thereafter a next group of equipment followed: turbines (TC4 and TC5), cables and grids, power electronics, batteries, lamps (TC34), appliances (TC59), and last photovoltaic (TC82).

The Agreement on Technical Barriers to Trade (World Trade Organization) tries to ensure that regulations, standards, efficiency measurement and certification procedures do not create unnecessary obstacles, while also providing members with the right to implement measures to achieve legitimate policy objectives, such as the protection of human health and safety, or the environment.

When an IEC standard is published no timing for implementation is generally given in IEC standards. In a small number of cases a voluntary "transition period" is suggested between the previous edition and this new edition of the International Standard itself.

3. How does IEC work?

IEC works from its Central Office (CO) in Geneva who supports technical committees in the development of standards. The operations of the CO and the setup of new TCs are guided by the Standardization Management Board (SMB) from elected members of NCs.

The members of the national committees are stakeholders from industry, academia, government and NGOs. The NCs operate generally from a national secretariat within their national standard organization. The NCs form the interested group of each TC by sending their experts to draft the technical content of standards; they vote in favor or against the proposed drafts and provide comments. Generally each NC has one vote. 75% of the votes are needed to approve a draft. The NCs setup national "mirror groups" for each IEC TC and rally their national experts to collaborate on a national level. The NC selects its representatives and sends them to attend meetings of the international TCs.

The TC consists of its experts delegated by the NCs. It elects the chairman who needs formal confirmation of the SMB. It develops its own business plan and tasks; it starts Working Groups (WG), selects their convenor and launches New Work Item Proposals. The WG and its convenor bear the largest share of the work to draft a new standard. The process of drafting a new IEC standard is laid out in the procedures for the technical work [3]. It includes the following main steps (see Table 1):

	Step	Minimum Delay
1	Launch of a New Work Item Proposal (NP) by a TC, circulation to NCs, decision by vote.	3 months
2	Setup of a Working Group (WG) in a specified TC or SC.	
3	Working Drafts (WD): internal drafts circulated within WG to reach consensus.	
4	Committee Draft (CD) circulated within NCs. Standardized format for comments. Discussion of comments at WG meetings.	3 months
5	Committee Draft for Voting (CDV) circulated within NCs. Standardized format for comments of NCs. Requires 75% acceptance by NCs to go forward. Discussion at WG meetings.	3 months
6	Final Draft International Standard (FDIS) circulated within NCs. Standardized format for comments of NCs. Requires 75% acceptance by NCs to go forward. Discussion at WG meetings.	2 months
7	Publication (after final editing and translation into French)	
8	Setup of maintenance team. Regular discussion at bi-annual TC meetings of need to renew, correct or withdraw of standard.	

Table 1 Steps and delays to draft and publish an IEC standard

The targeted delays for a standard are for the working draft (if not supplied with the proposal): 6 months; for the CD: 12 months; for the CDV: 24 months; for the FDIS: 33 months; and for the published standard: 36 months. If a new project is launched in a very decisive and clear way and consensus can be reached rapidly, the steps 1, 3, and 4 can be omitted. Theoretically the process for launching a new standard can then be shortened - if consensus can be achieved - to 6 months only.

The key goal of this international process is to achieve consensus among the NCs, the experts in the WGs and the stake holders involved. The success of this well established IEC procedure is due to its transparent and democratic decision-making process.

IEC provides each TC with a state of the art internet-based Collaboration Tool where each WG can access and store their documents and the meetings can be scheduled and messages sent to members. It also operates a public data base where all standards can be previewed and purchased via a web store.

4. IEC standards for motors

The International Electrotechnical Commission (IEC) is charged with international standards for electric rotating machines, i.e. motors and generators. Representatives from some 45 National IEC Committees (NCs), including 15 countries with observer status, work together on the development of motor standards in the Technical Committee 2 (TC2). The experts come from industry, government, universities, research and testing laboratories, and NGOs. All proposed new and amended standards go through a rigorous system of international scrutiny and are finally decided by voting by the NCs.

Basic characteristics and performance of electric motors are standardized in the following IEC standards, the first versions of which were started many years before energy efficiency standards were required: geometry, mounting, protection, vibration and noise:

- Motor Dimensions
  IEC 60072-1, edition 6, 1991: Dimensions and output series for rotating electrical machines - Part 1: Frame numbers 56 to 400 and flange numbers 55 to 1080
- Motor Mounting
  IEC 60034-7, edition 2.1, 2001: Rotating electrical machines - Part 7: Classification of types of construction, mounting arrangements and terminal box position (IM Code)

- Enclosure protection
  IEC 60034-5, edition 4.1, 2006: Rotating electrical machines - Part 5: Degrees of protection provided by the integral design of rotating electrical machines (IP code) - Classification
- Motor Vibration
  IEC 60034-14 (grade N), edition 3.1, 2007: Rotating electrical machines - Part 14: Mechanical vibration of certain machines with shaft heights 56 mm and higher - Measurement, evaluation and limits of vibration severity
- Motor Noise
  IEC 60034-9, edition 4, 2003: Rotating electrical machines - Part 9: Noise limits
- Explosive atmospheres
  IEC 60079-0 edition 6.0, 2011 (by TC/SC 31)

A general report on the standards development of IEC and CENELEC focusing on variable frequency drives has been presented by M. Patra at EEMODS 2011 [4].

5. IEC standards for the energy efficiency of motors

Here is a list of the current status of IEC standards prepared by IEC TC2 "Rotating Machinery" and its WGs that involve energy efficiency (see Table 2), plus the planned projects (see Table 3) also involving IEC TC22/SC22G:

IEC International Standard	Date of publication	Title	Status
IEC 60034-1	2010	Rating and performance	under revision, publication 2014
IEC 60034-2-1	2007	Standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles)	under revision, publication 2014
IEC 60034-2-2	2010	Specific methods for determining separate losses of large machines from tests - Supplement to IEC 60034-2-1	
IEC 60034-30	2008	Rotating electrical machines - Part 30: Efficiency classes of single-speed, three-phase, cage-induction motors (IE-code)	under revision, to be replaced by IEC 60034-30-1 and IEC 60034-30-2
IEC 60034-30-1	new, FDIS	Efficiency classes of line operated AC motors (IE-code)	publication 2014
IEC/TS* 60034-31	2010	Rotating electrical machines - Part 31: Selection of energy-efficient motors including variable speed applications - Application guide	
3) TS: Technical specification, to be reviewed after 3 years			

Table 2 List of current energy efficiency related motor standards and their revisions

In parallel to IEC TC2 also IEC TC22 SC22G "Adjustable speed electric drive systems incorporating semiconductor power converters" deals with variable frequency drives that have an impact on motor efficiency. So far no energy efficiency measurement standard or efficiency classification has been published. A new project has been launched:

IEC International Standard	Date of publication	Title	Status
IEC/TS 60034-2-3	new TS	Specific test methods for determining losses and efficiency of converter-fed AC induction motors	publication 2013
IEC 60034-30-2	new NP	Efficiency classes of variable speed AC motors (IE-code)	publication 2015
IEC 61800-9	new NP	Energy efficiency of adjustable speed electric power drive systems	publication 2016

Table 3 Planned energy efficiency standard for variable frequency drives and motors

A published IEC standard can be purchased in hardcopy and pdf from www.iec.ch. A preview including the title, foreword, introduction, table of contents and scope can be downloaded for free. A draft copy of a standard under work can be obtained from every national IEC committee.

6. How do IEC standards relate to national standards?

Technical regulations and product standards may vary from country to country. Having many different national regulations to obey and standards to follow makes life difficult for producers, exporters and national regulators. They push up costs for purchasers too. Repetitive product measurement and certification procedures are required by national authorities. If regulations are set arbitrarily, they could be used as an excuse for protectionism.

In many cases, national or regional standards precede international standards. So IEC work starts with a number of national and regional standards from a variety of professional organizations with the goal to unify them into an international standard. More recently, and with the increasing nature of global trade, many important issues are being developed first on the international level and subsequently adopted at the national level.

IEC cooperates with a number of regional and national standard bodies such as:

- African Electrotechnical Standardization Commission
- CANENA - Council for Harmonization of Electrotechnical Standardization of the Nations of the Americas
- CENELEC - European Committee for Electrotechnical Standardization
- COPANT - Pan American Standards Commission
- EASC - Euro-Asian Interstate Council for Standardization
- ETSI - European Telecommunications Standards Institute
- PASC - Pacific Area Standards Congress
- MERCOSUR - Mercado Común del Sur (Southern Common Market of South America)

It is not stated in IEC that a nation cannot start a new standard while an international standard on the same matter already exists. But all signatory countries to the World Trade Organization (WTO) under the "Technical Barriers to Trade" agreement (TBT) undertake not to do this. There is no enforcement method though; the TBT Agreement has various mechanisms, but the WTO approaches this problem only indirectly.

Some special coordination rules exist between IEC and regional standardization bodies, such as the EU's CENELEC. In CENELEC's case, these rules are governed by the Dresden agreement [5]. And cover drafting and parallel voting. Additionally, IEC has a cooperation agreement with IEEE that allows for certain standards to display a dual logo [6].

7. Standards, Labels, MEPS, certificates

Different institutions active in developing motor policy are distinguished by their geographical territory (national, regional, global) and their enforcement powers (voluntary, mandatory). They meet under the common goal of market transparency and market transformation towards more energy efficient products. The clear evidence from earlier developments in the USA is that markets for industrial products are only moved with minimum energy performance standards that are applicable mandatorily to all new products put onto the market. All earlier voluntary schemes, labeling systems etc. did not move the sales figures fast enough into the right direction. The three key actors are presented in Table 4:

Key actor	Main tasks and duties
Global standard makers	Based on formal rules to reach international consensus of stakeholders the standard makers can publish international standards and technical specifications for product performance, efficiency measurement and classification. This can include also the thresholds for efficiency classes to be used in labels and tiers of MEPS.
National and regional governments	Based on national laws (proposed by government and accepted by parliament) the national government can set up an energy agency for energy efficiency advice to consumers and a regulator's office for market control; it can thus allocate the

	necessary resources and authority to execute these tasks. Governments can then issue regulations covering minimum energy performance standards and energy labels based on national or international standards. The labels (see Figure 1) can be voluntary or mandatory, a certification mark or true energy label, an endorsement or information, a comparative or absolute value, a continuous scale or categorical. They can also set-up a check-testing system to watch compliance of regulations. Government can also implement a compliance scheme involving check-testing and sanctions.
Certification bodies	Global or regional and national certification bodies can define the voluntary requirements for product performance including energy efficiency and issue a marking on the product rating plate to signal compliance. They can accredit testing laboratories, train their personal and issue orders for instrumentation calibration. Some also stipulate round robin tests to secure the accuracy of the measurement results.

Table 4 Three basic actors in motor policy, label, MEPS and certification decisions

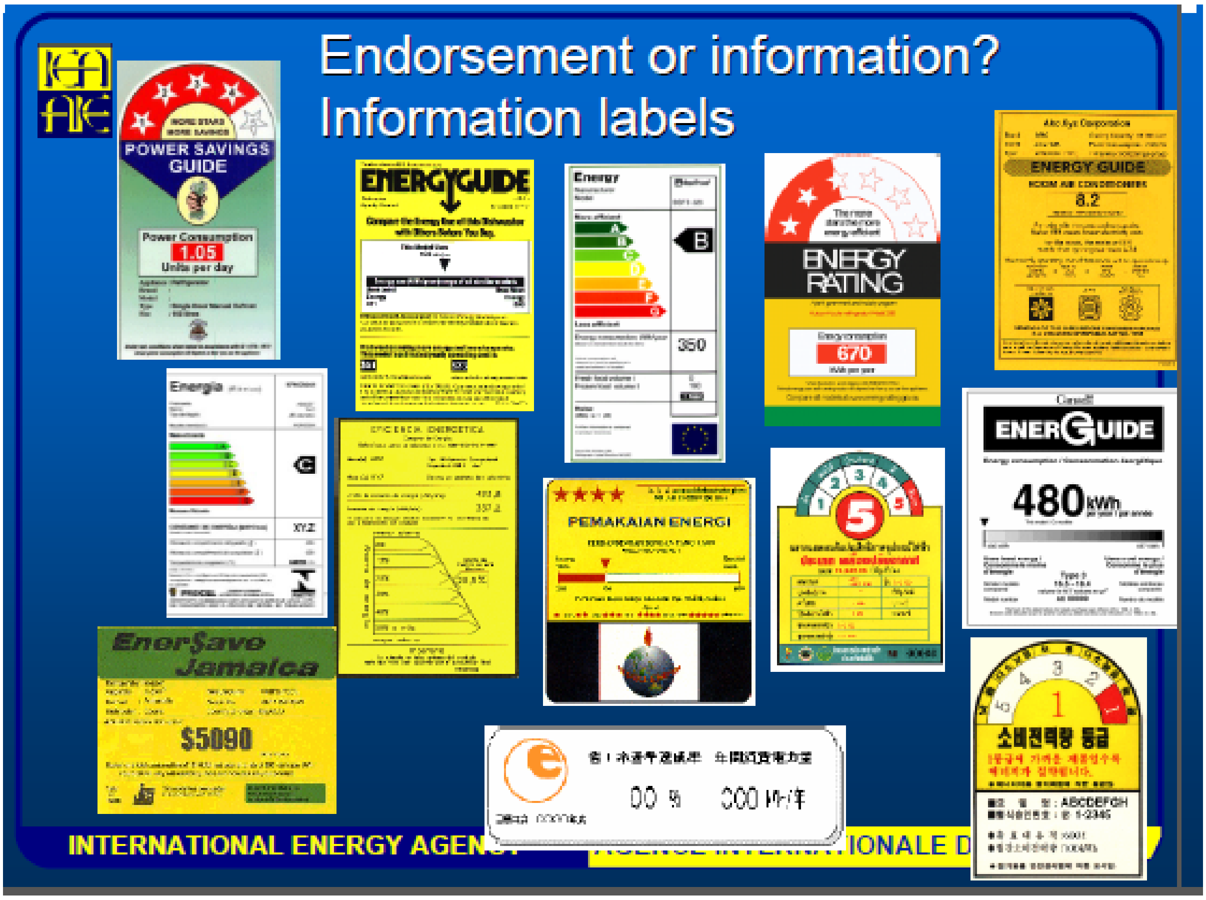

Figure 1 Typology of national labels (Paul Waide IEA, 2004)

8. The Motor standards and policy experience

The experience of the development of relevant standards for motors between 2007 and 2009 has been presented at eceee in 2009 [7]. A systematic approach to standardization for energy efficient electric motor systems between 2007 and 2013 has been presented to IEC SG1 in January 2013 [8]. It includes the introduction of the concept of uncertainty, the definition of a preferred measurement method of energy efficiency and the introduction of an energy efficiency classification system of motors.

The process of global harmonization started from the controversy in 2004 that the USA in its testing standard IEEE 112 had a method B [9] that included the measurement of the motor output with torque and speed and the calculation of additional stray load losses. The rest of the world was using the older IEC 60034-2 measurement standard with segregated losses that avoided the use of torque meters and included stray load losses only with an insufficient constant addition of 0.5%. This measurement method was in Europe considered sufficiently accurate and robust for a long period.

Meanwhile standard IE3 electric motors with output sizes over 100 kW achieve 96% efficiency. This is of course a challenge for every measurement and verification method. Small differences in methodology start to distort the results and become rapidly a nuisance to manufactures competing in the same market.

Ample scientific evidence [9] and [11] that the two key standards did not agree on the resulting efficiencies were published in a number of conference papers before the IEC TC2 was ready to reconsider. The USA motor industry complained about inappropriately higher efficiency ratings in European, Japanese and Chinese motors. The development of more reliable (but still costly) torque meters allowed for a bold step towards aligning the two basic measurement methods with IEC 60034-2-1 in 2007. This required of course many industry laboratories to upgrade their measurement instrumentation and to train their laboratory personnel accordingly.

In a historic encounter of an IEC TC2 WG31 delegation with an IEEE[3] and NEMA[4] delegation on 10/11 May 2007 in Washington DC the cooperation agreement on measurement was extended to also include the efficiency classification. This harmonization was complicated by the fact that in the countries supplied by their electrical power utilities with 60 Hz frequency (USA, Canada, Mexico, part of Brazil, and part of Japan) an electric motor rotates 20% faster than in the 50 Hz countries. The higher output power produces considerable lower losses. The IEC efficiency classification needed to bridge the 50 Hz IEC world with the 60 Hz NEMA world and account for this difference caused by laws of physics. At that time several large European industries (Siemens, ABB) were manufacturing motors in the USA according to US standards for the US market and in Europe with European standards for the European market. It was obvious that harmonization was needed.

A new motor efficiency classification scheme was necessary also because the earlier European motor efficiency scheme developed by the Joint Research Center of the European Commission together with the manufacturers association CEMEP (eff1, eff2 and eff3) was still based on the old incomplete testing standard and could therefore no longer be upheld. The IEC and the European industrial community were hesitant at the time to adopt the IE-code which eventually prepared the way in 2009 for MEPS for motors in the Ecodesign Regulation no 640 [12]. The main reason was that the smaller motor output sizes in the USA have a slightly larger frame in NEMA standards than in IEC. The necessary additional copper wire to reach IE3 can be easily accommodated within the diameter and length of an USA frame, but it was tight and more difficult to do so in IEC frames.

The European motor industry association CEMEP finally agreed with its members in 2008 on mandatory requirements. The key element for the change of policy was the understanding that only MEPS at IE2 level could successfully eliminate low cost, low efficiency imported products. The final adoption of the EU's Ecodesign Regulation led to a compromise which industry favored: the user shall have a choice in 2015 between selecting an IE3 motor or an IE2 motor together with a variable frequency drive (VFD).

9. The standard format

The necessary standards include an array of documents in five groups that cover the most important issues at stake (see Figure 2):

[3] IEEE: Institute of Electrical and Electronics Engineers
[4] NEMA: National Electrical Manufacturers Association

1	2	3	4	5
SCOPE	**TESTING**	**EFFICIENCY CLASSES**	**GUIDE**	**CERTIFICATION**
IEC 60034-1	**IEC 60034-2-1**	**IEC 60034-30**	**IEC/TS 60034-31**	**IECEE e3**
standard use conditions, only selected technologies in the scope	one preferred testing method, procedure prescribed in detail (accuracy, repeatability); check-testing!	3 major efficiency classes: IE1 > IE2 > IE3, open to advanced technology (IE4)	background, application, context, system integration, tools?	conformity assessement, lab accreditation, expert training, round robin, global label

IECEE: System of Conformity Assessment Schemes for Electrotechnical Equipment and Components

Figure 2 The necessary five elements of a standard format for standards in sequence

a) A well-defined product and clear operation scope: IEC 60034-1 includes the definition of the types of products involved (motors and generators, DC, AC synchronous and asynchronous), operating environment (temperatures, height above sea levels, etc.), the operation modes (continuous S1 or intermittent), the measurement instrumentation (ambient and motor temperatures, voltage, current, frequency, rotational speed, torque, etc.) and their allowable tolerances, the display of the rated performance data on the rating plate and in the product documentation. With motor efficiency reaching 96% the tolerance definition and band widths need to be reconsidered. The losses (1 minus efficiency) are the base for the tolerance definition. Currently for electric motors up to 150 kW a 15% tolerance for the losses is allowed (above 150 kW: only 10%). This makes a motor below 150 kW with 96% efficiency tolerate also 95.4% and a bigger motor also 95.6%. The tolerance is of course masked by both the variation in performance from product to product plus the measuring tolerance in the laboratory stemming from the instrument precision, the training of the personnel and the clarity of the measurement standard.

b) The progressively amended IEC standards for determining losses and efficiency measurement: The efficiency measurement standard IEC 60034-2-1, edition 1 from 2007 was continuously improved based on systematic research in a number of both independent and manufacturer's testing laboratories. Efficiency (η) is defined as output (mechanical power) over input (electrical power). The measurement of the mechanical output at the motor shaft involves torque and rotational speed; these measurements require sophisticated instruments and have higher tolerances as electrical properties on the input side. This is the reason why a method of measuring segregated losses delivers more accurate results as a pure output and input measurement. The standard aims for better accuracy and good repeatability when the same motor is measured again at the same lab or shipped to another lab and measured there. It includes the concept of uncertainty: the available efficiency measurement methods are classified as high/medium/low according to their uncertainty; but a quantitative description of the uncertainty was not yet established. In 2007 IEC TC2 launched an international Round Robin testing campaign to compare the accuracy of key available measurement methods. The findings published in 2011 [13] are based on results from 17 laboratories from 11 countries that had submitted a total of 194 individual measurement sets of 75 different motors. In its revised edition IEC 60034-2-1, edition 2, it includes the concept of a "preferred method", i.e. all motors of the same type are measured with one single method to determine their efficiency rating. It also sets much stricter standards for procedures as to the sequence and delays of measurements and the necessary temperature equilibrium (see Figure 3). The current revision is ready to be published in 2014. The revised standard promises to be a good tool for regulators and compliance institutes that have the difficult task of check-testing products put onto the market.

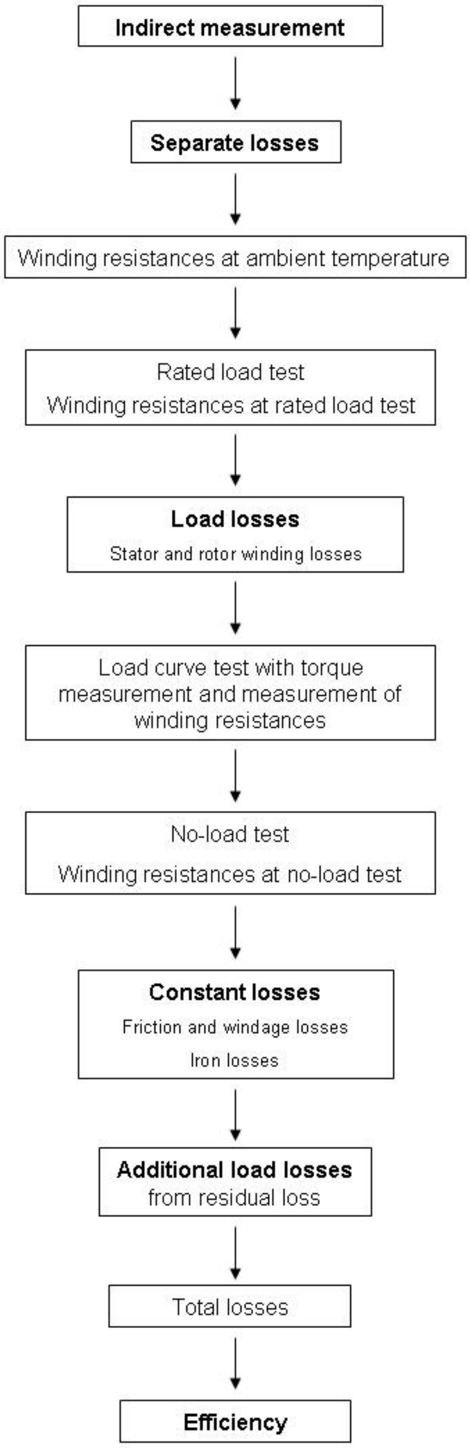

Figure 3 Preferred measurement method: Motor efficiency measurement sequence (IEC 60034-2-1, FDIS 2013)

c) The IEC energy efficiency classification: IEC 60034-30 in 2008 was based on the advanced efficiency measurement standard in IEC 60034-2-1 and defined the new IE-code with three levels of motor efficiency classification: IE1 Standard Efficiency, IE2 High Efficiency and IE3 Premium Efficiency. It is applicable for electric motors operated on a grid frequency of 50 Hz or 60 Hz, with an output power ranging from 0.75 kW up to 375 kW, and with 2-, 4- and 6-poles. In its revised edition IEC 60034-30-1, it enlarges the scope to smaller motors with 0.12 kW up to larger motors with 1000 kW; it also includes 8-pole motors and defines now also the IE4 Super Premium Efficiency level (see Figure 4). It allows all motor technologies to be classified: motors to be capable of running online in IEC 60034-30-1, motors only capable to be operated with a VFD: IEC 60034-30-2. And it closes loopholes of the scope of motors to be included. The current revision is ready to be published in 2014.

Today the following 40 countries (including EU 27) have adopted mandatory MEPS, individually set at IE1, IE2 or eventually at IE3 levels with a dedicated time plan for the upgrade (see Table 5).

All of these countries use the IE-Code in IEC 60034-30 as a reference and the respective procedure to establish efficiency classes for electric motors.

Australia
Brazil
Canada
China
Costa Rica
European Union (27)
Israel
Korea South
Mexico
New Zealand
Switzerland
Taiwan
Turkey
USA

Table 5 Motor MEPS countries (2013)

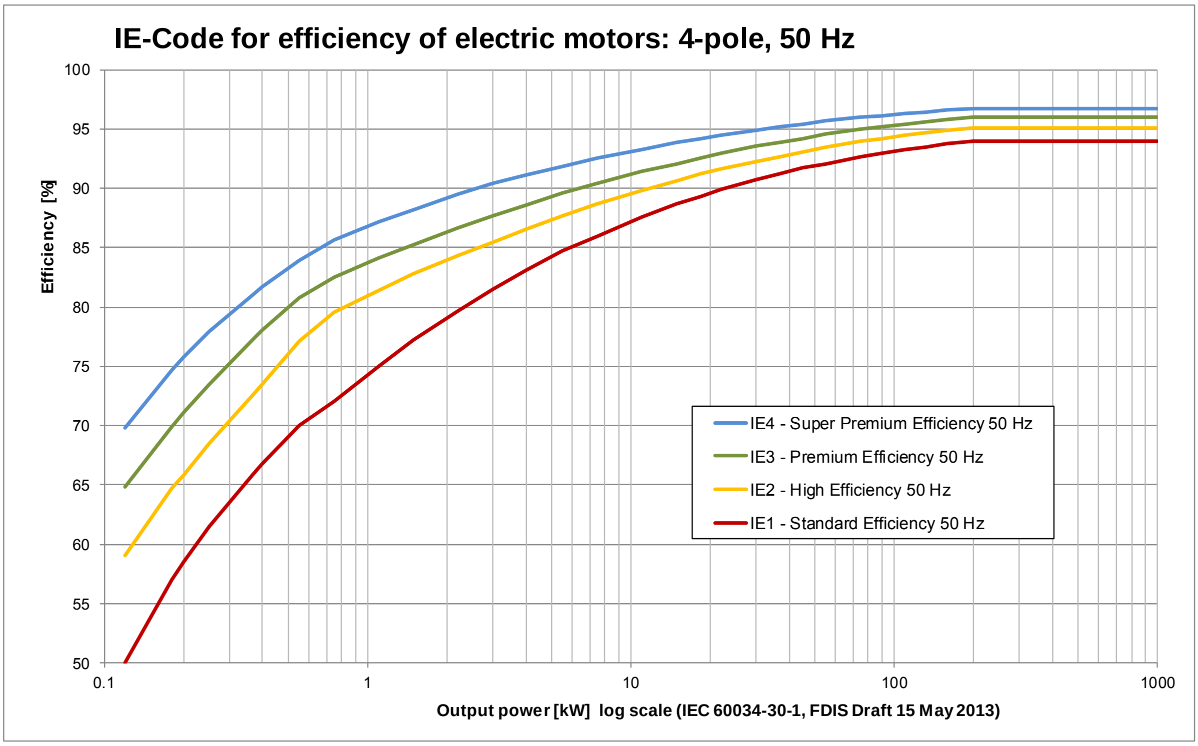

Figure 4 Motor energy efficiency classes at 50 Hz (Source: data from draft FDIS IEC 60034-30-1, 2013)

d) The IEC motor systems standards: With the description available for the performance of the key motor component of an integrated electric motor system, now the need starts to include also various other components into the efficiency classification of a complete drive system. The efficiency measurement standard for motors driven by VFDs (IEC/TS 60034-2-3, 2013) and their efficiency classification (IEC 60034-30-2, 2014) are well under way. The new project of a standard for the systems efficiency of a motor plus VFD in IEC 61800-9 (2016) is a start into this direction (see Figure 5).

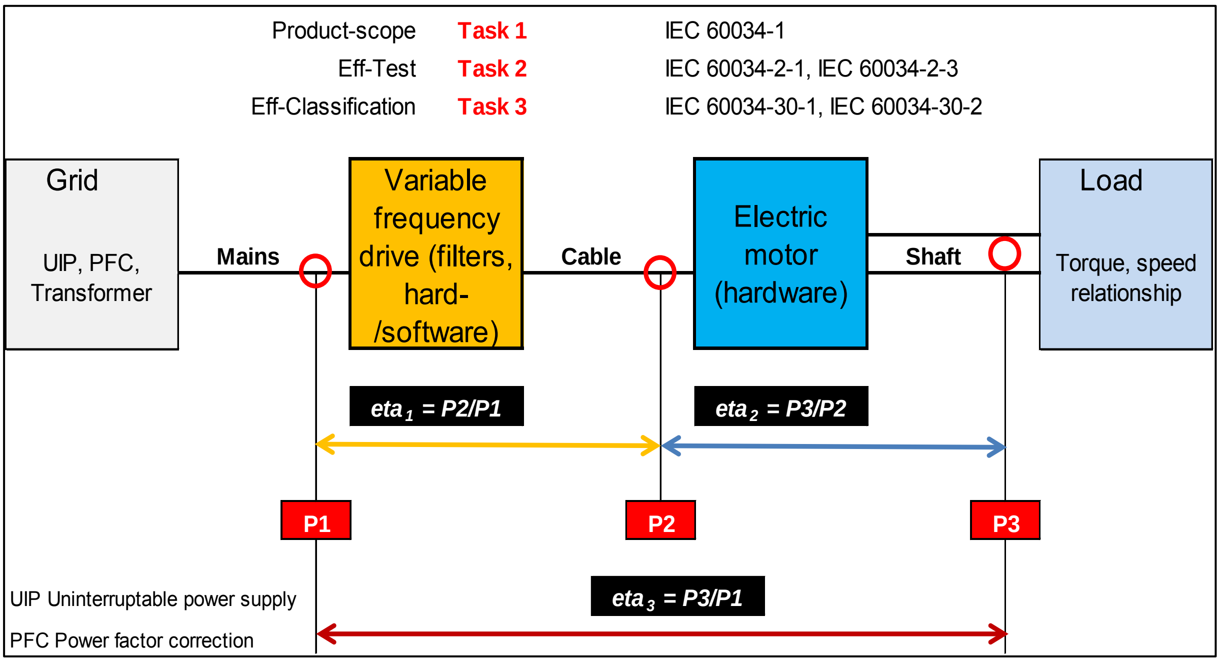

Figure 5 The scope for measurements and efficiency classes electric motors and variable frequency drives (Source: IEC 61800-9, draft 2013)

e) IECEE certification and labeling: Based on the clear product scope (a), its standardized method of determination of losses and efficiency (b), and an agreed efficiency classification (c) the next logical step requested by industrial product users and government regulation agencies includes a certification system that also issues a label for products that comply with all the necessary requirements. An important element still to be clarified is the product registration. Several countries have introduced as part of their MEPS policy, a registration system that requires each manufacturer (like in the USA) or even each product group (like in Australia) to register its product and show the respective number on the rating plate. The use of RFID (radio frequency identification) or bar codes can facilitate access to the respective data set on the plate or at a manufacturers' database.

10. Lessons learned for other electrical products

Many of the lessons learned from the motor standards could, if all relevant stakeholders were prepared to agree, readily be adapted to many other electrical products like lighting (lamps, ballasts, and luminaires), household appliances, consumer electronics, office equipment, transformers, etc.

The key element is to prepare a coherent set of global measurement and performance standards that can be easily used later as base for national MEPS [14] [15]. Previously, inclusion of efficiency classification performance standards had been resisted by a number of Governments who felt that IEC's role was to determine the measurement methodology only - the setting and amending efficiency performance levels being seen by some Governments as their responsibility. After all, this was the fundamental delivery tool for their policy. On the other hand, in the last decade several IEC TCs have refrained to include efficiency classifications into their standards out of fear of overstepping their competence into the field of national legal requirements. This is clearly not the case: IEC standards can set efficiency classes, national governments are free to adopt the levels thy see fit for their economies at a given point in time.

On the other hand, if standards for measurements and bands of graduated performance standards are globally harmonized and national MEPS enforced, then the burden for manufacturers for additional testing and product certification is diminished. Their global marketplace expands as a level playing field for domestic and imported products, based solely on the product performance. Additionally, those Governments that work together to adopt exactly the same performance standards, are then in a powerful position to leverage improved performance standards through their harmonizing the adoption of future more demanding standards.

The key elements for this standard format for IEC standards see Table 6:

1	Clear scope	Standard with clear definition of product scope: which products and conditions included, which ones excluded. No loopholes for exploitation by less scrupulous suppliers.
2	Measurement standards	Energy efficiency (defined as output/input) requires measurement standards with high accuracy and repeatability, including the definition of a preferred method. In some products with high efficiencies (>> 90%) the segregation of losses instead of an output/input measurement is necessary to avoid the inaccuracies coming from division of two similarly large numbers. Definition of measurement tolerances. In non-motor products the definition of the output can require more detail to understand and describe the energy service delivered clearly: i.e. televisions where measurement standard disagree on the definition of the output as the readability of the produced image.
3	Efficiency classification	Efficiency classification scheme with clear thresholds set between classes including maximum allowable tolerances (measurement and product quality). The open scale should allow for further improvements. This allows national decisions on the classifications for energy labels and performance tiers for MEPS. Large freedom of national speed to upgrade the tiers to higher performance levels. The formerly stated fear that an IEC standard could not set efficiency classes is based on the confusion of IEC standards and government MEPS.
4	No technology bias	No bias for various technologies in delivering a certain output, instead an open competition between different technologies to succeed in better performance and cost effectiveness. Market conditions, and the need to comply with the ever more demanding regulated energy efficiency levels, will give the better products a better chance of success in the market.
5	Tools for users	Provide tools for users like the Motor Systems Tool (MST) to design and optimize complex systems.
6	Global certification	Globally recognized certification scheme operated by renowned international agencies like IECEE.

Table 6 Key words for standard format of IEC standards, applicable for other products

While leaving from the field of Rotating Machines in IEC TC2 to apply the lessons learned to many other types of electrical equipment like lamps (TC34), appliances (TC59), and TVs (TC110) the definition of energy efficiency becomes more complex. In the underlying equation

$$\text{Efficiency} = \text{Output} / \text{Input}$$

the "output" definition needs more specific attention. While the mechanical output of an electric motor can be defined as torque and rotational speed, the output of lamp, a refrigerator or a TV is much more complex to describe (see Table 7). Nevertheless, this added complexity in non-mechanical applications of electrical equipment should not hamper the use of the future standard format for IEC standards.

Process	Equipment	Output	Side effects
Lighting	Lamp (plus auxiliary equipment: ballast, luminaire)	Light (lumen), distribution of wave length (color), color rendition, light distribution (concentrated or diffuse)	Start-up time with color change, decay (loss of lumen and color change)
Refrigeration	Refrigerator and freezer	Hermetically enclosed volume for foodstuff at lower than ambient temperature, fixed inside temperature with small deviations, different temperature per compartment, speed to cool stored material down to cooling temperature.	Noise, equal temperature distribution within compartment, icing and defrosting, condensation, stand-by for displays
Image	TV, monitor	Image (size, brilliance, contrast, color rendition),	Sharp image with moving pictures, start-up time, stand-by loss
Washing	Laundry washing machine, dish washer	Volume (weight) of clean laundry or dishes, residual water content after wash	Noise, textile damage, detergent use
Drying	Laundry dryer	Water content of laundry	Noise, textile damage, fibers clog filters
Cooking	Oven	Enclosed volume at higher than ambient temperature, fixed temperature with small deviations, different temperature per compartment, speed to heat stored material to hot temperature.	Noise, coagulation of fat, cleaning procedure, equal temperature distribution within compartment
Print & copy	Printer, copier, facsimile, scanner	Printed paper (per second), black/white or color, paper size, image density/quality (dpi), color rendition, time to first page	Time to have image dry, stand-by loss, printed image margin, image input (scan, data file)
Compute	Personal computer	Calculations per second (Flops: floating point operations per second)	Storage capacity, communication capabilities
Data transfer	Router	Data rate (bps bit/s)	Storage capability

Table 7 Output definitions for various types of electrical equipment

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[3] ISO/IEC: Directives, Part 1, Geneva Switzerland, 9th edition, 2012

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Ecodesign of Electric Motors and Drives – The EuP Lot 30 Preparatory Study

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Abstract

The importance of electric motor systems as a major consumer of electricity in industry and commerce has been recognised for a long time, with a series of successful SAVE studies showing the energy saving potential for these products. The recent EuP study on motors (Lot 11) highlighted the importance of introducing Minimum Efficiency Performance Standards (MEPS) related to these products in Europe.

On the follow up of the Lot 11 study, the European Commission issued a regulation setting minimum efficiency requirements for electric motors (Regulation 640/2009).

The Lot 30 preparatory study aims at identifying the environmental improvement potential of products outside the scope of Regulation 640/2009 on electric motors, such as:

- Motors in power ranges outside the 0,75 kW – 375 kW power range namely above 120 W and high power motors above 375 kW up to 1000 kW.
- Explicit exclusion to the Regulation such as Brake Motors.
- Motors using technologies other than Induction Motors, such as Permanent Magnet Motors.
- Motor Controllers such as Variable Speed Drives and Soft-Starters

The study is based on a methodology for the Ecodesign of Energy-using Products (MEEuP,) developed for the European Commission, which is common to all the EuP preparatory studies and will identify: a) Market characteristics for the products under consideration; b) Relevant environmental aspects of the products and their technical/economical potential for improvement; c) Existing relevant legislation and self regulation by industry and standards; d) LCC assessment of average products; e) Technical analysis of the Best Available Technologies (BAT) and of the Best Not Available Technologies (BNAT); f) Scenario, policy, impact and sensitivity analysis. In this paper, a description and the main results of the study are presented.

Key Words:

Motor, Drives, Variable Speed Drives, Soft-Starters, Policies, Energy Efficiency, Life Cycle Analysis

1. Introduction

As a consequence of the Ecodesign Directive 2005/32/EC [1] of the European Parliament and of the Council, a preparatory study (Lot 11) [2] to identify and recommend ways to improve the life-cycle environmental performance of electric motors at their design phase was carried out and the results published in 2008. On the follow up of the Lot 11 study, the European

Commission issued a regulation regarding ecodesign requirements for electric motors (Regulation 640/2009) [3], set up in three stages, as follows:

1. from 16 June 2011, motors shall not be less efficient than the IE2 efficiency level
2. from 1 January 2015: motors with a rated output of 7,5-375 kW shall not be less efficient than the IE3 efficiency level, or meet the IE2 efficiency level and be equipped with a variable speed drive.
3. from 1 January 2017: all motors with a rated output of 0,75-375 kW shall not be less efficient than the IE3 efficiency level, or meet the IE2 efficiency level and be equipped with a variable speed drive.

These requirements apply to single speed, three-phase 50 Hz or 50/60 Hz, squirrel cage induction motor that:

- has 2 to 6 poles,
- has a rated voltage U_N of up to 1 000 V,
- has a rated output P_N between 0,75 kW and 375 kW,
- is rated on the basis of continuous duty operation.

The following types of motor are excluded:

- motors designed to operate wholly immersed in a liquid;
- motors completely integrated into a product (e.g. pump or fan) where the motor's energy performance cannot be tested independently from the product;
- motors specifically designed to operate:
  - at altitudes exceeding 1000 meters
  - where ambient air temperatures exceed 40°C;
  - in maximum operating temperatures above 400°C;
  - where ambient air temperatures are less than –15°C (any motor) or less than 0°C (air-cooled motors);
  - where the water coolant temperature at the inlet to a product is less than 5°C or exceeds 25°C;
  - in potentially explosive atmospheres as defined in Directive 94/9/EC;
- brake motors.

To evaluate the possibility of broadening the scope of the current regulation a new preparatory study was commissioned by the European Commission (EC).

The product group (Lot 30) is defined in the invitation to Tender as "*Products in motor systems outside the scope of the Regulation 640/2009 on electric motors, such as special purpose inverter duty motors (asynchronous servo motors), permanent magnet motors, motors cooled by their load (fans), including motors and products under Article 1, Points 2(b), (c) and (d) and including drives, such as soft starters, torque or variable speed drives (VSD) from 200W-1000kW. The study should also cover motors in the scope of the Regulation 640/2009 from 750kW 1000kW".*

The short description for Lot 30 is quite broad, encompassing products in motor systems outside the scope of Regulation 640/2009 on electric motors. This includes, not only the motors that are specifically excluded in Article 1 of the Regulation, such as brake motors, but also other induction motors (single phase and 3-phase outside the 0.75-375 kW power range), motors specifically designed for inverter duty, and motors with different design such as permanent magnet motors. Furthermore, it also includes motor drives and controllers (e.g. electro-mechanical starters, soft starters, VSDs, etc.).

The pertinence of the introduction of regulatory measures for the above mentioned products will be evaluated based on Article 15 of the Ecodesign Directive, specifically, products with large sales, high environmental impact and high potential reduction of that environmental impact.

For the purpose of this evaluation the established MEEuP methodology [4] will be used. This sets out a common method to gather information to help evaluate whether and to which extent a product fulfills the above criteria that make it eligible for implementing measures under the Directive. The method involves the use of a simplified reporting tool (EuP EcoReport) that helps translate information gathered during the first stages of the process into environmental impacts.

In particular the study will: a) Develop a product definition and its categorisation; b) Identify and briefly describe relevant existing legislation and standards; c) Collect economic and market statistics for the products, including market structure and trends; d) Characterise the current products on the EU-market and emerging, state-of-the-art technologies; e) Evaluate the significant environmental impacts of the product using the EcoReport tool; f) Identify design options and their monetary impact on consumers; g)Identify least life cycle cost options; h) Evaluate the environmental improvement of said options; i) Assess the investment, design and production costs, and other necessary economic conditions for cost-effective ecodesign requirements; j) Identify policy options, draw scenarios and quantify the improvements; k) Estimate the impact on consumers and industry.

2. Product definition and categorisation

For the purpose of the study, motors are divided into three major categories according to output power:

- **Small motors** in the power range of 120 W[1] to 750 W.
- **Medium motors** in the power range of 0.75 kW to 375 kW. This is the power range covered by the existing EC regulation, so special attention is to be given to exclusions, non-induction motors and to their improvement potential.
- **Large motors** in the power range above 375 kW, up to 1000 kW. This group includes motors up to 6,600 V.

The high savings potential of Variable Speed control in certain applications is also widely recognized and is to be the subject of analysis including hardware, software and interaction with the motor, to evaluate its combined efficiency.

The environmental advantages of other motor controllers, such as soft-starters and electro-mechanical starters, which can be applied in fixed speed applications, will also be evaluated.

3. Efficiency Testing and Classification standards

Recently developed standards on motor efficiency testing and classification (IEC 60034-2-1 and IEC 60034-30), which harmonise different efficiency test methods and efficiency classification schemes in use around the world, allowed to overcome the difficulties manufacturers encounter when producing motors for a global market and helped to make a more transparent market.

Other standards in development regarding test methods for converter-fed motors (IEC 60034-2-3), and test methods and classification of Power Drive Systems and motor controllers (CLC 52800-x), will hopefully become the basis for efficiency standardization of these products with high potential for environmental impact reduction.

[1] Although the initial lower limit was 200 W it was decided to further lower this limit to 120 W to keep in line with the upcoming edition of IEC 60034-30-1

Almost all the major economies have some kind of voluntary or mandatory regulatory scheme regarding induction motor efficiency. An overview of different motor efficiency regulation in use around the world is given, showing an increasing stringency on the adopted efficiency levels.

4. Market

The global stock of electric motors is estimated at 2,23 billion. As it can be seen in Fig. 1, small motors, under 750 W, account for 90% of the electric motors population (approximately 2 billion) but use only 9% of the overall electricity consumption. There are around 230 million medium motors, in the 0.75 kW to 375 kW power range, about 9% of the installed motors, which are responsible for 68% of the electricity consumed by motor systems. Large motors, with powers over 375 kW represent the smallest number, with only 0,6 million motors installed globally but, nevertheless, they are responsible for 23% of the energy use [5].

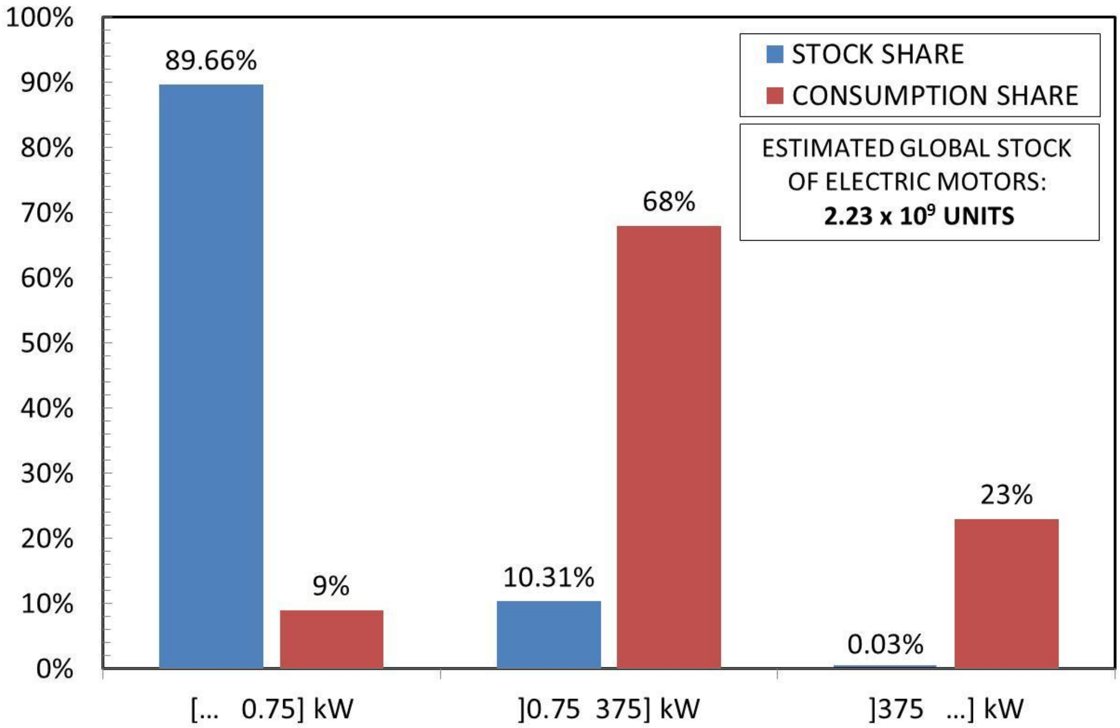

Fig. 1. Global stock and electricity consumption share for electric motors.

Table 1 ProdCom data for electric motors and generators sold, in thousands (EU-27, 2010) [6]

	Power range					
	≤ 750 W		> 0,75 & ≤ 375 kW		> 375 kW	
	n. units	%	n. units	%	n. units	%
DC Motors and Generators	128 176	*56*	4417	*21*	1	*5*
AC Single-Phase	67 019	*29*	6379	*30*	n/a	*n/a*
AC Multi-Phase	11 700	*5*	10175	*49*	28	*95*
Universal	23 228	*10*	n/a	*n/a*	n/a	*n/a*
Total	**230123**		**20970**		**30**	

In 2010 over 250 million motors were sold in Europe, 91 % of which were in the small power range, that is, under 750 W. The share of large motors is very small (only 0,01%). The remaining 9% of motors sold are in the medium power range. These values are consistent with the available estimates of global sales of motors.

Data provided by CEMEP (Association of European Manufacturers of Electrical Machines and Power Electronics Equipment) for induction motors slightly differs from the ProdCom data presented, as can be seen in Table 2 and Fig. 2.

Table 2 Induction motors sold, in thousands, and revenue in million € (EU-27, 2010)
Source: CEMEP

	Power range					
	≤ 750 W		**> 0,75 & ≤ 375 kW**		**> 375 kW**	
	n. units	Million€	n. units	Million€	n. units	Million€
AC Single-Phase*	800	48				
AC Multi-Phase	7 300	580	8 100	2 700	13-13,5	320-340
Total						

* Only in typical industry applications.

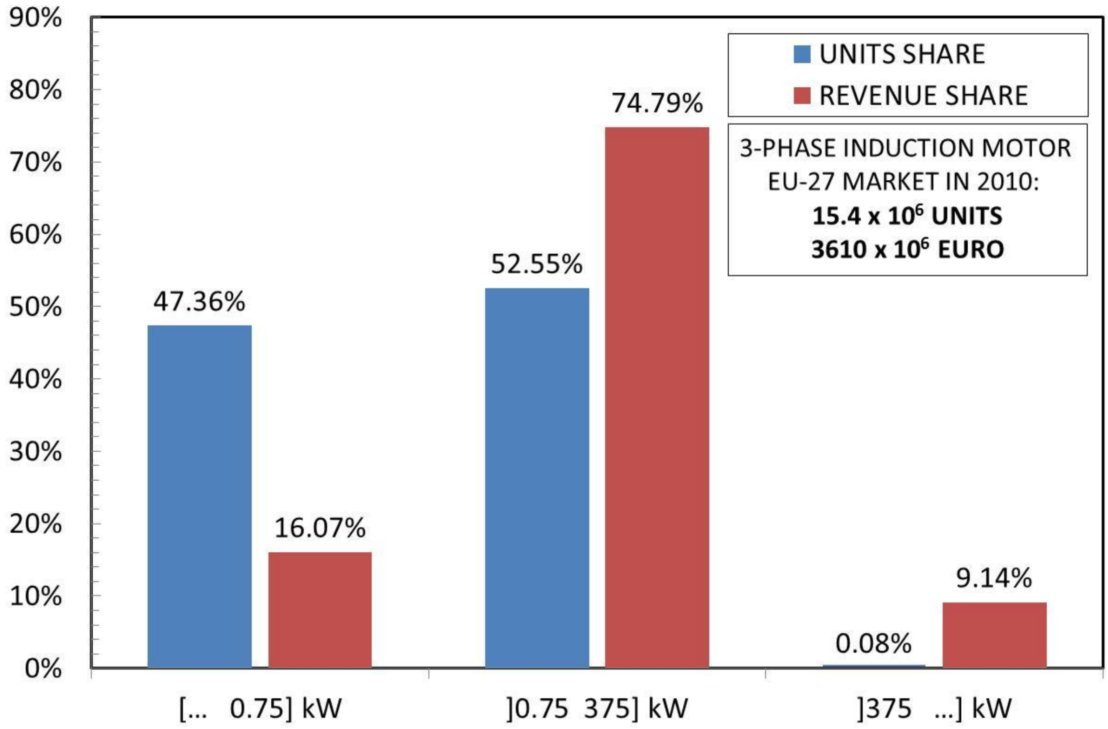

Fig. 2. Estimated EU-27 polyphase induction motor market in 2010 (Data Source: CEMEP).

The number of AC Single-Phase motors sold provided by CEMEP only relates to motors used in industrial applications. However, these motors can be found in a number of other applications, such as household appliances. The total number of AC Single-Phase motors sold according to ProdCom is in-line with other market studies [7]

The number of induction motors sold in the large power range, between 375 and 1000kW, both low voltage and medium voltage can be seen in Table 3.

Table 3 Number of Large AC Multi-Phase motors sold in thousands (EU-27, 2012)
Source: CEMEP

Power range		**n. of units sold**
> 375 kW but ≤ 1000 kW	Low Voltage	10
	Medium Voltage	3 – 3,5
Total		**13 -13,5**

VSD market data for the power ranges considered in the study, is shown in table 4 and Fig. 3.

Table 4 Number of VSDs sold and revenues by power range (EU-27, 2012)
Source: CEMEP

	Power range					
	> 120 W ≤ 750 W		**> 0,75 kW & ≤ 375 kW**		**> 375 kW ≤ 1000 kW**	
	n. units	Mio €	n. units	Mio €	n. units	Mio €
VSDs	1,13 Mio	200	2,89 Mio	2.500	7.000	260

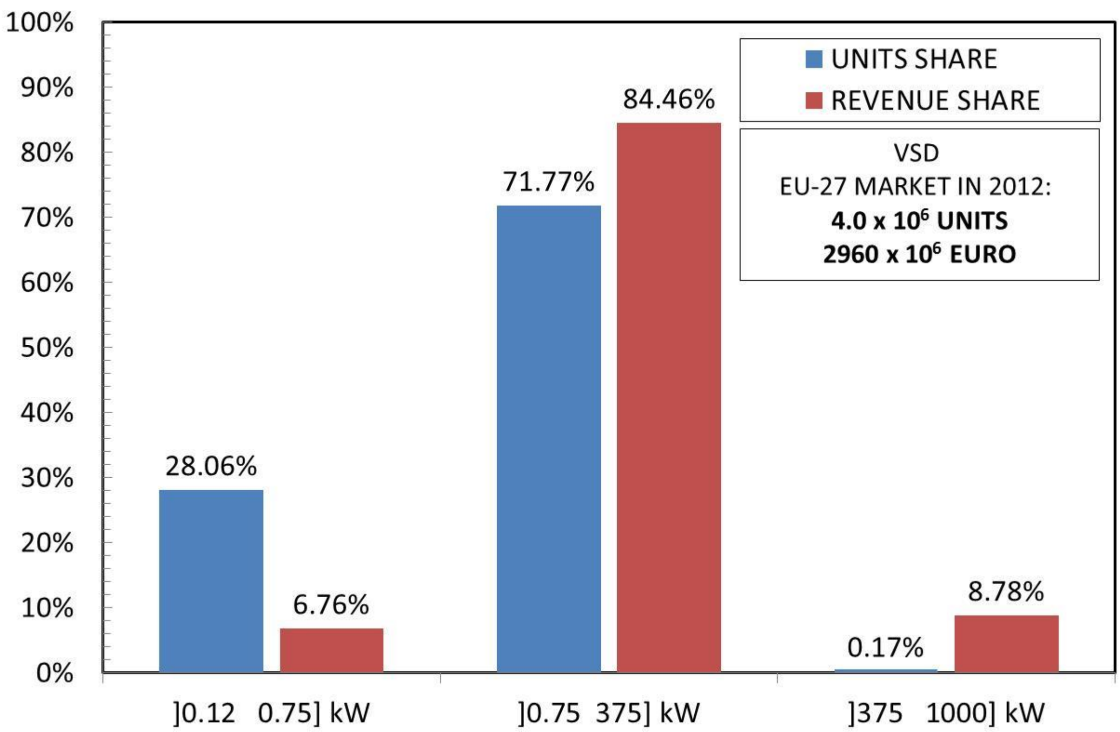

Fig. 3. Estimated EU-27 VSD market in 2012 (Data Source: CEMEP).

Market data for Soft-Starters and Electro-Mechanical starters according to CAPIEL - European Low Voltage Switchgear And Controlgear Manufacturers Association, can be seen in Table 5 and Figs. 4 and 5.

Table 5 Number of Soft-Starters and Electro-Mechanical starters sold (in thousands) and revenues (in million €) by power range (EU-27, 2012)
Source: CAPIEL

	Power range					
	> 120 W ≤ 750 W		**> 0,75 kW & ≤ 375 kW**		**> 375kW ≤ 1000 kW**	
	n. units	€	n. units	€	n. units	€
Soft Starters	20	1,2	360	74	1	6,5
Contactors	10 300	103	19 200	575	3	4,5

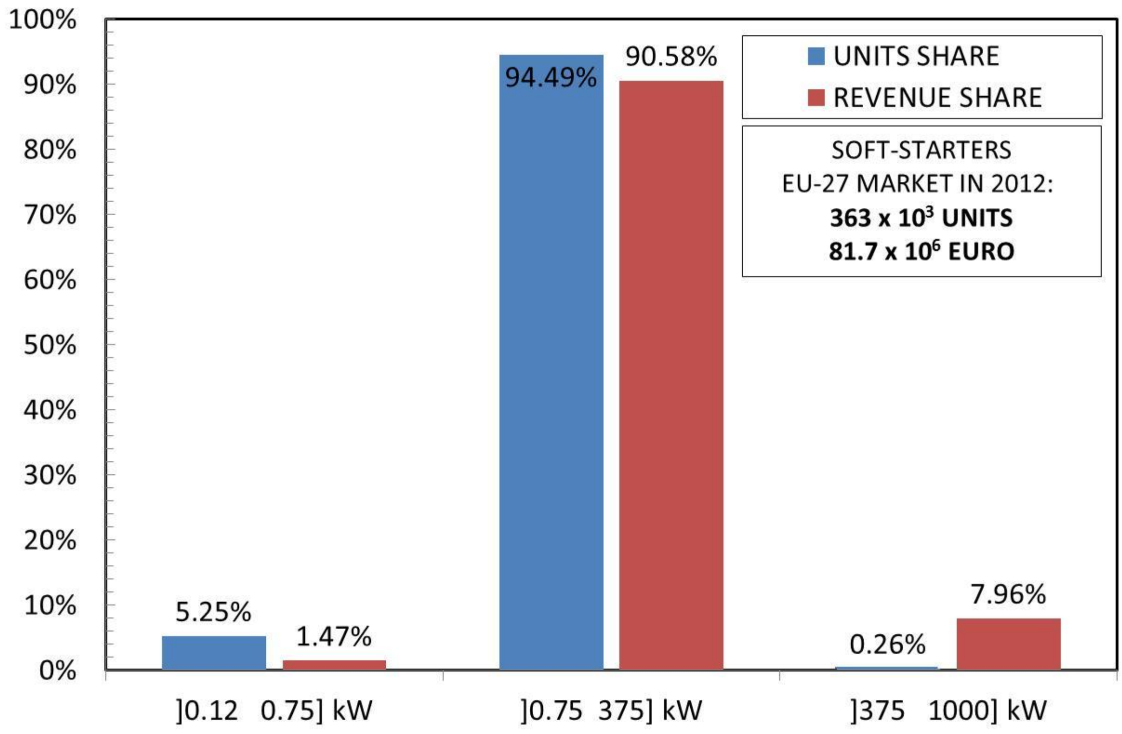

Fig. 4. Estimated EU-27 Soft-Starter market in 2012 (Data Source: CEMEP).

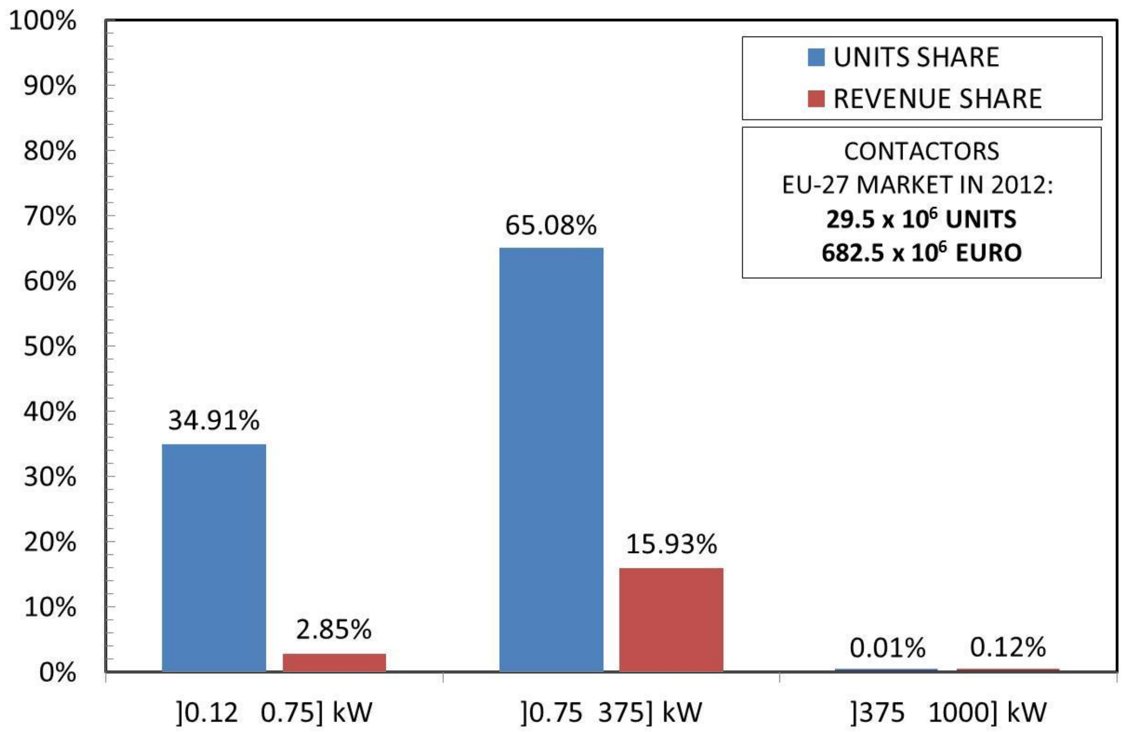

Fig. 5. EU-27 Contactors market in 2012 (Data Source: CEMEP).

In Fig. 6, the number of VSD, Soft-Starter and Contactor units sold in the EU-27 in 2012 is shown.

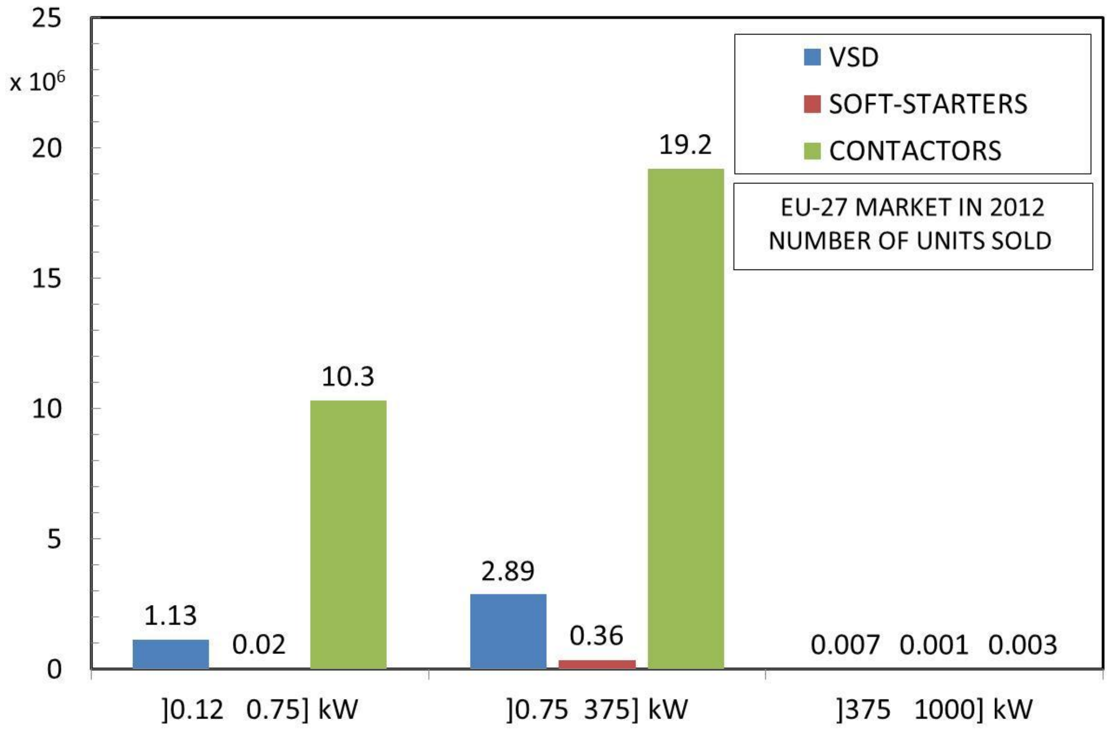

Fig. 6. EU-27 VSD, Soft-Starters and Contactors market in 2012 (Data Source: CEMEP).

Average prices and installation costs for motors under consideration in the study, are presented in Table 6.

Table 6 Motor Average Prices (2012)

Source: CEMEP

Description	**Power range (kW)**	**Unit Price (€)**	**Installation Costs (€)**
AC Single-Phase Motor (IE1)	0.12 -0.75	60	
AC Multi-Phase Motor (IE1)	0.12 – 0.75	80	
AC Multi-Phase Motor (IE2)	0.75 - 2.1	150	
	7.5 – 45	600	
	76 - 110	6 000	
	375 - 1000	25 000	1 000
	375 - 1000	40 000	3 000

In the medium power range motor prices can vary from around 150 € for an AC three-phase IE2 motor to around 50000 € for a 1000 kW MV motor. In general, the market is very competitive with large discounts (over 40%) offered to OEMs, although there are lesser pressures at higher power ratings as the degree of competition is not considered as fierce.

Average prices and installation costs for VSDs, soft-starters and electro-mechanical starters, which are presented in Table 7

. The installation costs can vary depending on several factors, including wiring, filters, environment, location and conditions of the application. The installation costs are estimated as a percentage of the unit price, which is a general estimate, accepting that there will be large variations in either side of these ranges.

Table 7 Average prices for VSDs, soft-starters and electro-mechanical starters (2012)
Source: CEMEP and CAPIEL

Description	**Power (kW)**	**Unit Price (€)**	**Installation Costs (€)**
VSD	0.12 – 0.75	200	50-300%
	0.75 – 2.1	280	50-250%
	7.5 - 45	1 130	50-200%
	76 - 110	5 320	50-175%
	375 - 1000	41 790	50-150%
Soft Starter	1,1	60	30
	11	100	70
	110	800	100
Contactors	1,1	12	20
	11	30	30
	110	140	40

5. Real Life considerations

Consumer behaviour can – in part – be influenced by product-design but overall it is a very relevant input for the assessment of the environmental impact and the Life Cycle Costs of a product.

Changes in the design of motors and use of controls has many impacts on the usage and hence duty patterns of motors. Of particular importance to this study are the following:

- Motors operate at an average load of 60%. Part load performance is therefore very important, and will vary between different types of motors. As previously noted, modern high efficiency motors will have a fairly even efficiency between 40-110%.
- Some types of motor can work at very high speeds or low torques, enabling system savings through the omission of transmissions and their losses.
- All controllers have internal energy losses, but when fitted in the right application the system energy savings they enable is much greater. Care must be taken that any regulations applying to products do not adversely impact possible system savings.
- Correct motor system design and programming of VSDs is essential in order to maximize system performance and minimize motor losses.
- VSDs increase the losses in induction motors, and so care must be taken that any regulations do not simply lead to the shifting of losses from the VSD to the motor or vice versa.
- As motors become more efficient they become more expensive, so encouraging their repair rather than replacement with more efficient types.
- Motors are almost exclusively recycled, but research is in place to look at better ways to reclaim valuable materials, in particular permanent magnets.
- The transformation from the process requirements into a certain system structure and control strategy and thus in a resulting load profile decides mainly about the energy consumption of the application. Care must be taken that users and system designers are aware of their possibilities and responsibilities.

6. Definition of Basecases

BaseCases are the reference point for further improvements, and should therefore ideally represent the average new EU product. The BaseCases need to be representative of the whole spectrum of products for each category, both in terms of design features and size. This is necessary so that the outputs from the EcoReport tool for single products can be extended to be representative of the entire range of sizes and styles of that sub-type.

The following BaseCases for motors will be analysed, divided into three major categories according to output power:

For **Small motors** in the power range of 120 W to 750 W, two BaseCases will be considered:

- BaseCase 1 – 1-Phase Induction Motor (IM), 370 W, IE1
- BaseCase 2 – 3-Phase Induction Motor (IM), 370 W, IE1

Medium motors in the power range of 0.75 kW to 375 kW

- BaseCase 3 –1-Phase IM, 1,1 kW - IE3
- BaseCase 4 – 3-Phase IM, 1,1 kW - IE3
- BaseCase 5 – 3-Phase IM, 11 kW - IE3
- BaseCase 6 – 3-Phase IM, 110 kW - IE3

Large motors in the power range above 375 kW, up to 1000 kW.

- BaseCase 7 – 3-Phase IM, 750 kW LV, IE2
- BaseCase 8 – 3-Phase IM 750 kW MV (6600V), IE2

The efficiency levels for all of the above motors are based on IEC 60034-30 standard.

For the analysis of Variable Speed Drives (VSDs) one additional BaseCase will be considered for all of the above motor powers, when coupled with a VSD.

Three BaseCases will also be considered, on a first approach, for Soft-Starters coupled to 1.1 kW, 11kW and 110 kW motors for the evaluation of the environmental impact of such equipment.

For each of this BaseCases additional data was collected relating to each of the Life Cycle Phases: manufacturing (bill-of-materials), distribution, use and end-of-life. Our preliminary analysis shows it is the "In use" or energy consumption that dominates for the motors, and so the focus of the study should indeed be on efficiency and the related operating hours.

7. Next Steps

The data collected, so far, during the study will be used for the evaluation of the environmental impact and Life Cycle Costs, of the defined BaseCases using the EcoReport software tool. The outputs will serve as the level for comparison with Best Available Technologies (BAT) and Best Not Available Technologies (BNAT). BAT can be defined as a technology that is at prototype level, which means that is technically well characterised, and on which the economics are well understood. BNAT is a technology that is still at the development stage where further work is required, and which may not actually reach commercialisation. The performance and economics of these products are subject to greater margins of error.

For each base-case, the first step will be the identification of a list of BAT ecodesign options which could potentially be applied. Information about possible BAT options provided through stakeholder consultation, expert consultation and further literature review will be analysed.

From this, a new dataset will be compiled that will focus on the incremental performance, material and price differences between each BAT and the basecase model. In particular, key barriers to take-up will be explored, such as the requirement for most alternatives to the induction motor to have a controller rather than work directly on-line.

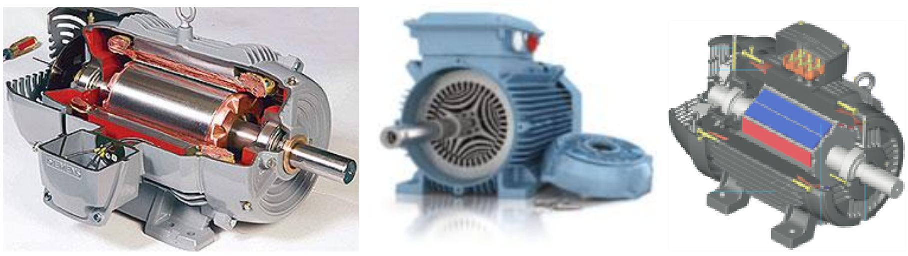

Figure 1. Possible functional replacements for the standard induction motor (BAT 1 - Cast copper rotor induction motor, BAT 2 - Synchronous reluctance motor, BAT 3 - Permanent magnet motor)

The analysis of this products follows a data collection process similar to the one carried out for the BaseCases. The collected data will then be run through the software tool to evaluate the improvement potential of these technologies in terms of:

- Environmental costs and benefits
- Optimum solution in terms of Least Life Cycle Cost

The LLCC level is the lowest level of consumption that is both technically feasible and is cost-effective to the consumer (the lowest point on the life cycle curve). Cost effective means that the extra purchase cost is recouped by the lower running costs to the consumer. Feasible means it is proven technology, either on the market or very close to being on the market.

Finally, suitable policy options to achieve the identified improvements and its impacts will be analysed against a Business as Usual Scenario.

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The SEAD Global Efficiency Medal Competition: Accelerating Market Transformation for Efficient Motors

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Abstract

The SEAD Global Efficiency Medal competition is a global and regional awards recognition program that encourages the production and sale of super-efficient products and is a cornerstone activity of the Clean

Energy Ministerial's Super-efficient Equipment and Appliance Deployment (SEAD) Initiative. This winner-takes-all competition guides buyers towards the most efficient product choices and spurs efficiency innovation among manufacturers.

Electric motors and systems (EDMS) account for 44%-46% of electricity end-use globally. The operating cost of a medium or large size motor can be several-fold (sometimes an order of magnitude) the purchase price. Hence, even small increases in efficiency can result in significant reduction of ownership (capital plus operational) costs of the motor. In the U.S. alone, it is estimated that cost-effective efficiency technologies and practices can reduce the electricity demand from motors by 11%-18% (62 TWh to 104 TWh) and save US$3 billion to $5 billion a year (Waide and Brunner 2011) [Ref 2]

The SEAD Global Efficiency Medal competition for electric motors seeks to advance efficiency improvements by:

- Recognizing products with the best energy efficiency;
- Guiding buyers who want to purchase the most energy efficient products; and
- Demonstrating the levels of efficiency that are achievable with commercially available and emerging technologies.

By recognizing both induction and new technology motors, the competition aims to accelerate efficiency gains in existing technologies and promote emerging technologies in the market. In addition, this competition is an opportunity to harmonize performance testing globally by allowing governments to recognize comparable and transparent test procedures for energy efficient products. Harmonizing these test procedures will make it easier for manufacturers to operate in the global market and consequently provide more cost-effective products for consumers.

The competition for electric motors launched in June 2013, runs through November 2013 and winners will be announced in September 2014. There are 18 award categories across 4 geographic regions. The award categories include both National Electrical Manufacturers Association (NEMA) and International Electrotechnical Commission (IEC) standard induction motors, and new technology motors. This paper discusses the framework and requirements of this competition, as well as the program design challenges faced in developing a global awards competition for electric motors.

Introduction

Figure 1. SEAD Global Efficiency Medal award logo.

The SEAD Initiative

The Super-efficient Equipment and Appliance Deployment (SEAD) Initiative of the Clean Energy Ministerial (CEM) is a voluntary international government collaboration whose primary objective is to advance global market transformation for energy efficient products. SEAD seeks to achieve this objective by engaging both the public and the private sector. To this end, SEAD is engaged in the following five activities: awards (the SEAD Global Efficiency Medal competition), procurement, incentives, standards and labelling, and technical analysis. The first three activities focus on mechanisms to increase demand for energy efficient products, the fourth facilitates exchange of technical information, and the last creates a strong analytical foundation for SEAD activities.

The SEAD awards program is led by government representatives from Australia, Canada, India, Japan, Sweden, the United Kingdom, and the United States. The Collaborative Labeling and Appliance Standards Program (CLASP) serves as the Administrator of the SEAD Global Efficiency Medal competition [Ref 1]. Each activity is managed by a working group comprised of government representatives from CEM participating countries. The policy makers of the SEAD working groups have been advised by a variety of international technical experts to collaboratively accelerate the pace of efficiency standards and labelling programs of specific product categories, including electric motors.[1]

Motors

Electric motors and systems (EMDS) account for 44%-46% of electricity end-use globally and result in 6040 Mt of CO_2 emissions [Ref 2]. Motors are segmented in three broad categories; (1) small motors that are rated less than 0.75 kilowatts (kW); (2) medium motors from 0.75 kW to 375 kW; and (3) large motors that are rated higher than 375 kW. While the number of units in the market of the first category far exceeds the other categories, the profile of the cumulative electricity consumption of the categories is quite different. Small motors account for 9% of all electric motor power consumption, medium motors account for 68%, and large motors account for 23%[Ref 2]. Due to its considerable share of electric motor power consumption, medium motors are the focus of the SEAD Global Efficiency Medal competition, as they provide the greatest opportunity to drive significant energy savings.

SEAD Global Efficiency Medal Competition

The SEAD Global Efficiency Medal competition is a global and regional awards recognition program that encourages the production and sale of super-efficient products; a cornerstone activity of the SEAD Initiative. This winner-takes-all (single winner per category) competition seeks to advance efficiency improvements by:

- Recognizing products with the best energy efficiency;
- Guiding buyers who want to purchase the most energy efficient products; and
- Demonstrating the levels of efficiency that are achievable with commercially available and emerging technologies.

By recognizing both induction and new technology motors, this competition aims to accelerate efficiency gains in existing technologies and promotes the introduction of new technologies into the market. This competition complements existing standards and labeling programs in promoting energy efficient products.

With increasing global production of motors, the SEAD Global Efficiency Medal competition is also an opportunity to harmonize performance testing globally. Global harmonization allows more standardized comparison of products available in different markets, which in turn can drive the demand for more efficient products within each market. In addition, global harmonization reduces the burden on manufacturers by allowing them to test once and sell globally and can therefore result in lower prices for those more efficient

[1] The SEAD collaboration for motors has recently initiated a project to devise internationally comparable compliance, certification, and enforcement (CC&E) data definitions, reporting requirements, and scope definitions that reflect commonalities (and differences) among different national and international standards and definitions for electric motors. This project is expected to be completed in January 2014.

products. Through this competition, governments may more readily recognize comparable and transparent test procedures for energy efficient products and through broad adoption of these test procedures make it easier and more cost effective to operate in the global market.

The SEAD Global Efficiency Medal competition for motors launched in June 2013 and will run through November 2013, with winners being announced in September 2014. There are 18 different award categories across 4 international regions, covering both National Electrical Manufacturers Association (NEMA) and International Electrotechnical Commission (IEC) standard induction motors, and new technology motors. The SEAD awards program is led by government representatives from Australia, Canada, India, Japan, Sweden, the United Kingdom, and the United States. The Collaborative Labeling and Appliance Standards Program (CLASP) serves as the Administrator of the SEAD Global Efficiency Medal competition.

Competition Considerations

The primary objective of the SEAD Global Efficiency Medal competition is to drive energy savings by increasing the market share of energy efficient products. Since general purpose AC induction motors between 0.75 kW (1 horsepower [HP]) to 375 kW (500 HP) account for the largest share of power consumption among motors and will continue to dominate the market for price reasons, SEAD seeks to encourage the production of super-efficient motors and realize the efficiency gains in this particular size category.

The last few years have seen the commercial introduction of new technology motors with efficiencies beyond those possible with AC induction motor technology. However, these new technologies still have a significant price premium and/or require an electronic controller for their operation. SEAD seeks to promote new technologies that show promise of being commercially available in the near future through a separate New Technology category in the competition.

Increasing the market share of products is also influenced by shipment thresholds. Given the prevalence of AC induction motors, nominated products in this category are required to have plans to ship a certain number of units within a more immediate time period. The New Technology category nominations are required to become commercially available within two years of winning the SEAD Global Efficiency Medal. The shipment thresholds also ensure that nominated products are not custom-made products or prohibitively expensive.

While innovation is encouraged, it is recognized that the use of standard frame sizes for induction motors is a major benefit when new technologies are being introduced. Accordingly, this competition stipulates adherence to the following accepted norms:

- Continuous rated duty
- Standard frame sizes
- Rated voltage in the range 230 – 600 VAC
- 4 pole speed for induction motors, (tested at 1800 revolutions per minute (RPM) for new technology motors)
- Totally enclosed fan cooled
- Standard torque: speed characteristics

Regional Awards and Differences

The motors competition covers four regions – Australia, India, Europe and North America. . Motors products are not homogenous across the markets within these regions and may differ in both frame sizes and frequency. Generally, the NEMA frame standard dominates the North American markets with motors designed for 60 Hertz (Hz) operations. The IEC frame standard is designed for 50 Hz operations and is the norm in Australia, Europe, and India.

Induction motor efficiency is critically dependent on the mains frequency, as a 50 Hz motor will be larger than an identically rated 60 Hz motor. Therefore the cost effectiveness of achieving a given efficiency will be different. Further, the IEC and NEMA frame sizes do not match exactly; so it may not be possible to replace an IEC motor with a NEMA motor and vice-versa. However, guided by the main purpose of this competition to maximize efficiency gains and energy savings within the respective markets, the SEAD Global Efficiency medal competition targets the most common product categories in each market, i.e. 60 Hz NEMA motors in North America and 50 Hz IEC motors in the other regions. In reality the markets are more complex than this, with different frequencies used in some parts of these regions. (For example, NEMA motors may be made with 50 Hz designs for use in equipment built for export). In addition, the competition includes an IEC category for the North American market in order to allow for comparison of motors globally.

The above choice will inevitably result in nominations that are not entirely comparable, including between the North American NEMA products and the IEC products from the various regions. This situation is a classic example of the significant challenge in designing a global competition: balancing the need for (1) standardization (whether it be product definitions, common test procedures, or eligibility requirements) and the accurate comparison of motor efficiency across markets, and (2) flexibility to address market-specific requirements, such as variations in motor design and sizes, to ensure that winning products represent a significant share of their respective markets.

Part-load Weighted Efficiency

The design of this competition also tried to ensure that the efficiency evaluation criteria accurately represented real-world performance. Although motor efficiency regulations are based on full load efficiency, in practice electric motors spend the majority of time at a lower load.

Accordingly, the SEAD Global Efficiency Medal competition was designed to evaluate efficiency performance of nominated induction motors at part loads using a weighted efficiency scheme (see *Figure 2*). The competition uses an assumed typical load profile, with losses at each load point weighted in proportion to the time spent at each load point. In using a weighted efficiency scheme for this competition, SEAD hopes to encourage the regulators, manufacturers and users alike to consider performance at various load points since evaluating efficiency at the rated (100% load) point is not necessarily representative of real-world usage.

$$\eta_{AVG} = (0.05 \times \eta_{25\%}) + (0.20 \times \eta_{50\%}) + (0.40 \times \eta_{75\%}) + (0.35 \times \eta_{100\%})$$

Where:

η_{AVG} *is the calculated weighted average efficiency;*
$\eta_{25\%}$ *is the efficiency measured at 25% load;*
$\eta_{50\%}$ *is the efficiency measured at 50% load;*
$\eta_{75\%}$ *is the efficiency measured at 75% load; and*
$\eta_{100\%}$ *is the efficiency measured at full load.*

Figure 2. Weighting scheme for part load conditions for induction motors

Award Categories

Induction Motor Size Classes

As previously discussed, the size categories for the competition focused on medium size motors between 0.75 kW (1 HP) and 375 kW (500 HP), as they represent the largest share of electric motor power consumption. Further analysis of North American market data suggested that 5 HP (NEMA 184T) and 15 HP (NEMA 254T) motors represent the greatest energy savings potential, as calculated by the number of units in sales and the expected per unit improvement (Figure 3).

In determining the appropriate IEC induction motor size equivalent to the 5 HP NEMA induction motor, this competition was again faced with the challenge of balancing comparability for a global award while accommodating market-specific trends. In India, 3.7 kW (IEC 112M) motors are more common and generally regarded as the equivalent to 5 HP motors, whereas 4 kW (IEC 112M) motors are more common in Australia and Europe. This could have resulted in a slight disadvantage for the 3.7 kW category compared to the 4 kW motor. Hence, 3.7 kW was established as the size category for India whereas the Australian and European region has a 4 kW (IEC 112M) size category. On the other hand, the IEC equivalent of the 15 HP motor is the 11 kW (IEC 160M) motor size category in all the regions. The best performing IEC induction motor in each size class among all of the award regions will be declared an "international winner" for the size class. A total of up to ten (10) awards will be granted in the IEC Induction Motor Category, with eight (8) regional awards and two (2) international awards,. A total of up to two (2) winners in North America will be granted in the NEMA Induction Motor Category (see *Figure 3*).

		Region				
Category	**Size Class**	Australia	European Region	India	North America	Inter-national
IEC Induction Motor	3.7 kW - 4 kW	•	•	•	•	•
	11 kW	•	•	•	•	•
NEMA Induction Motor	5 HP				•	
	15 HP				•	

Figure 3. Induction Motor Award Categories

New Technology Motor Category

The New Technology Motor Awards are designed to promote the efficiency improvements that are emerging in the market. This competition seeks to showcase IEC motors that achieve the high efficiency IE4 levels and NEMA motors that meet the Premium level+1 efficiency band. While new technologies have already begun to drastically improve efficiency in large motors, few have succeeded in reducing energy consumption of relatively smaller motors. Therefore, SEAD Global Efficiency Medals will be awarded to new technology motors that demonstrate the greatest potential to reduce energy consumption of motors with a maximum output rating of less than 75 kW and 100 HP (see *Figure 4*). Furthermore, the winners in the new technology motor category are required to be commercially available within two years of receiving the SEAD Global Efficiency Medal to ensure that these products will result in meaningful energy savings.

	Region				
Category	Australia	European Region	India	North America	Inter-national
New Technology Motor (< 75 kW)	•	•	•	•	•
New Technology Motor (< 100 HP)				•	

Figure 4. New Technology Award Categories

Shipment Requirements

The purpose of establishing shipment threshold requirements is to ensure that winning products represent a sufficient share of the market to result in significant energy savings. Applicants may nominate products for consideration in any of the four award regions, regardless of the location of the manufacturer of the product, provided that the region sales/availability requirements are satisfied for each product nominated (see *Figure 5*). For example, a product manufactured in Japan and sold globally may be entered in any and all regions.

Minimum Shipments (units)	IEC Induction Motor		NEMA Induction Motor	
	3.7 kW - 4 kW	11 kW	5 HP	15 HP
Australia	1400	500		
Europe	1400	500		
India	1400	500		
North America	420	150	980	350

Figure 5. Minimum projected annual shipment of motors (start date 3 June 2013 to 1 September 2014)

Test Methods

Three major goals of the SEAD Global Efficiency Medal competitions are to support test procedure harmonization, provide internationally-comparable and transparent test results, and support test laboratory capacity building in the participating regions. The competition uses a well-established and internationally accepted test method, when possible, to validate manufacturers' energy efficiency performance claims of nominated products. In the previous SEAD competitions for televisions and computer monitors, this was achieved by utilizing the internationally-accepted test method IEC 62087 Ed.3. However, utilizing a single efficiency test procedure for the electric motors competition is impossible under the design choices described above.

Separate Test Methods for IEC and NEMA Induction Motors

IEC motors are tested using the IEC 60034-2-1 Summation of Losses method whereas NEMA motors in North America are tested against the IEEE 112b test procedure. Therefore, the respective test procedure used in the different regions will be consistent with the test procedure that is appropriate for the market. The test methods are similar and competition officials are considering opportunities to contribute to test procedure harmonization.

IEC 60034-2-1 Revision

Although selecting the IEC test method to verify the efficiency performance of nominated IEC induction motors appeared to be relatively simple, there were a number of complications. The IEC is currently in the process of revising the IEC 60034-2-1 test method, which was previously published in 2007. Industry stakeholders and international policy makers alike strongly recommended that the SEAD Global Efficiency Medal competition use the revised test method in performing verification testing since the 2007 version does not thoroughly outline testing protocols and can cause problematic variances in test results. Unfortunately, the revision of IEC 60034-2-1 is not scheduled to be finalized and published until February 2014, well after the launch of this competition.

Many of the issues found in IEC 60034-2-1:2007 have been addressed by the International Energy Agency's Efficient Electrical End-use Equipment program Electric Motor Systems Annex (IEA-4E EMSA) *Guide for the Use of Electric Motor Testing Methods Based on IEC 60034-2-1, Version 1.1* (heretofore referred to as the "EMSA Guide") [Ref 3]. The IEC has incorporated much of the EMSA Guide in its revision of IEC 60034-2-1. Therefore, this competition adopted IEC 60034-2-1:2007, Summation of Losses Method and followed the methodology and sequencing detailed in the EMSA Guide to validate the energy efficiency performance of nominated IEC induction motors.

New Technology Motor Test Methods

There are no established test methods for measuring the efficiency performance of new technology motors. Hence, this competition utilizes direct output:input test methods and includes loss measurements within any electronic controller. Because there are slight differences between new technology motors that are built with output ratings measured in kilowatts and those measured by horsepower, this competition utilizes different, but very similar test methods for each award category, as shown in *Figure 6*. For new technology motors with a maximum output of 75 kW, efficiency is measured using the IEC 60034-2-1:2007 Direct Test Method: Out/Input. Nominated new technology motors with a maximum output of 100 HP are measured using the IEEE direct input-output test method, IEEE Standard 112, Efficiency Test Method A.

Award Category	Test Method
IEC Induction Motor	IEC 60034-2-1:2007, Summation of Losses Method
NEMA Induction Motor	U.S. Department of Energy test procedure for Electric Motors and Small Electric Motors, as specified in 10 CFR part 431
New Technology Motor (< 75 kW)	IEC 60034-2-1:2007, Direct Test Method: Out/Input
New Technology Motor (< 100 HP)	IEEE Standard 112, Test Procedure for Polyphase Induction Motors and Generators, Efficiency Test Method A, Input-Output

Figure 6. Test methods to be used for measuring motor efficiency

Test Laboratory

Nominated products are expected to be fairly similar in terms of energy efficiency. In order to eliminate any testing variations between the motors, SEAD will test all nominated motors in a single laboratory to verify manufacturers' energy performance claims.

Winners Selection and Desired Outcomes

Manufacturers are invited to nominate energy efficient induction and new technology motors through 29 November 2013. CLASP, as the competition Administrator, will identify the presumptive winning models based on each product's claimed efficiency performance. Randomly selected samples of these models will then undergo testing to verify energy performance claims. Upon completion of verification testing, nominated products whose efficiency performance is successfully validated will be awarded SEAD Global Efficiency Medals.

As challenging as it was to design a global competition for motors that accommodates both internationally-standardized and market-specific requirements, the program design process provided significant insight for the governments responsible for overseeing the SEAD Global Efficiency Medal competition. It is hoped that the lessons learned and data that result from this competition will accelerate international efforts to harmonize existing regulations for induction motors, and will result in an internationally-accepted efficiency test method for new technology motors. The ultimate objective, however, is that this competition will incentivize (1) buyers to purchase these award-winning motors, and (2) manufacturers to produce highly efficient medium electric motors, thereby achieving market transformation and significantly reducing motor energy consumption globally. SEAD also hopes this competition will result in additional spill-over benefits, such as more stringent energy efficiency standards and labels and test laboratory capacity building.

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Ten Years of Minimum Efficiency Standards for Induction Motors in Brazil: From Standards Class until Super Premium Motors

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Abstract

The year 2012 marked the 10th anniversary of publication of Presidential Decree no. 4508/2002, which set forth minimum efficiency standards for induction motors in Brazil. Within this context, the present article focuses on the importance of implementing minimum efficiency standards in Brazil and elsewhere and presents the state of the art in domestic and international legislation and standards pertaining to induction motors. It also covers advancements in motor technology, by means of an analysis of motors currently on the market, and trends in said technology, with particular emphasis on the search for new materials for permanent magnet manufacturing. The results of experimental testing of a permanent-magnet motor and a Premium-efficiency induction motor are presented and discussed, with the objective of contributing to definition of the IE4 standard and to the goal-oriented Brazilian efficiency program. The present article described the results of experimental testing with an induction motor and a line-start permanent-magnet motor and concluded that permanent-magnet motors are superior in performance to induction motors at loads between half and full, with an efficiency advantage of up to 6.7%. However, in applications with wide variations in load, with motor operation below half load, use of permanent-magnet motors is not economically feasible, as the current cost of these motors exceeds that of induction motors. Another relevant finding concerns the current harmonic distortion observed during testing. The tested permanent-magnet motor exhibited a distortion of up to 13.5%, exceeding IEEE 519/2001-recommended limits. This behavior must be clearly specified and taken into account by future standards that define the Super Premium class, lest the impact of harmonic distortion prove detrimental to industries that adopt these motors for their processes.

I. Introduction

Electric motors account for over half of total electricity consumption in the majority of countries—approximately two-thirds of all electrical power used by the industrial sector and just under half of that used by the household and commercial sectors. By way of example, the annual expenditure on driving of electric motors is estimated at US$100 billion in the U.S. alone [1]. In Brazil, industry accounts for a large portion of total electricity consumption: as of 2010, 44.5% [2]. Electric motors, in turn, account for 68% of this use (116 GWh/year) [3]. In this scenario, the establishment of minimum efficiency standards for induction motors is a relevant strategy for reduction of electricity consumption. In Brazil, the initial framework for these standards was laid down in 2002, with the publication of Presidential Decree no. 4508 [4].

Induction motors are characterized by their relatively simpler construction as compared with other motors. The principles of electric motor operation resemble those of transformers; the term induction refers to electric current induced at the rotor by the stator. Electric motors convert electricity into mechanical energy; as in any conversion process, some energy is lost. When an electric motor converts electricity, it is first converted into magnetic energy, which is in turn converted to mechanical energy when the magnetic field formed interacts with the stator and rotor. These magnetic fields are produced by windings at the rotor and stator. An electric motor will also include a cooling system to dissipate heat at the windings, iron core, and bearings.

Most induction motors currently on the market have a squirrel-cage rotor, in which the winding is made up of conductive bars set into grooves on the rotor shaft and shorted at both ends by conductive rings [11][12]. As energy flows through the stator winding to the rotor winding, power is lost at the following sites: stator winding, stator core, rotor winding, rotor core, cooling system, and motor bearings. The five major types of motor losses are:

-stator resistance: influenced by motor voltage rating and starting requirements. The higher the terminal voltage, the thicker the winding insulation and the smaller the winding wire—and, consequently, the higher the stator resistance.

-rotor resistance: determined by rotor groove size and conductive bar material;

-core losses: factors contributing to core losses include type of electrical steel, power supply frequency, and air-gap flux density.

A critical aspect of motor design is the ratio of copper losses to iron losses. Copper losses correspond to the electrical power lost at the motor windings, whereas iron losses refer to power lost at the motor core;

-fan and friction losses: motor speed and type of cooling system will influence losses at the fan and friction losses; consequently, losses are less significant in motors with fewer poles, and machines running at a frequency of 60 Hz exhibit greater losses than machines running at 50 Hz;

-stray losses.

According to Li and Curiac [15], between the end of World War II and the early 1970s, there was a trend toward manufacturing of largely inefficient motors, due to restricted use of raw materials such as copper, aluminum, silicon steel, etc. These motors were smaller than their predecessors and their initial cost was low, but operating costs were high. When electricity prices began rising rapidly in the mid-1970s, most of the major motor manufacturers introduced high-efficiency motor ranges. These motors feature an optimized design, electric and magnetic circuits that minimize losses, and higher-quality materials. High-efficiency motors are constructed in much the same manner as the aforementioned motors, but include optimizations at the major sites where loss occurs, reducing losses by up to 30%. The modifications included in high-efficiency motors are [13]:

- Higher copper content of stator windings;

- Optimized groove design;

- Oversized rotor bars;

- Lower magnetic field intensity;

- High-quality magnetic strips;

- Proper bearings;

- Optimized fans;

- Homogeneous air gap;

- Improved insulation.

Nevertheless, high-efficiency motors may be disadvantageous in certain settings [13][7]. The cited authors note that use of high-efficiency motors is infeasible in low-utilization factor applications and that improved analysis is required for use of these motors with high inertia loads, depending on the operating cycle. Furthermore, depending on motor design, increased efficiency may decrease the power factor, as losses contribute partially to active power. Use of high-efficiency motors in pump and fan applications is also considered disadvantageous, as lower rotor resistance increases speed under nominal conditions, increasing power consumption [13][14].

The following sections will address current legislation and standards defining minimum efficiency levels for induction motors in Brazil, the U.S. and Europe, describe the current state of the art in induction motors, and provide an analysis of the impact of the introduction of permanent-magnet motors as replacements for three-phase induction motors and the potential implications of this introduction for the Brazilian government's energy efficiency program.

II. Laws and Standards for Electric Motors

In the early 1980s, some U.S. manufacturers introduced induction motors that performed more efficiently than those marketed before. However, there were no standards or technical recommendations defining energy efficiency classes for such motors. Within this context, in 1987, the U.S. began to develop specific laws that defined minimum efficiency standards for induction electric motors.

To provide a broader outlook on the importance of standardization of efficiency ratings, Table I lists a selection of countries that defined minimum efficiency standards as a public policy strategy for energy conservation [5][6]. The table described whether each country has a defined standard, whether a motor test procedure is employed, whether the standard is mandatory and which efficiency classes have been adopted.

Table I. Worldwide legislation on minimum efficiency of induction motors.

Country	Test procedure	Mandatory standard	Efficiency class
USA	Yes	Yes	P /HE
European Union	Yes	No	P /HE
Canada	Yes	Yes	HE
Mexico	Yes	Yes	HE
Australia	Yes	Yes	HE
New Zealand	Yes	Yes	HE
South Korea	Yes	No	HE
Brazil	Yes	Yes	HE
China	Yes	No	HE
Costa Rica	No	Yes	STD
India	Yes	No	STD/HE
Israel	Yes	Yes	STD

STD-Standard; HE- High Efficiency; P-Premium.

Among these countries, the U.S., Canada and Mexico—which began implementation of their standards as early as the 1990s—stand out. The definition of a specific motor test procedure is an essential factor, as different test procedures may yield different efficiency ratings [9][10]. Another relevant factor is whether compliance with standards is mandatory or optional, as in some countries, compliance with energy efficiency standards is voluntary. In Brazil, for instance, mandatory regulations exist for induction electric motors, but for other devices, such as air conditioners, compliance with minimum efficiency standards is voluntary, as consumers are expected to choose the product that consumes the least energy. Efficiency classes are another essential factor, and are also dynamic, as they are updated periodically and, in practice, achievement of an efficiency class is often used as a goal; this, in fact, is one of the purposes of the Brazilian goals program [7], in analogy to the NEMA and IEC standards, which began with the Standard efficiency class and now extend to the Premium class.

The establishment of such standards is characterized by a protracted implementation period, as it entails implementation of changes to productive processes, replacement of raw materials, and liquidation of existing stocks. The following sections provide an overview of the standardization process in the U.S., European Union, and Brazil.

A. United States

Standardization of electric motors began in the United States, with National Electrical Manufacturers Association (NEMA) Standards Publication MG1-1987. This publication gave rise to the U.S. Energy Policy Act (EPAct) of 1994, which would enter into force as a mandatory standard in 1997. The NEMA Premium standard was published for voluntary compliance in 2001 and became mandatory in December 2010, pursuant to the Energy Independence and Security Act (EISA) of 19 December 2007, which adopted the NEMA Premium standard as a reference. Many other voluntary recommendations exist, such as IEEE 841-2001, which defines efficiency standards for motors designed for use in the petroleum and chemical industry.

Table II lists the EPAct, IEEE 841-2001, and NEMA Premium efficiency standards.

Table II. Comparison between standards for 4-pole motors

Power (hp)	EPAct	IEEE 841-2001	NEMA Premium
1	82.5	84.0	85.5
1.5	84.0	85.5	86.5
2	84.0	85.5	86.5
3	87.5	88.5	86.5
5	87.5	88.5	89.5
7.5	89.5	90.2	89.5
10	89.5	90.2	91.7
15	91.0	91.7	91.7
20	91.0	91.7	92.4
25	92.4	93.0	93.0
30	92.4	93.0	93.6
40	93.0	93.6	93.6
50	93.0	93.6	94.1
60	93.6	94.1	94.5
75	94.1	94.5	95.0
100	94.5	95.0	95.4
125	94.5	95.0	95.4
150	95.0	95.4	95.8
200	95.0	95.4	96.2

B. European Union

In Europe, a landmark in standardization was the standard developed by the European Union and the Committee of European Manufacturers of Electrical Machines and Power Electronics (CEMEP) in 1998. The standard established three efficiency classes for motors sold on the EU market: Eff 1 (high efficiency), Eff 2 (standard efficiency) and Eff 3 (other motors).

In 2008, the International Electrotechnical Commission (IEC) published standard 60034-30, which set forth three efficiency classes—IE1, IE2 and IE3—as part of the so-called IE-Code and proposed class IE4. The acronym “IE” stands for International Energy Efficiency Class. In addition to defining minimum efficiency levels, this standard sought to harmonize the different efficiency classes defined for electric motors. For motors with a nominal frequency of 50 Hz, classes IE1 (standard efficiency) and IE2 (high efficiency) are based on CEMEP-UE standard Eff2 and Eff1 limits respectively. Limits for class IE3—Premium efficiency—represent losses of 15 to 20% less than those of the IE2 standard. For motors with a nominal frequency of 60 Hz, class IE1 limits are based on Brazilian regulations and class IE2 and IE3 limits are based on the 2007 U.S. EIAS standard.

Classes IE1, IE2, and IE3 are currently in force. Class IE4, which recommends limits for Super Premium motors, has yet to come into force; this is expected to occur with the next revision of the 60034-30 standard.

C. Brazil

Since Presidential Decree 4508 of 11 December 2002, Brazil has adopted minimum efficiency standards for three-phase induction motors. This standardization culminated in Inter-Ministerial Ordinance 553 of 8 December 2005, which ruled that only high-efficiency motors could be manufactured in the country 4 years after its entry into force and gave manufacturers an additional 6 months to liquidate their existing stocks, thus making high-efficiency motors mandatory in Brazil as of

January 2010. Table III provides a timeline of Brazilian legislation and government decrees pertaining to the energy efficiency of three-phase induction motors.

Table III. Timeline of the regulation of induction motor efficiency in Brazil.

Year	Law / Decree
2001	Law 10.295: Establishes a national policy for the conservation and rational use of energy.
2002	Presidential Decree 4508: Defines minimum energy efficiency levels for three-phase induction motors, dividing them into standard-efficiency and high-efficiency ranges.
2005	Inter-Ministerial Ordinance 553: Establishes new minimum efficiency levels for induction motors, eliminating the distinction between standard-efficiency and high-efficiency ranges.
2009	INMETRO Ordinance 243: Approves requirements for compliance assessment of three-phase induction electric motors.
2010	INMETRO Ordinance 488: Approves revised requirements for compliance assessment of three-phase induction electric motors.

The efficiency levels defined in Ordinance 553/2005 are currently enshrined in ABNT/NBR standard 17094/2008, - Máquinas elétricas girantes - Motores de indução - Parte 1: Trifásicos [Rotary Electric Machines – Induction Motors – Part 1: Three-Phase], which establishes minimum requirements for three-phase induction motors. Methods for calculation of efficiency and power factor are set forth in ABNT/NBR standard 5383-1/2002, Máquinas Elétricas Girantes – Parte 1. Motores Trifásicos – Ensaios [Rotary Electric Machines – Part 1. Three-Phase Motors: Assays].

The first-ever minimum efficiency ratings established in Brazil were developed in 1998; compliance was voluntary. These ratings served as a basis for the Procel energy efficiency labeling program.

According to Soares, 2006 [7], the Brazilian regulatory framework was based on the following guidelines:

- Broad scope: the Brazilian legal framework stands out from that of other countries for its broad scope, covering approximately 80% of all motors available on the market;

- Lessons learned from North American regulatory framework: establishment of U.S. regulations, which took 2 years, was a very well-documented process. These documents served as guidance for Brazilian policy makers, helping prevent some challenges which, otherwise, would have most likely arisen;

- Secure previous gains: ensure the continuity of advances made as a result of voluntary improvements during the 10 years preceding mandatory compliance with standards, preventing setbacks.

Furthermore, according to [7], Brazil and the U.S. have the strictest efficiency testing standards. Another innovative aspect of the Brazilian regulatory framework is its goals-based program, which provides a mechanism for progression of efficiency standards and includes a survey on domestic experience in the manufacturing of high-efficiency motors in an attempt to identify technological barriers, particularly those imposed by the need for steel alloys with better electromagnetic properties.

The standardization of minimum efficiency requirements is a variable that influences the electric motor market (even if indirectly) and has implications for the search for novel technologies by manufacturers. The following section covers technological advancements in induction motors.

III. Technological Advancements and Energy Efficiency in Electric Motors

Induction motors have been in use for two centuries, and yet, they are still at the state of the art in terms of development. Technological advancements in induction motors mostly involve efficiency and power density (mechanical power output in relation to motor size), although the shape, materials, cooling systems, drive systems, and control systems of these motors have also evolved.

In the 1970s, technological advancements were mostly driven by shortages in raw materials, which led to a need for optimization of energy consumption. This need persists, although for different reasons, and current trends in advancement include the use of novel materials and the replacement of induction motors with synchronous permanent-magnet motors, in view of the superior efficiency of the latter.

A. Premium Motors

Premium motors constitute the first advancement in high-efficiency motors, with improvements brought about by the use of higher-quality materials and optimized designs, particularly with regard to heat dissipation. The advent of Premium motors was a consequence of the U.S. policy of minimum efficiency standards for induction motors, as described in section 2 of this article. According to Kreith and Goswami [1], Premium motors command a 15–25% cost premium over EPAct “Standard” motors, which translates into an additional cost of $8–40/hp. Regarding return on investment, when used for novel applications and with a high number of duty hours, ROI is usually reached in 4 years after switching from EPAct-standard motors to Premium motors and in 2 years if switching from legacy standard-efficiency motors to Premium motors.

B. Super Premium Motors

With constant advancements in induction motor manufacturing techniques, current standards are gradually being exceeded. In 2010, NEMA Premium compliance became mandatory; in parallel, the IEC published the level IE3 standard and suggested level IE4. These initiatives will pave the way for further advances in standardization, as well as for the natural struggle for market share among manufacturers.

Current research in the field of induction motor manufacturing focuses mostly on the use of cast copper rotors instead of aluminum rotors and improved steel rolling. According to Malinowski et al, 2004 [8], the use of copper rotors minimizes loss, as the conductivity of copper is approximately 60% superior to that of aluminum. Table IV shows the results of testing of a 15-hp motor by Malinowski et al, 2004 [8].

Table IV. Comparison of motor losses [8].

	Aluminum (W)	Copper (W)
Stator loss	507	507
Core loss	286	286
Rotor loss	261	157
Fan and friction loss	115	72
Stray loss	137	105
Total	1306	1127

The table shows that changes in rotor material can yield an overall loss reduction of 35%, distributed across rotor losses (39%), fan and friction losses (37.4%), and stray losses (23.4%).

C. Permanent Magnet Motors

In recent years, synchronous motors have arisen as a more efficient alternative to induction motors. This was made possible mostly due to increases in power density, which, in turn, were achieved with the use of novel magnetic materials starting in the early 2000s. Increasing research and development of permanent magnet motors has been underway since the 1990s, driven by a scarcity of specific resources (rare earth elements) and by the need for improved efficiency of electric motors in response to growing energy saving requirements. The main focuses of research were improvements in efficiency, magnetic designs, torque, and environmental advantages over induction motors [15]. With the achievement of technological advancements and cost reductions in permanent magnet materials between 2008 and early 2010, permanent magnet motors with power densities equivalent to those of induction motors began to appear on the market. Most of these early models fell into one of two categories: traditional synchronous motors or synchronous squirrel-cage motors, also known as line-start permanent-magnet (LSPM) motors [15][16]. Although these are not induction motors, they are rated Super Premium, as their efficiency exceeds that of Premium motors currently on the market.

According to Almeida et al [17], more information on the performance of these motors is still required, as is further development of more efficient drive and control technologies. Melfi et al [15] note that the current (and future) market for electric motors favors high power density, operational efficiency, variable speed, and low cost. Permanent magnet motors are currently able to meet these expectations. In many industrial applications, motor size and inertia are critical. Motors with a high power density may provide a performance advantage in applications such as paper production, but high power density cannot compromise reliability and efficiency. Furthermore, increased energy deficiency is desirable, as are low noise and the ability to operate at variable speeds. In view of improvements in the magnetic and thermal properties of permanent magnet materials over the past 20 years and substantial recent cost reductions, particularly between 2008 and 2010, synchronous permanent magnet motors now constitute economically viable alternatives.

Permanent magnets have been employed in motion control motors for many years. Over the last four decades, magnetic materials have undergone substantial changes related to the cost of their basic chemistry. Materials are now available that provide much higher power densities, enabling manufacturing of high-efficiency motors. Figure 1, below, lists the main materials used in permanent magnet manufacturing and their respective maximum operating temperatures.

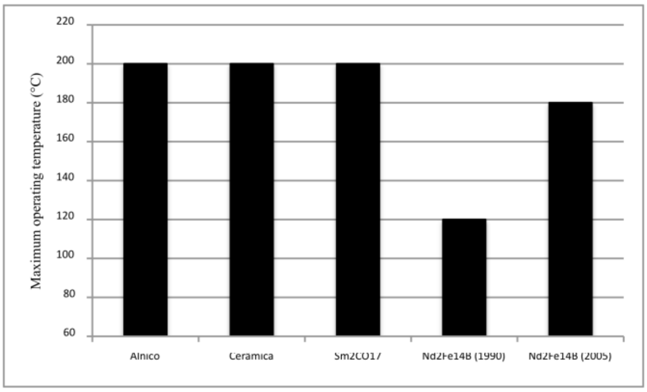

Figure 1. Operating temperature of permanent magnet materials.

The price of neodymium has varied widely in recent years [16], as the following figure shows. The cost of neodymium rose 106% between 2010 (US$31/kg) and February 2011 (US$64/kg). This valuation is attributable to high demand and limited supply [16][19].

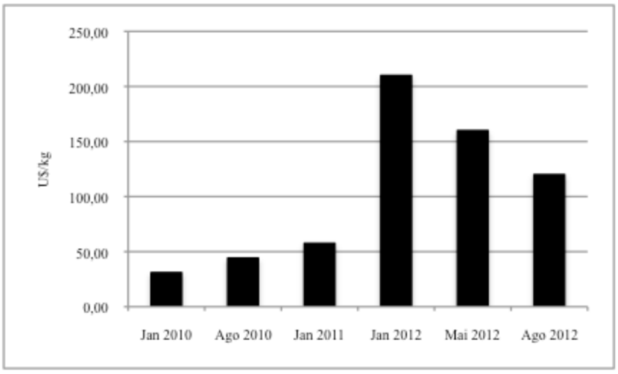

Figure 2. Fluctuations in the price of neodymium.

The high demand for rare earths is justified, as they are used in the manufacturing of computing devices (particularly tablet displays) and photovoltaic panels and as components in so-called super magnets, an essential feedstock for the manufacturing of permanent-magnet machines. In addition to the low supply/high demand issue, rare earth output is dominated by China, which accounts for 97% of the worldwide output of these elements. Brazil ranks third in production of rare earth elements, but this accounts for only 0.4% of worldwide output, as shown in Table V [16].

Table V. Worldwide rare earth output, 2011.

Country	Output (tons)	Output (%)
China	130,000	97.32
India	3,000	2.25
Brazil	550	0.41
Malaysia	30	0.02

Within the context of this limited supply and highly concentrated output, research on the use of other materials, such as layered ferrite [20][21], instead of rare earths for permanent-magnet motor manufacturing has yielded encouraging results. According to Petro, 2011 [21], this can be achieved with the use of geometries that enable concentration of magnetic flux from ferrite components, which gives permanent-magnet motors made with such components the ability to reach efficiency and power density levels similar to those of rare-earth permanent magnet motors, but at lower cost and bypassing raw material availability concerns. The following section presents the results of the use of standardized efficiency ratings, including the findings of studies on expected savings and the current impact of standardization actions.

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The following section presents the results of the use of standardized efficiency ratings, including the findings of studies on expected savings and the current impact of standardization actions.

IV. RESULTS OF MINIMUM EFFICIENCY STANDARDS IMPLEMENTATION

According to a study by Cardoso, 2009 [23], of 12.9 million motors in current use, for a total energy consumption of 120 TWh, the replacement of standard-efficiency motors with high-efficiency motors in Brazil may provide actual savings of 428 GWh and potential savings of 551 GWh.

The potential for electricity savings with implementation of minimum efficiency standards in Brazil was also estimated by Garcia [22], using 2002 standards as a basis. The Garcia et al. estimate was based on the premises that the average motor used in Brazilian industry has a power of 7.5 hp, operates at 75% of nominal load for 2000 h/year on average and has a service life of 12 years. Replacement with standard-efficiency motors could achieve estimated savings of 86.11 GWh/year, and replacement with high-efficiency motors, savings of 1.58 TWh/year. From the aforementioned energy savings scenarios, Garcia et al [22] inferred several potential implications for the Brazilian electric motors market, such as:

- Limitation of buyer choices, enabling expansion of the market for a single range of motors;

- Need for manufacturer investment in migration of production lines and reorganization of raw material logistics;

- Increased motor manufacturing costs. As of 2003, the manufacturing costs of a high-efficiency motor in Brazil were 25% higher than those of a standard-efficiency motor.

In reality, regulation provided a minimum standard for domestic manufacturers, which have continued to diversify their product ranges. There is indeed a continuous need for adaptation of production ranges, particularly due to the introduction of permanent-magnet motors. Some influence on the foreign market cannot be ruled out, as Brazilian efficiency standards are essentially those employed by U.S. manufacturers, which may facilitate sale of Brazilian-made motors overseas. Currently in Brazil, is the sale of electric motors from the high efficiency to super premium level. As the data presented in Figure 3.

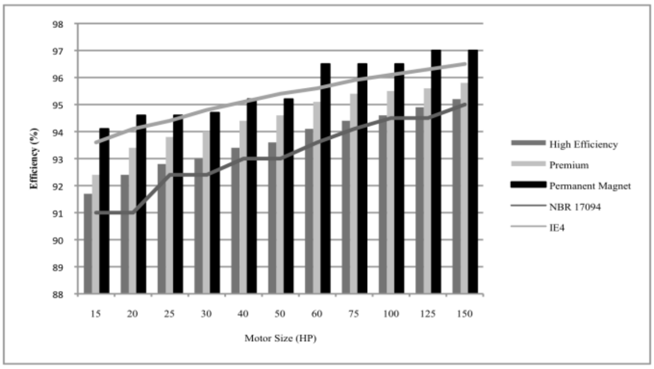

Figure 3. Efficiency of 15–150 hp motors available on the Brazilian market.

VI. Comparative Testing of an Induction Motor and a Permanent Magnet Motor

This section presents the results of comparative testing between an induction motor (IM) and a line-start permanent-magnet motor (LSPM), with the objective of contributing to development of the IEC 60034-30 standard and of the goal-oriented Brazilian efficiency program.

Both test devices were Brazilian-made 1-hp, 4-pole motors. The IM had a nominal efficiency of 82.8%, nominal current of 2.9 A and speed 1725 rpm. The permanent-magnet motor had a nominal efficiency of 87.4%, nominal current of 3.08 A and speed 1800 rpm. The test itself consisted of application of decreasing loads to each motor, starting at 150% of nominal load and ending at no-load condition. Motors were operated under no load for 60 min before testing, so as to ensure stable temperature at the start of data collection.

A Foucault-type eddy current brake was used to vary the load applied to the tested motors. The following test devices were employed:

-Motor analyzer – Explorer 3000(Manufacturer: SKF);

-Electromagnetic brake (Manufacturer: Equacional Electromechanical);

-Power quality analyzer - Fluke 435 (Manufacturer: Fluke);

-Torque and speed meter (Manufacturer: HBM);

-AC power source (Manufacturer: Equacional Electromechanical).

Motors were loaded at 150%, 125%, 100%, 75%, 50%, 25%, and 0% of nominal load and the following parameters were measured in descending order: line voltage (V), line current (A), input power (W), speed (rpm), torque (N·m), THDv (%), and THDi (%). The results are summarized in Table VI.

Table VI. Results.

Parameter	Load (%)						
	150	125	100	75	50	25	0
I_{MIT} (A)	4.7	3.8	3.0	2.4	2	1.7	1.6
I_{LSPM} (A)	4.0	3.3	2.8	2.4	2.2	2.1	2.0
P_{MIT} (kW)	1.6	1.3	0.9	0.7	0.5	0.2	0.1
P_{LSPM} (kW)	1.4	1.1	0.9	0.7	0.5	0.3	0.1
$THDi_{MIT}$ (%)	3.2	3.7	4.8	6.1	7.8	9.9	7.3
$THDi_{LSPM}$ (%)	8.8	8.0	9.2	12.7	13.5	10.3	7.7
η_{MIT}	70.5	74.9	78.9	81.3	81.4	75	56
η_{LSPM}	82.1	84.5	85.6	85.4	82.5	70.3	40.1

Above nominal load, current levels were lower in the LSPM than in the IM (Figure 4). However, as load was lightened, current values gradually rose and eventually exceeded those measured in the IM.

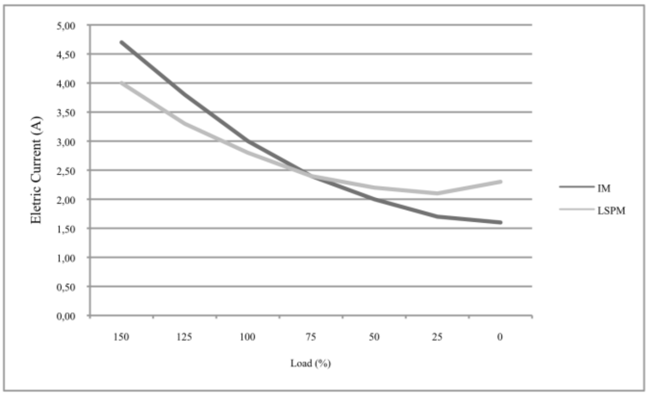

Figure 4. Comparative analysis of current levels.

Throughout the load range, THDi remained higher in the LSPM than in the three-phase induction motor. THDi levels were also significant, as the impact of the distributed use of a motor with such distortion levels across an industrial plant could lead to power quality issues throughout the entire facility.

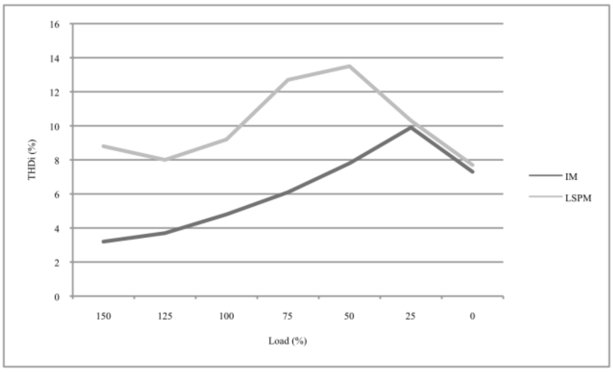

Figure 5. Comparative analysis of current harmonic distortion.

Regarding efficiency, observe in Figure 6, the LSPM was superior to the IM from overload through half-load, with efficiency declining thereafter, until it became less efficient than the IM when under <25% loads. LSPM efficiency was superior at the top end of the operating range, but inferior at 25% load and below. This is a relevant finding, as it entails increased power consumption in variable-load applications.

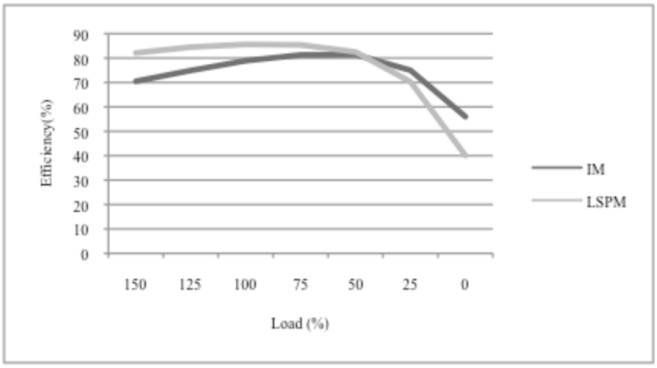

Figure 6. Comparative analysis of efficiency.

VII. CONCLUSION

Electric motors account for a substantial portion of the electricity consumed by the industrial sector. Hence, they constitute an interesting instrument for dissemination of an energy-efficient culture, as operationalized by minimum efficiency standards; in Brazil, a mandatory set of such standards was published on 11 December 2002. Contrary to the predictions of some studies, standardization did not restrict the choice of electric motors available to consumers; in fact, some IE4-rated (Super Premium) motors, in compliance with the IEC 60034-30 standard, are already available on the market.

Nevertheless, as the standard itself warns, in-depth studies and analyses are required before this class of motor is made available to manufacturers. Within this context, the present article described the results of experimental testing with an induction motor and a line-start permanent-magnet motor and concluded that permanent-magnet motors are superior in performance to induction motors at loads between half and full, with an efficiency advantage of up to 6.7%. However, in applications with wide variations in load, with motor operation below half load, use of permanent-magnet motors is not economically feasible, as the current cost of these motors exceeds that of induction motors.

Another relevant finding concerns the current harmonic distortion observed during testing. The tested permanent-magnet motor exhibited a distortion of up to 13.5%, exceeding IEEE 519/2001-recommended limits. This behavior must be clearly specified and taken into account by future standards that define the Super Premium class, lest the impact of harmonic distortion prove detrimental to industries that adopt these motors for their processes.

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Measuring & Maintaining Energy Efficiency
Effective Metering plus Effective Management

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Abstract

ISO 50001:2011 Energy management systems — Requirements with guidance for use **.** [1]
This is based on the well known "Plan — Do — Check — Act" principle. Applying it to a Motor Driven System, you need effective measurement — Metering.

ISO 50001 deals with Energy Management Systems, which is just a branch or form of overall management. Like all management systems, it needs the correct Inputs; without these, a management system cannot make the right decisions – namely generate the correct Outputs.

So if a financial management system cannot operate without detailed accounting for income & expenditure, how can an Energy Management System operate without the necessary metering & monitoring ?

The presentation will look at ISO 50001, its application to Motors and at how best to ensure that the input into the ISO 50001 system is the necessary valid data — focussing predominantly on the application of electricity metering:

- How web-enabled meters allow remote monitoring of Motor Driven Systems;
- How a single Meter can monitor up to 60 FHP motors.

The author has over 35 years experience in Energy Management, particularly in metering. He is a member of the European Committee that wrote EN 16001, and of ISO TC242 [2], which is responsible for the ISO 5000x series of standards. He also acts as liaison between IEC & ISO on subjects related to Energy Management. In this work, he acts on behalf of ESTA (Energy Services & Technology Association). [3]

Management Standards

Management standards provide structure and continuity to their field of activity. Though not suggesting that Energy Management Systems have not operated successfully in the past, they have been very dependant on personnel; the departure of a good manager could lead to the loss of several years of energy savings. ISO 50001 provides a systematic structure, thus providing continuity.

ISO 9000, the first ISO Management Systems standard, was published in 1987. It was based on the BS 5750 series of standards which were proposed to ISO in 1979. However, its history can be traced back some twenty years before that, to the publication of the United States Department of Defence MIL-Q-9858 standard in 1959. MIL-Q-9858 was revised into the NATO AQAP series of standards in 1969, which in turn were revised into the BS 5179 series of guidance standards published in 1974, and finally revised into the BS 5750 series of requirements standards in 1979 before being submitted to ISO.

This was followed in 1996 by the ISO 14000 family dealing with Environmental Management, based on BSI 7750. Other Management System Standards followed including ISO 27001 on Information Security.

In 2006, work started in Europe on the first Management System Standard dealing with Energy Efficiency — EN 16001. This was based on existing national standards, such as the Irish IS 363:2005, Danish DS 2403 & Swedish SS 627750. In order to make application simpler, the structure followed ISO 14001. EN 16001 was formally published in 2009.

Background to ISO 50001

Work on ISO 50001 started in late 2008. The decision had been taken that this standard should follow the structure of ISO 14001. As such, EN 16001 and the recently revised ANSI 2000 (revised so that its structure followed ISO 14001) provided material for the initial drafts. Notice was also taken of other national standards, including documents from China, Korea & Thailand and the UK PAS 99:2006.

The first edition of ISO 50001 was published in 2011; EN 16001 was withdrawn the following year; although there were some minor differences between the documents, it was felt that these were so small that 50001 could be considered a suitable replacement.

Status of ISO 50001

ISO 50001 can be considered as a framework which other standards, from whoever source, can reference. ISO TC 242, which authored ISO 50001, is concerned with the generic requirements of Energy Management; specific requirements for different product groups are the responsibility of the specific product committees — ISO, IEC or other as applicable.

Five associated standards are in development:

- 50002 Energy audits
- 50003 Energy management system audits and auditor competency
- 50004 Guidance for the Implementation, Maintenance and Improvement of an EnMS
- 50006 Energy Baseline General Principles and Guidance
  Energy Performance Indicators (EnPIs) General Principles and Guidance
- 50015 Monitoring, measurement, analysis and verification of organizational energy performance

There are further projects under consideration, but there is a significant lack of the necessary experts

Figure 1
ISO 50001 Standards

Structure of ISO 50001

ISO 50001 is based on the well known “Plan, Do, Check, Act” principle introduced in ISO 9000, but specifically applied to Energy Management.

There is an Annex which provides some basic help with implementation, and a table showing correspondence between 50001 and some of the other ISO Management Standards.

The future standards are designed to help with the implementation of the Management System.   For the Energy Specialist, there will be standards on Management Systems; and vice versa for the Management Specialist.

The key is in Section 4: Energy management system requirements.   A large part of this obviously deals with management operations and requirements, but the heart is in Clause 4.6.1: Monitoring, measurement and analysis.;

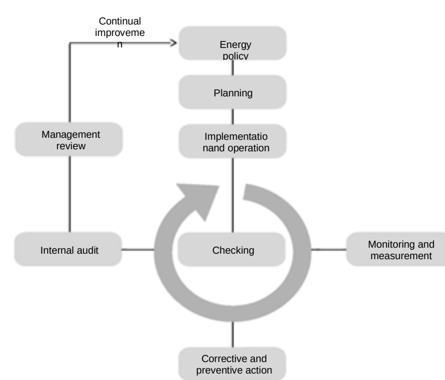

Figure 2
ISO 50001 “Plan Do Check”
(ISO 50001, Fig. 1)

ISO 50001, Clause 4.6.1

Monitoring, measurement and analysis

The organization shall ensure that the key characteristics of its operations that determine energy performance are monitored, measured and analysed at planned intervals.
Key characteristics shall include at a minimum:

a) significant energy uses and other outputs of the energy review;

b) the relevant variables related to significant energy uses

Thus, if compliance with ISO 50001 is being sought, it is effectively impossible to achieve without suitable measurement & metering – particularly in the case of motors. There also needs to be systems for collecting and storing this data; and for analysis. In addition the "*relevant variables related to significant energy uses*" (commonly called Drivers) need to be identified, measured and stored. For a manufacturing plant, this may be as simple as the production volume while for offices however, a better measure would typically be Degree Days. For a pump, it would be volume, head & temperature (as this may affect viscosity). This data can be measured or can be obtained in a general manner from various sources via the web. For Degree Days, customised data commissioned from certain organisations.

A point to note is that repeatability of measurement is far more important than absolute accuracy; it is the comparative change that is important. Also, for electricity meters, the working life is over 10 years so regular re-calibration is not a need. If something is to go wrong, the most likely result is a total failure of the meter.

A Practical Approach

When applying ISO 50001 with the intent of reducing energy consumption, rather than just gaining another certificate, there are five key questions that need to be answered:

- Why do we use so much ?
- What do we do with it ?
- Who uses what ?
- Where is it used ?
- When is it used ?

To answer these questions, the overall consumption figures provided by the main meter need to be disaggregated; namely by fitting sub meters across the site together with a system for collecting and storing the data, and some method of analysing the results. However, if this is to be successful, it requires the full commitment of senior management. Responsibility needs to be devolved down to the relevant managers who need to be assured that not only are they responsible for the energy consumption of their departments, but they also have the necessary authority for control of this and are accountable for the results. Without all of this, the whole operation is likely to be a total waste of time, money & other resources.

Metering Plan

A metering plan is essential. The topography of the energy distribution system needs to be mapped and matched to the management structure such that each metered sector is under the control of a defined manager. He has the management information he needs (including meter readings) to control his department, he is responsible for the consumption and has the authority to control it.

Typical metering plan for a department would include all significant loads plus general loads such as lighting, ventilation, etc. When selecting loads, such as motors, it may be cost effective to group them if convenient. The effect of any load on total departmental consumption also needs to be considered; if a 500kW motor is one key load, it is pointless to individually monitor 5kW motors.

It is also essential to measure the 'driver', a measure of the activity that directly affects energy consumption. Examples include production throughput, volume of liquid processed, etc.

aM&T

aM&T (automatic Monitoring & Targeting) ensures that the correct information is automatically provided. With suitable software, the process can be automated with the manager being provided with just the information he needs – and no more unless requested.

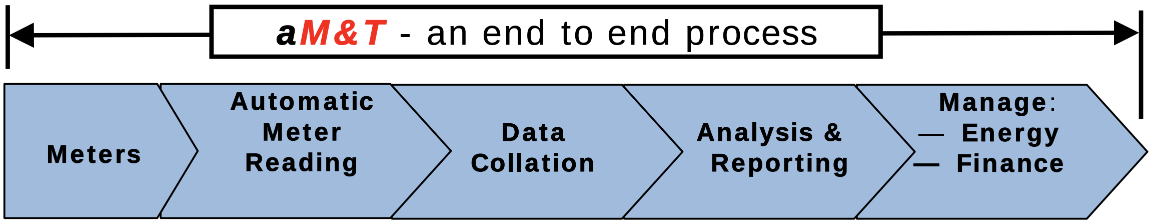

Figure 3
The aM&T process.
Image courtesy of ESTA

Energy Saving

There are two simple approaches to analysing the consumption in a way that can assist with reduce consumption. A scatter diagram of consumption against whatever driver is applied (see right) can be analysed to give a base load and a per unit consumption (the slope).

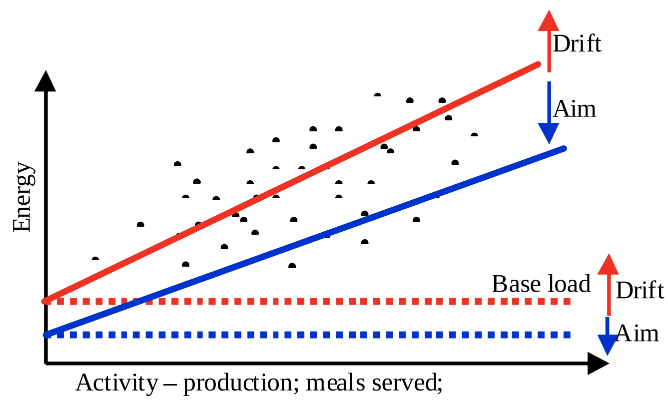

Figure 4
Regression Analysis Method
Image courtesy of ESTA

The alternative (or complementary) approach, commonly called the 'Top Hat' method, is based on a daily profile. The aim is to squeeze the hat into a smaller space:

- Reduce the Out-of-Hours consumption
- Shorten the time during which the equipment operates
- Make the equipment operate more efficiently & turn off unnecessary equipment

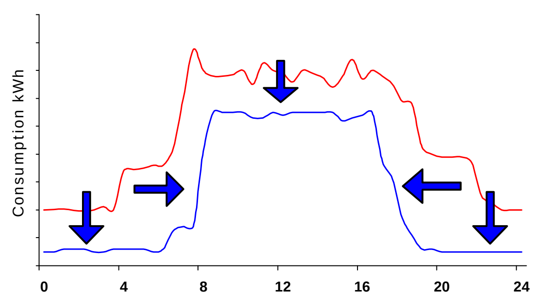

Figure 5
Top Hat Method
Image courtesy of ESTA

Information flows

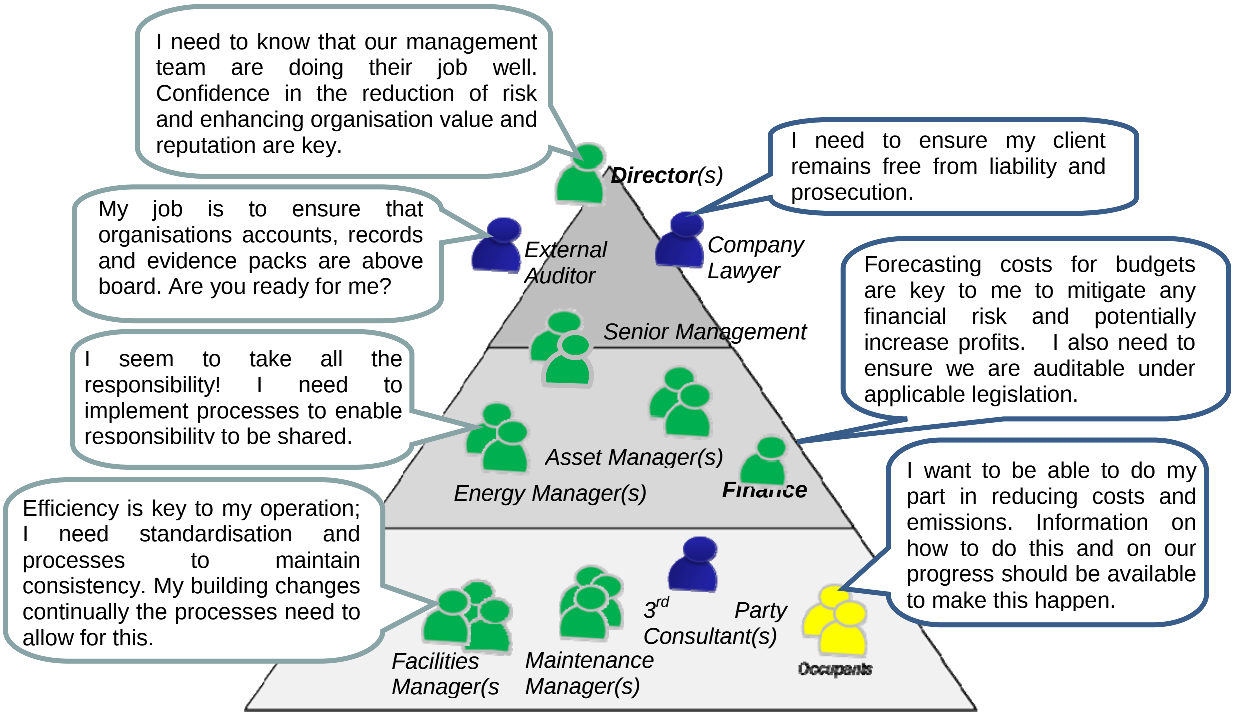

Figure 6
Information Flows **With thanks to i-prophets**

There is a lot of information that can be provided from an Energy Management system. For maximum efficiency, only relevant information should be provided to the applicable parties. That is not to say that data should be discarded; modern Data Mining software could be used at a later date to further analyse consumption trends; the UK is looking at analysing 5 minute interval data from the Smart Meters being installed — over 50 million of them.

Modern Sub-Metering

Sub meters are totally different to utility meters; both measure energy in kWh, but there the similarity ends. The utilities demand security against theft, compliance with national regulation and a very low price (they purchase by the million – all the same). The result is a standardised product with little variation over the years. Convenience to the local user is of minor importance.

Sub-Meters on the other hand are designed to provide the user with the information necessary for controlling their consumption, and ideally contributing to other processes such as planned maintenance. (Sub-meters can warn of impending breakdown of a motor by monitoring leakage and voltage harmonics). Sub meters are also normally fitted with digital communications, thus allowing them to be linked to SCADA[a] systems (using MODBUS RTU or MODBUS TCP protocols) or directly to the intranet for remote monitoring.

Web-Enabled Meters

Web-enabled meters can be the most cost-effective solution for monitoring remote sites. They connect straight into the local intranet (directly or via wireless), use standard internet protocols and the Energy Management software is either embedded or web based. Any internet connection provides direct access to any meter.

Applications include both retail chains & industrial sites. Based on a typical 10% saving and 3 year payback, such a system can be cost effective with an annual energy cost of less than $5000.

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[a] SCADA (supervisory control and data acquisition) is a type of computer controlled industrial control system that monitors and control industrial processes.

Multi-Channel Meters

With the need to minimise total installed cost, multi-channel meters are becoming significantly more popular, particularly where multiple loads need to be monitored, say at sub-distribution panels. Smaller and far more cost-effective than traditional metering, they can also be expanded on site as necessary up to 60 x 1ϕ loads or 20 x 3ϕ loads (or a mixture); and can all fit into a 4U rack unit. (420 x 165 x 96 mm or 16½ x 6½ x 3¾ inches).

Such meters are a fine example of technology being applied to solve a system requirement rather than just a product. Size & capital cost are not the only savings; so is installation cost with a single voltage connection and just one communications point.

Retro-fit

Many metering systems still use the traditional 5 Amp current transformers (CTs), particularly on new installations. Unfortunately, retro-fitting 5 Amp meters is not that simple — you either have to disconnect circuits to thread cables through CTs or use a split-core device, large & heavy.

The industry is being transformed with the introduction of miniature mV output current sensors. Available as both ring & openable, these significantly reduce installation time. The benefits are not just size and weight; installation is simpler & quicker and there is no problem with extending the cables.

A typical 100 Amp CT with a 5 Amp output is about 4½ inch square and 1¼ inch deep (115 x 115 x 30 mm) and weighs up to 2kg. An equivalent mV sensor weighs less than 100 gms; its size is 50 x 45 x 37 mm (2 x 1¾ x 1½ inches).

Figure 7
100 Amp Current Sensors

Practical Examples

As of 12th August 2013, 3562 sites [4] have been accredited to ISO 50001. Some may have gone through the accreditation process to gain a tax advantage (as in Germany), but most in order to be able to effectively manage their energy, and thus achieve savings.

One example is Schneider Electric in the UK. [5] This project predominantly covered manufacturing although some office space was included. Their rationale was simple and included:

- Puts a structured methodology (EnMS) in place to manage energy consumption. This ensures: Senior Management commitment – "From Boiler Room to Boardroom"
  Continual improvement of energy efficiency
  Increased competence and awareness of staff
- Reduced energy waste – reduced energy spend and reduces environmental impact

They started down the road in 2010 and by the following year had implemented their internal energy management system; ISO 50001 accreditation was achieved for 15 sites by the end of 2012. Initially, there was a lot of work, but now 'nothing special'. The benefits reported included:

- Easier more efficient Reporting
- Engaged workforce — People like to work for a "green company"
- Energy savings of 11% in 2011, 5.5 % in 2012 with a target of a further 4.5% in 2013.
  The bulk of savings came from motor systems such as compressors, air conditioners, fans, etc.

A second example comes from Agfa Graphics. [6] They had originally achieved ISO 14001, but in retrospect did not find it rigorous enough for energy management. They consider that, if they had achieved ISO 50001 with ISO 14001 in 2005/6 (had it been available), the time spent since then on energy saving would have been halved. Achieving ISO 50001 was an education, even for an organisation which considered itself knowledgeable about energy management. As an example, the payback on fitting motors with modern drives is less than 12 months.

The savings, in millions of Euro word wide, are such that the business is now built around standards; ISO 50001 accreditation is being rolled out across all plants world-wide. One powerful and effective system ensures continuity.

Conclusion

Successful Accreditation to ISO 50001 is no guarantee to energy savings, certainly not if it is undertaken as a paper exercise. Nor is the deployment of sub metering, as was exemplified by the way some construction companies conformed to the UK building regulations; meters were fitted as required by law but the law however did not require them to be installed – so they just sat there doing nothing while the cost of energy keeps rising.

But the growth in the number of organisations world wide that are accredited to ISO 50001, particularly in those countries where this does not confer a tax benefit., is a clear indicator of the benefits of following a structured programme of Energy Efficiency. The importance of metering in achieving energy savings is also clear; if not by Lord Kelvin's statements: "*To measure is to know*"; "*If you can not measure it, you can not improve it*" which are often misquoted as: "*You cannot manage what you do not measure"* than by the growth rate of the sub-metering industry at over 9% p.a. [7]

"You cannot manage what you do not measure"

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[5] Schneider presentation

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Industrial Motors & Drives: A Global Market Update

Alex Chausovsky

Research Director - Electric Motors Group - IMS Research

Abstract

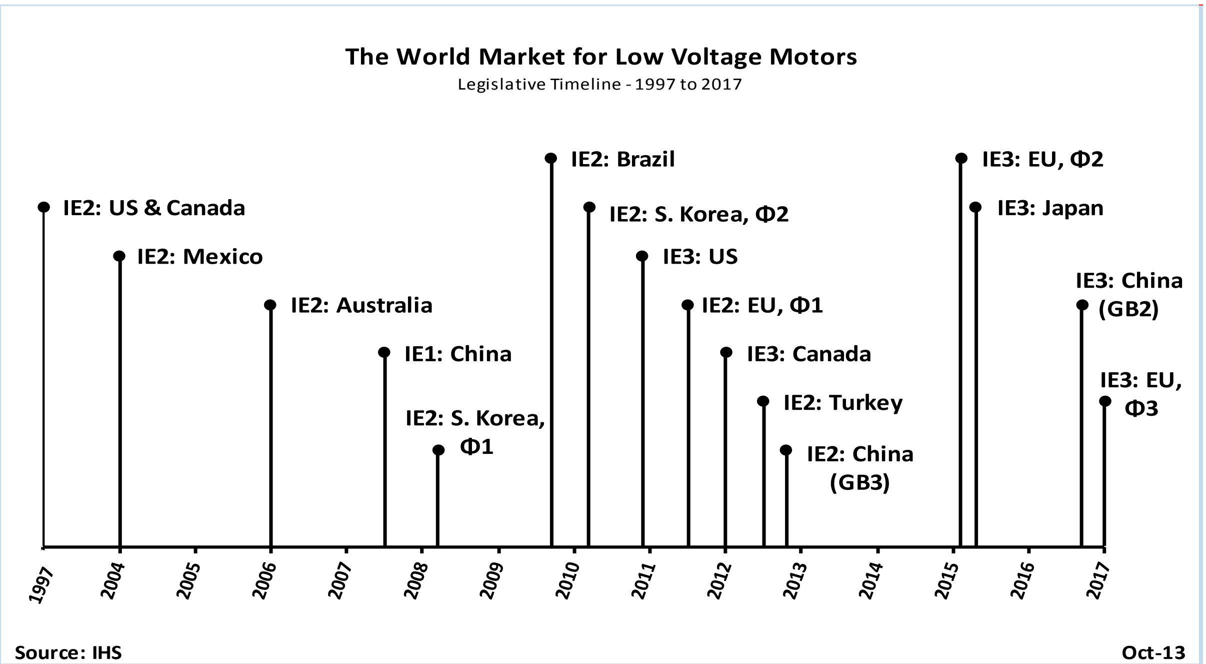
This paper is an overview of the worldwide low voltage motors and drives markets in 2012 and 2013, with projections to 2017. The global market for low voltage motors and drives, with a combined value of nearly USD$27 billion according to the latest data from IMS Research (recently acquired by IHS) (www.imsresearch.com), experienced a year of tempered growth in 2012. Total market revenues grew by less than 4% last year, but are projected to grow at nearly double that rate this year. IMS Research predicts that total revenues for low voltage motors and drives will grow by more than 7% in 2013. This increased performance of the markets can be attributed to the fact that sales of these products are heavily dependent on demand for machinery. Because worldwide machinery production grew more than 10% during 2011, the markets for low voltage motors and drives also witnessed double-digit growth compared to 2010 levels. In contrast, machinery production slowed considerably in 2012 due to the weak economic environment in Europe and Japan, as well as the slowing growth in China. Political uncertainty also hindered the US machinery, motor and drive markets in 2012, as companies were in a waiting period to see the outcome of the presidential election and the “fiscal cliff” debate. New leadership in China that will focus its efforts on stimulating economic growth, a projected marginal improvement in the fiscal performances of Europe and Japan, and the resolution of key political and financial factors in the US, which should lead to more stability, are expected to benefit the global low voltage motor and drive markets in 2013.

Introduction

This paper is an overview of the worldwide low voltage motors and drives markets in 2012 and 2013, with projections to 2017. The global market for low voltage motors and drives, with a combined value of nearly USD$27 billion according to the latest data from IMS Research (recently acquired by IHS) (www.imsresearch.com), experienced a year of tempered growth in 2012. Total market revenues grew by about 4% last year, but are projected to grow at nearly double that rate this year. IMS Research predicts that total revenues for low voltage motors and drives will grow by more than 7% in 2013. This increased performance of the markets can be attributed to the fact that sales of these products are heavily dependent on demand for machinery. Because worldwide machinery production grew more than 10% during 2011, the markets for low voltage motors and drives also witnessed double-digit growth compared to 2010 levels. In contrast, machinery production slowed considerably in 2012 due to the weak economic environment in Europe and Japan, as well as the slowing growth in China. Political uncertainty also hindered the US machinery, motor and drive markets in 2012, as companies were in a waiting period to see the outcome of the presidential election and the "fiscal cliff" debate. New leadership in China that will focus its efforts on stimulating economic growth, a projected marginal improvement in the fiscal performances of Europe and Japan, and the resolution of key political and financial factors in the US, which should lead to more stability, are expected to benefit the global low voltage motor and drive markets in 2013.

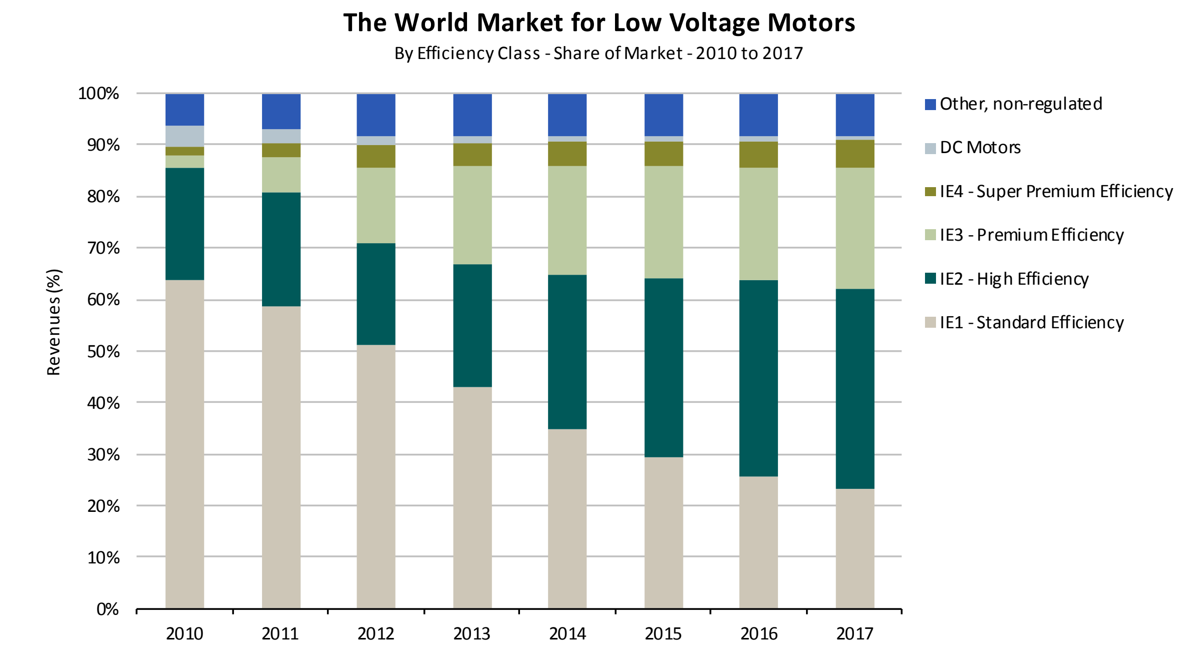
Low Voltage Motors Market Update

In the case of low voltage motors, a market that was valued at nearly $15 billion in 2012, revenues have grown more rapidly than unit shipments due to various motor efficiency legislations being enacted around the world (Fig 1). As a result of these legislative initiatives, motors that are more energy efficient and more expensive are being mandated to manufacturers, OEMs and end-users alike. This substantially inflates the revenue growth of the low voltage motors market, particularly when compared to other industrial automation product markets. Low voltage motor revenues increased by more than 10% in 2011 as the market continued recovering from the recession. The revenue growth was bolstered by the transition to IE3 (Premium efficiency) motors in North America, and the European shift to IE2 (High efficiency) motors, which went into effect mid-2011. In 2012, low voltage motor sales revenues increased by more than 5%, despite the economic difficulties, as the residual effects of the American transition to IE3 and the full impact of the European IE2 legislation were further boosted by the Chinese shift to IE2 motors, which was implemented in September of last year. More than 48 million units shipped globally in 2012, but unit growth was more tepid at only about 3%. The market's revenue growth will continue outpacing unit growth, as future updates to the various regional initiatives will continue increasing motor efficiency requirements resulting in higher motor prices, or possibly expanding the scope of the covered motors, as in the case of the US market.



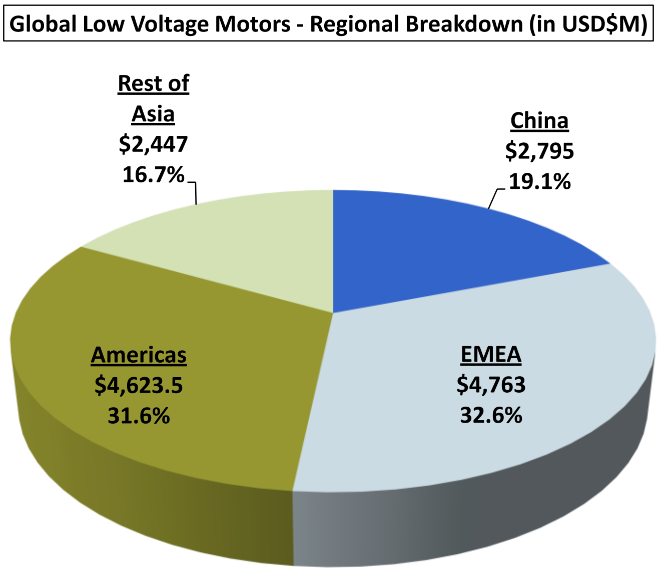
After accounting for 64% of the market's revenues in 2010, IE1 (Standard Efficiency) motors made up an estimated 51% of the market in 2012, and are expected to comprise less than 25% of market revenues by 2017 (Fig 2). These products are sold mainly in the emerging markets that have yet to adopt any type of efficiency regulations. IE2 motors represented an estimated 22% of market revenues in 2010, but are expected to account for nearly 40% of total market revenues by 2017. The main market for these motors through 2011 was in North America, but starting in 2012 and beyond both the European and the Chinese transitions will significantly increase demand for these motors. IE3 motors accounted for only 2% of global revenues in 2010, but made up more than 15% of market revenues in 2012, and will see another rapid uptick in demand starting in 2015 when the European Union moves to implement the next phase of its motor efficiency legislation.

The IE4 (Super Premium Efficiency) category, which consists mainly of squirrel-cage permanent magnet, synchronous and switched reluctance machines, accounted for less than 2% of market revenues in 2010. However, this segment of the market doubled to 4% of revenues by 2012, and is forecast to comprise 5% of all sales by 2017. Although sales of IE4 motors are expected to grow faster than the overall market, rare-earth magnet price and supply concerns are expected to persist, and coupled with how expensive these motors are, these factors will limit the growth potential of this market segment in the short term.



Source: IHS Oct-13

The low voltage motor markets in North and South America accounted for nearly 32% of global market revenues in 2012 (Fig 3). The US was the largest individual country market for low voltage motors in 2012, with revenues equal to more than 21% of the worldwide total. The EMEA region comprised a similar-sized market to the Americas, with approximately 33% of global revenues during the year. China was the largest individual country market for low voltage motors in Asia in 2012, with revenues comprising more than 53% of all sales in the region and approximately 19% of all global revenues. Although the Chinese market experienced a very difficult year in 2012, contracting by more than 7%, it is expected to resume growth this year. Grouping the Chinese market together with the rest of the Asian country markets illustrates that Asia comprised nearly 36% of global revenues in 2012, a share that will remain fairly constant through 2017.



The top industry sectors for low voltage motors include Commercial HVAC, food, beverage and tobacco, mining, utilities, paper, material handling, automotive, packaging, plastics and oil & gas. The leading suppliers of low voltage motors on a global level include ABB (including Baldor), Siemens, Regal Beloit, WEG, Teco, Leroy Somer, Toshiba, Huali (China), Hyundai, Hyosung and Nidec.

Low Voltage Drives Market Update

The world market for low voltage motor drives experienced strong growth in 2011 similar to that seen in the low voltage motors market. However, 2012 was a relatively flat year for the motor drives market, mainly due to reduced growth in machinery production. Total 2012 low voltage motor drive revenues were estimated to be more than $11 billion, reflecting less than 1% growth over 2011 levels, while total unit shipments were estimated to be more than 19 million. Although low voltage motor drive revenues do not directly benefit from the positive effects of the minimum motor efficiency legislation the way that low voltage motor revenues do, the overall drives market does benefit from the greater focus on system efficiency. In the future, it will also benefit more directly via the second and third phases of the European legislation. Beginning in 2015, the EU mandate requires the use of either an IE3 efficiency motor or an IE2 efficiency motor coupled with a variable frequency drive for motors with a power rating of 7.5kW or more. Starting in 2017, the legislation will apply to motors between 0.75kW and 7.5kW, which account for nearly 95% of all unit shipments. In variable speed applications motor drives have the potential to save massive amounts of energy. In the future, as energy costs increase, the economic benefit from installing a motor drive will also continue increasing exponentially.

Variable frequency drives (VFDs) have been around since the 1970s and have been gaining widespread acceptance due to the energy efficiency benefits that they provide. The drives market is expected to continue to be one of the fastest growing industrial automation equipment markets in the future. Applications where motors are typically running at full speed on continuous duty cycles, but could benefit from variable speed operation, represent opportunities where return on investment (ROI) is most quickly realized and are high growth markets for drives. These applications include blowers, compressors, fans and pumps. In addition, motor drives are increasingly being designed with a focus on controlling different types of motor technology, including traditional AC induction motors, squirrel-cage PM motors and servo motors.

Conclusion

In conclusion, while 2012 featured timid performances by the low voltage motors and drives markets, 2013 is poised to be a year of growth for all product types. Machinery production is expected to remain at healthy levels while large projects in many process industries, particularly in the oil & gas sector, are also expected to do very well. This will present many opportunities for suppliers of both low voltage motors and drives.

NEMA and IECEE GMLP "Global Motor Labeling Program"

Daniel E. Delaney, Regal, USA

Abstract

This paper will present the efforts between NEMA (National Electrical Manufacturers Association) and IECEE (IEC System for Conformity testing and Certification of Electrotechnical Equipment) to jointly develop a "Global Motor Efficiency Labeling Program". This joint proposal between NEMA and IECEE is intended to address the multitude of difficulties that motor manufacturers face when complying with the various global country regulations for motor efficiency. Many countries (US, Canada, Mexico, Brazil, Argentina, European Union, India, China, Russia, Australia, Japan, Korea, etc.) have existing motor efficiency regulations but can vary greatly when it comes to the test standards, laboratory accreditation, certification process and labeling requirements. This joint proposal will determine consistencies in these requirements and establish a global set of harmonized requirements from the laboratory accreditation to the test standards and finally the certification process and the final motor labeling. The NEMA Premium License program is currently the leading global motor efficiency labeling program and was the first such program to develop requirements for verification testing after initial certification. An international task force has been formed to convert the NEMA Premium License program into an IEC globally accepted motor labeling program. This international task force consists of members of both NEMA and IEC standards organizations along with an international list of motor manufacturers.

This paper will also share its findings regarding the various national and regional differences for motor efficiency regulations around the globe. This paper will discuss how this new program will look to address these national differences and create one global program. The program success will be defined by whether it can be readily adopted by each of the established country regulation bodies. It is expected by the time this paper is presented a draft of the joint proposal should be circulated among industry manufacturers.

Introduction

Electric motor systems account for approximately 45% of all global electricity consumption [1]. Over the past twenty years the motor industry has made significant efforts to provide more energy efficient motor products to improve electric motor energy performance. Arguably the most effective stimulus to increase the demand for these energy efficient motors has been MEPS (Minimum Energy Performance Standards) and national energy efficiency regulations. Currently there are over 15 national or regional global energy efficiency regulations for motor energy efficiency [2] with many more in development. Table 1 below provides a list of a few of the national and regional Motor MEPS programs operating around the world today.

Efficiency Levels	Efficiency Classes IEC 60034-30	Testing Standard	Country MEPS (Minimum Energy Performance Standard)	Country MEPS Regulation
Premium Efficiency	IE3	Low Uncertainty (IEC 60034-2-1, IEEE 112B or CSA C390)	USA (1-200HP)	EISA 2007 / US DOE 10 CFR Part 431
			Europe: 2015* (>7.5kW); 2017* (>0.75kW)	ErP Directive, Regulation 640/2009
			Canada (1-200HP)	Canadian EEA, CSA C390
			Mexico (1-500HP)	NOM 016-ENER-2010
			Korea: 2015-2017	MOCIE/KEMCO
High Efficiency	IE2		USA (201-500HP)	EISA 2007 / US DOE 10 CFR Part 431
			Canada (201-500HP)	Canadian EEA, CSA C390
			Australia (1-250HP)	AS/NZS 1359:2004
			New Zealand (1-250HP)	AS/NZS 1359:2004
			Brazil	NBR 17094-1
			Korea	MOCIE/KEMCO
			Argentina	IRAM 62405
			China	GB 18613-2010
			Europe	ErP Directive, Regulation 640/2009
			Turkey	SMG-2012/2

Table 1 – Global MEPS Programs

One of the major obstacles for motor manufacturers is navigating the various rules and regulations at the national and regional levels. While many of these regulations have similar registration processes, each one varies from the next. Below are important considerations in the typical motor energy efficiency regulation process.

- Motor Efficiency Test Standard
- Product Definition (Scope of Regulated Motors)
- Test Laboratory Qualification
- Registration and Certification
    - Minimum number of test samples
    - Labeling or Product Marking (Nominal Efficiency Definition – National Differences)
    - MEPS (Minimum Energy Performance Standard)

Enforcement and Compliance TestingDifferences in the various national regulation processes can be as simple as a different label to as complex as having to coordinate dozens of motor samples to be tested in the local country. These inconsistencies in global regulations have resulted in limiting the customer’s choices for compliant high efficiency motors. Lastly, most of these regulations lack a robust enforcement or verification policy to ensure compliant motors stay compliant and restrict non-registered motors from entering the marketplace.

In 2010 NEMA attempted to address this lack of enforcement issue with the development and subsequent release of the NEMA Premium License program [3]. This voluntary motor efficiency program provides a certification program based upon the US DOE (Department of Energy) motor energy efficiency regulation codified in the Code of Federal Regulations (CFR) at 10 CFR Part 431. The major item that NEMA attempted to address with this program was the installment of the verification testing process. Each year NEMA randomly selects a motor rating and then instructs the participating members to provide this motor sample from their distribution network to an independent third party motor test laboratory for verification testing. If the motor sample is found to be non-compliant as marked, the manufacturer faces the penalties of the program which can result in fines and revocation of the NEMA Premium license as a participating member. One additional feature of the program is the ability for each member to challenge another participating member or other motor manufacturer not participating in the program. If the challenged motor manufacturer is validated as compliant then the challenger must pay the administrative and testing costs for the challenge. This program has been a global success with 17 global motor manufacturers participating [4].

Global Motor Efficiency Program

In the effort to continue the benefits of the program's success NEMA began looking for ways to expand the global reach of the NEMA Premium License. Following the 2011 EEMODS conference in Washington, DC NEMA, CLASP (Collaborative Labelling and Standards Program) and IECEE members informally met to discuss efforts to develop a "Global Motor Efficiency Program" or GMLP. The discussion focused on the following key issues that need to be addressed for a successful program.

- Lack of common certification process (registration, sample selection, test laboratory requirements, test standards, efficiency levels and efficiency marking)
- Lack of globally recognized label or mark for motor efficiency
- Lack of enforcement policy (verification testing and border enforcement)
- Global certification program that can be adopted by developing nations and regions
- Benefits to existing national and regional regulations to alternatively accept a globally recognized efficiency program

Shortly after the initial meeting between NEMA and IECEE it was clear that both organizations were looking to develop similar programs to address the same concerns around energy efficiency certification, compliance and enforcement. After a series of informative discussions it was decided to work towards development of an IECEE conformity assessment scheme based solely around the NEMA Premium License. The IECEE currently operates the globally recognized CB (Certification Body) Scheme [5] in addition to other associated programs such as IECEx [6]. The CB Scheme is the only globally recognized conformity assessment scheme and is widely accepted in all parts of the world for electrical and electronics products with over 50 countries participating.

IECEE Working Group 2D - GMLP

After the initial discussions between NEMA and IECEE it was decided this program would be best developed under the IECEE organization. Per Figure 1 below Working Group 2D (Business Development-GMLP) was formed under the IECEE Certification Management Committee (CMC). Working Group 2D is organized into two separate task forces with WG2Da "Strategic" focused on the planning and marketing of the program while WG2Db is concentrated on the technical and certification details of the program. The next step was to recruit a global team of motor manufacturers, certifying bodies and other interested participants. Figure 2 provides the list of current team members.

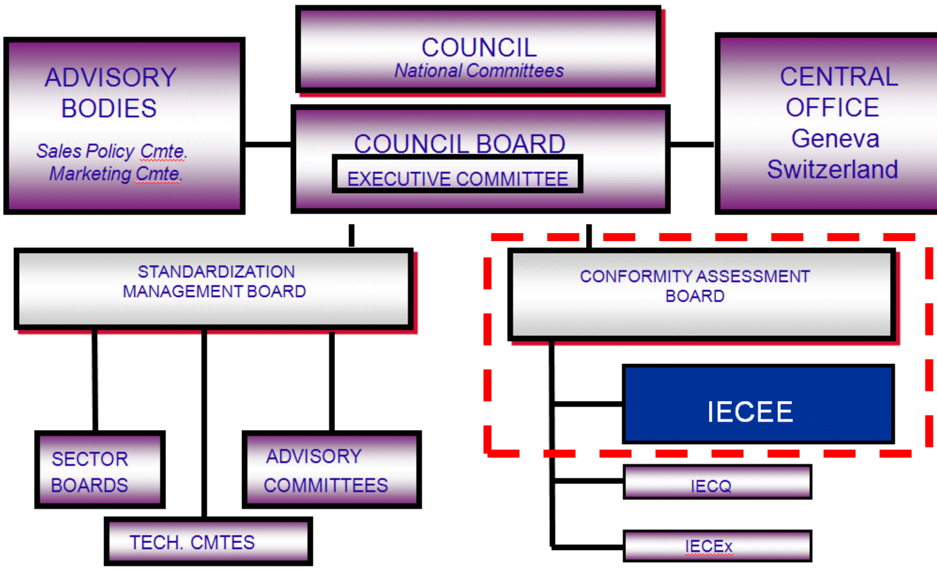


Figure 1 – IEC Organization

Organization/Affiliation	Member	Working Group
IEC-IECEE-Switzerland	Mr. Pierre de Ruvo (Convenor)	WG 2DA
Regal Beloit Corporation	Mr. Dan Delaney (Convenor)	WG 2DA / 2DB
IEC-Germany	Prof. Martin Doppelbauer	WG 2DA / 2DB
IEC- Germany	Prof. Bernd Ponick	WG 2DA / 2DB
IECEE-Australia	Mr. Ron Collis	WG 2DA
IEC-Sweden	Mr. Thomas Korssel	WG 2DA
IECEE-CSA International-Canada	Mr. Shawn Paulsen	WG 2DA
Panasonic Corporation-Japan	Mr. Toshi Kajiya	WG 2DA
IECEE-UL-USA	Mr. Steven Margis	WG 2DA
MOTOR SYSTEMS - Switzerland	Mr. Conrad Brunner	WG 2DA / 2DB
NEMA-USA	Mr. William Hoyt	WG 2DA
NIDEC MOTOR CORPORATION-USA	Mr. Rob Boteler	WG 2DA
Australia	Mr. Andrew Baghurst	WG 2DB
Brazil	Mr. Paulo Quintaes	WG 2DB
Liaison between TC2 and TC22	Mr. Peter Zwanziger	WG 2DB
Canada	Mr. Pierre Angers (Canada)	WG 2DB
IECEE-CSA International-Canada	Mr. Jean-Pierre Boivin	WG 2DB
IECEE-UL-USA	Mr. Frank Ladonne	WG 2DB
SAUDI ARABIA MOTOR INDUSTRY	Mr. Thani Alanazi	WG 2DB
IECEE-KTL-Korea	Mr. Byung-Guk Kang	WG 2DA / 2DB
SIEMENS (USA)-Germany	Mr. Bill Finley	WG 2DB
General Electric (USA)	Mr. Manny Gonzalez	WG 2DB
Lenze (Germany)	Mr. Michael Kriese	WG 2DB
VDE (Germany)	Mr. Ulrich Pfau	WG 2DA

Figure 2 – IECEE WG2D Members

After a series of preliminary teleconference meetings the first formal face to face meeting was held in December 2012 at the Motor Summit conference in Zurich, Switzerland. During this meeting the team reviewed the existing IECEE certification programs (CB-Certification Body Scheme and FCS-Full Certification Scheme) available in the IECEE as well as their conformity assessment designations per ISO Guide 17067 [7]. It was determined that a rigorous ISO Type 5 process would be necessary to support the development and protection of a global labeling program. The ISO Type 5 process includes certification, testing as well as manufacturing audits to ensure compliance to the applicable IEC standards. IECEE Executive Secretary Pierre de Ruvo presented a few preliminary IECEE labels and members provided feedback on the various options. The following action steps have been outlined for each of the task forces for WG2D.

WG2Da – Strategic Actions

- GMEE/GMLP Business Plan

- Marketing Materials on Program Process Flow (GMEE and GMLP)

WG2Db – Technical Actions

- Motor Efficiency Test Standard Comparison
- Develop IEC Efficiency Test Report Form
- Certification process instructions (number of samples, number of tests, lab qualifications, AEDM / math models, etc.)
- National Differences (Country Specific variations regarding test procedure, lab qualification, regulations, marking, certification, verification, etc.)

Following the December meeting and based on feedback from industry, past IECEE program successes and a desire to decrease program launch time it was decided to break efforts into a two phase approach. Phase 1 titled GMEE (Global Motor Energy Efficiency) would simplify the program into an IECEE CBTC (Certification Body Test Certificate) process and Phase 2 would continue as the GMLP and incorporate the full labeling program. The goal of this two phase approach is to quickly provide a conformity assessment motor efficiency program for motor manufacturers and through implementation get feedback on improvements for Phase 2. Figure 3 below provides a summary of the proposed two phases. Before NEMA and IECEE had met the IECEE was developing an "E3" program to develop a statement of results approach for energy efficiency products [8]. This E3 program did not include motors and is not being considered for this project.

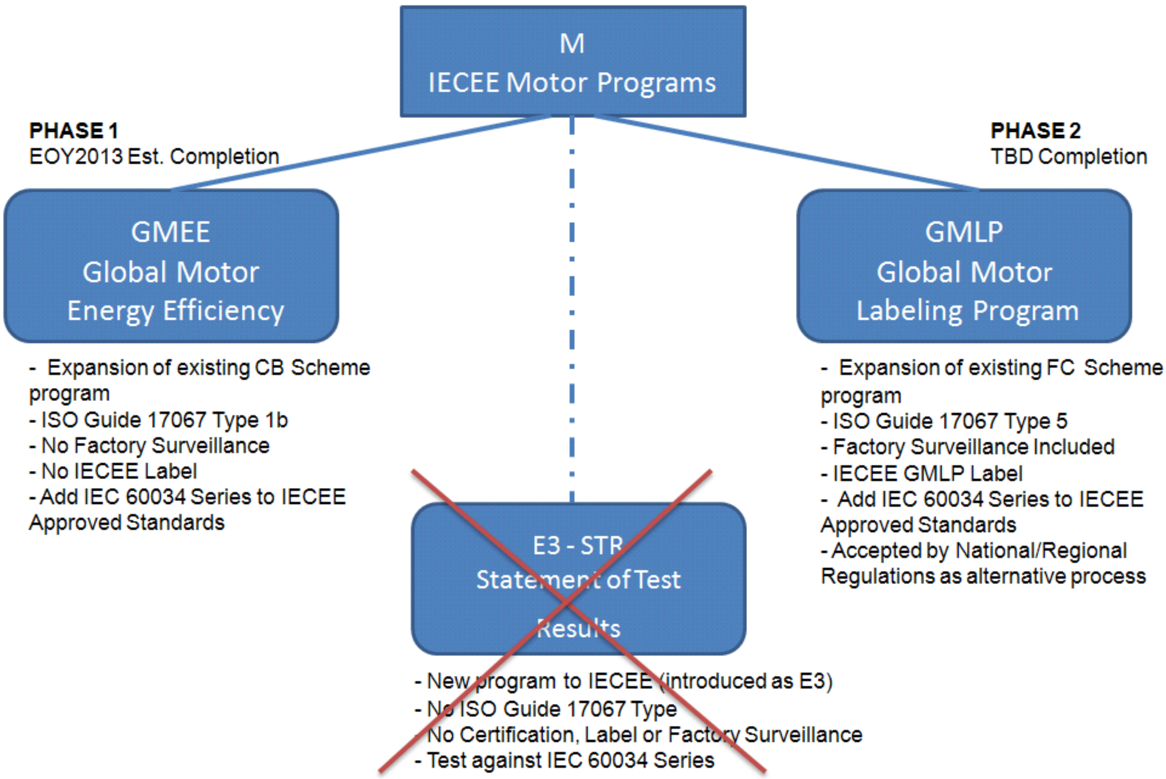


Figure 3 – Two Phase Approach

GMLP Next Steps

It is the goal of WG2D to have Phase 1 of the GMEE program launched by the end of 2013. Phase 2 of the GMLP currently does not have a completion date, but WG2D will divert full attention to Phase 2 once Phase 1 is completed and launched.

In order to develop and launch a successful global motor efficiency program it will take effective collaboration between motor manufacturers, national/regional regulators, certification bodies and customers. The IECEE WG2D is committed to developing this program to provide a consistent scheme that helps existing and new MEPS-based programs address the key elements of a successful motors initiative. Participation in this program is welcome from all parties interested in improving the final product.

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Addressing swimming pool and spa pump energy efficiency in Australia

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Abstract

In Australia, 12% of households have a swimming pool, and ownership is expected to rise to almost 15% (1.32 million pools) by 2020. Pool pumps can be responsible for over 15% of a household's electricity consumption.

In 2010, pool pumps in Australia consumed 2156.9GWh, which is over 3% of total household electrical energy use (66,556 GWh).

Considerable opportunities for energy savings exist through the use of more efficient pumps and by pumping water through the filter at reduced flow rates. The increasing use of multi-speed and variable speed pumps allow a much lower flow rate to be used for most of the time for filtration and then higher flow rates only when cleaning is required. There has been a tendency to over-size pool pumps.

In April 2010, a Voluntary Energy Rating Labelling Program (VERLP) commenced with support from manufacturers and suppliers. The ten largest manufacturers have tested and labelled over 35 of their more efficient pool pump-units. Industry has also undertaken significant research and development leading to increases in efficiency of single speed pumps and a shift to more energy efficient variable speed pumps.

Work is progressing on analysing the benefits of mandatory labelling and MEPS for pool pumps. This includes amending Australian Standard AS 5102 in response to issues that have arisen in the operation of the VERLP. This paper will also address the latest progress on the European Energy Using Product Preparatory Study on pool pumps. The VERLP is designed to draw the attention of consumers to the potential savings available by using energy efficient pumps; for instance, using an Australian tariff of 25 cents per kWh, a household can save approximately $260/year by switching from a two star rated pump to an eight star rated pump).

A regulatory proposal is also being developed to specify the integration of demand response interfaces for swimming pool pumps. This will help to manage the problem of peak electricity demand by creating a market for direct load control. The costs and benefits of direct load control are being investigated, including the option to mandate integration of a demand response interface in these products.

Background

Pool pump ownership

In 2010, approximately 1,288,500 Australian domestic households had pools or outdoor spas installed, representing 15.2% of Australian households. Of this, 1,019,000 were swimming pools (12.0%), while outdoor spa ownership was approximately 269,500 (3.2%).

Swimming pool installations fall into two main categories, above ground and in-ground. In-ground are the more popular, representing 84% of total pool installations in 2010 while above ground pools represented only 16%.

State	Number of Pools ('000s)
New South Wales	337.6
Queensland	312.3
Victoria	146.4
Western Australia	129.3
South Australia	57.1
Northern Territory	21.4
Australian Capital Territory	8.1
Tasmania	6.7
AUS	1,019.0

Table 1: Number of pool installations by State and Territory. (ABS, 2010)

Table 1 shows that over 60% of installed domestic swimming pools are located in New South Wales and Queensland. The scale of pool ownership broadly reflects general population sizes, but is also influenced by climatic factors within and between jurisdictions.

Energy use

Total residential sector swimming pool and outdoor spa electrical energy consumption in fiscal year 2010/11 was estimated at about 2156.9 GWh (projected to rise to 2,678 GWh by 2020 [Figure 1]). With a total residential electricity consumption estimated at 66,556 GWh (EES, 2008a), swimming pools and spas consume just over 3% of domestic energy use.

The annual electricity consumption of a pool can be estimated from the run times, the power of the pump motor (typically about 1 kW for a 50,000 litre pool), the time clocks and other controls (about 10 W) and the salt electrolysis cell, if present (about 180 W). A pool run for the recommended times will use about 2,200 kWh annually (the pump accounts for about 70% of the energy use [NAEEEC, 2004]). Some householders will over- or under-run their pool pump. If householders do not ensure that they reset the time clock, and thereby retain the summer settings all year round, electricity use could go up to 3,100 kWh per year. Even at 2,200 kWh the pool would be the largest single source of electricity usage in the average household, aside from households that use an electric water heater (Living Greener, 2013).

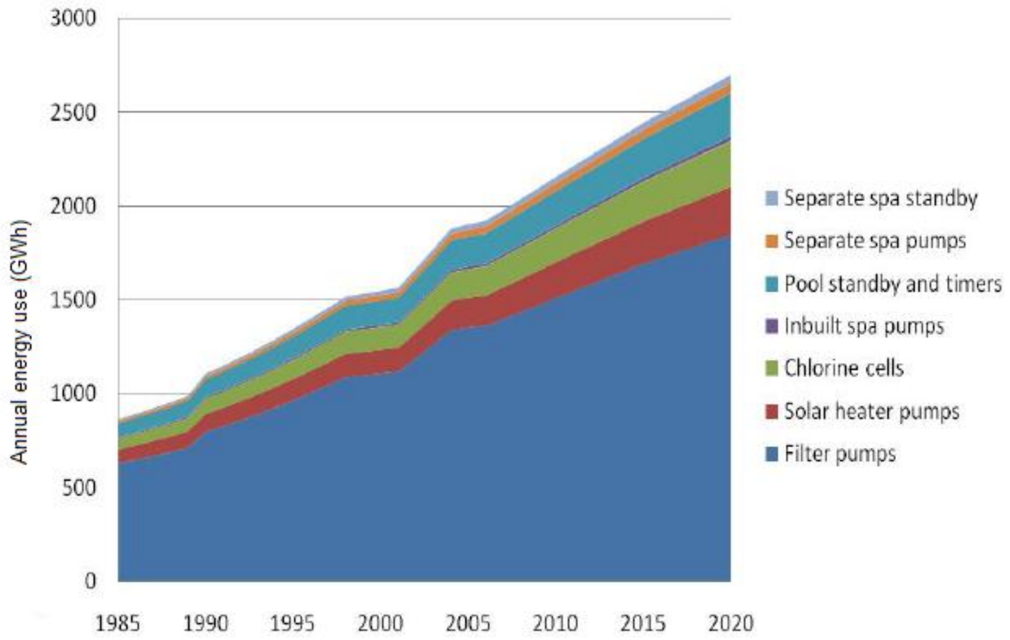

Figure 1: Projected annual energy use of swimming pool and spa pumps. (EES, 2008a)

Energy saving potential

The potential for delivering energy savings through the implementation of regulation can be approached in terms of the depth and breadth of the problem.

The depth of the problem

There is a wide range of efficiencies within the pumps available on the Australian market (Figure 2). This indicates that there is a potential for energy savings by obtaining a higher market penetration of the more efficient pump-units.

A good indication of the energy efficiency of a pool pump is the number of litres that it can pump per Watt hour, which is referred to as the 'energy factor'. Pump testing undertaken in 2010-2011 revealed that energy factors for pool pump-units available in Australia varied from 11 to 42 litres per Wh.

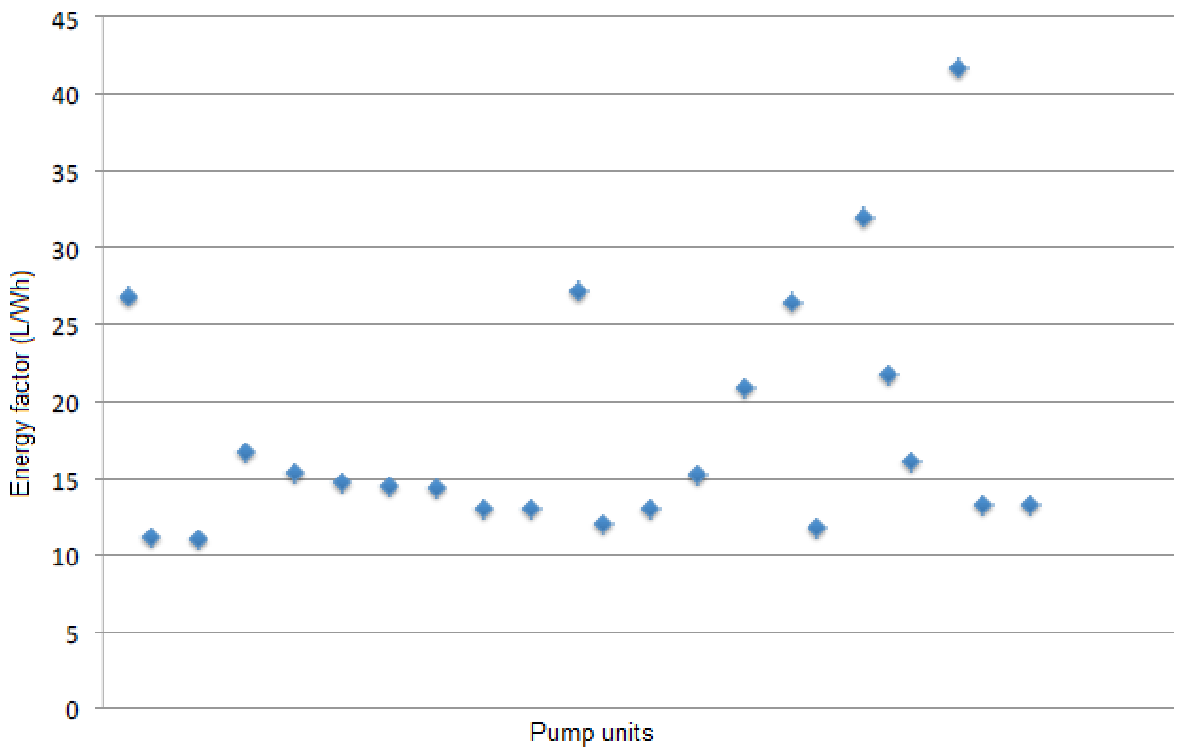

Figure 2: Pool pump test results. (Waterco, 2010)

Test results delivered by AusEng (2009) show that with the current Star Rating Index algorithm high performing pumps can deliver five times the efficiency of their low performing counterparts. As the pump is generally the largest energy user in a household (averaging 15% of the total household consumption [ESS, 2008]), there are potentially large energy savings to be made by using an energy efficient pump. (e.g. using an Australian tariff of 25 cents per kWh, a household can save approximately $260/year by switching from a two star rated pump to an eight star rated pump [Living Greener, 2013]).

As the lifetime cost of pool pumps is comprised of approximately 20% capital costs and 80% operating costs (mostly made up of energy costs) these savings may be considered highly relevant by consumers.

The breadth of the problem

In regard to the breadth of the problem, swimming pool and spa pump-units comprise over 3% of residential energy consumption. Excess consumption by inefficient pump units could potentially represent a large percentage of the total consumption. The scope of the problem is therefore large and significant enough to allow consideration of options to address the issue.

Voluntary Energy Rating Labelling Program

Concept

Swimming pool pumps consume high amounts of energy. In most households, they are the single largest source of electricity usage. Unfortunately, there is very little information available to pool owners about how much energy is used by their swimming pool pump-units. Energy efficiency labelling, using the Energy Rating Label, would address this information failure to the benefit of consumers without significantly altering price, product quality or the competitiveness of the market.

Implementation/rules

While there is no obligation for swimming pool pump suppliers to participate in this program, if a supplier does decide to participate and attach the Energy Rating Label to a particular pump, the supplier must abide by the following rules:

- Suppliers who choose to participate in the Program, and give notice to the administrator that they intend to label specific qualifying pump-units, must provide a copy of all the test reports containing the test results in relation to those pump-units to the administrator. In-house test reports are acceptable.
- The supplier must cover the costs of the testing.
- Suppliers are responsible for adhering to these rules and for ensuring that their authorised representatives (advertising agencies, dealers, retailers, etc.) also adhere to these rules.

Current status

The VERLP was launched in April 2010. Participants in the Program include the 10 largest international manufacturers who have registered 35 pump-units to date (with 3 more applications currently being processed).

Manufacturers tend to register only their high performing, energy efficient pumps under the labelling program. Star ratings of registered pumps range from 5.5 to 8 stars. A report on minimum energy performance standards and labelling conducted by Beletich Associates (2012) found that pumps labelled with the Energy Rating sticker sold well in comparison to those that did not. In order to truly assess the impact of the VERLP we would require data on the sales of pool pumps before and after being registered under the program.

Issues

Since April 2010, the VERLP has provided invaluable real-world experience of pool pumps testing and the energy labelling algorithms. This experience has led to the discovery of a range of issues:

- Motor characteristics are strongly temperature dependent, mostly because of the effect of temperature on motor winding losses. The temperature of the rotor is of particular importance, because slip at a given load torque, and therefore shaft speed, is significantly influenced by rotor circuit resistance. In order to be able to make reproducible measurements on a given motor, these measurements must be made when the temperature is stable, ideally at a fixed ambient temperature. The Department of Resources, Energy and Tourism recently opened the standard for peer review and is in the process of incorporating a requirement for conditions which constitute temperature stability in rotating electrical machines, such as those described in IEC 60034-1.
- In the manufacturing stages of an electric motor, depending on the test procedures, it will be run for varying amounts of time at varying speeds. In some cases, the testing is not long enough to “run-in” the motor. Regardless of temperature stability, motor performance will not stabilise until seals have been worn-in and bearings have been sufficiently coated in grease. We are therefore incorporating a provision for a “run-in” time to the standard.

Proposed Mandatory Program

Market problem – justification of regulatory proposal

To make an optimal purchasing decision, a consumer needs to consider two different types of costs with regards to the purchase of a pump-unit: the initial up-front, or capital, cost of the pump-unit; and the running cost or operational cost of the pump-unit. In an optimal situation, users would consider the total lifetime cost of the pump-unit and act to minimise that cost.

Currently, it is difficult to obtain information on the energy efficiency of a pool pump before purchasing it. As such, it is not unreasonable to speculate that consumers are purchasing pump-units with little consideration of the lifetime cost of the device. As energy operating costs can comprise 80% of the lifetime cost of the pump-unit, choices made without consideration of operating costs are unlikely to be efficient.

Further information is required on whether purchasing decisions are driven by factors other than energy consumption. There could be other product features that have a stronger appeal to customers than energy efficiency. For instance, there are secondary functions (such as backwashing) on swimming pool pumps that can require high powered performance over short time periods – having the capacity to reach these higher power requirements could potentially affect the energy efficiency of the device during normal operation. More data is needed to understand this issue.

Many new swimming pool pumps are sold as part of a complete pool package. The pump normally comprises only a small part of the cost of installing a pool and may therefore get little attention from the purchaser. This is demonstrated by a survey by Winton (2009) that states that only 50% of owners can recall the brand of their current pool pump. Installers who are not emphasising the eco-benefits of their products may try to reduce their costs by including a cheap pump-unit. Pumps tested under the VERLP have shown that there is a correlation between the efficiency of a pump and its price. This indicates that some pool owners may be obtaining inefficient pumps without being adequately informed.

According to a report by AusEng (2009), 30% of pump sales are provided by pool servicers as a replacement for defective pumps. This process often starts with owners having pool service suppliers assess if a broken pump can be repaired. In cases when a replacement is necessary and insurance does not require the pump to be replaced with an identical model, owners frequently take the recommendation of service staff. Recommendations of service staff can be based on a number of considerations:

- Some servicers have preferential pricing arrangements with manufacturers for certain brands or models, thus making the sales of particular brands or models more attractive to them. In this case, it is unlikely that the energy efficiency of the pump will be a major consideration.
- For ease-of-connectivity reasons, servicers could recommend replacing a pump with the same model or one with similar fittings. In this case energy efficiency may be a consideration if it was considered when the original pump was purchased.
- Servicers may make their recommendation based on their own financial interests (generating revenue and/or profit for their business). In this case there may either be an incentive to promote the energy-efficient pumps or the larger, less efficient pumps as they are both at the more costly end of the spectrum.

These practises are poorly understood at the present time. It is hoped that the consultation period of this regulatory process will expand our knowledge of this.

Scope

The proposed scope Australia is investigating will cover all pump-units intended for use in the operation of residential swimming pools and spa pools that:

- Are used for the circulation of water through filters, sanitisation devices, cleaning devices, water heaters (including solar), spa or jet outlets or other features forming part of the pool.
- Are single phase.
- Are capable of a flow rate equal to or greater than 120 L/min.
- Are single-speed, dual-speed, multi-speed or variable speed.
- Have an input power of less than or equal to 1800 W for any of the available speeds.

Regulatory options

Maintain the status quo

Under business as usual (BAU), suppliers will have the option to register their products and undertake testing for the purposes of energy efficiency performance. However, this will not be a requirement in order to supply pool pumps to the local market. The voluntary labelling scheme aims to present highly technical information in a format that can be readily understood and provide consumers with a comparison of the energy performance standard of one product to another. The voluntary program has been effective in drawing attention to the scope of the problem at hand and has provided high quality data evidence to be used in a regulatory investigation.

As time progresses under the BAU option, there are likely to be changes to the current market arrangements. The market is likely to respond to the problems to some degree. As consumers become more aware of energy use they may better understand operating costs and suppliers may therefore have greater incentive to provide information. Higher energy costs and increased recognition of greenhouse gas implications could further encourage this. Technological progress in the development of pool pump-units globally will also provide for improvements in the energy efficiency of pump-units in Australia.

Implementing a mandatory labelling scheme

By extending the voluntary labelling scheme to a mandatory one, all pool pumps supplied in Australia would be required to be registered and carry a label describing the energy performance of the particular model. This will overcome information barriers caused by the difficulty to estimate the lifetime cost of a pump unit. It will provide the opportunity for rational purchasing decisions for consumers.

Implementing mandatory Minimum Energy Performance Standards (MEPS)

Under a mandatory MEPS scheme a supplier will be subject to certain energy performance standards for their pool pumps. Responsibility for compliance will lie with the supplier of the products. Each product (or family of products) will need to be registered. The mandatory MEPS would apply to new stock of pool pumps within the scope of the standard that are manufactured or imported on or after the implementation date. A decision as to the stringency of the MEPS would be necessary. A MEPS at an energy factor of 11.25 L/Wh for instance would remove any pump rated below two stars on the current Star Rating Index and will preclude machines above 1800 W.

The main concern from a policy perspective is the potential for a mandatory MEPS to reduce the choices available to consumers. By its nature, a mandatory scheme will reduce choice or force suppliers to use better components to make products compliant. This however, is part of its benefit, as it prevents consumers from making sub-optimal decisions that result in over-consumption of energy.

Implementing both Mandatory MEPS and Labelling

This would combine the above schemes, aiming at both eliminating poor performers and allowing consumers to make choices from the remaining products.

Issues arising

For evidence-based policy making on swimming pool pumps there is a requirement for high-quality data in order to:

- Understand the current economic situation;
- Evaluate the efficacy of the existing program (the VERLP); and
- Prioritise future programs and interventions.

Only partial data is currently available and while it is hoped that the consultation period of the regulatory process will deliver some of the data required, this is not guaranteed. The greatest concern in delivering evidence based policy is obtaining reliable, high-quality data.

Finally, a swimming pool system curve for the purpose of rating pump-units can be challenging to establish. There are numerous variables and configurations of pool hydraulic systems, which can affect the energy consumption of the pool pump. These include:

- Filter type.
- Pipework material, internal diameter, length and number of elbows.
- Type and number of pool fittings.
- Presence of pool heater, chlorinator and suction cleaning device.
- Pool size.
- Pump operating regime, including frequency of backwashing (to clean filter and thereby reduce pump head).
- Pump efficiency.

With the great variety of Australian pool designs, finding a single pool system curve to represent the 'average pool' is problematic.

EU perspective

In Europe, the European Commission is funding an Energy Using Product Preparatory Study on various types of pumps, including domestic swimming pool pumps. This study is being conducted by Bio Intelligence (France) and Atkins Ltd (UK), and is due to be completed by mid-2014. The objective of this work is to provide robust techno-economic analysis of the technical and economic energy saving potential of improved swimming pool pumps, from which policies for the EU-27 countries can be developed. It is estimated that there are almost 5 Million domestic swimming pool pumps in Europe, consuming 18 TWh of electricity per year, so even small savings would have a significant impact on carbon emissions.

Policies may either be of the form of mandatory regulation or of a voluntary agreement with manufacturers. Options include labelling, information requirements or Minimum Energy Performance criteria. At the time of writing this paper, there was no clear indication of the form that any such market intervention will take, but it is expected to include consideration of both the efficiency of the motor and pump, and the effectiveness of the controls. Initial challenges include characterising the existing market, and also understanding clearly the function of the pump, which is driven largely by necessarily conservative health considerations. This is further complicated by regional variations in required swimming pool pump duties. A key early observation is that the level of technical knowledge varies considerably between different retail suppliers, with the end-user generally having only a modest understanding of how to optimise the pump use.

Details of the progress of the study, including completed interim reports, can be found at http://lot29.ecopumps.eu/ .

Demand/Response

Peak electricity demand is a growing problem for the electricity supply system in Australia. The electricity network infrastructure must be designed to cope with the highest demand for electricity, the cost of which is passed on to consumers. It is estimated that 25% of retail electricity costs is accounted for by peak demand that occurs for less than 40 hours per year (less than 0.5% of the year).

An important part of the solution to the problem of peak demand is direct load control (DLC). Under the DLC approach, consumers have a choice to allow certain household appliances, such as swimming pool pumps, to be remotely controlled by their electricity provider, which will reduce the demands placed on network capacity at peak times. The main benefit of DLC is the reduced need for investment in costly electricity network infrastructure.

For a DLC market to operate, appliances must be equipped with a demand response interface. These interfaces enable communication between distribution network service providers and specific appliances. To achieve this, a proposal has been prepared to mandate the inclusion of ‘smart appliance’ interfaces in air conditioners, swimming pool pumps, water heaters and electric vehicle chargers. If this proposal is implemented, it will create a DLC market.

Modelling projects that DLC could permanently offset 3 to 5 years of growth in peak electricity demand. If these benefits were passed on to all householders equally, it could result in a reduction in electricity bills of $60 to $120 per household per year from 2014 to 2028.

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Present situation of China’s motor manufacturing industry and energy efficiency standard for motor systems

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Abstract

This paper is about the present situation of the motor manufacturing industry and the newest development of energy efficiency standard in China. Electric motors are the electric equipment widely used in various industries of national economy. As it is used in large quantity with a long running time, there is a great energy-saving potential during motor’s selection and application. Especially for the small- and medium-sized motors which are used in large quantity with wide-range application, the energy-saving effects are even more apparent. Reducing motor loss and increasing its output efficiency are now commonly concerned issues all over the world, and it is also the key energy-saving and emission-reduction field in which the Chinese governments emphasize as one of the world's largest energy-consuming and carbon dioxide-emitting countries, how China deals with the challenges of energy and environment issues is currently the top issue to be solved for sustainable development.

1. Development of China’s motor industry

Electric motor is the electric equipment widely used in various industries of national economy. As it is used in large quantity with a long running time, there is a great energy-saving potential during motor’s selection and application. Especially for the small- and medium-sized motors which are used in large quantity with wide-range application, the energy-saving effects are even more apparent. Reducing motor loss and increasing its output efficiency are now commonly concerned issues all over the world, and it is also the key energy-saving and emission-reduction field in which the Chinese governments emphasize.

With the constant growth of China’s economic level and further speeding up of industrialization and urbanization construction work, the national economy has achieved relatively fast development. The China’s economic growth promoted the increase of motor demand and output. The sales quantity of small- and medium-sized three-phase asynchronous motors in China market in 2011 was about 140 million KW with a growth rate of 14.3%. Although the export share was not high, the export growth rate in 2011 reached as high as 45%.

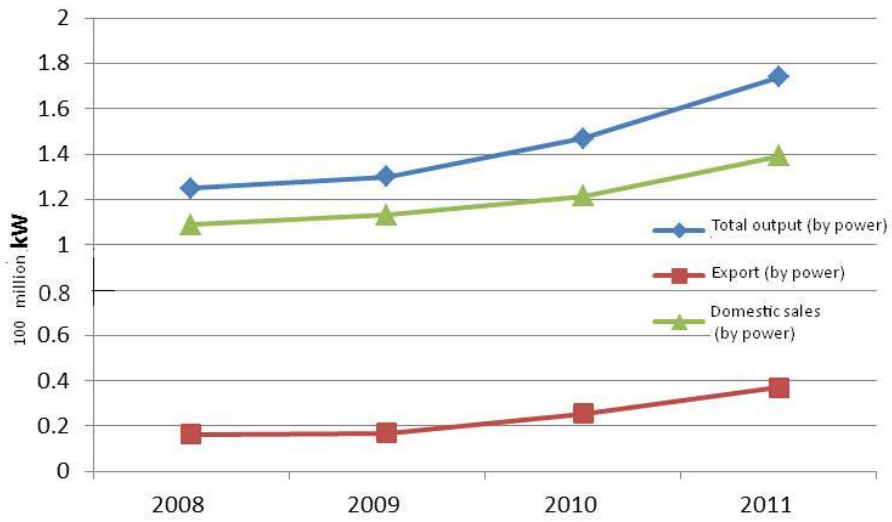


Figure 1 Total output, domestic sales quantity and exported quantity of small- and medium-sized three-phase asynchronous motors in China

Source: China Motor Market Study 2011, by ICA & CNIS

According to China Motor Market Study 2011 co-conducted by ICA and CNIS, there are currently a total of more than 2,000 motor manufacturing enterprises in China. They are mainly distributed in Zhejiang, Jiangsu, Fujian, Shandong, Shanghai, Liaoning, Guangdong and Henan provinces or municipalities, which account for 76.1% of total nationwide motor enterprise number. Among those, the enterprise number in Zhejiang province accounts for 28.0% of the national total.

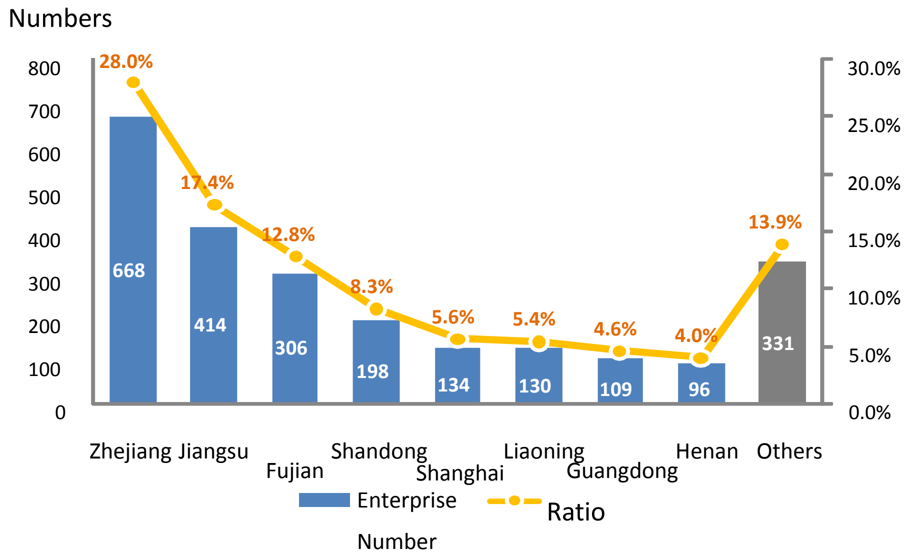


Figure 2 Number and ratio of motor manufacturing enterprise distribution in China's main areas

Source: China Motor Market Study 2011, by ICA & CNIS

As one of the world's largest energy-consuming and carbon dioxide-emitting countries, how Chinese government deals with the challenges of energy and environment issues is currently the top issue to be solved for sustainable development. The Chinese government is always dedicated to energy-saving work for motor systems.

2. Chinese government emphasis on motor energy-saving work

Under the guidance of China's of energy development strategy of "implementing energy-saving and development tasks simultaneously and putting the energy-saving task in the first place" and the basic national policy of "saving resources", Chinese government organizations including the National Development and Reform Commission (NDRC) jointly prepared and issued the Opinions on Implementation of Ten Key Energy-Saving Projects During the 11th Five-Year Plan Period (hereinafter referred to as the "Ten Energy-Saving Projects") in as early as July 2006. Among them, the energy-saving of motor systems was one of the Ten Energy-Saving Projects which proposed systematic and specific goals and tasks for China's motor system's energy-saving work. At the same time, new growth points for promoting the application of high-efficiency motor and the development of motor industry were provided. After that, China issued in 2008 the Notice of the State Council on Further Strengthening Fuel-Saving and Power-Saving Work which clearly put forward the motor system's energy-saving measures including three main aspects as follows:

(1) Speeding up elimination of inefficient motors and driving equipment: Formulating lists and plans for elimination of inefficient motors and driving equipment, introducing incentive policies so as to speed up elimination progress and promoting the high-efficiency motor manufacturing scale from both the demand end and the motor market.

(2) Promoting high-efficiency energy-saving motor and relevant equipment: Encouraging enterprises to purchase and use high-efficiency energy-saving products including small- and medium-sized three-phase asynchronous motors, high-voltage motors, DC and AC permanent magnetic motors, ventilators, water pumps and air compressors, offering tax-reduction and tax-exemption treatments for products complying with the regulations in the Preferential Enterprise Income Tax Directory for Energy-Saving and Water-Saving Equipment and awarding the motor system energy-saving renovation projects based on the energy-saving amount according to relevant regulations.

(3) Strengthening motor system power-saving management: Formulating high-efficiency energy-saving motor product standards, speeding up and perfecting the compulsory energy-efficiency standards and the running standards for motors and driving equipment, accelerating establishment of motor inspecting and testing institutions and taking the energy-efficiency index of motors and relevant equipment as a key content for ex-factory inspection.

China entered its 12th Five-Year Plan Period in 2011, and the overall work for energy saving and emission reduction will be continuously push ahead by taking the development mode transformation and economic structure adjustment as the mainline. As a component of China's energy-saving work, the motor system energy-saving measures are systematically and strictly regulated and implemented. The successive introduction of motor energy-efficiency standard and relevant energy-saving policies include high-energy consumption product elimination system, preferential income tax for energy-saving and water-saving special equipment manufacturing enterprises, energy-saving product certification, government procurement directory for energy-saving products, motor energy-efficiency labeling, energy-saving evaluation and inspection for fixed-asset investment projects, national supervision and spot checks for three-phase asynchronous motor product quality, motor benefiting-people project and energy performance contracting. These energy-saving policies laid good foundation for thoroughly carrying out China's motor energy-saving work.

3. Energy-saving policies implemented

The goal of the energy-saving policies is to improve the energy utilization rate, control energy consumption and reduce pollutants emission. In addition, it is also an effective means to prevent and solve the atmospheric pollution and improve human survival environment. Under China's current market-economy conditions, the government adopts compulsory means to control the energy-consuming product market in a bid to eliminate high-energy-consuming products and promote energy-saving products by using the encouraging polices for the economic entities which use high-efficiency and energy-saving products. Therefore, the mode of China's motor energy-saving policies is basically the same with the international one, which includes two main parts, namely encouraging policies and compulsory management systems. Following is a detailed description of the two parts:

3.1 Incentive policies

(1) Financial subsidy policies for energy-saving products

Legal basis: The Article 61 of the Energy Conservation Law of the People's Republic of China (PRC) "The state supports the promotion and utilization of energy-saving products such as energy-saving lighting appliances through using financial subsidy method" and the Notice of the Ministry of Finance and the NDRC on Carrying Out "Benefiting-People Project of Energy-Saving Products";

The state invested a total of over 16 billion yuan of the central finance to subsidize energy-consuming products with energy-efficiency rating of Class 2 and Class 1 such as energy-saving lamps, double-ended fluorescent lamps, LED lamps, energy-saving and new-energy vehicles, motors and room air conditioners during the 11th Five-Year Plan Period. The Ministry of Finance and the NDRC issued a notice about the Implementation Rules on Promotion of High-Efficiency Motor in Benefiting-People Project of Energy-Saving Products on May 31, 2010 and subsidized the users which used high-efficiency and energy-saving small- and medium-sized three-phase asynchronous motors, high-voltage motors and rare-earth permanent magnetic motors in three batches. In addition, China officially issued the Implementing Rules of Benefiting-People Project in November 2012, in which industrial products including clear water centrifugal pumps, ventilators and displacement air compressors are listed in the benefiting-people project. To further promote the application of high-efficiency motors, the Implementing Rules of Benefiting-People Project requires that the supporting motors of the clear water centrifugal pumps, ventilators and displacement air compressors subsidized by the benefiting-people project be selected preferably from the high-efficiency and energy-saving motors with energy-efficiency rating Class 2 and above. The scope of the products subsidized by China's benefiting-people project is the scope of the relevant energy-efficiency standard. In addition, the subsidizing amounts for energy-efficiency Class 1 and Class 2 products are different, namely the subsidizing amount for energy-efficiency Class 1 products is higher than that for Class 2 products.

(2) Preferential income tax policy for energy-saving products

Legal basis: The Article 61 of the Energy Conservation Law of the PRC "The state implements supporting policies such as preferential tax for the energy-saving technologies and energy-saving products which are necessary to be supported in the promotion directory specified in the Article 58 of this Law. "

The Article 100 of the Regulation on the Implementation of Enterprise Income Tax Law of the PRC "The tax amount deduction and exemption specified in the Article 34 of this Law means that the enterprise purchases and actually uses the special equipment for purposes including environmental protection, energy saving, water saving and safety production, which are specified in the Directory of Preferential Enterprise Income Tax for Environmental Protection Special Equipment, the Directory of Preferential Enterprise Income Tax for Energy-Saving and Water-Saving Special Equipment and the Directory of Preferential Enterprise Income Tax for Safety-Production Special Equipment. 10% of investment value for the equipment can be deducted and exempted from the tax payable of the enterprise in the very year. If the tax payable in the very year is not enough for the deduction and exemption, the balance amount can be continuously deducted and exempted in the following five tax years."

Implementation situation: China already issued the Directory of Preferential Enterprise Income Tax for Energy-Saving and Water-Saving Special Equipment (for trial implementation) and products complying with the directory can enjoy the income tax deduction and exemption.

(3) Certification system for the energy-saving products

Legal basis: The Article 20 of the Energy Conservation Law of the PRC "The energy-using manufacturer and seller can, on the voluntary basis and according to China's relevant energy-saving product certification regulations, submit the energy-saving product certification application to the energy-saving product certification institution certified by the certification supervision management department of the State Council. After the energy-use product passes the certification, the energy-saving product certification certificate is granted, and the energy-saving product certification mark can be used on the energy-use product or its packing."

Implementation situation: A total of over 50 types of energy-use products can apply for energy-saving product certification, including small- and medium-sized three-phase asynchronous motors, small-power motors, clear water centrifugal pumps, ventilators, displacement air compressors and AC contactors.

(4) Government procurement of energy-saving products

Legal basis: The Article 51 of the Energy Conservation Law of the PRC "Products and equipment listed in the directory for government procurement of energy-saving products and equipment should be preferably purchased in the public institution procurement of energy-use products and equipment. Energy-use products and equipment already eliminated by the state are forbidden to be purchased." and the Notice of the General Office of the State Council on Establishing the System for Government Compulsory Procurement of Energy-Saving Products.

Implementation situation: Product passing the national-level energy-saving product certification can be listed in the directory for government procurement of energy-saving products, which is the necessary condition for the product to participate in the public bidding of national financial subsidy project for energy-saving products.

3.2 Management system

(1) System for eliminating high-energy-consuming product

Legal basis: Articles 17 and 70 of the Energy Conservation Law of the PRC: "Production, import and sales of the energy-use products and equipment already eliminated by the state or incompatible with the compulsory energy-efficiency standard are forbidden. Utilization of energy-use equipment and manufacturing process already eliminated by the state is forbidden." and "Those who produce, import and sell the energy-use products and equipment incompatible with the compulsory energy-efficiency standard should be ordered by the product quality supervision department to stop production, import and sales, and the energy-use products and equipment illegally manufactured, imported and sold, as well as the illegal income should be confiscated. In addition, a fine valued between one and five times of the illegal income will be imposed. And the business license for those with serious consequences will be cancelled by the industrial and commercial administrative department."

Implementation situation: To date, China already issued three versions of motor compulsory energy-efficiency standards for small- and medium-sized three-phased asynchronous motors since 2002, namely GB18613-2002, GB18613-2006 and GB18613-2012, which played important roles as the technical basis in eliminating J0 series motors as well as Y, Y2 and Y3 series motors.

(2) System for energy-efficiency labeling management

Legal basis: The Articles 18 and 19 of the Energy Conservation Law of the PRC “The state implements energy-efficiency labeling management for energy-use products such as household appliances with wide applications and large energy consumption. The product directory and implementation method for implementing the energy-efficiency labeling management should be formulated and published by the State Council’s department responsible for energy-saving work along with product quality supervision department of the State Council.” and “Manufacturers and importers should mark the energy-efficiency labeling for the energy-use products listed in the directory of products for national energy-efficiency labeling management, make a description on the product packing or in the instruction book and submit the information of the products with energy-efficiency labeling to the institution, which is jointly authorized by the product quality supervision department of the State Council and the State Council’s department responsible for energy-saving work, for filing according to the regulation.”

Implementation situation: The energy-efficiency labeling system is compulsory. Once a product is listed in the directory by the state, the product to be sold in China market must be stuck with the energy-efficiency labeling. To date, China already issued nine batches of directories of products for energy-efficiency labeling management for 27 types of products, and the small- and medium-sized three-phase asynchronous motor is in the third batch issued by the state. The implementation of the energy-efficiency labeling provides the reliable means for increasing the market share of high-efficiency energy-saving products.

(3) System for fixed asset assessment and audit

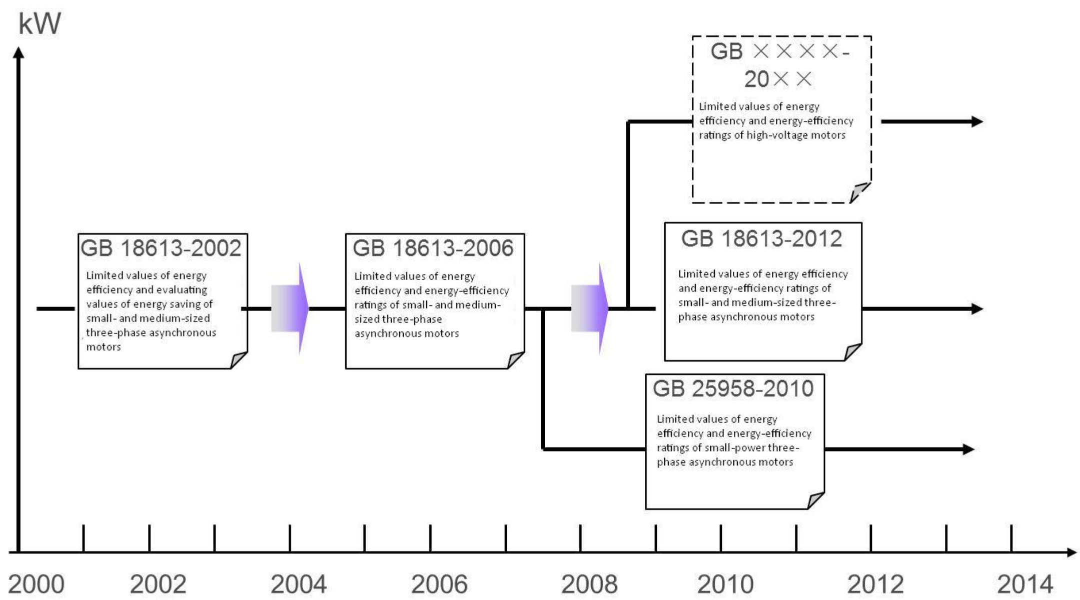
Legal basis: The Article 15 of the Energy Conservation Law of the PRC “The state implements the system of energy-saving assessment and audit for fixed asset investment projects. Project incompatible with the compulsory energy-saving standard should not be approved for construction by the organizations responsible for project assessment and approval in accordance with the law, the construction company should not construct such project, and such project already constructed should not be put into production or utilization. The detailed measures will be formulated by the energy-saving management department of the State Council together with relevant departments of the State Council.”

Implementation situation: The NDRC issued the Measures for Temporary Implementation on Energy-Saving Assessment and Review of Fixed Asset Investment Project on September 17, 2010. The NDRC organizes the assessment and review for central government's fixed asset investment projects each year. For non-central government's fixed asset investment project with annual comprehensive energy consumption above 3,000 ton standard coal, its energy-saving assessment report should be separately prepared and reviewed so as to avoid the use of low-efficiency and obsolete motors and ensure that motors purchased for the project are high-efficiency and energy-saving products.

4. Development of China's motor energy-efficiency standards

Energy efficiency, namely energy utilization efficiency, is to assess the energy utilization quality of the product or equipment. There are both compulsory and recommended indexes in China's energy-efficiency standard. Therefore, China's energy-efficiency standard belongs to clause-compulsory standard.

China's compulsory motor energy-efficiency standard mainly includes contents such as energy-efficiency limited value, target energy-efficiency limited value, energy-efficiency rating, energy-saving appraisal value and the testing method. Among them, energy-efficiency limited value is compulsory and the remaining ones are recommended. With the constant revision of the standard according to China's policy implementation requirement for motors, the contents in the motor energy-efficiency standard are constantly changing. The roadmap of China's motor energy-efficiency standard development is shown in Figure 3.



5. Energy-efficiency standard of small- and medium-sized three-phase asynchronous motors

5.1 Background of standard revision

To further guide the energy-saving product market, provide technical basis for China's energy-saving policies, overall improve the energy-efficiency level of domestic products and establish a fair competitive environment for enterprises to constantly increase product's energy efficiency in the market competition, China successively made two revisions and supplements for the motor energy-efficiency standard.

5.2 Situation of standard revision

5.2.1 Scope of standard of GB18613

The general-purpose motors or general-purpose explosion-proof motors with voltages at 690 V and below, 50Hz three-phase AC power supply, rated power between 0.55kW and 315kW for energy-efficiency Class 2 and 3 and between 3kW-315kW for energy-efficiency Class 1, pole number at 2, 4 and 6, single-speed self-fan-cooled closed-type, and N design.

The revised scope in 2012 version is: The general-purpose motors or general-purpose explosion-proof motors with voltages below 1,000V, 50Hz three-phase AC power supply, rated power between 0.75kW and 375kW, pole number at 2, 4 and 6, single-speed self-fan-cooled closed-type, N design and continuous running type. The difference between the previous and revised standards lies in motor voltage grade and rated power scope. The revision is to make the scope closer to the provisions of international standard IEC 60034.

5.2.2 Technical requirements

(1) Basic requirements

The clause "The general performance, safety performance, explosion-proof performance as well as noise and vibration requirement of the motor should comply with relevant standard respectively" means that the implementation of the energy-efficiency standard is for the motors which should firstly meet the quality standard, namely the energy-efficiency standard only puts forward energy-efficiency requirements for qualified products.

(2) Energy-efficiency rating of motor

"The energy-efficiency ratings are classified into three classes among which the Class 1 is the highest grade. The actual measured efficiency of various classes of motors at the rated output power should not be lower than those specified in Table 1. The tolerance should comply with those specified in Chapter 12 of GB 755-2008. The efficiency of the motors whose rated output power values are not listed in the table can be determined by using the linear interpolation method." There are five-grade and three-grade energy-efficiency classification methods in China. In general, the energy-efficiency index of household appliances adopts the five-grade classification method, and the energy-efficiency index of industrial products and lighting products adopts the three-grade classification method. Therefore, China's energy-efficiency standard for motors adopts the three-grade classification method.

The rated power scope in GB 18613-2012 version is any value between 0.75KW and 375kW. For example, the rated powers at 12kW, 40kW and 100kW are not included in the 2002 and 2006 versions of the standard. But considering the energy-saving requirement and the trend of relevant international standards, the motors of these rated power types are all included in the 2012 version standard. Although the energy-efficiency values of these types of motors are not given in the standard, they can be obtained by using difference calculation method based on the energy-efficiency values of the motors with rated powers higher and lower than those of motors whose energy-efficiency values are not given.

(3) Energy-efficiency limited values of motors

"The efficiency of motor energy-efficiency limited value at rated output power should not be lower than that of Class 3 specified in Table 2." The preface of GB18613-1012 states that the limited values of energy-efficiency in this standard are compulsory. The compulsory energy-efficiency index is equivalent to technical regulations, namely manufacturing motors with energy-efficiency below Class 3 belongs to an illegal activity, which will be punished according to the *China Energy Saving Law* and the *Measures for the management of energy efficiency labeling*.

(4) Target energy-efficiency limited value of motors

"The efficiency of motor target energy-efficiency limited value at the rated output power should not be lower than that of Class 2 specified in Table 1. The targeted energy-efficiency limited value for motors with output powers between 7.5kW and 375kW will be implemented four years after the implementation date of this standard. The targeted energy-efficiency limited value for motors with output powers below 7.5kW will be implemented five years after the implementation date of this standard, and at the same time, the regulations for Class 3 in Table 2 will be replaced." The target energy-efficiency limited value is to give the guided prompt to motor manufacturing enterprises that the energy-efficiency limited value indexes will continue to increase, and may possibly increase to the current Class 2 level four or five years later.

(5) Energy-saving appraisal value of motor

"The efficiency of motor energy-saving appraisal value at the rated output power should not be lower than that of Class 2 specified in Table 2." This content means that motor with energy-efficiency rating at 2 and above can be called as energy-saving motor. Enterprises which manufacture energy-saving motors can apply for energy-saving certification and enjoy relevant energy-saving incentive policies.

5.2.3 Test methods

“Motor efficiency should be measured according to Method B -- the loss analysis method by measuring input and output powers in GB/T 1032”.

The following table is the comparison between the energy-efficiency rating level in GB 18613-2012 standard and the international level. Figure 4 is the comparison curve between China’s 4-pole-motor energy-efficiency level and the efficiency of IE1 international standard.

Table Comparison between energy-efficiency rating level and international level

Energy-efficiency level	**International level**	**Energy-efficiency rating**	**Energy-efficiency value**
Level 1	IE4	Energy-efficiency Class 1	Leading index
Level 2	IE3	Energy-efficiency Class 2	Energy-saving appraisal value
Level 3	IE2	Energy-efficiency Class 3	Energy-efficiency limited value
Level 4	IE1	Previous energy-efficiency Class 3	Product to be eliminated

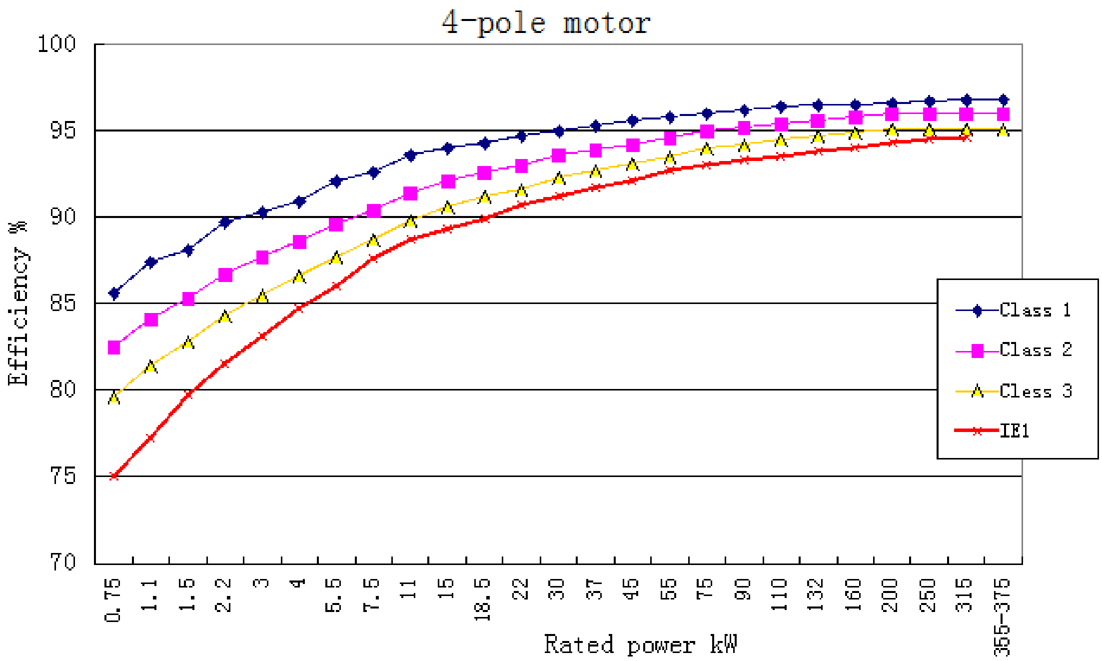


Figure 4 Efficiency comparison curves of small- and medium-sized three-phase asynchronous motors

The Motor Systems Tool - The Continued Development

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Abstract

Following the successful presentation of the Motor Systems Tool at the EEMODS '11 Washington D.C. and the presentation and workshop held at Motor Summit '12 in Zürich Switzerland, December 2012, this paper presents the latest developments of the Motor Systems Tool at the EEMODS '13 Rio de Janeiro, Brazil.

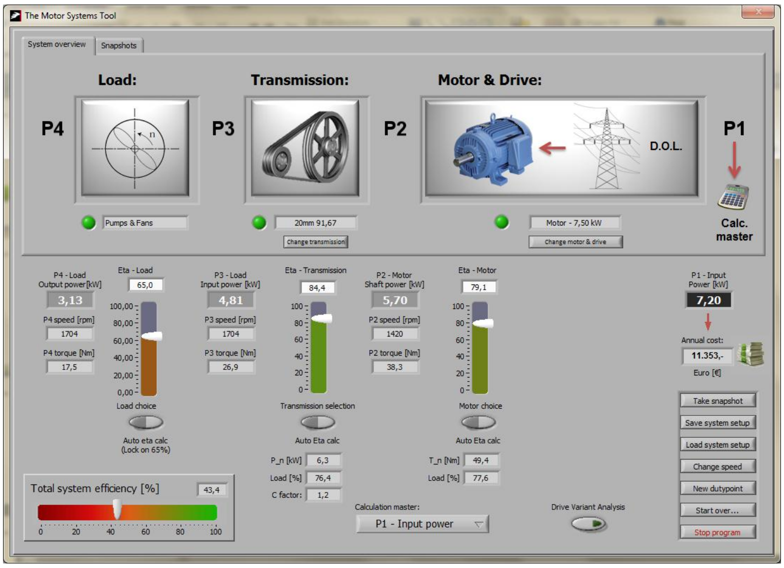
IEA 4E-EMSA
The main goal of the task: Capacity Building in the 4E EMSA project is to upgrade the capacity of motor system users all over the world, by utilizing tools and guides etc. making everything easy accessible as online content. This is done by the Motor Systems Tool.

The task has, in conjunction with Danish public means, produced an impartial calculation tool in which the efficiency of complete motor systems is calculated. The aim was to create an easily accessible tool which gives good technical support for choosing the optimal motor system and is available for a broad audience.

Since EEMODS '11 a lot of development of the tool has taken place. Of the more vital improvements developed a few will be mentioned here: Fully implemented models for gears (worm, bevel and helical), fully integrated interface for dynamic application (table input etc.) and optimized models for both motors and/or converter driven systems (Asynchronous, PM motors etc.)

This paper demonstrates the next generation of the Motor Systems Tool with a few calculation examples combined with illustrations of the models used.

Main screen of the Motor Systems Tool, spring 2013:



The Motor Systems Tool is available for download for free
– *registration required* – at the EMSA website: http://motorsystems.org

Introduction

Optimizing motor driven systems is about choosing the right components and getting them to work well together - thereby achieving maximum energy efficiency of the entire system.

In the Motor Systems Tool a system is defined as the entire system from the wall outlet to the power delivered by the application, for instance a pump that delivers hydraulic power such as P_4, in Figure 1.

By definition a motor driven system consists of the following four components:

- The driven machine – load (pump, fan, compressors, conveyor belts etc.)
- The transmission – if any (belt, gear, gear motor etc.)
- The motor – that's a given
- A possible drive (soft starter, frequency converter or other VSD equipment)

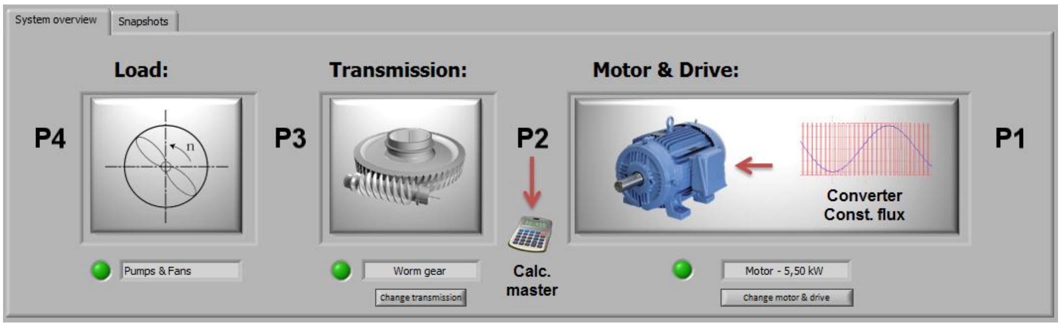


Figure 1 – Potential components of a motor driven system

Basic build up

The heart of the MST-Tool basically consists of simplified models of standard components all giving the efficiency at a specific duty point based on the input speed and load, $\text{Eta}_{(\text{speed, torque})}$

Most of the models used are based on real life measurements during the last decade in former energy projects, carried out at the accredited laboratories of the Danish Technological Institute, in combination with the known theory of certain components, anonymous data from manufacturers, legislation rules, actual compliance testing, etc.

In many cases a variable speed and torque input makes the basis for a mathematical 3D "plane" which can be "simplified" and described as a certain equation with a number of variables involved. All of these mathematical models for each component are handled and calculated inside the MST-Tool dynamically.

This build up allows the possibility for very easy documentation and extraction of existing models (for use in spread sheets), verification of models, and optimization and improvement of all the models. It has also proven valuable – in retrospect, to be able to extend the valid boundaries of the models.

This method also keeps "the door" open for implementation of new models (e.g. new motor technologies, new components and so forth). If a component can be described by $\text{Eta}_{(\text{speed, torque})}$ it can easily be implemented in the MST-Tool.

Figure 2 – Illustration of a standard model

Structure of the MST-Tool

A simple flow chart was carried out to define the program structure:

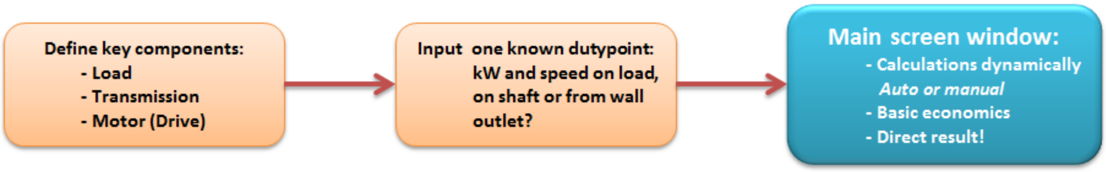


Figure 3 – MST flowchart

When selecting load and motor – suggestions are provided by the tool if you're in doubt regarding your system. Quite often in real life the available information is limited.
In this way you can get a very good estimation of your system performance – even with very little knowledge about your actual system.

Describing the MST-Tool

Step 1 – Selecting key components
First step of the tool is to pick the key components of the system. This is, as a minimum, a load and a motor, but it can also be a transmission (belt or gear) and a VSD-drive.

Load
Load is at this point in the program selected as a torque profile
(One of four different speed/torque relations)

Transmission
Transmission selection has proven to be somewhat impossible to simplify completely. The user has to have some knowledge of the transmission chosen. There are default values in the tool, but if not selected carefully, calculated values can be quite inaccurate. Included are transmissions (as of spring 2013), many different belt types, and three gear models (helical, worm and bevel)

Motor (drive)
If known the user can input the actual motor nameplate data but when such information is not available, the user can choose a standard size motor. As of spring 2013 the table from the present IEC 60034-30 definition of IE1, IE2 and IE3 can be selected (1 through 500 horsepower, 50 Hz).

After the motor selection screen the user must input the method by which the motor is connected. The possibilities are: direct on-line (D.O.L.), soft starter and frequency converter either constant flux or automatic energy optimization (AEO).

Step 2 – Input of a duty point
All calculations inside the MST-Tool are based on only one known duty point. The user is free to choose this duty point, based upon equipment design and operating criteria, anywhere from wall outlet P_1 to actual load P_4 but it's vital to emphasize that all calculations originate from this one point.

Step 3 – Main Screen of the tool

Having overcome these few steps the user is now presented with the main screen of the Motor Systems Tool and already by now a qualified “guess” of the total system efficiency:

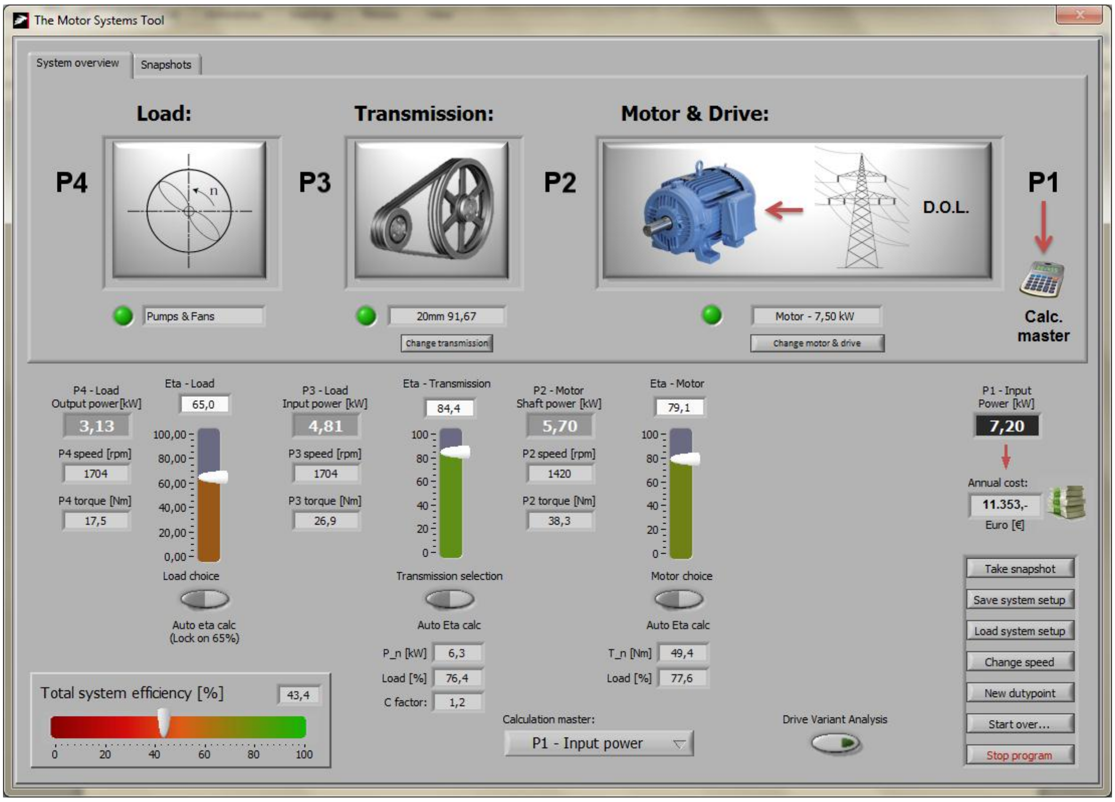


Figure 4 Main screen of The Motor Systems Tool

The top third of the main screen is merely a representation of the choices previously made and the rest are the calculated efficiencies of the respective components, the kilowatt powers in all of the split points of the entire chain, P_1 through P_4, and finally a presentation of the total system efficiency in the duty point selected.

In this case the total efficiency is calculated to approximately 43 %. *(This is calculated from the known duty point P_1 = 7.2 kW)*

Below the kilowatt indications values like speed, torque and load percentage are also shown. If desired the calculated efficiency of a certain component can be overridden manually.

From this screen it’s possible to calculate and document both before and after situations when for instance a user wants to see the difference between an IE1 and an IE3 motor in a given application.

From the main screen of the MST-Tool a lot of different features and functions are available. Input and ideas on how to fill out these, can be found in both formerly published papers on the tool and also on the 4E EMSA web page:

References:

[1] – Paper from EEMODS’11
[2] – Paper from Motor Summit ’12
[6] - 4E EMSA webpage

The motor model

The model for standard 3 phase cage induction motors used inside the MST-Tool was originally a simplified mathematical description of a standard shape for efficiency in the whole range of motors (0.75 kW through 375 kW) The Danish Research Institute – DEFU have made a mathematical expression based on the motor nominal efficiency, the nominal power and a constant (alpha) which is dependent on motor size. This gives the following shape of efficiency as function of load where maximum efficiency is achieved somewhere around 70 – 80% load:

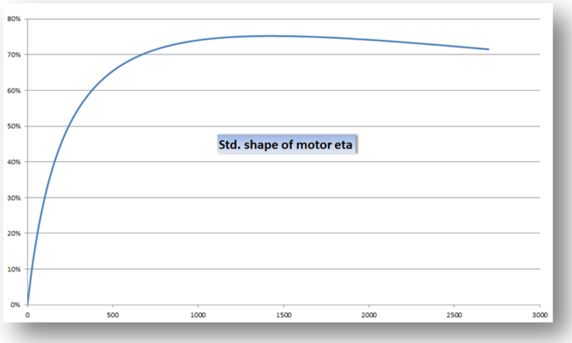


Figure 5 – Standardized shape of motor efficiency vs. load

Danish compliance testing – EU regulation

In the years 2011 and 2012 the Danish Technological Institute performed compliance testing for the Danish government, regarding the European motor regulation. This regulation (640/2009) turned into force on 16th June 2011. A total of 41 motors (sizes 0.75 kW – 18.0 kW) have been tested and it was decided that these test results should form the basis for a new model for the smaller motors in the MST-Tool.

The outcome of this was a model directly calculating the losses inside the motor as function of speed and torque:

$$P_{loss} = 0{,}3969 \cdot \left(\frac{n_{actual}}{n_{nom}} \right)^2 \cdot (P_{1,nom} - P_{2,nom}) + 0{,}6680 \cdot \left(\frac{T_{actual}}{T_{nom}} \right)^2 \cdot (P_{1,nom} - P_{2,nom})$$

Verifying this new motor model proved successful using it also on other motor measurements:

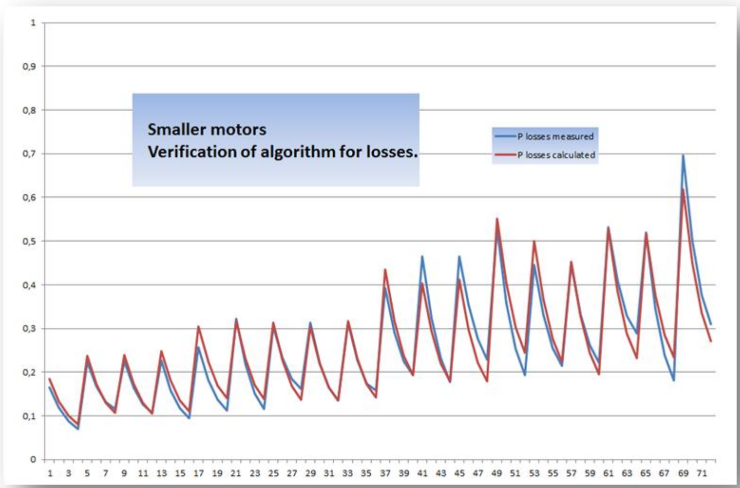
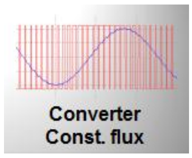


Figure 6 – Comparison between measured and calculated losses

The converter model



The model inside the MST-Tool for frequency converters is based on a Ph.D. study from Aalborg University, 2000 [3], where the impact on efficiency on converters was investigated when using automatic energy optimisation (AEO) vs. scalar mode.

The study clearly shows the advantage of AEO mode on partial loads on all sizes of motors investigated:

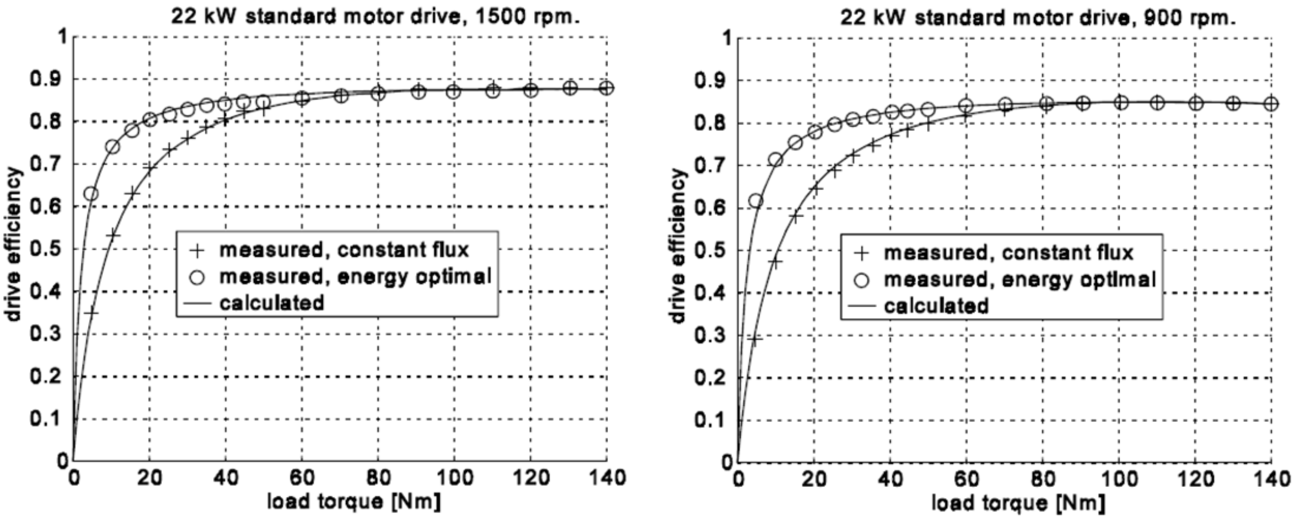


Figure 7 – Example of measured and calculated losses by Abrahamsen, anno 2000

For the purpose of the MST-Tool the same methodology as for the motor model was used. Losses were calculated as a function of nominal losses, partial speed and partial load. The nominal values used in the equations are both taken from the motor name plate.

Two sets of equations were developed, one for standard mode and one for AEO mode. Both have been tested and compared to actual measurements and found lying within the demands for precision in the MST-Tool.

$$P_{losses} = 0{,}249 \cdot (P_{1,nom} - P_{2,nom}) + 0{,}320 \cdot \left(\frac{n_{actual}}{n_{nom}}\right)^2 \cdot (P_{1,nom} - P_{2,nom}) + 1{,}03 \cdot \left(\frac{T_{actual}}{T_{nom}}\right)^2 \cdot (P_{1,nom} - P_{2,nom})$$

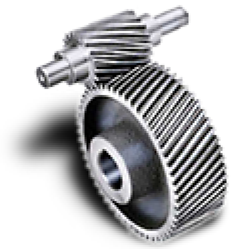
Figure 8 – Equation for using standard scalar mode drive

$$P_{losses} = 0{,}169 \cdot (P_{1,nom} - P_{2,nom}) + 0{,}287 \cdot \left(\frac{n_{actual}}{n_{nom}}\right)^2 \cdot (P_{1,nom} - P_{2,nom}) + 1{,}18 \cdot \left(\frac{T_{actual}}{T_{nom}}\right)^2 \cdot (P_{1,nom} - P_{2,nom})$$

Figure 9 – Equation for drive with automatic energy optimisation (AEO)

In the time to come there are plans to develop and improve even further on the models for drive efficiency.

The gear models



The models for the gears inside the MST-Tool have up until spring of 2013 been quite simplified and based on relatively few actual measurements.

During a former Danish energy project about systems optimisation [9] a number of gear motors were tested for efficiency both as a total unit and afterwards after dismantling and testing, the "isolated" motor.

The behaviour of efficiency for three different gear types: helical, bevel and worm gears were then deducted and put in to a very simplified linear "plane", where relation of both speed and load vs. efficiency were defined.

The outcome of this in all three cases was an equation where efficiency is depended on partial load and speed as well as the nominal efficiency and a constant:

$$\eta = \alpha \cdot \left(\frac{Load_{actual}}{Load_{nom}} \right) + \beta \cdot \left(\frac{Speed_{actual}}{Speed_{nom}} \right) + \eta_{nom} + Const$$

Figure 10 – Standardized equation for gears

When illustrating these equations as 3D planes the linearity of the equations becomes very clear. It also becomes clear that there's a potential problem with the calculated efficiency when approaching both zero speed and zero load.

Inside the MST-Tool the user will be warned by a flashing light when coming "close" to this area when calculating.

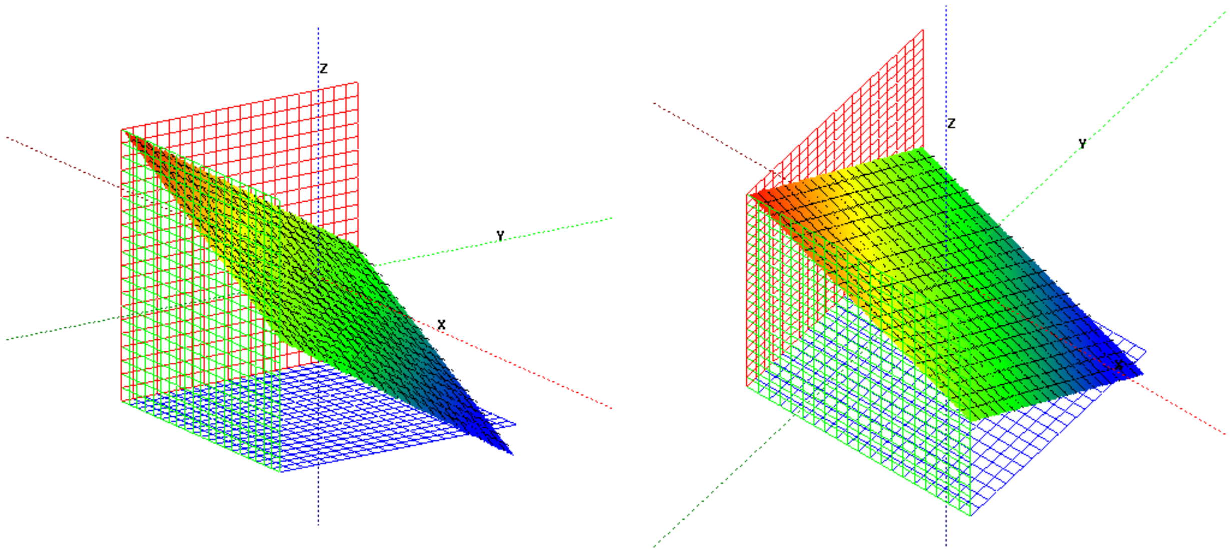


Figure 11 – 3D illustration of gear equations

During spring and summer 2013 a series of further measurements on gears and gear motors with and without VSD-drives are to be undertaken and these results will be implemented in the coming generations of the MST-Tool, ensuring even better efficiency calculations on gears.

Final comment

The MST-Tool has been available for download from the EMSA web page since September 2011. According to Google statistics the tool has been downloaded close to one thousand times by unique downloads.

This fact underlines the interest and necessity of an impartial tool helping users to understand relations between components in a complete motor system.

The MST-Tool is by no means “perfect” or “finished” and many users will probably argue against the models used, the precision of the calculated efficiencies and the lack of inputs to make everything more exact. In spite of this the tool still is capable of providing a useful “guess” on a given efficiency in a given system which will be valuable to many.

There is room for improvement – for sure – and the on-going project in both Denmark [7] and the 4E EMSA project will ensure further development of the MST-Tool in the years to come. Furthermore Danish Technological Institute has started co-operation with the Belgian University Howest which have done – and still are performing – quite a few measurements on gears, belts and drives. These results are also to be implemented in the MST-Tool.

Bullets:
The Motor Systems Tool is impartial using “self – made” standardized models for all implemented components, thereby helping to ensure that no specific products or manufactures are being favoured over others. This also means that results are general rather than exact.

The Motor Systems Tool is the obvious choice to use to inform and train not only engineers working in industrial plants but also energy consultants, original equipment manufacturers, trainers and teachers at schools and universities as well as government officials responsible for creating policy instruments.

Finally – best of all – The Motor Systems Tool is free of charge and it can be downloaded from the EMSA web-page http://motorsystems.org

The software comes in a self-extracting zip file and installs itself with a just a few clicks.
The only thing required is a registration on the EMSA page – for statistical purposes only

Summary of calculation models:

The present version of The Motor Systems Tool includes the calculation models below. The tool can handle any combinations of these.

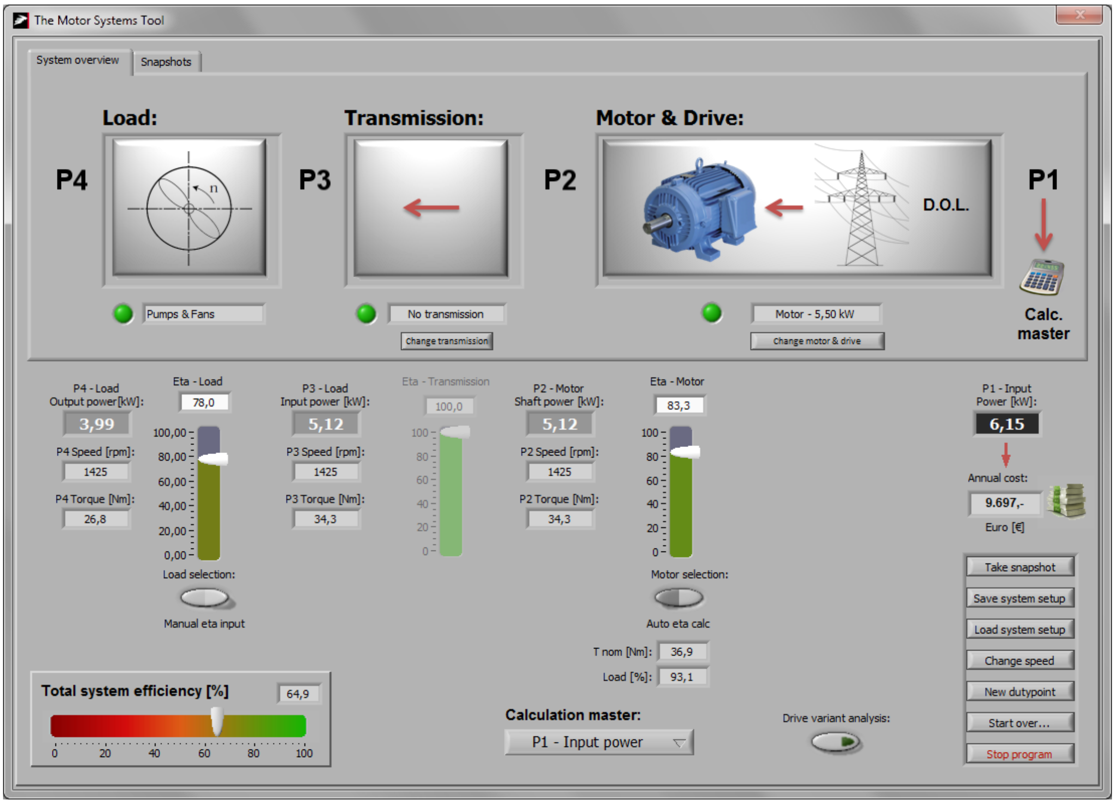
Load:
4 variations of torque vs. speed: $T_{(n)} \sim n^{-1}$, $T_{(n)} \sim n^{0}$, $T_{(n)} \sim n^{1}$ and $T_{(n)} \sim n^{2}$

Transmission:
Direct coupled, belt drives and gear motors.

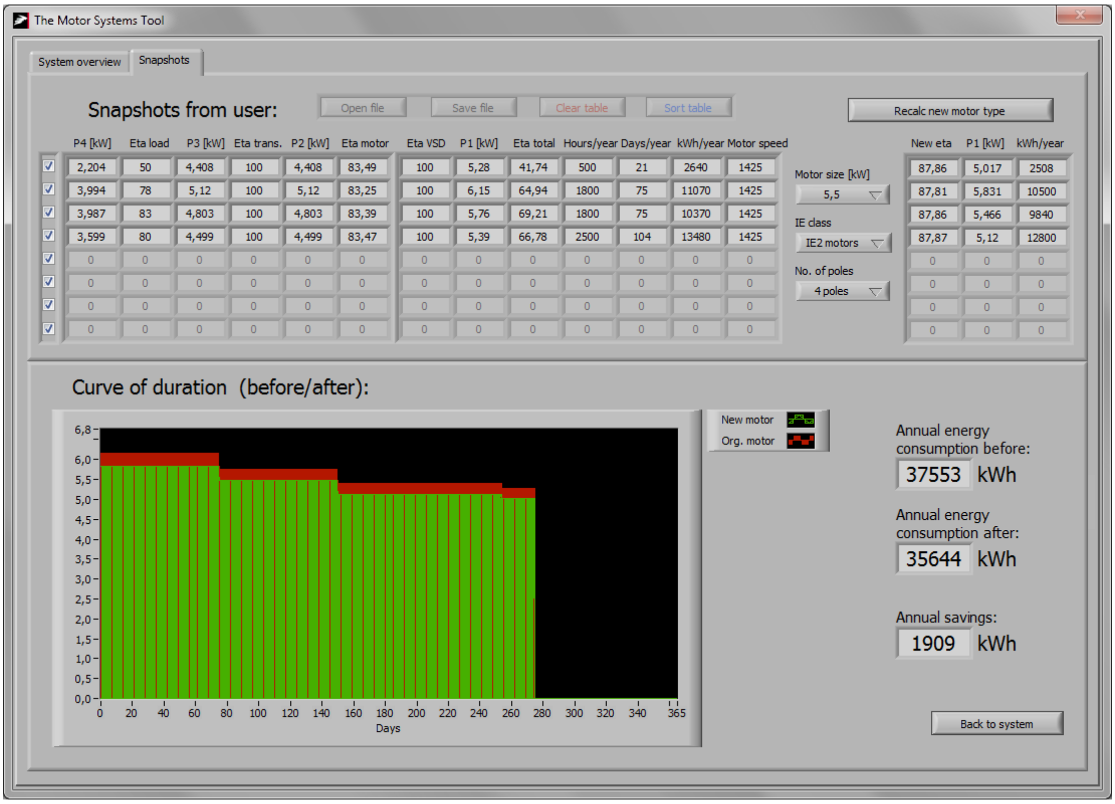
Motor & Drive:
AC squirrel cage asynchronous motors 50 Hz models, D.O.L., connected through soft starters, VSD constant flux and VSD with automatic flux optimization.

Appendix A: Screenshots from 4E EMSA exercise solved

The following screenshots are from the downloadable exercise “Exercise for a fan installation” which can be found on the 4E EMSA web page: http://motorsystems.org. Please download the exercise for elaboration of numbers illustrated.



Before situation – Calculating right to left, existing motor running at 93 % load, eta fan deducted from datasheet: 78 %. Situation saved in line two below.



After situation – Calculating left to right, from very little input, annual savings potential are revealed provided the duty of the fan is unchanged.

References

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Methodology For Implementation of Energy Efficiency Actions in Brazilian Industrial Sector

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Abstract

This paper describes the Industrial Energy Efficiency Program - Procel Industria as an inducer of energy efficiency policies in micro and small enterprises and medium and large industries, with the experience acquired in 10 years of activity in those sectors. The actions are mainly focused on industrial motor driven systems, whose end use is 62% of electricity consumption in the industrial sector. The Program seeks to consolidate partnerships with industry association class and intensive energy industries to deploy energy efficiency actions and energy management to reduce the electricity consumption in that subsectors. The paper analyzes the technical, economic and market potential actions of the methodologies used by the program to develop the induced and autonomous progresses and energy efficiency initiatives in the industrial sector, included in the National Energy Plan (PNE) and National Energy Efficiency Plan (PNEf), emphasizing the subsectors covered, the results obtained and estimated with the replication of energy efficiency actions to other industrial subsectors.

Introduction

The Eletrobras (Brasil's largest electric utility) created the PROCEL Industria – Industrial Energy Efficiency Program – in 2002 by means of National Electrical Energy Conservation Program – PROCEL considering the importance of industrial sector in the electrical energy consumption at Brazil.

PROCEL Industria was created during the crisis of electricity supply around 2001, as the brazilian government established the council of management of crisis of electricity supply – CGE [3]. The objective was to elaborate a strategic plan for emergency power in order to increase the electricity supply and to ensure the energy demand decreasing the risks of load contingency, avoiding the damage to the population, restriction in economic growth, undesirable impacts in the jobs and income generation, beyond to implement the energy efficiency actions.

Designed this concept, the PROCEL Industria supports the industries in improving their energy performance of their facilities, in partnerships with National Confederation of Industry (CNI), States Federations of Industries and Industry Associations, beyond to the institutions as much as Support Service for Micro and Small Enterprises of the State of Rio de Janeiro (Sebrae-RJ), Public Universities and power utilities.

The main focus of PROCEL industria are projects for the optimization of industrial motor systems, since they are responsible for about 62% of electricity consumption in industrial sector [5] and 28% of total electricity consumption in the Brazil, overcoming the electricity consumption in residential and commercial sectors. The figure 1 shows the final electricity use in brazilian industries.

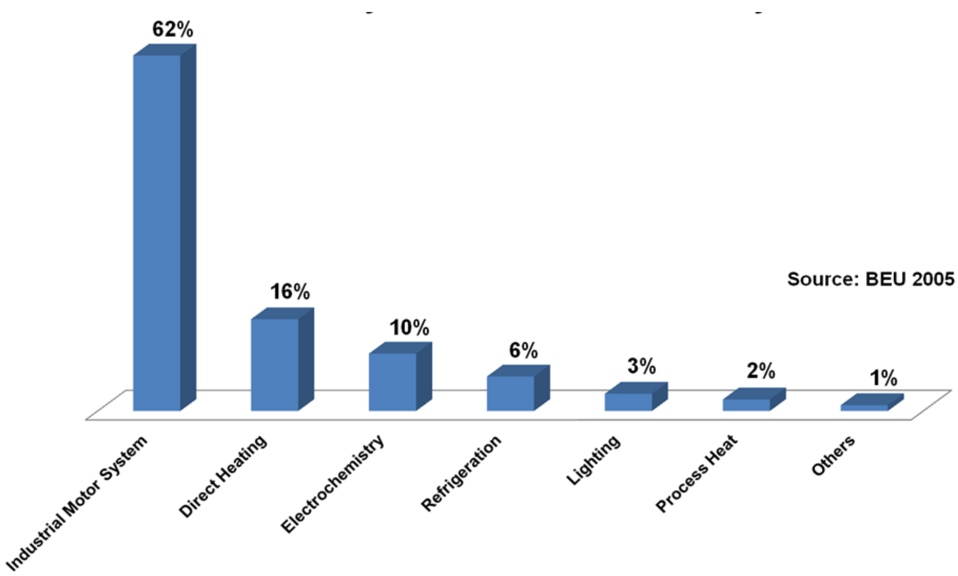

FIGURE 1: Industry – Final use for eletricity

This paper describes the ongoing initiatives or initiatives to be developed by the PROCEL Industria in brazilian large industries, and the outcomes after implementation of the proposed actions. In order to define the size of enterprise or industry, the program utilizes the consumption, the energy efficiency potential and the criterion of number of employees defined in [6], according to table 1, neglecting the companies revenues. According to [6], the total of enterprises and industries is about 5.1 million.

Table 1 – Classification of enterprises and industries considered by the Program

Size	N.º of employees	Percents of enterprises and industries by size
Micro and small enterprises	until 99	99,1%
Medium industries	100 a 499	0,7%
Large industries	≥ 500	0,2%

The classification of industries by economy sector is necessary for characterizing each sector.

- For micro and small enterprises, the actions seek to reduce energy consumption and associated costs, acting in the processes and equipment and final use, in order to improve the competitiveness of the sector.
- In medium industries, the performance of industrial motor systems is assessed by means of simple energy audits in which the opportunities of energy savings in these systems are identified.
- The approach for large industry also includes energy efficiency opportunity identification in industrial motor systems through more in-depth energy audits, besides being required greater sample period for the parameters used in the analysis. The assessment also examines the enterprises energy management system and the energy savings opportunities with adoption of energy management systems.

Actions in medium industries

Two main actions are detached in the medium industries sector:

Energy Eficiency Program in Zona Franca de Manaus

Actions of energy efficiency are provided in 10 industries of the industrial pole of Manaus – IPM, specifically in compressed air systems, in partnership with Eletrobras Amazonas Energia, Eletrobras Cepel, SUFRAMA – Superintendence of the Industrial Pole of Manaus and State Amazonia Federations/Center of Industries – FIEAM/CIEAM. The energy efficiency program in zona franca de Manaus aims to establish a methodology for using of funds from the PEE ANEEL – Energy Efficiency Program of National Electricity Agency (ANEEL) under the responsibility of Eletrobras Amazonas Energia.

The goal of the program is to reduce the electricity costs in IPM, improve the energy efficiency of industrial plants evaluated and minimize the environmental impacts, in such a way to promote sustainable practices and the local industrial growth, in addition to seek the reductions of financial costs and increase of sectorial competitiveness. At the same time, the program also seeks to implement the actions provided in [2] that represent the great opportunities of energy efficiency in the industrial sector.

The program expects to save 5.5% of the average annual consumption of 90 consumers who are served at 13.8 to 69 kV, totaling about 760 MWh.

Evaluate of methodology Industrial Assessment Centers – IACs

This effort came out of the Memorandum of Understanding signed by Ministry of Mines and Energy from Brazil and Department of Energy from USA, that provides the cooperation between two countries in the energy efficiency, renewable energies, nuclear power generation, oil and gas areas.

The actions of energy efficiency promoted by means of IACs are taken by professor teams aided by undergraduate students focused on small and medium industries. The work consists in the implementation of energy audits at the industrial utilities and process systems and aims to identify opportunities of improvements in productivity, reductions of wastes and energy savings [8].

Factors like analysis of methodology, support of universities in actions of energy efficiency and promotion of sustainable practices able to increase the productivity and growth of industry were regarded. These practices make up a database that allows the university teams to draw an energy profile of medium industries, in addition to create local centers for dissemination of good practices in relation to energy use in industrial sector.

Two industrial plants were diagnosed to test the methodology and the results obtained forecast a reduction of electricity consumption (by around 13% and 8%, respectively). Two main lines of actions were identified:

1. Energy and Processes management: (a) average reduction of demand is 6.3%, (b) Replacing of electrical motors obsolete/rewound by similar high performance motors; (c) monitoring and reducing compressed air leaks; (d) turn down of lighting and fan coils used eventually; (e) control of the operational parameters of boilers.

2. Capital Improvements: (a) installation of variable speed drive in environmental conditioning systems; (b) Use of efficient lamps with lower power and presence sensor; (c) acquisition of multistage compressor and changing the air intakes of the compressor room; (d) insulation for the steam lines.

Actions in large industries

Agreements of technical cooperation

Since 2002 the PROCEL industria has an agreement with the state federation of industries focused in industrial motor systems, regarding the importance of systems in the industries, according to the figure 1. The agreements include, among other actions, professional training courses in optimization of industrial motor systems and accomplishment of success case studies.

The professional training courses have a workload of 180 hours and seek to capacitate professors and experts in energy efficiency so they can train others. Participants are called “multipliers”. These multipliers transmit the acquired knowledge to other engineers and technicians in the industry, called industrial agents. On the other hand, the industrial agents are responsible for leading the energy audits in their industries. The industries then implement the economically attractive actions. After the implementations of actions, measurements are made in order to confirm the ex-ante savings estimates.

Twelve agreements with states federations of industries were fulfilled in which 206 multipliers, 2907 industrial agents of 690 industries were trained. The program received 133 energy audits, 80 of which were approved and register an energy saving of 38 GWh with pay back 14 months per industry.

Nowadays, the agreement with the Rio Grande do Sul State Federation of Industries is ongoing and 21 multipliers and 133 agents of 83 industries were trained. The program received 28 energy audits, 24 of which were approved and register an energy savings of 3.7 GWh/year with pay back 10.7 month per industry. The goal is to elaborate 40 energy audits, saving approximately 6.5 GWh/year.

Cooperation Protocol

The cooperation protocols aim to set the technical actions between the Eletrobras/PROCEL, industrial associations and large industries with the objective to promote the efficient use of energy (electricity or thermal energy) and water, identify opportunities in R&D that contribute to the development of national industrial sector, and to implant energy efficiency actions in the signatory industrial sectors. These actions aim at the reduction of energy wastes and adoptions of operational strategies to the use of new technologies, and the optimization of projects, equipments and process. The Rio de Janeiro state Federations of industries – FIRJAN, the Brazilian technical Association of Pulp and Paper Industry – ABTCP and BRASKEM (Brazilian Petrochemical Industry) are some of the signatories.

The actions developed in the cooperation protocols are categorized in five lines:

Training: (a) technical training of industry managers that act in the planning and implementation of programs and projects for increasing the productivity and the process efficiency; (b) technical training of industry engineers and technicians for the implementation of energy audits and actions to reduce energy waste and water; (c) disclosure of sectorial institutional programs of technical training.

Management: (a) use of performance indicator and behavior patterns more suitable in such a way to improve the consumption and demand indicators of electricity and water; (b) Improvement in the industrial processes, under the point of view of energy management systems; (c) implementation of ISO 50,001 in the national industrial sector, identifying the barriers and suggesting solutions for its application.

Technology: (a) contribution to the evolution of the technical specifications of materials and efficient appliances; (b) support the industrial projects that take into account issues on the efficient use of energy and water; (c) support the use of efficient technologies in the industrial processes by means of government programs as, for example, PROCEL and PBE (Brazilian label Program); (d) encourage the development of new technologies that leverage news business in the national industrial sector; (e) encourage the actions of energy efficiency provided in [2] for the industrial sector.

Financing: (a) Identify the financing lines and support the participation of financing agents in projects of energy efficiency and hydric resource management.

From the actions provided in the cooperation protocols, the follow results are expected:

Training: (a) Training focused on energy management and industrial energy efficiency designed from the requirements of industries; (b) training of 30 industries and experts in energy efficiency.

Management: (a) consolidation of main sectorial indicators; (b) implementation of three projects for energy management based on three previous performance indicators and management tools and on ISO 50001.

Technology: (a) adoption of efficient equipments that have the PROCEL label or Inmetro label by industries; (b) adoption of best practices in maintenance and operation of the industries, including the shutdown of inoperative equipments, periodic clearance and inspection, optimization of production, aside from the other specific actions for each industrial sector (c) encourage the partnership with university or research center for the development of R&D + I in energy efficiency.

Financing: (a) Identify the main financial institutions and financing lines, aside from the sector funds available for purchase of efficient equipments and energy efficiency services.

The technical potential of energy conservation in the industrial motor systems [1] regarded by program from the actions established in the protocols are shown in Table 2.

Table 2 – Potential of energy saving in industrial motor systems and markets coverage of protocols

Potential of energy saving	ABTCP	FIRJAN
technical (20,3%)	1.160 GWh	2.499 GWh
market (3%)	35 GWh	75 GWh
coverage (20%)	7,0 GWh	15 GWh

The PROCEL Industria provides the enlargement of its activity for other industrial sector, beyond the sectors considered by the cooperation protocols. Sectoral studies conducted by Eletrobras in partnership with the National Confederation of Industry (CNI) show that there is a significant potential for possible energy consumption reduction. In the table 3, the subsectors are shown as well as its respective technical potentials defined by the sectorial studies from [9] to [12], and market potentials defined by average obtained from the energy efficiency provided in [1] and the consumption indicated in [5].

Table 3 – Potential of electricity consumption reduction in industrial motor systems per subsector

Economic Potentials	Subsector					
	Cement	Textile	Pulp and Paper	Ceramic	Food & Beverages	Chemical
Technical	1.589 GWh	605 GWh	1.685 GWh	282 GWh	2.052 GWh	783 GWh
	27,5%	7,5%	9,3%	7,9%	9,3%	4,4%
Market (6%)	345 GWh	476 GWh	1.070 GWh	214 GWh	1.297 GWh	1.101 GWh

Concluding Remarks

The PROCEL Industria identified a series of acting according to the industrial sector in which all the ongoing projects and to be developed are aligned with the guidelines established in [2], adding to the achievement of targets of electricity consumption reduction established in [2] and to continuity of energy efficiency in the industrial sector.

In the medium industries, the program foresees the introduction and diffusion of energy efficiency actions in order to reduce the energy consumption and costs in the sector, improving its competitiveness. As additional advantages, the energy audits and the adoption of similar actions by other industrial units will contribute to promote the approach between the Eletrobras Amazonas Energia and its industry customers.

For large industries, the program seek to introduce the energy efficiency in the industries planning and operation, to reduce the energy consumption and promote the integration between maintenance, production and energy management areas to optimize the load factor of energy-intensive industries. Thus, the applicability of ISO 50,001 becomes a key component of this effort.

The realization of just 1% of the potential market among the six sectors evaluated would result in an energy savings approximately 45 GWh/year, regardless of executing agent (industries or government program). This energy saving would match the virtual power plant of 10.3 MW with a cost avoided of R$ 20.6 million.

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Electrical Apparatus Service Center Accreditation Program

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Abstract

It has been proven that electric motor efficiency can be maintained during repair and rewind by following defined good practices. The Electrical Apparatus Service Association (EASA) has developed an international accreditation program for service centers based on the sources of these good practices, namely ANSI/EASA AR100 *Recommended Practice for the Repair of Rotating Electrical Apparatus* and the *Good Practice Guide* of the 2003 study, *The Effect of Repair/Rewinding on Motor Efficiency*. The intent of this groundbreaking accreditation program that will roll out in 2014 is to evaluate service centers for evidence of compliance to assure that they are using prescribed good practices to maintain motor efficiency and reliability during electrical and mechanical repairs of electric motors. Repair processes that will be assessed include rewinding, core testing, bearing replacement, bearing journal rebuilding, dynamic balancing; and electrical testing, mechanical measurements and calibration. Conformance to the program will be verified by objective third-party audits. This paper will detail the EASA service center accreditation program and the third-party audit process that is an ancillary and key component of it.

Introduction

The rewind study of 2003 sponsored primarily by the Electrical Apparatus Service Association (U.S.) and the Association of Electrical and Mechanical Trades (U.K.) proved that electric motor repairs that followed prescribed good practices maintained efficiency. The 2010 edition of ANSI/EASA AR100 incorporated the remaining good practices from the 2003 rewind study that were not already in the AR100 document. Despite the findings and conclusions from that study a significant number of end users continue to hear the myth that electric motors cannot be repaired without reducing efficiency; and also, that reliability of a repaired motor is reduced by repair. As a proactive measure to dispel this misinformation, EASA has embarked on a service center accreditation program to evaluate service center conformance to the good practices.

Membership in EASA will not be a prerequisite for participation in the service center accreditation program. It will be offered globally to both non-members and members of EASA. The program will assess, by independent third-party auditing, that a service center has adopted the good practices as outlined in ANSI/EASA AR100 [1] (Figure 1) and the Good Practice Guide part of the 2003 rewind study [2] (Figure 2). Independent external audits will be supplemented with internal audits by the participating service centers. In addition to maintaining (or improving) efficiency the program objectives also include maintaining or improving the reliability of the repaired motor. As such, the scope of the program includes mechanical repairs as well as electrical rewinding. Electric motors that conform to the requirements of the criteria in the associated checklists are to be labeled by the service center with an EASA approved sticker. Conversely, motors that do not meet the requirements cannot be labeled. The program is in the final development stages and is scheduled to be rolled out in 2014.

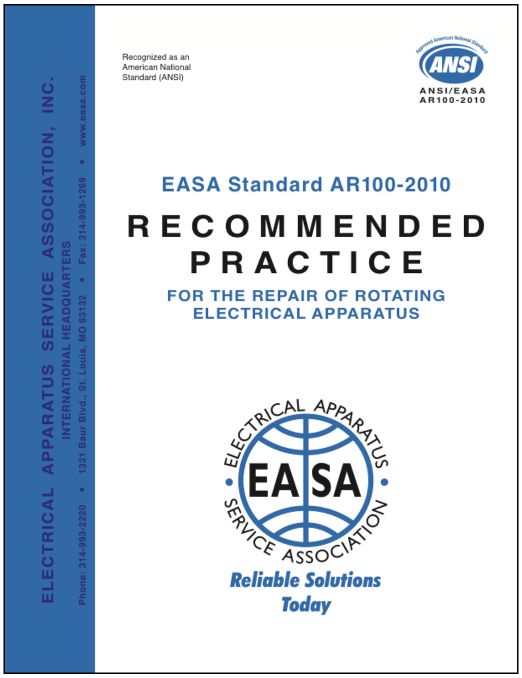

Figure 1: The cover page of ANSI/EASA AR100-2010

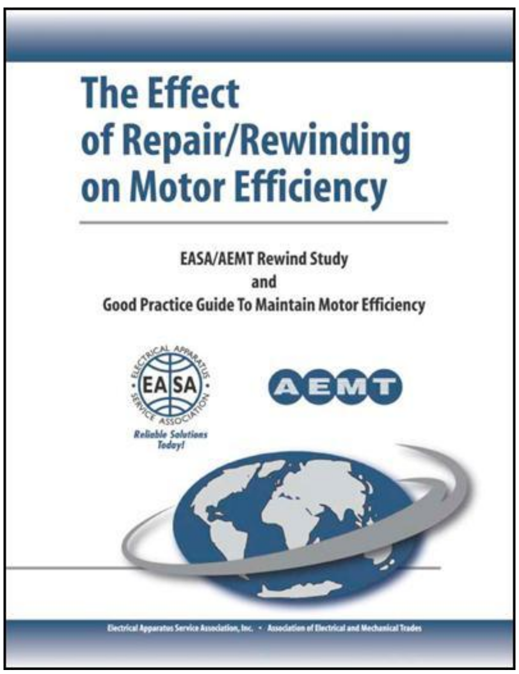

Figure 2: The cover page of the EASA/AEMT Rewind Study

Accreditation Program Overview

The accreditation program utilizes a checklist consisting of 23 categories (Table 1) for the more than 70 mandatory criteria elements.

Table 1: Checklist Categories and Key Criteria

Category	Key Criteria
Housekeeping	Evaluates the cleanliness and orderliness of work areas and equipment in the service center since these are indicators of professionalism and a controlled (and safe) repair environment.
Training	Evidence of internal training of technicians is required; with external training encouraged, but not mandated. Technical training includes topics related to electric motor rewinding, machining, mechanical assembly or disassembly; and theory, principles, applications, failure analysis and design/redesign.
Internal audits	Annual internal audits are performed and documented. If applicable, corrective actions for internal audit findings are taken and documented.
Identification and condition assessment	Among the requirements are that original nameplate data (if present) is recorded; incoming inspection findings recorded; primary apparent cause of failure determined and recorded; and repair records retained for at least 3 years.
Terminal leads, connectors and boxes	The terminal leads are labeled for identification; terminal lugs (if used) properly crimped; and terminal box integrity checked. Confirm terminal crimpers function checked at least quarterly for wear and proper crimp.
Cooling system	Internal and external cooling fans and cooling fan cover (if applicable) integrity is checked; and a check performed for damaged or missing cooling system components.
Shafts	Before and after repair shaft dimensions are recorded; shaft integrity checked; and shaft orientation (e.g., NEMA F1 versus F2) verified. Confirm outside micrometers calibration is current.
Bearings (ball, roller; sleeve)	Replacement bearings are equivalent to the original, or better suited to the application; original and replacement bearing numbers documented; as-received, and if rebuilt, post repair bearing fits documented; and if possible, the mode of failure documented. Confirm inside and outside micrometers calibration is current.
Lubrication	The service center is to have documentation indicating that the lubricant used in the motor is compatible with the customer's lubricant; and the service center is to identify the lubricant used in the motor.
Frame and bearing housings	Frame and bearing housing integrity is checked; a check performed for damaged or missing components; and parts are match marked in accordance with service center policy. Confirm inside and outside micrometers calibration is current.
Squirrel cage rotors	Check is performed for evidence of rotor damage or overheating; rotor is growler and/or single-phase tested; and if repaired, original electrical and mechanical characteristics are maintained. Confirm growler is function tested, and that ammeter is functional and calibration is current.
Balancing	Dynamic balancing of the rotating element is to the level specified by the customer; or in the absence of a requested level, dynamic balance is to ISO quality grade G2.5, or better; and original and final balance values are documented. Confirm calibration and functionality of balancing machine.
Accessories	Check is performed for evidence of damaged or defective components; if replaced, components are identical with or equivalent to the original devices. Confirm calibration and functionality of associated test equipment.

Winding removal and core integrity	Core testing is performed before burnout or other equivalent process, and after winding removal, and the results documented. Evaluation assessment of core acceptability (watts per lb (kg) and temperature rise) is documented. Burnout oven has part temperature control set to 700 °F (370 °C) or less; water mist and analog or digital recorder are functional. *(See the complete example that appears later in this document.)*
Rewind data (specification)	Details of as-received winding are documented; data is verified for accuracy; and winding changes made to maintain or improve efficiency of a rewound motor are documented.
Stator windings, insulation system, conductors and coils	Voltage rating and insulation class of winding system are equal to or greater than the original unless redesigned by agreement with, or at the instruction of, the customer; coil extension lengths are not to exceed original; and winding wire cross-sectional area per amp (CMA) is at least equal to original. Confirm calibration and functionality of associated equipment including outside micrometers and verification of winding machine turns counter.
Winding impregnation	Windings of rewound motors are preheated, varnish/resin treated and cured in accordance with varnish/resin manufacturer instructions; bake oven temperature control set in accordance with varnish/resin manufacturer instructions; and varnish maintenance tested in accordance with manufacturer instructions. Confirm calibration and functionality of temperature meters.
Winding insulation and coil tests	Stator winding insulation resistance is tested and results documented; and stator winding resistance, phase balance or surge test is performed. Confirm calibration and functionality of associated equipment including megohmmeter, milli-ohmmeter, ammeter and surge tester.
High-potential tests	New and reconditioned windings and accessories are high potential tested and results documented. Windings and accessories of windings not reconditioned are insulation resistance tested and results documented. Confirm calibration and functionality of megohmmeter and high potential tester.
Bearing insulation	If applicable, bearing insulation is insulation resistance tested and results documented. Confirm calibration and functionality of megohmmeter.
No load tests	No-load running test using test panel is performed at rated voltage. No-load currents and voltages, and vibration levels, are measured and documented. Evaluation assessment of acceptability is documented (e.g, "OK to ship".) Confirm calibration and functionality of associated equipment including voltmeter, ammeter, and vibration meter.
Finish and handling	Motor is packed or packaged in a manner suitable for the form of transportation to be used. Oil-lubricated motors are shipped without oil, and the need for lubricant clearly identified. Motor is externally clean and painted (if applicable).
Calibration	Proof of current calibration to applicable national standard is available for all applicable instruments. Proof of current certification for gauge blocks (if applicable) is available. Calibration requirements apply to all instruments included in the Equipment List. *(See the discussion of Equipment List later in this document.)*

Even if not specifically noted in the above tabulation, all electrical, mechanical and physical measurements are recorded in the service center repair record. The auditor evaluates each criteria line item for evidence of conformity by review of applicable service center documents or by observation of service center practices. Review of the calibration program and calibration status of associated equipment is performed by the auditor.

The checklist is supplemented with a list of equipment that the service center will need to have so as to be able to provide good practice repairs. Periodic external audits by an independent auditor will provide objective assessment of the service center's conformance to the accreditation program criteria. Initial self-audits by a beta group of service centers has found that the checklist is comprehensive and does assess maintaining efficiency and reliability during repair. Further, in some cases the self-audits revealed areas where the service center needed to improve its practices; or simply, to employ the practices that they thought were being carried out.

The categories and of the checklist are in outline form and therefore an expanded text document will be provided for each category and the criterion within it. The primary purposes of the expanded text are to provide explanations of the technical criteria so that external auditors that are not from the electric motor industry can comprehend and consistently interpret and assess each criterion element. A secondary purpose of the explanations is to provide a brief tutorial for service center managers and other personnel to likewise be better able to understand and apply the good practice requirements.

In addition to the accreditation checklist and explanations the auditors and service centers will need to have copies of and be familiar with AR100 and the Good Practice Guide. The clauses of each document that apply to each of the 23 categories are identified in the checklist. Thus it will be clear as to what will be audited, how it will be assessed, and the specific reference sources for each of the requirements.

Example Checklist Categories and Criteria

To explain the content of the checklist categories and the associated criteria the following example (Table 2) will be used.

Table 2: Bearings (ball, roller; sleeve)

Criteria:		MS	Visually inspect bearings for evidence of fretting, fluting, scoring, or other damage.
		MM	As-received, and if repaired, post-repair bearing fit dimensions are documented.
		MM	If repaired, rolling bearing fits are rebuilt to applicable AR100 table size.
		MM	Replacement bearings are equivalent to the original, or better suited to the application; and original and replacement bearing numbers documented.
Equipment:	∅	∅	Confirm calibration and functionality of associated equipment.
		MM	Inside micrometers
		MM	Outside micrometers

Source references: AR100-2.2 GPG 2.3

The first four row entries are the criteria for evaluating bearings. The second column is blank and is used to enter the auditor assessment of each criterion. The assessments can be satisfactory (S), unsatisfactory (U), not observed (N) or not applicable (n/a). The "N" category allows for the possibility that a repair activity associated with a particular criterion may not be observable or have been performed in the time period since that prior audit. Similarly, the "n/a" category allows for the possibility that a repair activity associated with a particular criterion is not performed in the specific service center.

In addition to the repair criteria, the necessary calibrated equipment associated with the category is also identified and assessed by the auditor. For example, in the bearing category the calibrated equipment consists of inside and outside micrometers. The “∅” symbol is used in the checklist to indicate a cell that does not require an entry.

The third column is used to designate the level of the criterion. Mandatory requirements for which a nonconformity would result in a major finding are labeled “MM” (mandatory major). Similarly, mandatory requirements for which a nonconformity would result in a minor (slight) finding are labeled “MS” (minor slight). Findings are on an exception basis; i.e., defects or nonconformities in repaired product are reported; and corrective actions documented.

Nonconformities to major criteria can result in rescinding or suspending the certification of the service center. Nonconformities for minor requirements would typically result in requiring that they be corrected prior to the next audit; or within a shorter time period at the auditor’s discretion.

The source references are clauses from ANSI/EASA AR100 *Recommended Practice for the Repair of Rotating Electrical Apparatus* and the *Good Practice Guide* of the 2003 EASA/AEMT study, *The Effect of Repair/Rewinding on Motor Efficiency*. Although there are no conflicts between them, the applicable clauses from AR100 take precedence over those from the Good Practice Guide (GPG). The rationale for this is that AR100, which presently is the 2010 edition, is a document that is reviewed and revised periodically per the ANSI (American National Standards Institute) standard approval process. The GPG is essentially a static (yet most valid) document based on the findings of the 2003 study. Further, the 2010 edition of AR100 adopted the best practices for repair from the GPG that had not already been incorporated in it.

The auditor and the service center should both have copies of, and be familiar with the content of, the applicable clauses that are specifically referenced. For example, note that the bearing category references AR100 clause 2.2, and GPG clause 2.3. To illustrate the content of a specific category, the pertinent contents of these clauses for the bearing category are given below.

[AR100] 2.2 BEARINGS

Bearings should be inspected for fretting, fluting, frosting, scoring or other damage.

2.2.1 Ball or Roller Bearings

Bearing housing and shaft bearing fits should be measured and compared to design specifications (Reference: ANSI/ABMA Stds. 7 as a guide). Any fits that are not within tolerance should be restored. See Tables 2-13 and 2-14 [Not reproduced in this document.] Replacement bearings should be equivalent to the original manufacturer’s specifications.

2.2.2 Sleeve Bearings

When sleeve bearings are remanufactured or replaced by new bearings, the fit in the housing and the diametral clearance should be set to original equipment manufacturer’s specifications if available. See Section 9 [now Section 8] of the EASA Technical Manual for guidance on diametral clearances for oil-lubricated horizontally-mounted sleeve bearings. Measure the new bearing dimensions.
Sleeve bearings should be uniform in diameter, of proper fit in the housing, smooth internally, and suitably grooved for adequate distribution of lubricant.

[GPG] 2.3 Bearing sizes, types and clearances

Most motors have a ball bearing at each end. Some may have a roller bearing at the drive end to increase the radial load capacity, or thrust bearing(s) for high axial loads.
Always fit new bearings of the same type as those removed, unless they were misapplied.

Although not apparent in the bearing category, in most cases AR100 provides prescriptive recommendations and the GPG expands on the topic to provide implementation guidance. A better illustration of this concept can be found in the source references for the Frame and Bearing Housings category. Specifically these are AR100 clause 2.4 and GPG clause 2.2 and 5.3, given below.

[AR100] 2.4 FRAME AND BEARING HOUSINGS

2.4.1 General

Frame and bearing housings should be examined for defects. Cracks and breaks should be repaired and fits restored to manufacturer's specifications.

[GPG] 2.2 Orientation of end bracket and bearing caps

End bracket and stator frame rabbet/spigot fits are not always perfectly circular. End brackets and bearing caps should be installed in exactly the same positions as originally fitted. Therefore, indelibly mark all end brackets and stator frames at both ends of the motor (e.g., by punchmarking the components with a center punch) before dismantling the motor.

[GPG] 5.3 Housing [and frame] repairs

Fitting a new stator frame that is too tight a fit onto the stator core increases rotational loss in core. Rule of thumb is that interference fit should be 0.004 - 0.006 inches (0.10 - 0.15 mm). If it is too loose, the heat transfer from the core will be inhibited, and stator winding losses will increase. Clear blocked airways or cooling ducts; and repair broken cooling ribs, or replace missing ones.

Note in the above that AR100 states what is to be done, and that the GPG information expands into the reasons and importance of carrying out the prescribed actions. In a similar manner the criteria and equipment requirements of checklist categories are supplemented by expanded explanations for each category and associated criteria.

Example Checklist Categories, Criteria and Expanded Explanation

To illustrate the content and detail provided in the checklist the example that follows is from one of the categories that are relatively large in scope. Note that there is a text box below the checklist (Table 3) such that the auditor can record comments about any observations or findings. In general, the criteria provide specific details if that information can be concisely provided; otherwise, a reference source for the additional details is cited. For example, note that the burnout oven part temperature setting of 700 °F (370 °C) is given. Conversely, criteria that reference a great deal of information, such as bearing fits, identify the reference source. Using the bearing fit example, the criteria for it refer to the tables in AR100.

The combination of the checklists that identify the criteria and equipment for each category, and the expanded explanations, supplemented by the referenced AR100 and GPG constitute the complete document package that will be needed by the auditors and the service centers. That is, the accreditation requirements are completely provided in the four above-mentioned documents. This approach provides simplicity and clarity to facilitate compliance; and to make service center participation in the program more attractive.

Table 3: Winding removal and core integrity

Criteria:		MM	Core testing is performed before burnout or other equivalent process, and after winding removal, and the results documented. Evaluation assessment of core acceptability (watts per lb (kg) and temperature rise) is documented.

		MM	Burnout oven has part temperature control set to 700 °F (370 °C) or less; water mist and analog or digital recorder are functional.
		MM	If core test losses increase more than 20% between the before and after winding removal tests the core is repaired or replaced.
		MS	Parts are oriented and supported in oven so as to avoid distortion.
		MS	Check is performed that core slots are clean and free of sharp edges or particles.
		MS	Core teeth are not splayed, i.e., flared at ends of slots.
Equipment:	∅	∅	Confirm calibration and functionality of associated equipment.
		MM	Temperature meter
		MM	Water mist (functionality)
		MS	Analog/digital recorder (functionality)
		MM	Core tester (wattmeter, ammeter, and voltmeter integral with tester)
	∅	∅	or Loop test with separate/standalone:
		MM	Wattmeter
		MM	Ammeter
		MM	Voltmeter

Source references: AR100-2.5, 3.1.1, 3.3, 4.2.7 GPG 3.2-3.4, 5.1, 7.3.2-7.3.4, 7.4

Comments:

Audit Criteria Explanations

Core Test Criterion:

Core testing is performed before burnout or other equivalent process, and after winding removal, and the results documented. Evaluation assessment of core acceptability (watts per lb (kg) and temperature rise) is documented.

Core Test Explanation:

The Criterion in this clause apply to motors with windings that are to be rewound. Core testing of stators with windings that do not need to be rewound can be performed; however, that is not a requirement of this program.

Core testing can be performed by means of a commercial core tester or the loop test method. A core test is to be performed before the winding removal process and after completion of the burnout or winding removal process. Information that needs to be documented includes the amperes and turns of the test loop (1 turn if commercial core tester is used), the induced voltage (which is directly proportional to the magnetic flux in the core under test), the watts loss per pound/kilogram of core back iron weight, and the core temperature rise.

The before and after winding removal core test results and assessments (acceptable or unacceptable) should be documented in the repair record. The wattmeter, ammeter and voltmeter of a commercial core tester must have current calibration labels; and the wattmeter(s), ammeter(s) and voltmeter(s) used for any loop tests must also have current calibration labels. The oven part temperature meter must have a current calibration label. The analog or digital temperature recorder also must have a current calibration label. If the oven part temperature sensor is integral with the recorder, only the recorder must have a current calibration label.

Corrective action should be documented in the repair records for stators with after winding removal test values that exceed the acceptable watts/lb (kg) or temperature rise limits.

Burnout Oven Criterion:

Burnout oven has part temperature control set to 700 °F (370 °C) or less: water mist and analog or digital recorder are functional.

Burnout Oven Explanation:

The oven part temperature is typically detected by a thermocouple that is attached to the stator core. Temperature sensing of the oven air temperature is not acceptable because temperatures vary widely within the oven, and there is no direct correlation between stator (part) temperature and oven air temperature.

The water mist system is usually activated by the oven temperature controller. The system can be function tested with the oven at room temperature to confirm that water sprays from it by momentarily manually activating and observing the water spray. The temperature recordings should be archived after each oven operating cycle to provide evidence that the temperature recorder is functional. The stator(s) processed during each cycle should be marked on the applicable recording, or there should be a log that correlates the recordings to the stators processed.

Core Loss Criterion:

If core test losses increase more than 20% between the before and after winding removal tests the core is repaired or replaced.

Core Loss Explanation:

The watts/lb (kg) values from the before and after winding removal core tests for a stator are to be compared and evaluated. If the "before" value divided by the "after" value is greater than 1.20 (+20%), the core should be repaired or replaced. The corrective action taken when the value exceeds 20% should be documented in the repair records. If the core is repaired the final core test value is to be documented in the repair records. It is suggested that the auditor check at least one active or historical repair before and after core test assessment to verify that the ratio was correctly calculated and interpreted.

Parts Orientation Criterion:

Parts are oriented and supported in oven so as to avoid distortion.

Parts Orientation Explanation:

This good practice reduces the possibility of any frame distortion or collateral damage to other stators when multiple stators are processed in the same burnout oven cycle. The feet of the stator should be flat on the oven rack or other support structure. Keeping the feet on the same plane avoids stresses in the frame that could result in distortion. Arranging stators such that core bores do not axially align avoids the tendency of creating a "chimney" effect, which could increase the temperature of the air moving through the stators.

Core Slots Criterion:

Check is performed that core slots are clean and free of sharp edges or particles.

Core Slots Explanation:

Core slots that are not clean can reduce slot space available for the winding, and reduce heat transfer from winding to core. The slots should not have visual evidence of any foreign material. Sharp edges can abrade the magnet wire insulation, which could cause an electrical short. Similarly, small particles could also abrade magnet wire insulation; and large and sharp particles could puncture coil to ground insulation such as slot cells.

Core Teeth Criterion:

Core teeth are not splayed, i.e., flared at ends of slots.

Core Teeth Explanation:

Core lamination teeth that are splayed (flared out) at the ends of the core will increase the motor stray load losses. If that condition is found, the teeth should be tamped back in place. Although repair records need not indicate that this condition existed or was repaired, inspection of active stator rewind work in process should not indicate any flared laminations. Note that inactive rewind repairs such as those awaiting customer authorizations to proceed and those in the rewind queue are outside the scope of this inspection.

Equipment List

The implementation of the accreditation program requires a substantial investment in key pieces of equipment such as a temperature controlled, water mist burn-off oven, surge tester and test panel. However, since many EASA members, and other program candidate service centers, have already invested in this important equipment, additional outlays to bring equipment into conformity is expected to be minimal.

The complete list of required equipment is below (Table 4). Unless noted otherwise, all equipment listed must be on site and functional. Also, unless noted otherwise all instruments must be calibrated at least annually to applicable national standards.

Table 4: Required Equipment List

Electrical	**Mechanical**	**Physical**
Milli-ohmmeter	Inside micrometers	Temperature meters
Ohmmeter	Outside micrometers	Burnout oven part temperature control
Voltmeter (AC)	Dial indicators (verification by service center)	Burnout oven water mist (verification by service center)
Ammeter (AC)	Digital tachometer (verification by service center)	Burnout oven analog or digital recorder (verification by service center)
Wattmeter (AC)	Terminal crimpers (verification by service center)	Bake oven temperature control
Megohmmeter	Vibration measurement	Winding machine with turns counter (verification by service center)
High potential tester	Balancing machine**	VPI system vacuum gauge****
Surge tester	Gauge blocks (if applicable)***	VPI system pressure gauge****
Core tester*	- -	- -

Loop test*	- -	- -
Growler (functional; ammeter calibrated)	- -	- -
Test panel (to motor rated voltage; individual instruments calibrated)	- -	- -

* Must have either one or both of these items
** Outsourcing permissible
*** Periodic verification by gauge block manufacturer or other qualified external source.
****Only applies if service center has VPI system (VPI process outsourcing permissible)

Conclusion

With increased end user interest in energy efficiency and reliability it is logical that there are concerns about maintaining the efficiency and reliability of repaired electric motors. Although most of the outspoken concern has been about the energy efficiency of rewound electric motors, the Electrical Apparatus Service Association has developed an accreditation program for service centers that is more holistic. The accreditation program elements are good practices that provide objective proof that efficiency and reliability are maintained (or sometimes improved) in repaired motors; including mechanical rebuilding as well as electrical rewinding. The sources of these good practices are ANSI/EASA AR100 *Recommended Practice for the Repair of Rotating Electrical Apparatus* and the *Good Practice Guide* of the 2003 study, *The Effect of Repair/Rewinding on Motor Efficiency*. Independent external auditing supplemented by internal auditing will be used to evaluate service centers for evidence of compliance to assure that they are using prescribed good practices to maintain motor efficiency and reliability during electrical and mechanical repairs of electric motors.

When this paper is presented at EEMODS'13 the current status of the EASA Service Center Accreditation Program will be provided. It is expected that by that time the Checklist, the expanded checklist explanations for auditors and service centers, and selection of the external auditors will be complete; and that the roll out date will have been established.

References

[1] *Recommended Practice for the Repair of Rotating Electrical Apparatus*. Electrical Apparatus Service Association. (EASA), AR100. 2010.

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Tools to move towards better energy efficiency

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Abstract

Energy efficiency and the resulting energy savings in different kinds of applications can be achieved by various methods. This paper describes how energy efficiency can be managed during the whole life cycle of the motor driven system and how electrical equipment manufacturers can assist in the process. Here different tools from one manufacturer are introduced and it is evaluated how these tools can be used for different tasks: designing the system, collecting data from running the system or improving the efficiency of the existing system. Some of the introduced tools are included in the variable speed drive (VSD) and some are separate tools for PC use

Exact dimensioning gives a good starting point for energy efficiency in all applications. Designers can use a tool for dimensioning and selection for the transformer, motor and VSD when the basic rotating equipment and the needed motor shaft power are known. The tool also calculates current and voltage harmonics, motor losses, VSD losses and can easily be used to compare different combinations of the main electrical components. The energy efficiency can be calculated from the losses of the different components in the dimensioned system.

In motor driven systems the VSD, if installed, continuously collects information about the running application. The VSDs may have for example integrated energy calculators for estimating the energy consumption and savings, data loggers to help to tune the application to better or more energy efficient running mode or information available even to prevent failure or damage in the system.

After several decades of development and improvement this kind of tools have proven to be quite reliable. As global trends continue to move more and more towards energy efficiency in all areas, these tools will be further developed with equipment manufacturers and other instances to gain and maintain control over the whole process. To this end, there actually is a seamless way to monitor the energy efficiency of applications throughout the whole life cycle. The latest trend is to have the tools in mobile use like in smart phones and tablets.

1. Introduction

The world craves constantly for ever more energy. According to IEA, by 2035 the world needs 47 per cent more energy as compared to 2010. Electricity consumption will grow even faster: by 2035 we will need 90 per cent more electricity (Figure 1). [1]

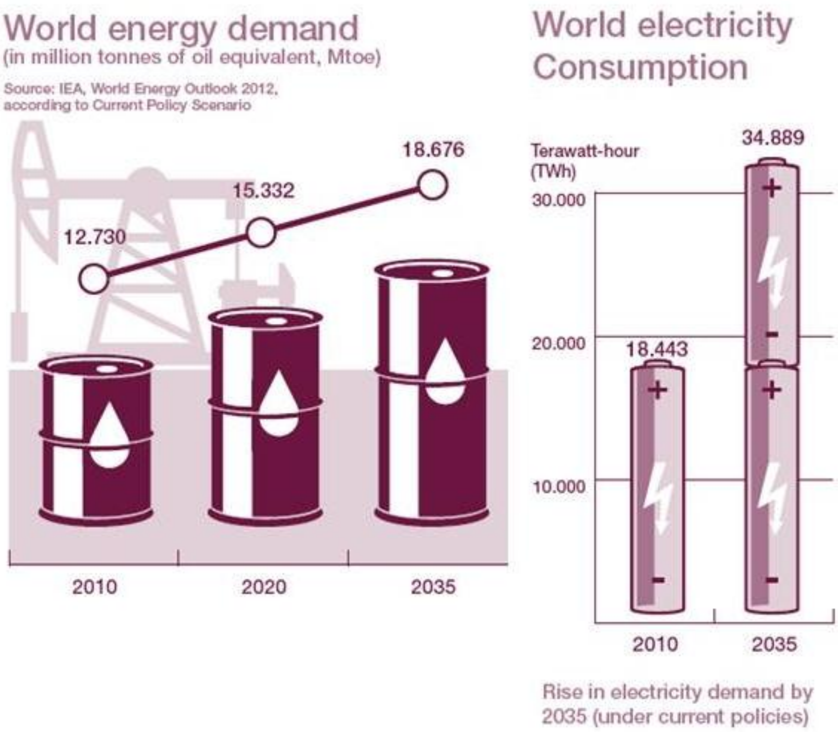


Figure 1. The demand for energy grows by almost 50 per cent and the demand for electricity almost doubles by 2035.

Most of the pump and fan manufacturers have tools for dimensioning the equipment and calculating the needed motor power. Moreover the motor and VSD manufacturers have similar kinds of tools and various tools for energy saving calculations. Those are rather difficult to compare with each other because the needed input data vary a lot and therefore also the calculated results tend to differ.

About 40 per cent of all electricity in the world is consumed by industries and motor systems consume about 28 per cent of the world's electricity. With variable speed drives the amount of energy used by centrifugal applications, mainly pumps and fans, can be dramatically reduced and in some cases savings of even 70 per cent can be achieved. As the duration curve in figure 2 suggests, in this kind of applications power is proportional to speed or flow.[2]

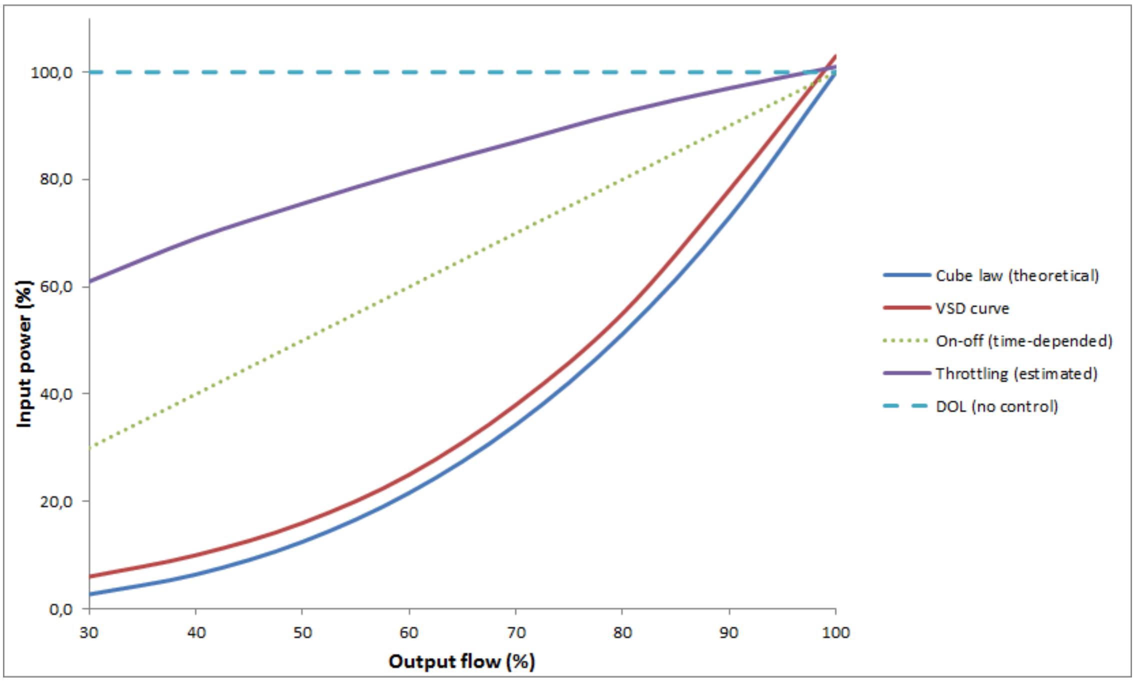


Figure 2 Input power of a centrifugal pump for different flow control methods

Pump systems annually consume approximately ten per cent of the world's electricity, around 1.84 gigawatt hours in 2010. As a theoretical thought, if all these pumps were controlled by variable speed drives instead of reducing the flow mechanically, the average saving potential would be 40 per cent, which translates into 740 terawatt hours annually. If the energy saving potential were widely adopted, many power plants could be shut down or no new plants would need to be built.

Regardless of whether being an end user or for example pump manufacturer, there are clear advantages from the use of this kind of dimensioning and energy saving calculation tools that are presented in this paper. With the help of these tools it can be evaluated whether a given head or a given motor size are really necessary or whether one could come by with smaller appliances when they are connected to a variable speed drive (VSD).

The tools have been developed since the 1980's. The required expertise has grown through the years, as for instance pump manufacturers have given feedback about how their equipment runs. All in all, the development of the assessment software has been a collaborative exercise, where different parties have contributed to the outcome.

The tools are freely available in the Internet and it has quite often been the case that the author of this paper has met pump and fan users who say that they have been experimenting with the software already.

2. Overview of the tools

An example of the anticipated savings would be an office building where the motors for ventilation run at 80 per cent of their nominal power at daytime and at night at 50 per cent. With these values savings of 45 per cent for a condensation pump in a ventilation system can be reached, which translate to a payback time, at current electricity prices (April 2013), of a few months.

With this kind of savings and also short payback time of the investment the question that comes to mind is why most pump and fan motors are not equipped with variable speed drives. Some simple answers to this question have arisen with empirical work among the end-users. When everything works alright, the end-users do not even come to think about other ways of doing things, thus inadvertently denying the savings potential. They are also being cautious because if a system works well, they do not want to touch it. Once the top management, however, gets familiar with the evaluations, things begin to happen.

At older industrial sites energy usage is only measured as a whole. The consumption of individual appliances, like motors, is not followed. In a green field project the machinery is often supplied by the builder who is not so interested in the long term electricity usage. To have lower initial costs, energy saving devices like variable speed drives are not installed. Likewise the builder may choose motors from a lower efficiency class to save money. The money saved in the price of the whole site will, however, cost the owner of the plant manifold in terms of higher energy bills. Here it would help if the builder was paid on the basis of the anticipated amount of energy used and the appliances would be chosen accordingly. [3]

Another reason for the slow adoption of the energy saving equipment is that most industrial sites have tens, hundreds and even thousands of electric motors. When these motors are looked at individually, as is often done, the savings potential is not so convincing as when the savings are added up.

After the initial investment decision has been made, companies tend buy more energy saving equipment – once they have assured themselves that the technology really does work as promised. It has also been seen in many cases that the companies use the software tools by themselves to evaluate the potential of next steps.

In the following chapters the tools will be introduced. With DriveSize (Chapter 3) the VSD can be dimensioned based on values of the motor and the drive. With the Optimizer tool (Chapter 4) the most suitable motor to the application can be chosen. With PumpSave (Chapter 5) an appropriately powered motor and VSD can be chosen for a pumping application. And with FanSave (Chapter 6) the same can be done for fan applications.

3. DriveSize

A tool called DriveSize is used for dimensioning the motor and the VSD on the basis of such values as power, voltage, torque and harmonics. Besides standard motors the tool can be used with tailor-made motors. The tool allows the quick selection of drive items with user inputs and default settings.

DriveSize offers several functions for dimensioning the electrical components to a motor driven system. Among others the following items are available: motor temperature rise class, curves for variable torque and constant torque, supply unit data, power factor, and thermal loss calculations. Motor specifications can also be changed later. A full list can be found in the DriveSize user manual. [4]

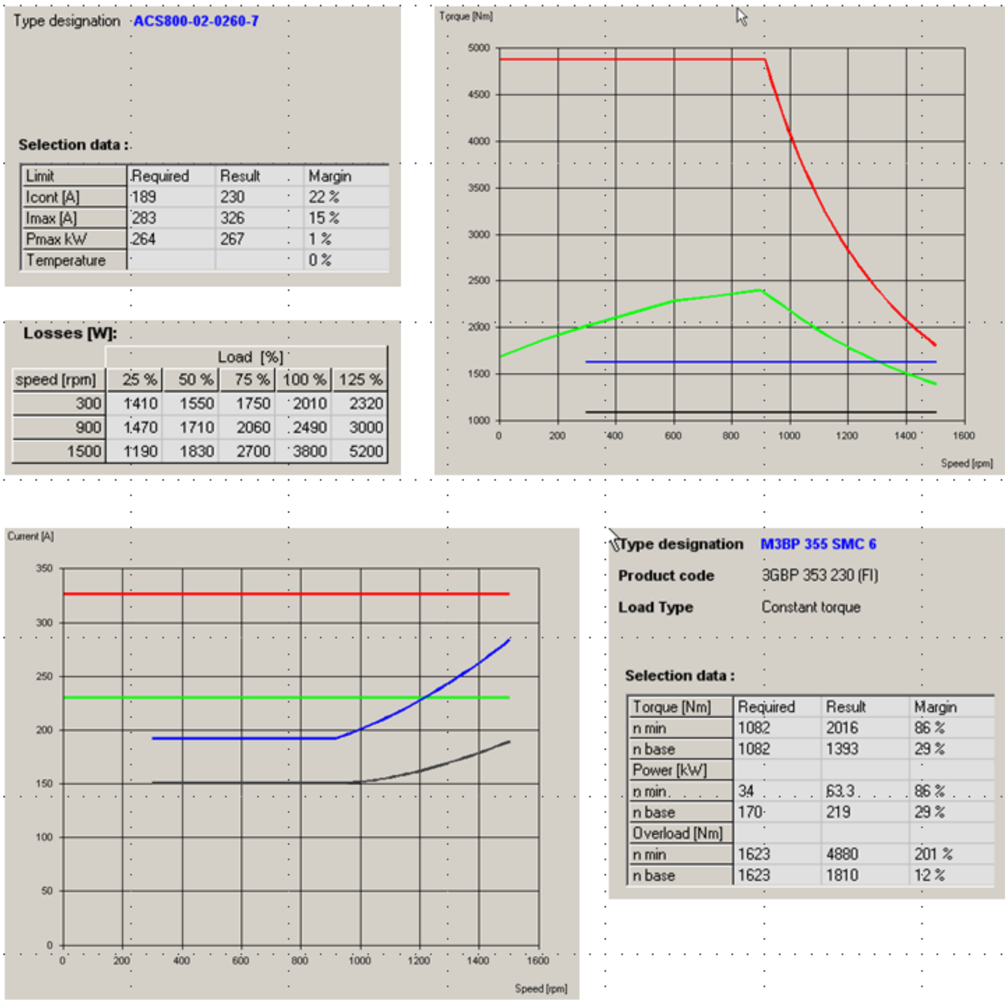


Figure 3. DriveSize results in graphical form

The results are shown in graphical form (Figure 3). Torque and power curves highlight the maximum limit and thermal limit and also the maximum load requirement and continuous load or base load. With inverter currents maximum and continuous current limits and maximum current demand as well as calculated continuous current are illustrated. Numerical results include requirements, ratings, margins as well as losses and efficiency.

4. Optimizer

On a global scale low voltage motors are evaluated according to a scheme called MEPS (Minimum Energy Performance Standards) which sets mandatory minimum efficiency levels for electric motors. Harmonizing efficiency standards makes comparing the motors from different manufacturers much easier than before such standards. MEPS are followed, albeit the name may differ in different areas, in the largest market areas of the world. [5]

With a tool called Optimizer, the most suitable motor to each application can be chosen. It is possible to compare different kinds of motors on the market. The tool tells for instance what kind of motor efficiency requirements can be found in different parts of the world. This helps the user in choosing the right kind of motor. The same kind of efficiency classification will be applied to variable speed drives within the next five years.

The motor is selected according to the criteria that the user feeds in the easy-to-use interface in the Internet. Here the following criteria are asked: which MEPS area, efficiency class from IE2 to IE4, frame material, motor range, voltage, frequency, and output.

5. PumpSave

The PumpSave tool helps to evaluate the right motor power according to pump data like flow and head. The tool also calculates comparisons for a variable speed control against other usually existing types of control (throttling valve, on-off, hydraulic control). The outputs are exemplified in terms of saved energy, money, and reduced CO_2 emissions.

Different kinds of calculations can be made. For instance if the flow is controlled by throttling and this is fed in as a starting value, the tool generates the potential savings in electricity made by the use of VSD's. The tools can be used to evaluate existing set-ups as well as to evaluate new installations.

The calculations are based on typical centrifugal pump operating characteristics and some other data and assumptions of the motor driven system. Thus, the accuracy of the results is affected by the accuracy of the input data. It is emphasized that the results should only be used for estimating purposes. The calculation tool runs on Microsoft Excel. [6]

The calculations are based on data that include system data, pump data, existing flow control method, motor and supply voltage data and operating profile. System data consist of liquid density and static head. The pump data include nominal volume flow, nominal head, maximum head, and efficiency. On the basis of these parameters pump and system curves can calculated (Figure 4).

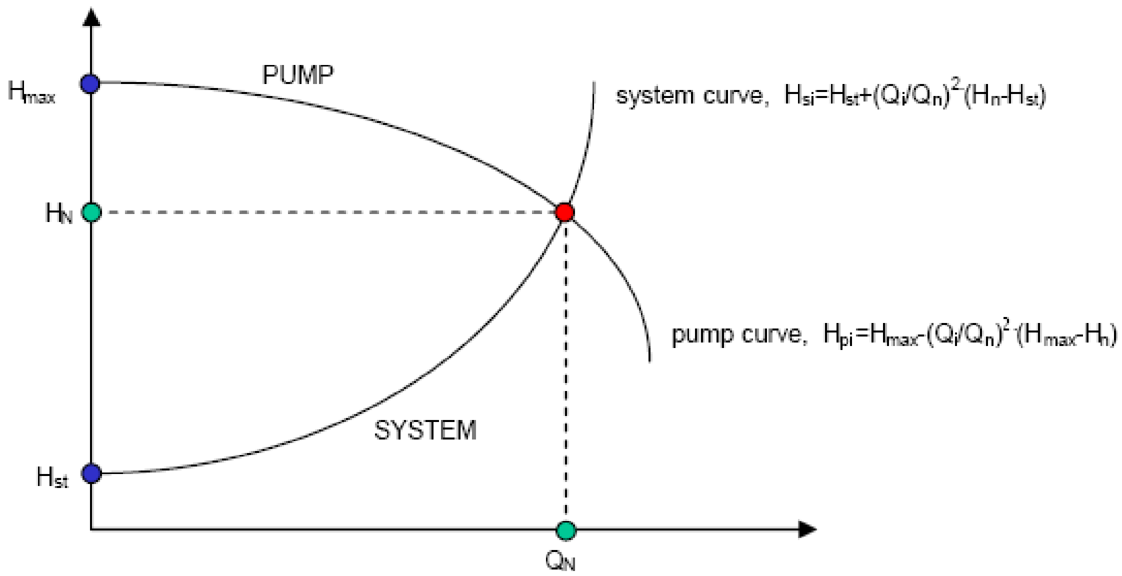


Figure 4. Typical pump and system curves

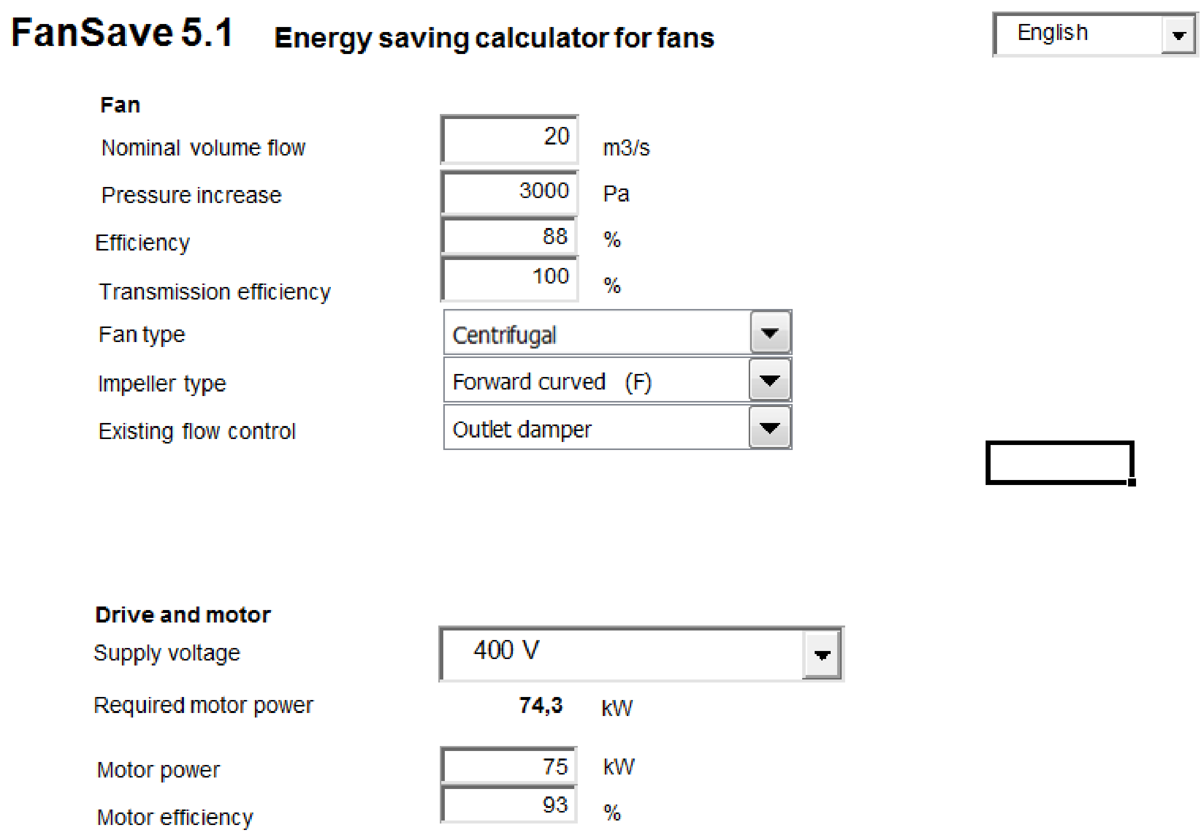
6. FanSave

FanSave is a similar calculation tool as PumpSave, but is intended for evaluating the energy usage of fans. Here comparisons in energy usage can be made with damper control, pitch control, single speed vane control and two-speed vane control. Calculations are based on typical fan operating characteristics. Figure 5 shows a view from FanSave. This exemplifies what kind of data is needed. Results are also shown on the same page. Thus it is easy to change input values while the results are displayed instantly.

The input data include information from the fan, transmission, existing control method, motor, and operating profile. With fan type the options are centrifugal and axial flow. If centrifugal fan is selected, the tool prompts for the impeller type from these options: forward curved, backward curved, and radial blades.

Important data are also annual running time and operating time at different flow rates. Also the price of electricity is fed in as a variable. After all the usage variables have been given, the tool gives an estimate of the savings in electricity. Here different control methods are compared: for instance vanes vs. VSD.

The calculation example features a typical oversized fan application where the needed air flow is 80 per cent during daytime and 50 per cent during nighttime and the total running time is 48 weeks a year.



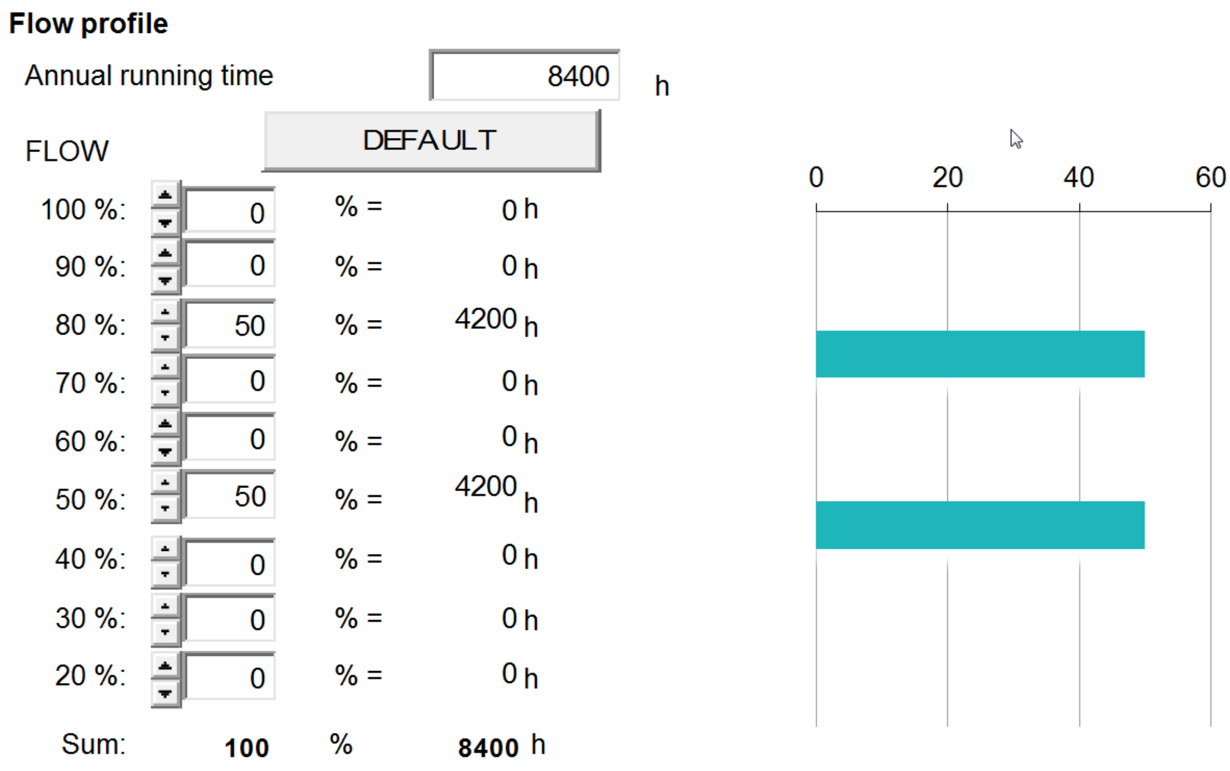


Figure 5. FanSave tool view

Figure 6 shows the results of the calculations that include the estimated annual energy consumption for the existing control method and for AC drive control. Also payback period can be calculated considering the investment costs of the drive.

Important data include the duration curve that tells how much the pump or fan is used annually. For instance in a school more ventilation is obviously needed at daytime. During nighttime the fans can be driven at much lower speed. Or in a process cycle the duration curve can show that maximum power and minimum power are not so much needed as the median power.

The idea behind these tools is to make it transparent where energy is being wasted. The above scenarios do not apply to only industrial sites. Even some new office buildings have used traditional technology where fans have damper control to restrict air flow to 70 per cent of full capacity, yet the motor runs at nominal speed. Variable speed drives could render savings after a payback period of just a couple of months.

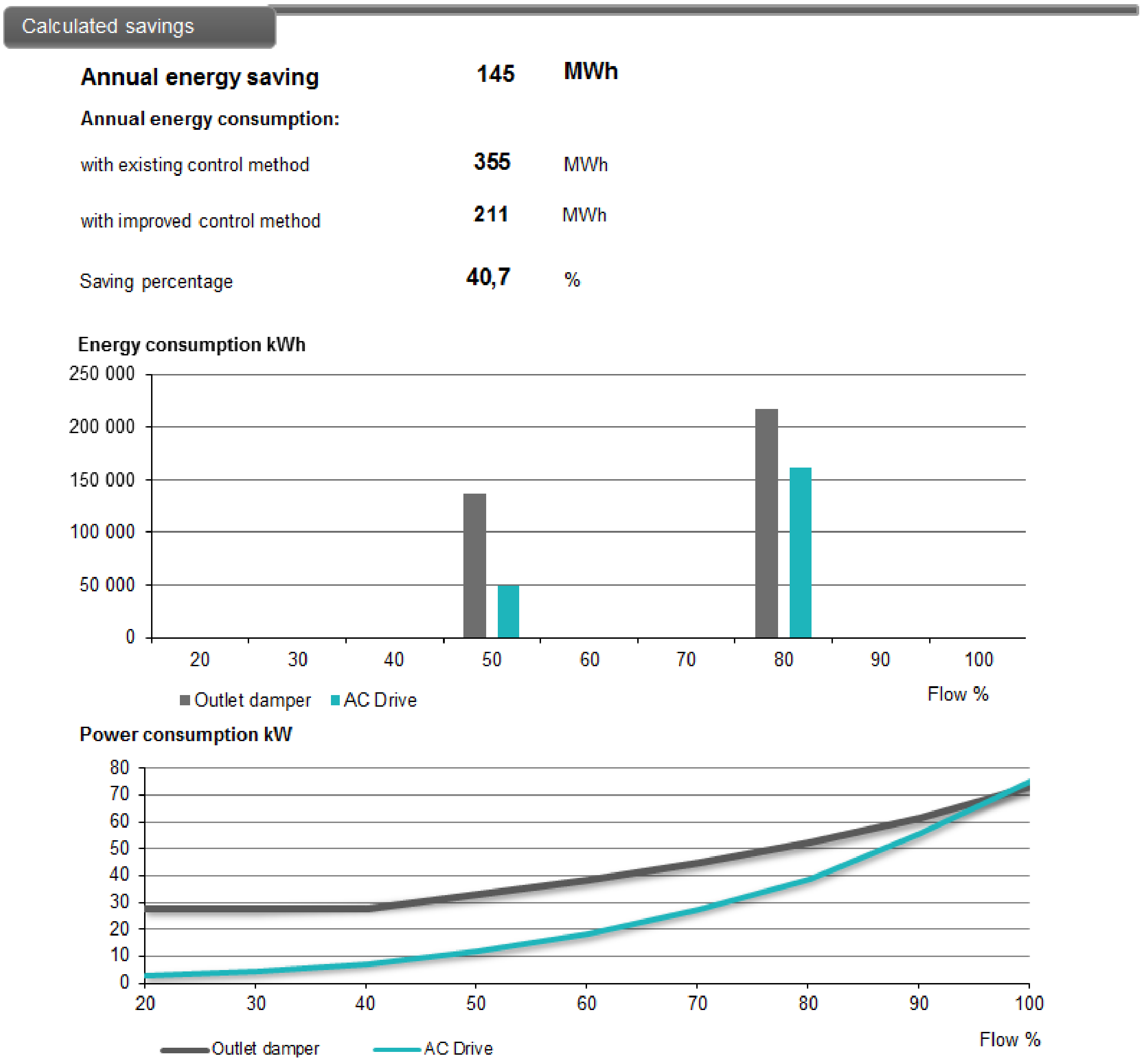


Figure 6. Calculated results from FanSave tool

7. Built-in energy efficiency characteristics

In the previous sections various tools were described with the help of which the underlying systems can be improved. Once a VSD has been installed it gathers information on the amount of energy that goes through it. On the basis of the information from the device the difference in energy usage with and without the VSD in place is calculated, thus giving the energy savings.

When the price of electricity is fed in, the tool calculates the savings in money. It also gives the amount of CO_2 that has not been set loose in the atmosphere. The tool also calculates a duration curve that tells the power level at which the motor has been running. If it turns out that the motor has been running mostly at half power, it is obvious that the motor is overdimensioned. However, it is questionable whether it pays to acquire a new motor instead. But if the efficiency of the motor is really poor when run at half power, it may be worth acquiring a new motor.

Feeding the motor direct on line (DOL) at nominal power and with an alternative control method, e.g. throttling, are compared with the power figures derived from the actual use of the drive. The resulting kilowatts will be used to calculate kilowatt hours that exemplify how much money is saved with the device (once the price of electricity has been fed in).

These kinds of calculations can be used to describe the energy and CO_2 savings during the entire life cycle of the drive.

8. Summary

In this paper different tools from one manufacturer are introduced to analyze the energy usage with and without VSD control. Moreover some of the introduced tools help to choose the most suitable electrical components to the motor driven system in question. The examples are centrifugal fan and pump applications where the energy saving potential during the whole life cycle is at its highest. And as noted above, pumps consume annually approximately ten per cent of the world's electricity. It would be interesting to compare the calculation results of tools from several sources and manufacturers, but that should be done in a separate study.

The tools can be used to evaluate the energy efficiency of applications during the life cycle when the process is in operation. Concrete tools for estimating energy savings in various centrifugal applications between existing control methods versus VSD control are introduced. Those tools have been developed together with other equipment manufacturers to get the best available information into use.

The tools can be downloaded free and used by anybody via the Internet. As the laws of physics apply to all equipment vendors, the results can be studied independently and can be used for better decision making. These kinds of tools should make the transition from the traditional control methods to new VSD based control easier. It should also be noted that VSD's are based on proven technology that has been developed since the 1980's. The kinds of barriers to usage discussed in section 2 should, nevertheless, be taken seriously, as the end users' approval of the technology is of vital importance. After all, it is the users who reap the benefits of better energy efficiency.

An efficiency classification was taken into use for motors last year in Europe. A similar NEMA classification scheme is already in place in the United States. Also China and other major markets are expected to pass similar legislation. The MEPS classification was briefly dealt with above in section 4.

There is also a motion about getting equivalent IE classes for variable speed drives. Here the efficiency spectrum of the devices is, however, quite limited, as even the lowest efficiency lies at approximately 97 per cent. Even with the best available technology the drives will not reach 99 per cent efficiency. Thus it is very difficult to categorize the devices on these grounds. Instead of classifying only drives on the basis of efficiency, they will probably be evaluated on the basis of energy losses generated by them in the motor driven systems.

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[3] Empirical evidence from the author's field work

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[6] PumpSave User's Manual – Energy Savings Calculator for Pump Drives, version 5.1. ABB Oy, 2012

Figure source

1. IEA Energy Outlook 2012

2. Figure drawn on the basis of various sources, among others
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3. DriveSize user manual. ABB Oy, 2009

4. PumpSave User's Manual – Energy Savings Calculator for Pump Drives, version 5.1. ABB Oy, 2012

5. FanSave Calculation results (figure taken from the tool). ABB Oy, 2013

6. FanSave Calculation results (figure taken from the tool). ABB Oy, 2013

METHODOLOGY FOR CALCULATING THE VALUE OF UNCERTAINTY OF EFFICIENCY OF BRAZILIAN LABELING PROGRAM AND DEFINITION OF CRITERIA FOR ACCEPTANCE OF INCOME FOR EACH OF MEASUREMENT UNCERTAINTY.

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Abstract

Experience shows that the question of uncertainty of measurement is still little explored in the programs of conformity assessment. According to the ISO/IEC 17025/2005 (General requirements for the competence of testing and calibration laboratories), test laboratories must have and apply procedures to estimate uncertainty of measurement. However, the compliance with these requirements is not enough to affirm that a certain accredited laboratory is able to really evaluate the service of a particular item under test to the tolerance specified in the regulation for conformity assessment.

During the last years CEPEL, Electric Power Research Center, has search a careful way to improve for the expression of uncertainty of measurement in test of determination of efficiency of three phase induction motors within the Brazilian Labeling Program. The current method, constant regulation conformity assessment follows established in the documents ISO GUM 95 and EA-4/02.

A critical analysis conducted by INMETRO in the results of the efficiency test of three phase induction motors within the Brazilian Labeling Program (PBE), demonstrated that level of uncertainty of the laboratories, in some cases, it is not appropriate to conduct an assessment in conformity of the product in relation to the tolerance limits established in the regulation for conformity assessment, which generates doubt _ the result of these tests. This situation is considered damaging in the programs for energy conservation, where the product should be classified within a certain range of energy efficiency rating.

The proposed objectives of this paper are:

Introduce the method adopted by CEPEL to the expression of determination of uncertainty in the determination of efficiency in the tests from three phase induction motors within the Brazilian Labeling Program;

Introduce a acceptance criterion of test results based on the proposed assessment INMETRO, demonstrating the application in 108 tests in the three phase induction motors performed by CEPEL.

Methodology

Mathematical Modeling of the Uncertainty of Measurement of efficiency

In the test of three phase electric induction motor measures are obtained directly and indirectly. We consider direct measurements as temperature, electrical resistance of the windings, voltage, current, active power, torque and speed. And as indirect measures as Power, Mechanical power, Stator winding losses and efficiency.

Then are shown the contributions of uncertainty estimate for each measure referred both as direct measurements and indirect measurement, showing the method of calculations with the objective of find the expanded uncertainty of efficiency.

Mathematical modeling of uncertainty of measurement obtained from by direct measurement

Temperature Measurement

$$T_x = T_m + (\sigma Im + \sigma rm + \sigma em)$$

Where:

σIm: Uncertainty of measurement of temperature meter;

σrm: Resolution of measurement of temperature meter;

σem:= Derives from the measurement of temperature meter.

Electrical resistance of the windings Measurement

$$R_x = R_m + (\sigma Im + \sigma rm + \sigma em)$$

Where:

σIm: Uncertainty of measurement of resistance meter;

σrm: Resolution of measurement of resistance meter;

σem: Derives from the measurement of resistance meter.

Average resistance windings Measurement

To determination of the arithmetic average of the resistance is adopted by two measures of resistance, one before and one after, applied in the no load test and load test. The average of uncertainty of measurement of the measurements of resistance is obtained by:

$$I_{RES} = \sqrt{(Ia)^2 + (Id)^2}$$

Where:

I_{RES}: Arithmetic average of uncertainty of measurement of resistance;

Ia: Uncertainty of measurement of resistance before the test (Load test and No Load test);

Id: Uncertainty of measurement of resistance after the test (Load test and No Load test);

Voltage Measurement

$$V_x = V_m + (\sigma Im + \sigma rm + \sigma em)$$

Where:

σIm : Uncertainty of the measurement of voltage meter;

σrm : Resolution of the measurement of voltage meter;

σem : Derives from the measurement of voltage meter.

Current Measurement

$$I_x = I_m + (\sigma Im + \sigma rm + \sigma em)$$

Where:

σIm : Uncertainty of the measurement of current meter;

σrm : Resolution of the measurement of current meter;

σem : Derives from the measurement of current meter.

Power Measurement

$$P_x = P_m + (\sigma Im + \sigma rm + \sigma em)$$

Where:

σIm : Uncertainty of the measurement of power meter;

σrm : Resolution of the measurement of power meter;

σem : Derives from the measurement of power meter.

Torque Measurement

$$\tau_x = \tau_m + (\sigma Im + \sigma rm + \sigma em + \sigma Lm)$$

Where:

σIm : Uncertainty of the measurement of torque meter;

σrm : Resolution of the measurement of torque meter;

σem : Derives from the measurement of torque meter;

σLm : linearity of torque meter.

Speed Measurement

$$S_x = S_m + (\sigma Im + \sigma rm + \sigma em + \sigma Lm)$$

Where:

σIm : Uncertainty of the measurement of speed meter;

σrm : Resolution of the measurement of speed meter;

σem : Derives from the measurement of speed meter;

σLm = linearity of speed meter.

Mathematical modeling of uncertainty of measurement obtained from by indirect measurement

Mechanical power Measurement (watt)

$$P_m = P_x + (\sigma Imt + \sigma rmt + \sigma emt + \sigma Lmt + \sigma Ims + \sigma rms + \sigma ems + \sigma Lms)(ci)$$

Where:

σImt : Uncertainty of the measurement of torque meter;

σrmt : Resolution of the measurement of torque meter;

σemt : Derives from the measurement of torque meter;

σLmt : linearity of torque meter.

σIms : Uncertainty of the measurement of speed meter;

σrms : Resolution of the measurement of speed meter;

σems : Derives from the measurement of speed meter;

σLms : linearity of speed meter.

To determine the uncertainty of measurement of the mechanical power is considered torque and speed measurements, and also the constant 9549. To calculate the uncertainty of measurement it's necessary to determine the sensitivity coefficients (ci) to be applied in the torque and speed sources, with the partial derivatives of the equation.

$$\mathrm{pm} = \frac{\tau \times s}{9549}$$

$\frac{\partial \mathrm{pm}}{\partial \tau} = \frac{s}{9549} =$ Coefficient to be applied under torque form;

$\frac{\partial \mathrm{pm}}{\partial s} = \frac{\tau}{9549} =$ Coefficient to be applied under speed form.

Stator winding losses

$$(\mathrm{I}^2\mathrm{R})\mathrm{x} = (\mathrm{I}^2\mathrm{R})\mathrm{m} + (\sigma\mathrm{Imi} + \sigma\mathrm{rmi} + \sigma\mathrm{emi} + \sigma\mathrm{Lmr} + \sigma\mathrm{Imr} + \sigma\mathrm{rmr} + \sigma\mathrm{emr})(\mathrm{ci})$$

Where:

$\sigma\mathrm{Imi}$: Uncertainty of the measurement of current meter;

$\sigma\mathrm{rmi}$: Resolution of the measurement of current meter;

$\sigma\mathrm{emi}$: Derives from the measurement of current meter.

σImr = Uncertainty of measurement of resistance meter;

σrmr = Resolution of measurement of resistance meter;

σemr = Derives from the measurement of resistance meter.

To determine the uncertainty of measurement of the stator winding losses is considered current and average resistance of winding, and also the constant 0,0015. To calculate the uncertainty of measurement it's necessary to determine the sensitivity coefficients (ci) to be applied in the current and average resistance of winding sources, with the partial derivatives of the equation.

$$(\mathrm{I}^2\mathrm{R}) = 0{,}0015 \times \mathrm{I}^2 \times \mathrm{R}\ (\mathrm{kW})$$

$\frac{\partial(\mathrm{I}^2\mathrm{R})}{\partial \mathrm{I}} = 0{,}003 \times \mathrm{I} \times \mathrm{R} =$ Coefficient to be applied under current form;

$\frac{\partial(\mathrm{I}^2\mathrm{R})}{\partial \mathrm{I}} = 0{,}0015 \times \mathrm{I}^2 =$ Coefficient to be applied under average resistance winding form.

Efficiency

$$\mathrm{I}_{\mathrm{FP}} = \sqrt{(\mathrm{I}_{\mathrm{PW}})^2 + (\mathrm{I}_{\mathrm{PMEC}})^2 + (\mathrm{I}_{\mathrm{EST}})^2}$$

Where:

I_PW: Uncertainty of measurement of power;

I_PMEC: Uncertainty of measurement of mechanical power;

I_EST: Uncertainty of measurement of stator winding losses.

Example of calculation of uncertainty of measurement of efficiency

Below is showed an example to calculation of uncertainty of measurement of efficiency. All data used in this example are providing from CEPEL data base, and represent the real case.

Data plate:

Power (kW): 22	Frequency (Hz): 60
Voltage (V): 380	Current (A): 40,8
Speed (rpm): 3550	Poles: 2
Efficiency (%): 91,3	PF: 0,90

In the table below the entire test data has been obtained from at the 100% of load.

Ambient temperature	25,2 ºC
Resistance of Load test (Before)	0,2272 Ω
Resistance of Load test (After)	0,2349 Ω
Resistance of No Load test (Before)	0,2277 Ω
Resistance of load test (After)	0,2275 Ω
Voltage (100% of load)	381,40 V
Current (100% of load)	39,90 A
Power (100% of load)	24,034 kW
Speed (100% of load)	3552,0 rpm
Torque (100% of load)	60,00 Nm
Output power corrected	22,017 kW

uncertainty of temperature

Where:

Mens: Measurand;

I term: Uncertainty of measurement of temperature system;

Res. Term.: Resolution of the measurement of temperature system;

Estab term: Long-term stability of the measurement of temperature system.

Mens.	**Source**	**xi (ºC)**	**DP**	**ν**	**Fd**	**ci**	**Ip (ºC)**	**Ic (ºC)**	**I (ºC)**
25,2 ºC	I term.	0,3	Nor	∞	2,00	1	0,15	0,19	0,4
	Res. term.	0,1	Ret	∞	$\sqrt{12}$	1	0,029		
	Estab term	0,2	Ret	∞	$\sqrt{3}$	1	0,115		

The result of the measure is: 25,2 °C ± 1,59%

Resistance of Load test (Before and After)

Where:

I term: Uncertainty of measurement of resistance system;

Res. Term.: Resolution of the measurement of resistance system;

Estab. term: Long-term stability of the measurement of resistance system.

Resistance of Load test(Before)

Mens.	**Fontes**	**xi (Ω)**	**DP**	**ν**	**Fd**	**ci**	**Ip (Ω)**	**Ic (Ω)**	**I (Ω)**
0,22720 Ω	I med.	4,54X10-4	Nor	∞	2,00	1	2,27X10-4	2,32X10-4	4,64X10-4
	Res. med.	1X10-4	Ret	∞	√12	1	2,89X10-5		
	Estab. term	6,82X10-5	Ret	∞	√3	1	3,94X10-5		
									I(%) =0,2

The result of the measure is: 0,22720 Ω °C ± 0,2 %

Resistance of Load test(After)

Mens.	**Fontes**	**xi (Ω)**	**DP**	**ν**	**Fd**	**ci**	**Ip (Ω)**	**Ic (Ω)**	**I (Ω)**
0,23490 Ω	I med.	4,7X10-4	Nor	∞	2,00	1	2,35X10-4	2,40X10-4	4,80X10-4
	Res. med.	1X10-4	Ret	∞	√12	1	2,89X10-5		
	Estab term	7,05X10-5	Ret	∞	√3	1	4,07X10-5		
									I(%) =0,2

The result of the measure is: 0,23490 Ω °C ± 0,2 %

Average Resistance:

$$R = \frac{0{,}22720\Omega + 0{,}23490\Omega}{2} = 0{,}23105\Omega$$

Uncertainty of measurement of average resistance of the Load Test:

$$I_{RES} = \sqrt{(0{,}2)^2 + (0{,}2)^2} = 0{,}28\%$$

The result of the resistance of the load test: 0,2311 Ω ± 0,28%

Resistance of No Load test (Before and After)

Where:

I term: Uncertainty of measurement of resistance system;

Res. Term.: Resolution of the measurement of resistance system;

Estab term: Long-term stability of the measurement of resistance system.

Resistance of no Load test (Before)

Mens.	Fontes	xi (Ω)	DP	ν	Fd	ci	Ip (Ω)	Ic (Ω)	I (Ω)
0,22770 Ω	I med.	4,55X10-4	Nor	∞	2,00	1	2,28X10-4	2,33X10-4	4,66X10-4
	Res. med.	1X10-4	Ret	∞	√12	1	2,89X10-5		
	Estab term	6,83X10-5	Ret	∞	√3	1	3,94X10-5		
									I(%) =0,2

The result of the measure is: 0,22770 Ω °C ± 0,2 %

Resistance of No Load test (After)

Mens.	Fontes	xi (Ω)	DP	ν	Fd	ci	Ip (Ω)	Ic (Ω)	I (Ω)
0,22750 Ω	I med.	4,55X10-4	Nor	∞	2,00	1	2,28X10-4	2,33X10-4	4,66X10-4
	Res. med.	1X10-4	Ret	∞	√12	1	2,89X10-5		
	Estab term	6,83X10-5	Ret	∞	√3	1	3,94X10-5		
									I(%) =0,2

The result of the measure is: 0,22750 Ω °C ± 0,2 %

Average Resistance:

$$\text{R} = \frac{0{,}22770\Omega + 0{,}22750\Omega}{2} = 0{,}22760\Omega$$

Uncertainty of measurement of average resistance of the No Load Test:

$$I_{RES} = \sqrt{(0{,}2)^2 + (0{,}2)^2} = 0{,}28\%$$

The result of the resistance of the No load test: 0,22760 Ω ± 0,28%

Current

Where:

Mens: measurand;

I med: Uncertainty of measurement of voltage;

Res. Med: Resolution of measurement of voltage;

Estab. med: Long-term stability of the measurement of voltage.

Mens.	Fontes	xi (A)	DP	ν	Fd	ci	Ip (A)	Ic (A)	I (A)
39,90 A	I med.	0,12	Nor	∞	2,00	1	0,06	0,07	0,14
	Res. med.	0,01	Ret	∞	√12	1	0,0029		
	Estab. med	0,06	Ret	∞	√3	1	0,03		
									I(%) =0,35

The result of the measure is: 39,90 A ± 0,35 %

Power

Where:

Mens: measurand;

I med: Uncertainty of measurement of Power;

Res. Med: Resolution of measurement of Power;

Estab. med: Long-term stability of the measurement of Power.

Mens.	Fontes	xi (W)	DP	ν	Fd	ci	Ip (W)	Ic (W)	I (W)
24033,92 W	I med.	72,10	Nor	∞	2,00	1	36,05	50,03	100,06
	Res. med.	0,01	Ret	∞	√12	1	0,0029		
	Estab. med	60,08	Ret	∞	√3	1	34,69		
									I(%) =0,42

The result of the measure is: 24,0 kW ± 0,42 %

Torque

Where:

Mens: measurand;

I med: Uncertainty of measurement of Torque;

Res. Med: Resolution of measurement of Torque;

Estab. med: Long-term stability of the measurement of Torque;

Lin. med: Linearity of torque measurement.

Mens.	Fontes	xi (Nm)	DP	ν	Fd	ci	Ip (Nm)	Ic (Nm)	I (Nm)
60,00 Nm	I med.	0,18	Nor	∞	2,00	1	0,09	0,098	0,20
	Res. med.	0,01	Ret	∞	√12	1	0,0029		
	Estab. med	0,06	Ret	∞	√3	1	0,035		
	Lin. med	0,03	Ret	∞	√3	1	0,017		
									I(%) =0,33

The result of the measure is: 60,0 Nm ± 0,33 %

Speed

Where:

Mens: Measurand;

I med: Uncertainty of measurement of Speed;

Res. Med: Resolution of measurement of Speed;

Estab. med: Long-term stability of the measurement of Speed;

Lin. med: Linearity of Speed measurement.

Mens.	Fontes	xi (rpm)	DP	ν	Fd	ci	Ip (rpm)	Ic (rpm)	I (rpm)
3552 rpm	I med.	0,71	Nor	∞	2,00	1	0,355	2,32	4,63
	Res. med.	0,1	Ret	∞	√12	1	0,0029		
	Estab. med	3,55	Ret	∞	√3	1	2,05		
	Lin. med	1,78	Ret	∞	√3	1	1,02		
									I(%) =0,13

The result of the measure is: 3552 rpm ± 0,13 %

Mechanical power

Where:

Mens: measurand;

I medτ: Uncertainty of measurement of Torque;

Res. medτ: Resolution of measurement of Torque;

Estab. medτ: Long-term stability of the measurement of Torque;

Lin. medτ: Linearity of Speed measurement;

I med S: Uncertainty of measurement of Speed;

Res. med S: Resolution of measurement of Speed;

Estab. med S: Long-term stability of the measurement of Speed;

Lin. med S: Linearity of Speed measurement.

Mens.	Fontes	xi (nm – rpm)	DP	ν	Fd	ci	Ip (kW)	Ic (kW)	I (kW)
22,318 kW	I medτ.	0,18	Nor	∞	2,00	rpm/9549	0,033	0,04	0,08
	Res. medτ	0,1	Ret	∞	√12	rpm/9549	0,011		
	Estab. medτ	0,06	Ret	∞	√3	rpm/9549	0,013		
	Lin. medτ.	0,03	Ret	∞	√3	rpm/9549	0,0064		
	I med S.	0,7104	Nor	∞	2,00	τ/9549	0,0022		
	Res. med S	0,1	Ret	∞	√12	τ/9549	1,8x10-4		
	Estab. med S	3,552	Ret	∞	√3	τ/9549	0,0129		
	Lin. med S.	1,776	Ret	∞	√3	τ/9549	0,0064		
									I(%) =0,36

The result of the measure is: 22,318 kW ± 0,36 %

Stator winding losses

Where:

Mens: measurand;

I med A: Uncertainty of measurement of Current;

Res. Med A: Resolution of measurement of Current;

Estab. Med A: Long-term stability of the measurement of Current;

I med R: Uncertainty of measurement of Resistance;

Res. med R: Resolution of measurement of Resistance;

Estab. med R: Long-term stability of the measurement of Resistance;

Mens.	**Fontes**	**xi (A – R)**	**DP**	**ν**	**Fd**	**ci**	**Ip (kW)**	**Ic (kW)**	**I (kW)**
0,551751 kW	I med A	0,1197	Nor	∞	2,00	0,003AR	1,66x10-3	2x10-3	4x10-3
	Res. med A	0,01	Ret	∞	√12	0,003AR	7,98x10-5		
	Estab. med A	0,0599	Ret	∞	√3	0,003AR	9,56x10-4		
	I med R	4,62x10-4	Nor	∞	2,00	0,0015A 2	5,5x10-4		
	Res med R	1x10-4	Ret	∞	√12	0,0015A 2	6,89x10-5		
	Estab. med R	6,93x10-6	Ret	∞	√3	0,0015A 2	9,56x10-6		
									I(%) =0,72

The result of the measure is: 0,551751 kW ± 0,72 %

Uncertainty of measurement of Efficiency

$$\sqrt{(0,42)^2+(0,36)^2+(0,72)^2}=0,91\%$$

Efficiency

$$Efficiency=\frac{100\times 22{,}017kW}{24{,}034kW}=91{,}6\%$$

The result of measurement of efficiency: 91,6 % ± 0,91 %

Tolerance

Zone of conformity

In the control of quality by variable, the numeric value of a product parameter is compared with the limits defined by tolerance. The tolerance represents a zone of acceptable values. Its extreme limits are named Tolerance Limit: Lower Tolerance Limit (LIT) and the Upper tolerance limit (LST). Each component, whose features are inside of these limits, must be approved by the quality control due to be in conformance with the specifications. This range that delimits the specification limits is also known like conformance zone.

The numeric value of the interval, calculated by difference between the upper and the lower tolerance limits is named tolerance interval. The figure 1 presents the three parameters used.

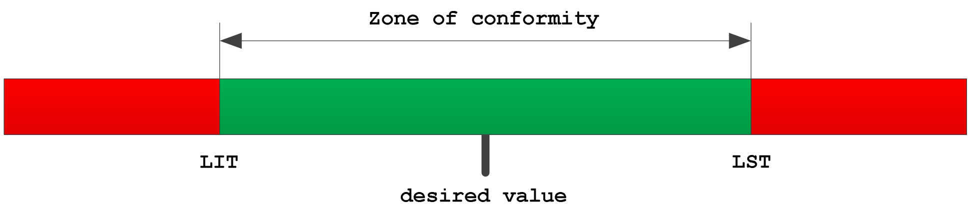

Figure 1 - Lower tolerance limit (LIT), Upper tolerance limit (LST) and desired value

Range of acceptance and rejection

In the quality control, the result of a variable, obtained by measurement, is associated to an uncertainty. Therefore, are necessaries some concerns in order to avoid that the measurement uncertainty can result in a wrong decision in the quality control. Based in this fact there is the range of acceptance. The group of values of the basic result, for what all result of the measurement is kept inside of the conformity range is named range of acceptance. Its limits are named Lower Acceptance Limit (LIA) and Upper Acceptance Limit (LSA).

Products that are not inside of the acceptance zone are rejected. Among the rejected there are some that clearly do not comply with the tolerances. However there are some presenting its results close of the tolerance limits, generating doubt if comply or not with the specifications. The rejection limits are defined as the limits for the –basic result outside of which there is no doubt about the non-compliance of the components or systems. Figure 2 graphically illustrates the construction of these limits.

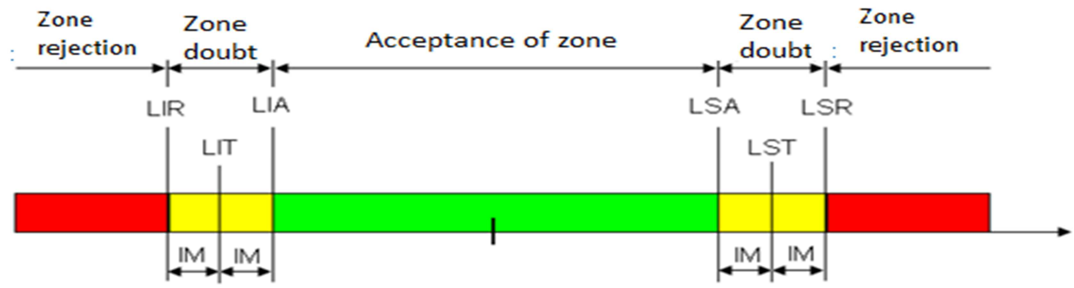

Figure 2 - Composition of the acceptance, rejection and doubt

LIT: Lower tolerance limit

LST: Upper tolerance limit

IM: Measurement uncertainty;

LIA=LIT+IM: Lower acceptance limit;

LSA=LST-IM: Upper acceptance limit;

LIR=LIT-IM: Lower rejection limit;

LSR=LST+IM: Upper rejection limit;

So can be verified that when the base result is beyond the limits of rejection, there is no question which do not comply the tolerance. Therefore also clear that the products are approved only which the base result is within the zone of acceptance.

By the production point of view, is interesting that the acceptance zone as closely as possible the area of compliance. The rule for that is the improvement of the uncertaint of the process for a tolerance interval, what includes additional cost: the quality cost.

The equilibrium point that minimizes the cost of quality is between two extremes: perfectionism and relaxation. Its position depends of each case. It should, therefore, to find the ratio between the tolerance interval and the optimal measurement uncertainty (IT/IM) corresponding to this equilibrium point. The experience shows that in a good portion of the industrial interest situation the equilibrium condition é reached when the process uncertainty is around a tenth of the tolerance interval. This value shall be considered like a guide and can be upper or lower depending of the case.

Tolerances in induction electrical motors

In the induction electrical three phase motors tests the conformity tolerance limits of the products changes due the efficiency range of the motor. In the specific requirement is defined a remoteness index result (IAR), which representing how the tested motor is remoteness of the manufacturer declared value, in other words, remoteness of the specified tolerance of the product. The equations 1 and 2 presenting the expressions of the IAR in function of the efficiency range. The denominator of the expression of the IAR representing the tolerance of the measurement.

For efficiency (η) ≥ 0,851, we have:

$$IAR = \frac{(Vd - Vm)}{0,2 * (1 - Vd)} * 100 \qquad (1)$$

For efficiency (η) < 0,851, we have:

$$IAR = \frac{(Vd - Vm)}{0,15 * (1 - Vd)} * 100 \qquad (2)$$

Where,

IAR: remoteness result index;

Vd: Value declared by manufacturer;

Vm: Value measured.

The following figures are a graphic representation of the results obtained to 3 efficiency test of the electrical three phase motors, performed at CEPEL. In the graphics are the tolerance limits, acceptance and rejection, in accordance with the acceptance test criteria presented in this work.

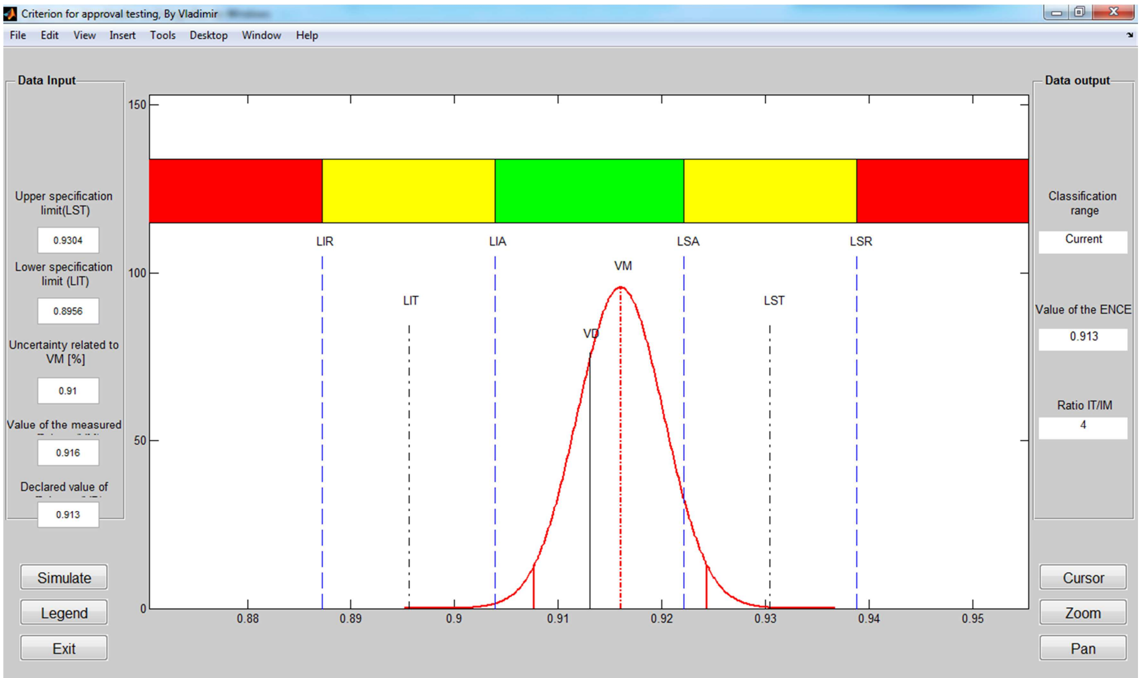

Figure 3 - Result for the sample 1 (Example of approved result).

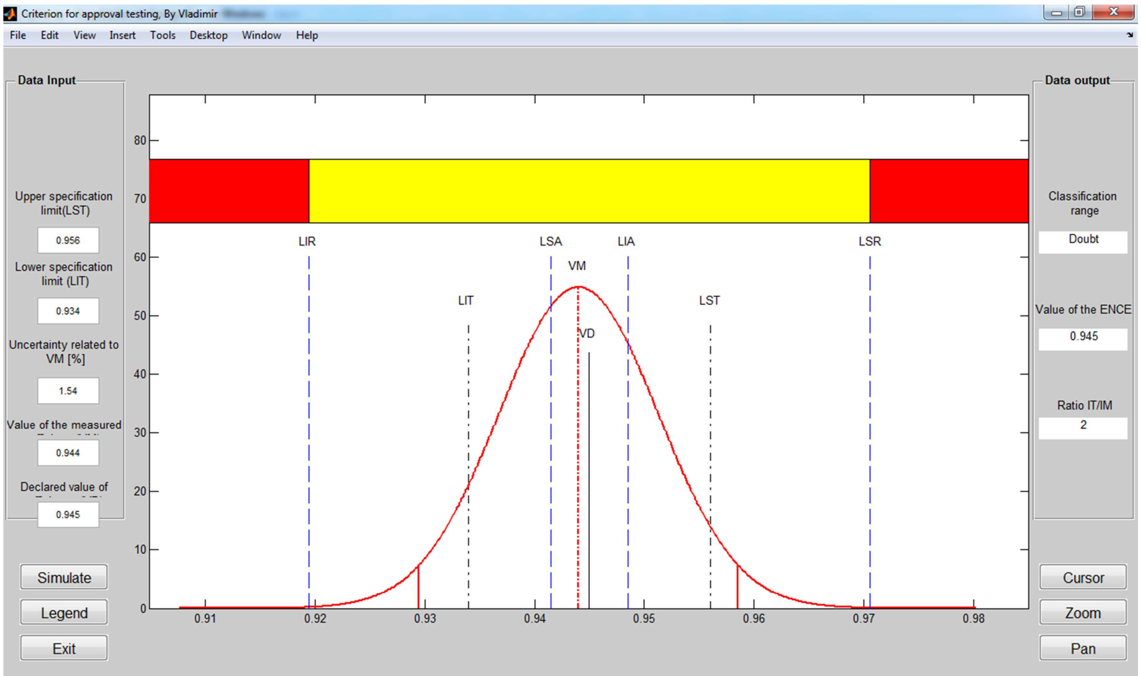

Figure 4 - Result for the sample 2 (Example of doubt result).

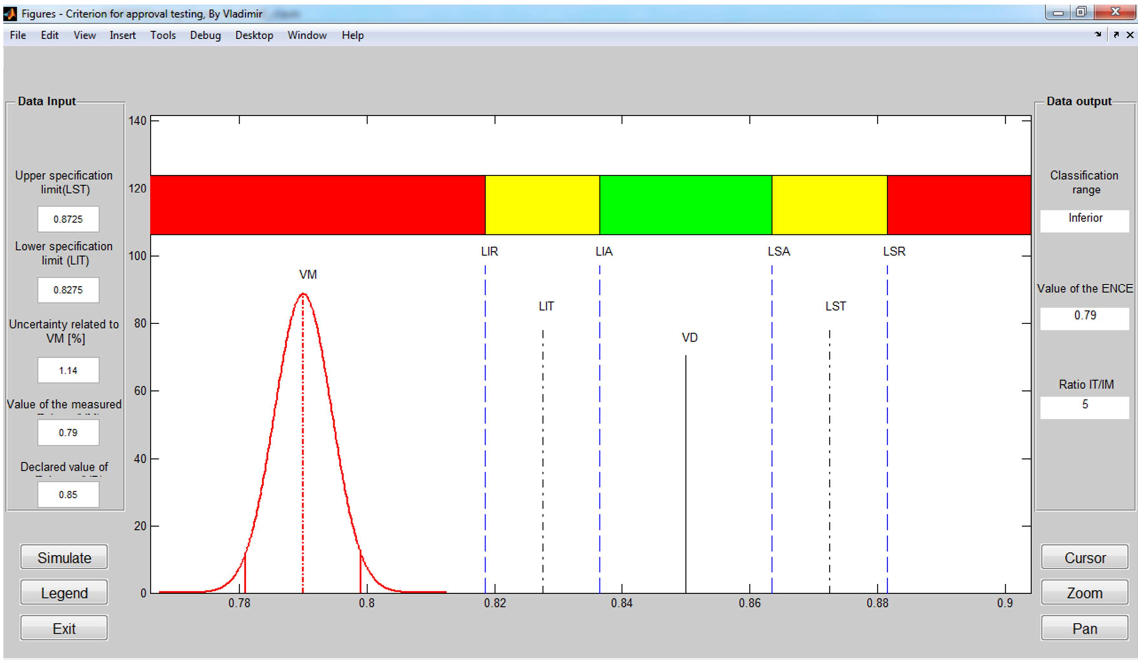

Figure 5 - Result for the sample 3 (Example of rejection result).

CEPEL, in order to measure the measurement capacity of its laboratory in the PBE Motors, has used the test approval criteria in this work in 108 motors with power between 0,75 kW to 185 kW. The result of this analyze is presented in the figure 6.

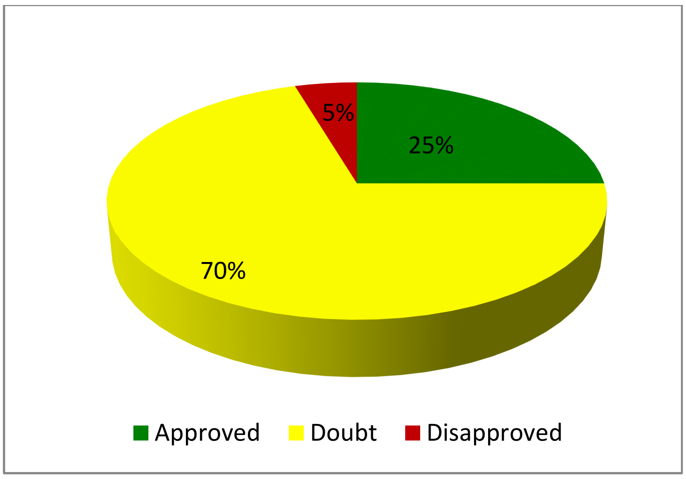

Figure 6 – Current scenario

By analyzes of the graphic of the figure 6, we can see that the majority (70%) of the test results are at the doubt region, or, there is no sure about the conformity or not of the product against the tolerance specified in the requirement.

Conclusion

The article has presented a test induction three-phase motor acceptance efficiency criteria taking account the measurement system uncertainty. The results found for 108 tests performed at CEPEL are quite worrying, face 70% of these are in a doubt region, or, cannot ensure that the tested motor was approved or rejected. In 30% remaining, being 25% approved and 5% rejected, is possible ensure that the measurement system uncertainty level is compatible with the requirement specified tolerance limits. The optimal condition would be there is no test results at the doubt region, independently of an approval or rejection motor test result.

The tolerance variation in the requirement due motor efficiency declared value by the manufacturer beyond, of course, of the proper variation of the measurement uncertainty concerned of each test, explain the fact there were (30%) with measurement uncertainty compatible with the tolerance and other (70%) out of the target.

Is important to say that the measurement uncertainty method, adopted by CEPEL has considered the biggest value of uncertainty calculated for each measurement range of the instruments used during the test. This decision can be considered conservative; however, it is described in the guide EA-4 02-S1.

The result obtained in this work reinforces the necessity of the determination of a method including all accredited laboratories in the Brazilian program efficiency motors, defining a ratio between efficiency measurement uncertainty and the tolerance defined in the specific requirement. First of all is necessary reassessment of the measurement methods, instrumentation used during the test, considered uncertainty sources, uncertainty measurement method and, necessarily, for a round of laboratory comparison. Only after this technical harmonization between the accredited laboratories, will be possible to establish a ration between measurement uncertainty and tolerance of approval, what can culminate in a likely change in the definitions of the specified tolerance in the requirement of the conformity assessment.

The target of this work is to give to society a metrological confidence, based in solid criteria with satisfactory results, during the conformity assessment performed in the Brazilian program efficiency motors.

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Implementing efficient electric motor systems and ISO 50001: opportunities for a 3 way approach in the Netherlands

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Abstract

Research and pilot projects show that system optimization and best available technology can deliver reductions of 20 - 30% in the electricity used within motor systems for industrial heating, cooling and ventilation systems and industrial production systems in the Netherlands. Obstacles in the marketplace and a low awareness of energy efficiency best practices and technologies are hampering their market penetration. Government and industry have started initiatives to overcome these barriers along the following lines of activity: energy management systems (EnMS) in voluntary agreement programmes, and participation in the IEA 4E Electric Motor Systems Annex (EMSA) combined with an electric motor systems (EMS) knowledge network. These activities are complementary to each other and bring more focus and attention towards the implementation of efficient electric motor systems in industry.

Large industrial companies engaged in voluntary agreements (VA's) with the government all have an EnMS in place. ISO 50001 provides a very good match with the Dutch standard that most of these companies already have in place; however, research shows that some aspects of the EnMS systems are not well implemented and that some of the main aspects of efficient electric motor systems within the EnMS applied are not covered in a satisfactory manner. Some new projects have been initiated to address these issues while assisting companies in their transition towards ISO50001 and supporting the implementation of electric motor systems.

NL Agency and the motor systems industry operate a 'knowledge network' to support the implementation of electric motor systems and to provide knowledge transfer and guidance on systems performance. Different activities, that include a quick-scan of electric motor systems, are being developed.

The Netherlands is also participating in the Electric Motor Systems Annex (EMSA) as part of the IEA 4E Implementing Agreement. The joint experience of the six member countries is applied to provide technical guidance, capacity building and knowledge transfer on performance and IEC/ISO systems standards.

Introduction

Electric motor systems (EMS) use about 69% of electricity in Dutch industry. Research and pilot projects show that system optimization and best available drive technology can deliver reductions in electricity demand of 20 - 30% in pumps, fans and compressors used in heating, cooling and ventilation systems and similar savings in industrial handling, processing and production systems; thus having a potential to lower the national electricity bill by 5 to 8% [1]. However, obstacles in the marketplace and a low awareness of best practice and technology are hampering the market penetration of these solutions. The Dutch government and motor systems industry have started initiatives to accelerate market penetration along three lines of activity: VA-programmes, technology network and EMSA.

1. Instrument of Voluntary Agreements

Series of 3 Voluntary Agreements on Energy Efficiency

There has been a succession of three Dutch Voluntary Agreements on Energy Efficiency (VA's) implemented in the form of covenants. VA1 began in 1992 as the first covenant on Energy Efficiency, at the initiative of the Ministry of Economic Affairs. Under this covenant, the Government established a voluntary, though binding upon signature, agreement on energy efficiency improvement targets with industry partners and institutions. The objective was to reduce the quantity of energy used per unit of product or service delivered through a 2 per cent per annum improvement in energy efficiency. Under VA1, the focus was on process efficiency. The programme is being operated via the the Netherlands Agency for Energy and Climate Change, NLAgency.

After VA1 came to an end in 1998, the parties continued the covenant through VA2. The focus was still on process efficiency, but was broadened to include sustainable energy and chain efficiency[1], amongst other aspects.

In 2008, in view of the success of the previous VAs, the choice was made to intensify, extend and broaden the VA2 programme into the VA3 programme. Amongst others factors, the intensification requires businesses to exert efforts to attain an improvement in energy efficiency of 30 per cent over the period 2005–2020. Roadmaps have been introduced to support this transition. There is also a greater focus on chain efficiency and cooperation across sectors (see also the paragraph on KnEMS).

For large industrial companies the LEE covenant was signed in 2009 and is based on VA3 (LEE stands for Long-Term Agreement on Energy Efficiency for ETS). LEE is designed for large industrial companies that are obliged to participate in the Emissions Trading System of the European Union (ETS). The LEE participants are also committed to a scheme of energy efficiency goals and activities, comparable with that of the VA-scheme. The LEE participants come wholly or partly under the ETS.

The current programme runs up to 2015 and is currently being evaluated to assess its results and potential for continuation.

Results

A total of circa 1,000 energy intensive companies from 40 different sectors, improved their energy efficiency in 2010 jointly by an average of 1.4% (over one year compared to 2009, LEE and VA3 together) [2]. In 2011 the figure was 1.9% compared to 2010 [8]. Compared to 2009, the energy consumption increased by 99 PJ in 2010. In the case of LEE, this is mainly due to an increase in

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[1] Chain efficiency in the context of efficiency gains within the supply chain starting from materials exploration, production of raw materials, semi-finished products and finished products, including distribution transportation and distribution activities.

production in almost all sectors. For VA3, that increase may also be attributed to an increase in production but also to the addition of some new sectors and companies.

The VA3-companies from industry, food and beverages and services sectors had an energy efficiency improvement of 2.3% in 2010. In comparison to 2005 the companies are 10.6% more energy efficient. This means that they are performing above the government target of 2%. They also conserved energy at an average rate of 2.1% a year. These results are due to measures made in the field of process and chain efficiency. By the start of 2012 the VA3 sectors will deliver their roadmaps, in which they define their energy efficiency strategy for 2030.

The LEE companies improved their energy efficiency by 1.1% in 2010, see Figure 1. This is due to the fact that this is the first full year for the LEE participants. They needed a starting period to start working with the methods of the new covenant. Besides this last year the production volume increased sharply and the companies partly delayed measures for energy efficiency improvement. By the end of 2012 these companies will be 8.2% more energy efficient compared to 2009 – based on the saving ambition in the Energy Efficiency Plans (EEP). These plans describe the energy saving measures that are to be taken from 2010 to 2012. In mid2012 the roadmaps of the LEE-sectors were prepared.

	Energy consumption 2010	Improvement in energy efficiency*
	PJ	%
LEE	626	1.1
LTA3	219	2.3
Joint result	**845**	**1.4**

*Savings resulting from measures in the production process and production chain within the Netherlands

Figure 1 Joint results VA and LEE in 2010 [2]

4 year cycle

The participating companies in VA3 have to implement a three-fold set of activities: (1) making an Energy Efficiency Plan every four years, (2) yearly monitoring of production levels and energy use and (3) having an up and running energy management system.

The Energy Efficiency Plan (EEP) describes the energy saving measures that are to be implemented over a period of 3 years, an assessment of the expected energy saving and the appurtenant time line. With these measures, the company or institution also creates the basis for the development of the energy paragraph in the environmental license (which is issued by local, regional or national government depending on the environmental impact of its products and processes). NL Agency performs an assessment to determine whether an EEP meets the requirements of a VA. On the basis of the individual plans, NL Agency has produced aggregate projections of the expected joint improvement in energy efficiency or the ambition of the companies.

In the past few years specific attention has been paid to motor system efficiency within the VA-approach. Working together with other countries in the Motor Challenge Program project (MCP) [9], all known measures from the MCP are listed on the VA measure lists as described above for use in formulating the Energy Efficiency Plans. The Motor System Action plan and IE3-motors from 7.5 kW up to 375 kW has been put on the Energy List of the Energy Investment Allowance (EIA). This is a tax relief programme which gives a direct financial advantage to Dutch companies that invest in energy saving equipment and sustainable energy. The net profit (on their investment in energy efficiency equipment) can amount up to 11%. Companies may also apply for Energy Investment Allowance support to cover the costs of an 'action plan' for electric motors. However, these costs are only eligible for EIA support if you have actually implemented the recommended energy measures.

The instrument of VA´s engages the companies with energy efficiency related activities like thematic workshops, pilot projects, energy audits and technology roadmaps. Participating companies operate a required energy management system, based on (elements of) ISO14001, which is being transformed towards standards such as ISO50001 and new methods such as the CO2 performance indicator.

EMSs are addressed within this framework and clear links towards organization, procurement and sustainability issues are being developed.

Energy management system

Energy management was introduced within the Voluntary Agreement (VA) programme in the Netherlands at the beginning of this millennium. The VA programme had been established in the late 1980's as a policy instrument to increase energy efficiency in Netherlands' industry. The programme showed good progress in its early years: i.e. it led to a 22.3 % average energy efficiency improvement (defined as a reduction in specific energy consumption) over the period 1989–2000. However in more recent times some participating enterprises found that the result achieved in previous years was eroded. This is illustrated for a specific enterprise by an observed increase in the energy efficiency index used as an energy efficiency indicator, after a previous period of decrease, see Figure 2. In this specific case a member of the board, who was very active in promoting energy saving, left the company. The result was that energy consumption ceased to be monitored, and energy use went up again. This became the reality, as opposed to expected trend shown in the dotted line.

The conclusion drawn was that there was a need for a structural approach in saving energy based on the Plan-Do-Check-Act (PDCA) approach [10]. This approach, which we nowadays simply call energy management, was introduced as an obligation within the Voluntary Agreement programme at the beginning of this millennium.

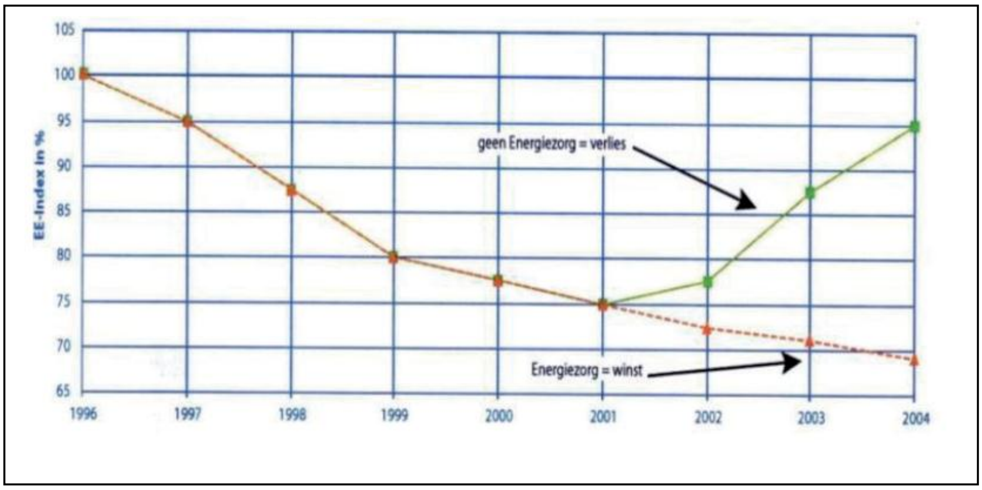

Figure 2 Energy Efficiency Index development for a specific enterprise: with and without active energy management [2]

Based upon the structure of ISO 14001, a new management system approach was designed for energy. This seemed very logical since energy could be addressed in the ISO 14001 framework, which sets out the criteria for an environmental management system, as soon as it is identified as a significant environmental aspect. This also guarantees alignment of the energy management system with the environmental management system. The other reason to do so is the familiarity of part of the Netherlands' enterprises with the ISO 14001 system structure. Currently up to almost 1900 organizations in the Netherlands hold an ISO 14001 certificate. Based on this structure the so called "Energy management specifications" were designed to be accompanied with a "Reference Guide" to facilitate implementation.

Monitoring quality of implementation of energy management systems

Currently approximately 900 organizations have implemented an energy management system. This is based on the "Energy management specification" mentioned above or is being integrated within the ISO 14001 environmental management system. Having implemented an energy management system doesn’t however always guarantee practical success in operation. To facilitate ongoing improvement yearly audits are being executed at a random selection of 50 organizations to assess how they meet the requirements of the “Energy management specifications”. These audits are done on behalf of NL Agency. On top of that several organizations are already being certified for ISO 50001 or are preparing for certification.

Highlights of the audits (on the quality of implementation of energy management systems) of 2011 were that Technical management moves to Facility support, leading to a reduced guidance on technical buying within companies. And a reduction of the number of operational (technical) personnel, leading to reduced time for development (of energy efficient measures). Also although there is the introduction of more automated process control, but less attention (or capacity) for energy consumption analyses. Overall there is a development towards less single-head technical responsibility within the participating companies.

The audits in 2012 shows that a general weak point in the operation of the systems lays within a weak or non-existent management review, leading to low involvement of the management, and reduced chances engagement of personnel in implementing the appropriate responsibilities and energy saving measures. Secondly a general weak aspect of the audited systems is the ‘checking-part of the system’. In short this means that the effectiveness of taken measures is not being monitored, nor is the mechanism of PDCA-cycle working correctly, since the ‘C’ of the checking part is missing.

The 3 main elements of the VA-program, i.e. 1) making an Energy Efficiency Plan every four years, (2) yearly monitoring of production levels and energy use and (3) having an up and running energy management system, give government and industrial companies a solid basis to develop and implement energy efficiency activities. For the Dutch government the VA-program strengthens the national climate and energy efficiency goals of the Dutch government. However, as the following paragraph shows, more actions from policymakers and industry is needed to come to an more successful implementation of efficient electric motor systems.

2. Knowledge network on electric motor systems (KnEMS)

Analyses of market and barriers for efficient electric motor systems

Analysis of the market of electric motors supply and maintenance in the Netherlands and the practices of the Original Equipment Manufacturers (OEM’s) and industrial end-users shows that for a successful acceptance of efficient electric motor systems all market parties have to get involved, see Figure 3. As a result of this and of the above mentioned market developments NL Agency broadened the focus of their activities on efficient electric motor systems from end-users alone towards addressing all market parties in a ‘knowledge network for efficient electric motor systems’. This KnEMS also lays more responsibility on to the market itself, which became necessary with a government which aims to meet new efficiency goals and effective ways in supporting businesses in their pursuit for energy efficiency [3].

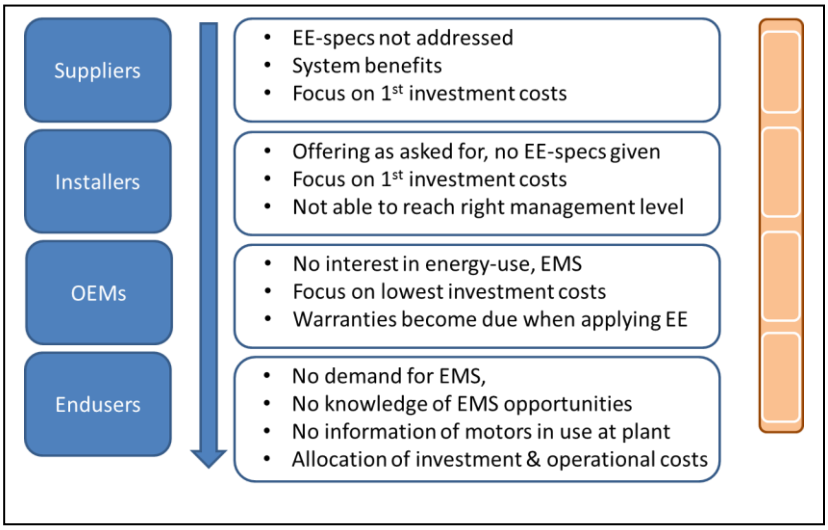

Figure 3 Obstacles in the marketplace for Efficient Motor Systems [3]

KnEMS (Knowledge network on electric motor systems)

In cooperation with NL Agency the motor systems industry has started a 'knowledge network' to support the implementation of Efficient Electric Motor Systems (EMS) and raise the awareness of its potential. Two Dutch sector associations, of suppliers (FEDA) and of installation engineers (Uneto-VNI), have joined the network and representatives of one OEM sector are also involved (the Dutch Pump Association (HPG)) [4].

A short film on efficient electric motor systems has been made to introduce the new EU regulation for efficient electric motors. Three managers of VA-participating companies show how they got involved in applying efficient electric motor systems in their businesses. The situations for two of them - end-users - are different, but the benefits and results are comparable as seen through large economic savings in HVAC, luggage handling and inside passenger transport systems, as well in industrial ventilation systems. The Original Equipment Manufacturer (OEM) applies the IE2 high efficiency motor as standard as part of its company policy in delivering high quality, modern equipment with low maintenance cost over its life cycle. An English version is available on www.motorsystems.org.

The network assists in organizing 3 workshops specific for VA-companies on the opportunities of efficient electric motor systems. This is an extra effort to bring efficient electric motor systems to the attention of companies and make a start with the transition towards motor management as an regular activity.

The network will also work on capacity building in the market as well with the end-users themselves. This will not only appeal to the technical representatives, but also the financial and general management representatives. A specific tool that is promoted is the EMSA Motor Systems Tool, developed by Danish Technology Institute. This tool is unique in how it is applying a system approach. Not only is the motor performance calculated, but also the transmission, drive and load itself are calculated and optimized (see: www.motorsystems.org/motorsystemtool). Best practices and factsheets will be produced that are suitable to inform both a technical and non-technical public.

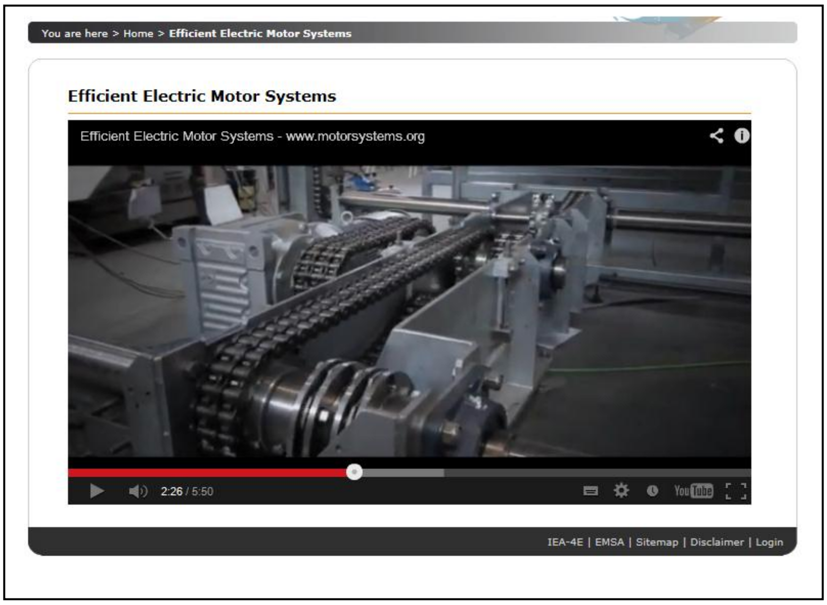

Figure 4 Screenshot of Short film on electric motor systems [4]

The KnEMS will also develop knowledge related efficient electric motor systems activities for sectors which have incorporated efficient electric motor systems in their technology roadmap for 2030. These are being developed for: several food sectors - dairies, meat and vegetables; the metallurgical sector; the paper industries; and the foundries and surface treatment companies. Examples include application of variable speed drives (VSDs) for motors used for cooling and ventilation, a more efficient cooling cycle for motors, fans and pumps; the replacement of motors, fans and pumps by well-fitted systems used in a process or installation; optimization of cooling and process set-up, as well as optimization of drives for utility-processes like pumps, compressors and equipment.

3. EMSA (electric motors systems annex)

Introduction on EMSA

The Netherlands is participating in the 4E Electric Motor Systems Annex (EMSA),which is part of the IEA Implementing Agreement for a Co-operating Programme on Efficient Electrical End-Use Equipment (4E).

The joint experience of the six member countries is applied to provide technical guidance, capacity building and knowledge on performance and IEC/ISO standards [5]. EMSA provides an excellent forum to develop and assess possible policies, strategies and actions to speed up the implementation of highly efficient motor systems, on a national, international and global level.

The 4E EMSA was renewed in 2012 and will run for three years. The Netherlands participate in several areas of interest of EMSA including International Standards. EMSA works for globally harmonized and robust technical standards for the classification and testing of motors and variable frequency drives through representation in standards working groups, and for implementing motor systems management as part of the energy management systems standard ISO 50001.

Implementing ISO 50001 and opportunities for efficient electric motor systems

The quality of the energy management systems implemented by the VA participants is monitored every year and opportunities are identified to improve the system and its effectiveness. The systems are based on (elements of) the standard ISO14001 and some participants have already started a transition towards ISO50001 [6], [7].

During the 2012 monitoring period of the energy management systems special attention was given towards the opportunities for efficient electric motor systems. The areas which offer the best opportunities are shown below – the 'starting position' in the energy management systems (EnMS) is show in Figure 5:

- Energy Planning: give specific attention to drives in relation to the electricity use in the energy review. Are the important groups of motor systems identified? ISO 50001 characterizes significant users also as users with a significant efficiency potential.
- Implementation, operation and monitoring: is 'motor management' identified and described as an activity? Is there adequate knowledge and capacity to implement this activity? Which part of the organization holds this domain?
- Maintenance and repair of electric motor systems. How are these technical issues organized? What procedures are in place for rewinding or replacement, for redesign or adjustment of drives and for preventive replacement versus replacement by failure? Is Total Cost of Ownership (TCO) a standard element in the business cases?
- Procurement and Design. Are minimum efficiency requirements for motors in place? Are they differentiated according to the motor system, e.g. processing equipment or pumps? How are the responsibilities allocated between engineering, energy and procurement? Are personnel trained in the use of TCO principles?

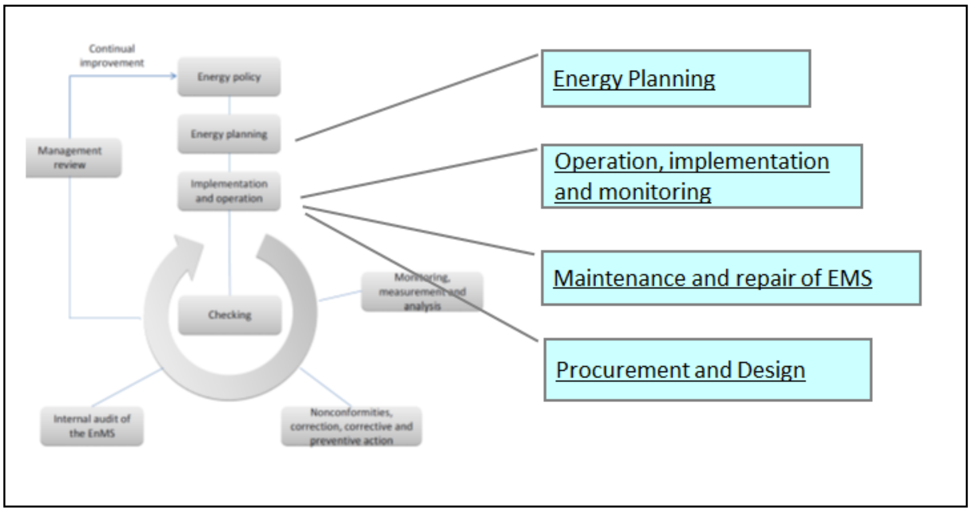

Figure 5 Opportunities for electric motor systems in energy management system ISO50001 [7]

The implementation of these specific aspects of and opportunities for electric motor systems in ISO 50001 will enhance the implementation of efficient electric motor systems within industry, and will help industry, Original Equipment Manufacturers, suppliers and maintenance parties to work more efficiently and increase their competitiveness.

EMSA provides a forum for the direct and in-depth exchange between members on their experience with motor systems efficiency policy, as well as a vehicle for collaborative projects. EMSA's research results are publicly available.

4. Conclusions

The three lines of activity of the Dutch government and the Dutch motor systems industry - VA-programmes, technology networks and EMSA - are complementary to each other and bring more focus and attention towards the implementation of efficient electric motor systems in industry. Representatives participate in these activities to enable an effective and efficient means of operation and to utilize the opportunities for synergy between the three approaches.

The VA-programme provides a framework for the participating companies to integrate energy efficiency activities into their daily operation, and to integrate energy management into their organization. Due to the specific characteristics of electric motor systems the VA programme alone is not enough for a successful uptake by industry.

Where the VA programme makes the companies accessible and engaged with energy efficiency activities, the KnEMS activities supply the companies with the information and knowledge on electric motor systems. The network forms a platform for the sector (suppliers, maintenance, services) to deliver objective and consistent information on electric motor systems for end-users and works actively on knowledge transfer via best practices, workshops and factsheets, for example.

The third line of activity, EMSA, brings in up-to-date knowledge on international practices on electric motor systems, on capacity building and the development of new standards. New tools and practices can be introduced and absorbed quickly by the members of the KnEMS and be brought to their own members and to end-users.

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Figure [source]

"INTERNATIONAL EXPERIENCE IN ISO 50001: ENERGY MANAGEMENT SYSTEMS"

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ABSTRACT: In the current situation of economic crisis and the concern for the environment, efficiency and energy savings has become a very important tool for companies and public institutions. Energy Service Companies (ESCOs) are the main precursor to realize projects in this area by seeking solutions, implementation and financing projects. But even ESCOs require tools for managing their own projects and installations where they act as energy management or ISO 50001 on Energy Management Systems, the main international precursor of Energy Management

1. Introduction

In recent years, energy management becomes one of the most important tools to increase the competitiveness of companies. To manage energy correctly, to promote the use of more energy efficient equipments or to develop the maximum potential deployment of renewable energy is a goal that the medium and large enterprise does not have to renounce.

2. ISO 50001 Standard

The requirements imposed by markets make environmental management and energy management in particular, key tools for the development of companies. Moreover, in the last few years, there has been lots of discussion related to energy use achieving the same conclusion: in order to ensure a sustainable future it is essential to rationalize the use of energy at a worldwide scale.

In the early 2000s, the first standardized energy management systems appeared in the world. Ireland [1], Denmark [2], Spain [3], Holland [4], or United States' standards [5], were the forerunners.

The European standard (EN 16001) [6] was published in 2009 and in 2011 the international standard ISO [7] was developed.

Nowadays, on January 2013, more than 1734 certifications have been issued in the whole world (see Figure 1).

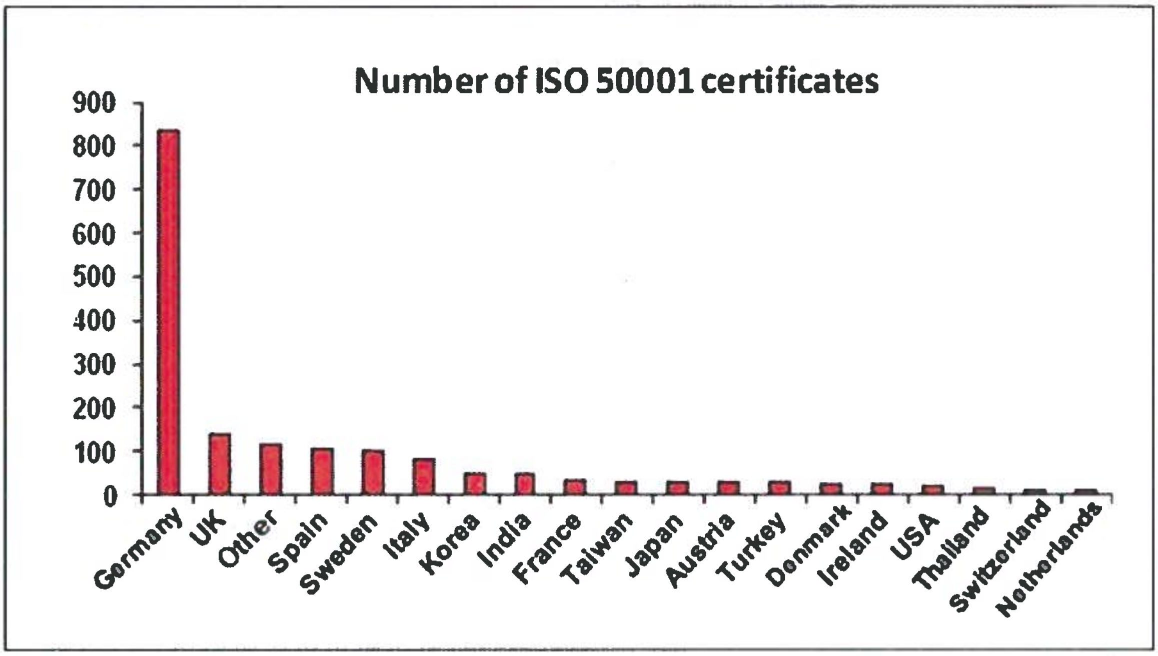

Figure 1. Number of ISO 50001 certificates

Nevertheless, it is estimated that during the present year the number of certificates will rapidly increase, due to the large number of EN 16001 certificates, the old European standard, that will soon be replaced by the ISO 50001 standard.

EN 16001 standard is strongly established in countries such as Germany due to the tax incentives defined by government in order to promote energy efficiency and energy management.

An Energy Management System (EnMS) aims to systematize the processes in an organization, providing energy management criteria, savings, and efficiency. The EnMS is a tool to facilitate organizations, no matter size or sector, reductions in energy consumption, financial cost associated, and consequently, greenhouse gases emissions. This standard provides continual improvement in the quality of energy use.

An EnMS is based on the Deming cycle (PDCA: Plan-DO-Check-Act):

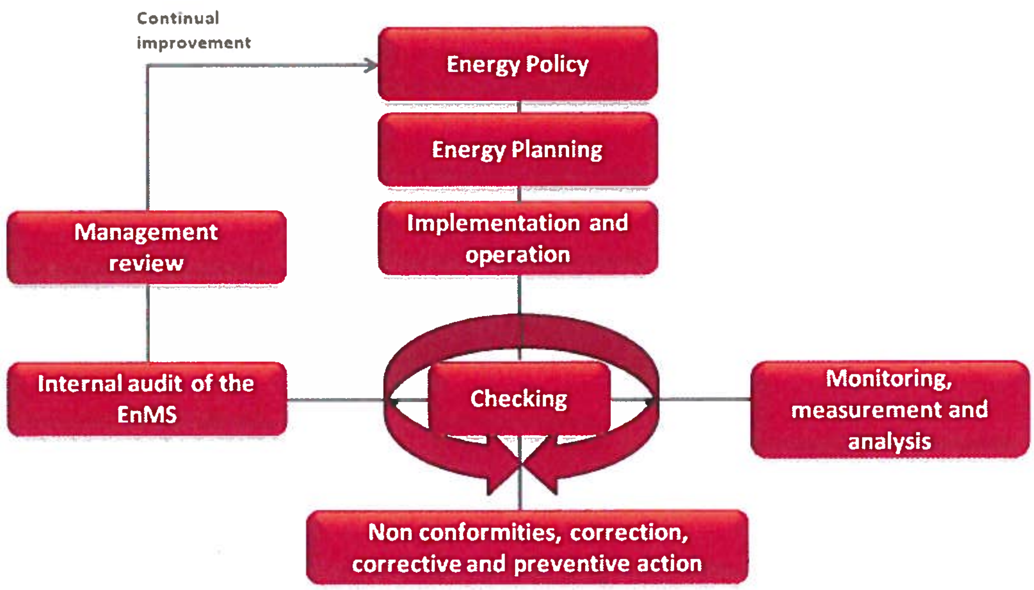

Figure 2. Energy management system model (PDCA)

ISO 50001 implementation allows organizations to have an exhaustive control of their energy consumption, which is a key in business competitiveness and Corporate Social Responsibility (CSR).

Over recent years, the adoption of sustainable energy policies has become one of the best cover letters for organizations. Establishing a sustainable performance provides many different benefits such as minimizing environmental impacts, optimizing use of raw materials, energy and water, production processes improvements, waste management and economic benefits related.

3. Energy Management Objectives

As it happens with other management systems, an EnMS implementation is voluntary and can be applied on any organization, no matter size or activity.

The main purpose of an EnMS is to facilitate the establishment of the processes and methodologies required, in order to improve its energy performance, including energy efficiency, energy use and energy consumption.

Other objectives of an Energy Management System according to the ISO 50001 are:

a) Achieve energy saving objectives

b) Adoption of an energy management culture

c) Improve both control and measurement methodologies for energy consumption

d) Improve the image of the organization, in terms of environmental responsibility

e) Establish continual improvement framework energy efficiency - based.

It must be pointed that ISO 50001 does not provide energy consumption requirements for an organization, but focuses on management and control.

3.1. Why energy management is necessary?

Usually, a facility's energy consumption has an upward trend over time. The source of these energy consumption fluctuations is related to the lack of a correct maintenance of the facilities, problems with information communication between workers or simply, the common use of equipments (see Figure 3).

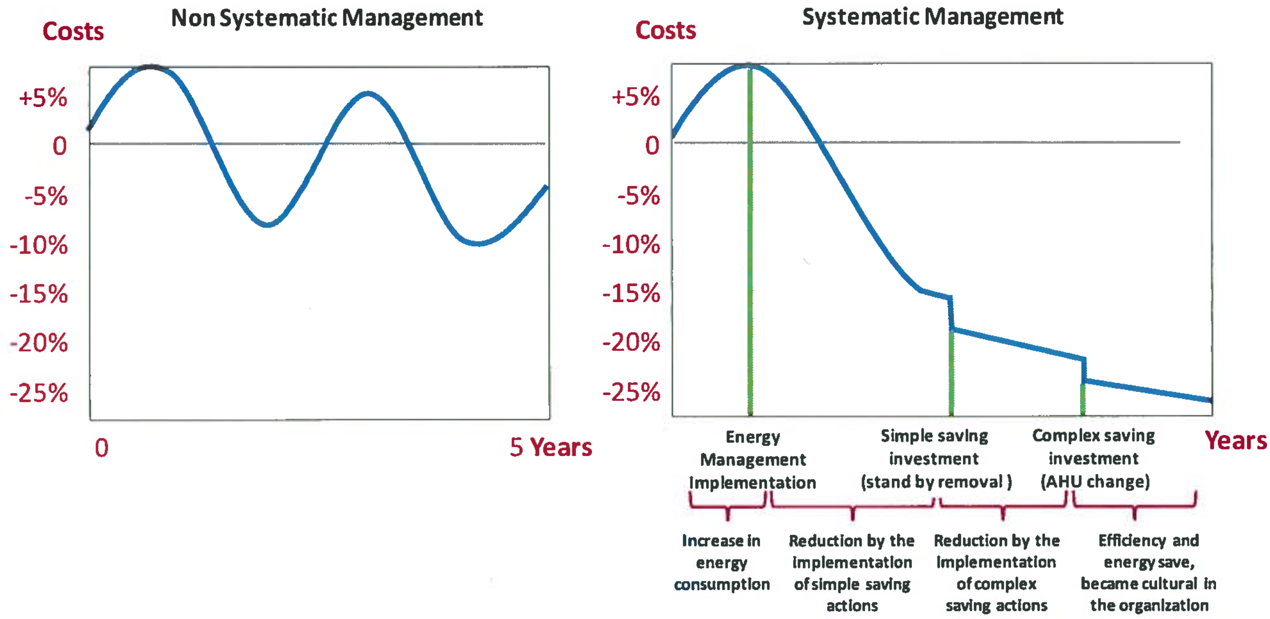

Figure 3. Differences between systematic and no systematic management of the energy consumption

By the use of energy management, an organization can achieve an adequate control of the energy consumption of its equipments.

Most organizations have heterogenic energy consumption because it does not depend on one person or a single process, but it rather is the result of multiple variables and processes. Hereby, it is essential to establish a systematic order within the facility's energy management. Considering this, an Energy Manager is needed to control the technical, administrative, training, and operation issues to optimize energy consumption.

At this point arises one of the basic premises of energy management: "Improvements require measures". It is essential to question When? How much? How?, Who? or Where? about energy inside the organization.

4. Energy manager

The role of the Energy Manager is essential for implementing and maintaining an energy management system. He is responsible for the optimization of all processes involving energy consumption in the organization. These are complex processes that usually implicate multiple departments and persons. The Energy Management System responsible is a key figure that handles energy consumption monitoring of the building or facility, analyses consumptions, controls energy supply, ensures compliance with energy legal requirements, identifies opportunities for improvement and proposes an improvement plan for energy efficiency, fund it if necessary.

In conclusion, an Energy Manager coordinates all tasks related to energy management.

The Energy Manager role is expected to become more important in coming years. A large number of countries are developing standards with different obligatory levels to incorporate this position in organizations. Moreover, international markets offers a wide range of Energy Management training courses.

The Energy Manager has a large variety of alternatives to perform his work. He can use an internal methodology; outsource the service through an ESCO; or implement an Energy Management System according to standards such as ISO 50001. This is an almost obligatory choice for those organizations working for the Public Administration, who will demand it in public contracts.

4.1. Energy Manager's tasks

Regardless of the option chosen, it should follow the same pattern, as seen on figure 4.

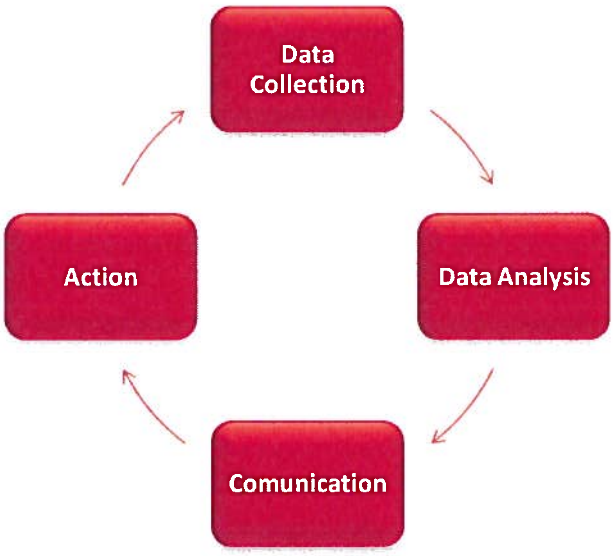

Figure 4. Energy manager tasks

Data collection and consumption monitoring will be done in a systematic and planned way. It is necessary to carry out two key tasks: identification, evaluation, registration and implementation of consumer equipment, and the adoption of legal and regulatory requirements on energy.

These data will allow the Energy Manager to analyze consumption and define comparative studies by setting ratios to create an operation program.

In example: an operation program for a pumping system should include:

- Equipment inventory.
- Analysis of energy consumptions (including timetables, variations during weekends, load curve, etc).
- Pumping requirements for each process.
- Energy performance indicators definition.
- Energy inefficiencies identification and quantification.

An energy balance must be done subsequently by the Energy Manager, as well as developed a performance program containing all the issues that affect the organization. This program should be used by workers and maintenance managers of the organization.

Moreover, the Energy Manager must set the guidelines to create an annual energy report to sum up the activities derived of energy management. Finally, he will have created an improvement program, which is based on the following points:

- Identification and quantification of the opportunities for improving energy performance. The experience of the Energy Manager and his knowledge of new equipment and solutions will be essential.
- Energy management of procurement and hiring. It must be done under previously defined requirements by the organization.
- Energy management of investment in facilities.
- Training, skills and competences to carry on energy management activities.

This report must be approved by the top management and shall be communicated internally and externally.

5. ISO 50001: Energy Management Systems

An Energy Management System establishes a structured group of methodologies and procedures for providing the organization a better energy behavior. ISO 50001 standard "Energy Management Systems" defines the minimum requirements these kind of systems need to have to ensure the success in energy management. Therefore, this is a tool that can help to the Energy manager in his daily job.

5.1. Gap analysis

Figure 5. Management Systems Integration

The process prior to the implementation begins by analyzing the existence of any other management system that the organization could have implemented, as well as the level of energy management that has already been done by the organization.

In the first case, having any other management system such as ISO 14001 or ISO 9001, greatly eases general documentation and procedures required by the standard. A correct implementation of ISO 50001 will be done by integrating it with other management system in this respect (see Figure 5). However, although this could be the most logical option it isn't essential.

Afterwards, the complexity level of the management system must be defined. The ISO 50001 standard does not require a certain level of complexity, but just enough to make a proper energy management. A high investment in consumption control equipment without an appropriate data management will be of no use. On the other side, a large analysis team with inappropriate measurement equipment will be under-valuated. It is therefore necessary to be consistent in making investments in human resources and technical equipments.

Moreover, it is necessary to define the limits of measurement. An Energy Management System can be controlling 10, 100, or 1000 processes in the same facility. That is, it is possible to control in a consumption matrix a large number of areas. The more complex the management is, the more accurate the control will be. But it also requires higher implementation investments on the day-to-day.

By contrast, a low number of consumption areas in an energy matrix, supported by a low number of measurement and control points will make the manage system less precise. However, it will be easier to control and more economic to implement.

Therefore, the discussion between a high or a low complexity level will depend on the resources the organization can allocate to energy management.

In the practice, the control level is established depending on consumption cost by time unit. That is, a facility where a bad management could cause high energy costs will need a high level of detail in management. On the opposite, an organization where a failure in energy management does not cause high costs will not need an elevated level of detail.

5.2. Implementation stages

Once the detail level has been defined, the implementation process starts. Apart from other requirements in common with other management systems (not considering in this article scope), there are key processes that make ISO 50001 a very technical standard, where consultants responsible for implementing it must have knowledge in energy engineering. These key requirements are:

- Energy review
- Energy baseline
- Energy objectives, energy targets and energy management action plans
- Operational control

5.2.1. Energy review

Probably, one of the most important stages is the Energy Review. It requires a high level of energy knowledge of the facility. To that end, an energy audit according for example to the Spanish standard UNE 216501 "Energy Audits" [8] would ease the way. However, this is not mandatory as there are many companies that have already done an energy balance and have already detected saving measures applicable to their organization.

The key of energy review is the determination of the organization's energy performance based on data and other information, leading to identification of opportunities for improvement.

The organization will be able to know as much as possible about use and consumption of energy through this study. Issues like how, where, why, when, etc., the energy is used in its facilities.

This process aims to create an energy matrix where different uses and consumptions from the organization are contained. By defining with the means of a balance the significance level of each one of these uses and consumptions the matrix is created.

Moreover, the energy review will help establish energy performance indicators (EnPI) to measure the facility consumption in the right way, based in variables that affect this consumption. These indicators will be a base to establish comparisons, benchmarking studies, or improvement objectives.

This process of identification and evaluation of the energy use should lead to the detection of improvement measures in the energy consumption of the organization. Making an Energy Audit would be of great use for this purpose. The key point in this phase is to define where the inefficiencies are and how it is possible to get rid of them. It can also be of great relevance to classify those improvement measures depending on variables such as the level of investment needed to implement it, its profitability or the quantity of energy that is going to save.

Energy Review shall be periodically updated, and whenever there is a significant change related to facilities, equipment, systems and processes which might significantly alter the use and consumption of energy in the organization.

5.2.2. Energy baseline

In this phase, a methodology for calculating the consumption baseline will be established. It is the quantity of consumption needed to be able to make an operation or process in normal conditions of operation. This baseline will not be a mathematical function but a relation or group of several base consumptions in the operation. One of the most used methodologies is EVO (Efficiency Evaluation Organization) although many others exist at a worldwide level.

Moreover, the relational causes that make the consumption to increase or decrease depending on certain factors must be established. This relational cause is established through statistical analysis between the consumption and a determinate variable, such as the temperature or humidity in thermal processes. The objective of this process is to identify these variables and factors which make the energy consumption increase. This will make it possible to take preventive actions in the future in order to correct it.

All the calculus process should be established in a well-contrasted and documented methodology.

5.2.3. Objectives and targets

Further, energy objectives and targets to achieve must be specified. These objectives and targets will be based on the implementation of energy saving measures or, at least, of consumption control and management. These must apply with the SMART criteria:

- Specific. That is, based in the improvement of something in particular.
- Measurable. Which can be measured or at least to estimate their impact.
- Attainable. They should be reached in a proper way by means and sources available .
- Relevant. Choose goals that matter.
- Time-bound. Important to define a target date.

Generally, as it is already mentioned, objectives and goals to achieve will be directly connected with the implementation of efficiency measures and energy management. However, the fact of finding a saving measure does not mean that it had to be implemented. Therefore, the organization must implement those saving measures that it considers necessary according to their energy policy and their possibilities.

5.2.4. Operational control

This is the moment when tools and methodologies will be established for a day-to-day proper operational control. That is, how essentially the performance of feeding system data is. To do that, it will be necessary to establish, for any consumption area, the way of capturing data, measuring, control equipment needed and also the measurement frequency.

It is also in this moment when it will be recognized if an implementation of new systems of measure and control are needed. Additionally, the organization shall establish a plan to calibrate measurement equipment which should be registered and normalized.

Operational control will also establish the operating plan of the facilities for the different conditions, setting the needs and procedures of each operating situation. This operation has to be focused on the optimization in energy use.

Maintenance plan, both preventive and corrective, also must be developed in this stage, involving responsibilities and actions to be carried out within the usual maintenance plan of the facility.

5.2.5. Other relevant requirements

Besides the mentioned procedures and stages, must also be undertaken some interesting requirements. Some of these will be, for instance, related with equipment purchase and new designs. A proper energy management system must ensure that the new equipment acquired by the organization meet energy efficiency criteria. Equally, new processes and facilities design must be addressed taking into account energy efficiency criteria.

In this section, it is of particular interest the procurement of energy from renewable resources. Or at least, that the energy manager is able to purchase the energy at the best price and under the best administrative contract conditions, optimizing all factors that had an impact on the energy cost.

6. Case Study. The Company CLECE

In April 2010, the Facility Management Company, CLECE, established in San Sebastián de los Reyes (Madrid), decided to carry out the implementation of an Energy Management System throughout the standard EN 16001 in their headquarters as a pilot case. This company provides services as an Energy Service Company (ESCO).

The work of implementation was initiated by the company Creara in the month of April of 2010 and finished in July 2010. The company BSI (British Standard Institution) was the responsible for the certification.

The system was designed to be integrated within other quality and environmental management standards already implemented in the company.

6.1. Implementation´s motivation

Such energy services involve the investment in equipment for the improvement of the energy consumption in their client´s facilities, assuming also the facility management and maintenance. Since it is an investing enterprise, it assumes a strong risk derived by non-achievement of the saving objectives established at the time of making the investment. That is the reason why any tool which helps with the improvement of the energy management of the facilities where investment has been taken will make a big impact in the profit figure of such an investment.

6.2. Results

The first few months after the implementation energy electric savings by 14.5% has been made (see Figure 6)

The saving made has been proved to be due to optimization of certain devices as energy-efficient lighting and more efficient equipment procurement. Furthermore, office and air-conditioning equipment were better managed in terms of stand-by use. Also, use protocols of heating and air-conditioning equipment have been implemented.

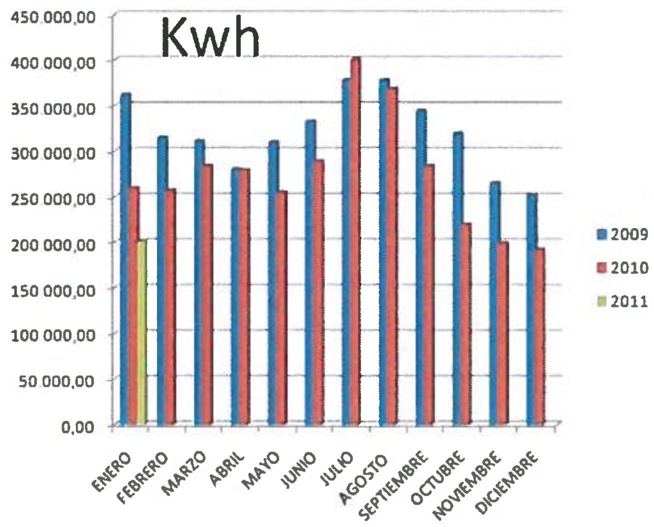

Figure 6. Electricity consumption evolution in Clece Company

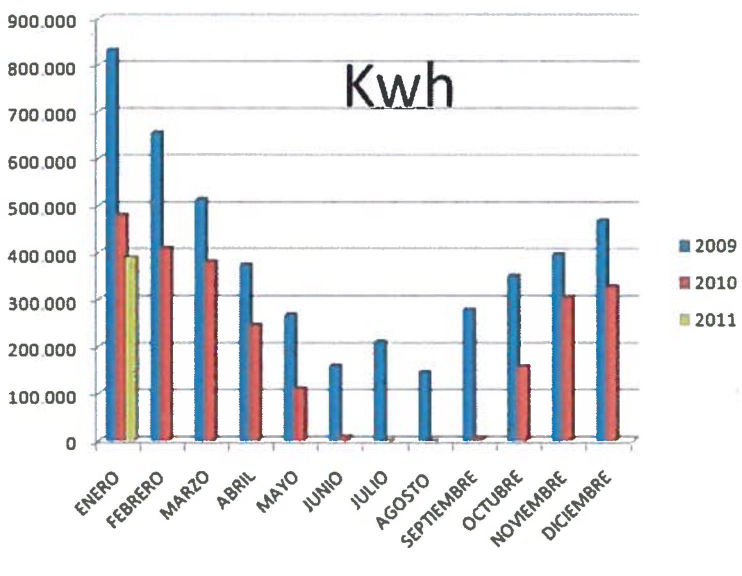

Figure 7. Gas natural consumption evolution in Clece Company

When it comes to saving from the natural gas use (see figure 7), savings has reached 47.7%, derived both by the on/off management and the combustion levels of the natural gas boiler responsible of the domestic hot water production and heat for the building heating.

7. Conclusions

Conclusions are set out here:

1) Implementation of an EnMS according to the International Standard ISO 50001 generally means a fast repayment investment thanks to reductions of consumption resulting from energy management.

2) An EnMS allows you to know systematically all different ways to reduce energy consumption (review of the state of the art) and also how to set measurable goals to the establishment of these measures.

3) It allows the permanent review of the methodology in the consumption data collection of the facility (verification and calibration)

4) The EnMS allows the organization to show externally (clients, providers, shareholders, public opinion) the implementation of an effective system of the energy management and, consequently, their commitment to environmental improvement and competitiveness.

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Energy management with ISO 50001 Standard

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Abstract

This paper intends to highlight the importance of the international standard ISO 50001, Energy Management System - in the role of creating a structure for the implementation of an energy management system that provides continuous improvement of energy performance.

ISO 50001 was built to enable implementation of an energy management system effective, durable and standardized. This is not a temporary program to deal with the energy bill, since energy management should not be linked only to the company's current management or transient situational questions, but should becoming an integral part of company's policy and this way the standard calls.

A standard makes the management is systematic and allows both perpetuate the achievements earned by energy performance improvement activities as the energy management system itself. These achievements are important milestones for the company and can neither weaken as the time goes nor to be lost, returning to the previous values.

Also performing as a strong ally to sustainability issue, energy management is handled in the Standard in technical and managerial aspects, addressing crucial issues in management practices and energy usage and consumption.

When examining the literature and testimony from professionals, the finding is that the shortcomings, difficulties and obstacles related to energy efficiency are common among companies and between countries. Therefore, the Standard, that has as one of its references the standard EN 16001 applied in European countries, was built with the participation of 33 countries, to take international feature and to meet worldwide needs in energy management.

INTRODUCTION

In order to enable organizations to establish systems and processes necessary to improve energy performance, including energy efficiency, use and consumption of energy, it was built the standard "ISO 50001 - Energy Management Systems - Requirements with guidance for use", issued in June of 2011.

Energy Efficiency (EE) in that standard is within a broader context, the energy performance which is as well under an even broader activity, energy management. However EE is the core of the intentions of the Standard, the heart that must be reached to obtain the expected results, reduction of energy costs and reduction of greenhouse gas emissions and other environmental impacts.

EE activities need to be performed with criteria and persistence to succeed. Discontinued initiatives do not solve the problem satisfactorily and is short-lived. Specific actions, individual, temporary or circumstantial cannot retain the gains and maintain a culture of continuous improvement. The ISO 50001 then appears to offer a framework that can host a process to operate the EE actions and retain the savings. Equipments become obsolete, technologies evolve, people retire, good habits can be abandoned, government programs change and even energies may be alternatives. A standardized management system, however, which seeks continuous improvement and is integrated with the company's policy, does not run back. Once implemented, gets gains and incorporates them into the routine of the company, creates and maintains a culture that can expand to efficient use of water and inputs. This culture also tends to expand and influence the entire supply chain.

Another reason why we can welcome the Standard is its strong environmental appeal. In item it is demonstrated its contribution to sustainability issue. In the conclusions we shall show how the

Standard, an international document which brought together a consensus about the contribution of experts from many countries, can be considered an organizer of energy management procedures with a view to EE, and perhaps the most extensive initiative in EE in recent years.

1 - EE as part of a management system

Energy management is a set of administrative procedures that allows the organization to control the use and consumption of energy in a systematic way and thereby improving their performance. Through good management, the organization can ensure that it has the knowledge of how energy is been used and can create a system that continuously detects and implements measures that aim to reduce energy consumption and costs. Energy management systems (EnMS) have become effective, so when organizations want to have a successful job of improving energy efficiency and through this, to reduce energy costs and climatic effects.

The basis for the system of power management of an organization is the mapping and analysis of energy use, commonly known as energy audits or energy diagnosis. In the Standard this concept is defined as "energy review." Identifying where energy use is significant it will also identify where the potential for energy performance improvements are. The goal is to find opportunities that could lead to more efficient use of energy and an increase in the share of renewable energy use.

Most of EE achieved in industry, for example, is accomplished through changes in how the energy is managed. A standard offers the possibility of to deal EE actions within a management system. In short, the management system structures the EE and the Standard structures the management system.

For an organization, the implementation of an energy management system enables significant advantages both in business as environment terms. The Standard deals with EE as a strategic issue, continuously improving the relationship "energy consumed / product or service" and counting emission reductions for the purpose of carbon credits, for example. Its high level of compatibility with the known management standards ISO 9001 and ISO 14001 also allows integration with existing management systems.

As these other management standards, this Standard is based on the structure of the PDCA. PDCA - plan, develop, check and act is a cycle of development that is focused on continuous improvement. It is applied to achieve results within a management system as a tool that assists in organizing the process of implementing improvements, giving a guideline for the conduct of projects and processes.

In the context of energy management, the Standard established their requirements within the PDCA

It is said that with the wide application of the national economic sectors, it is estimated that the Standard could influence up to 60% of energy use in the world.

"This estimate is based on information provided in the section -" World Energy Demand and Economic Outlook ", the International Energy Outlook 2010, published by the Energy Information Agency of the United States. Source: Primer on site or ABNT http://www.iso.org/iso/iso_50001_energy.pdf - english version)

2 - Overcoming barriers

The implementation of EE activities is a task that requires perseverance and criteria. EE projects are often supplanted by those that are related to the core business of the company or by bringing faster return.

The barriers encountered in the task of developing EE activities not usually vary greatly from company to company or even in international dimension, the problems are usually the same for all organizations in all countries.

Once the obstacles of EE activities are known, the Standard should provide the meeting with such obstacles and provide for their transposition, or at least its outline. Will be made following an analysis to assess the ability of the Standard in this role, allowing the actions not only be done, but that the gains are retained. For such an assessment were analyzed some sources of information that we have about these difficulties, described by experts in the field and experience mentioned in literatures. One of these sources is a study in partnership Eletrobras/Procel and the National Confederation of Industries (CNI), which are perhaps the best references for this review, at least for the Brazilian reality, since the data were collected through interviews with people from industry in Brazil. The study is very detailed and many results are stratified by industrial sectors.

The study identified barriers to the implementation of programs or simple actions EE. Part of the conclusion of this study is shown below, transcribed from the Executive Summary-Instruments used in the implementation of EE: (CNI, 2009)

> *“The most common barriers to the rational use of energy exist because the energy consumer has all the information for making rational decisions, costs and benefits of rationalization actions are not equally distributed, tariff structures and prices of non-energy reflect marginal costs and external costs, and the economic point of view, consumers rarely make purely rational decisions.*
>
> *A significant portion of barriers to energy efficiency is behavioral in nature, is the social point of view, or even from the point of view of restrictions imposed by the structure of organizations. Thus, not all mitigating actions can be induced by energy policies and regulatory measures. Moreover, it is evident that organizational changes can be induced by the public. [...]*
>
> *Agencies promoting the rational use of energy and outsourcing actions allow minimizing, and possibly even the elimination of technological risks associated with energy efficiency programs.”*

Below are listed the main barriers identified in the study and the books "Energy, Environment and Development" (Goldemberg, Lucon, 2008) and "Energy Revolution: Policies for a Sustainable Future" (Geller, 2003). Then an analysis of how the Standard can overcome these barriers through the implementation of its requirements.

A)"Lack of information" (CNI, 2009)

It is common not to have the necessary information on the drive where you want to act. Absence of records, tables or spreadsheets hinders the beginning of any planning. It is not considered here only the consumption values, although these are the most important, but there is still need of design information for facilities and equipment involved in the process. Changes in records and design parameters, performance records over the years of operation, all these data are important to set goals. All this associated information is useful for the observation of the relevant variables that influence the energy performance and should be considered in order to know the process.

The Standard favors the solution of this problem in that it enables the creation of a history for EE activities to create a management system and document and record values. Also when determining the involvement of top management, the appointment of a management representative and forming a team to address the energy issues, the company promotes the greatest interest in information related to energy performance.

B) "Technological Risks" (CNI, 2009), "The difficulty in making decisions and risks at the time of transition to a more efficient system" (Goldemberg, Lucon, 2008)

Risks exist, but if there is better planning these are mitigated. EE projects are often planned and executed through a performance contract model that depends on the gains for their remuneration. Therefore, the risks are present inherently demanding that calculations are accurate and feasibility analysis covers many different possibilities.

The contribution which gives Standard to overcome this hurdle is to enable companies to have a management system that goes through a detailed planning. Based on the recurring cycle of PDCA, where "P" represents the planning process, goals and objectives for the plan of action are carefully established with due consideration of the financial, operational, and business condition of the company. With such a planning process with an energy review which has entries trusted with the relevant variables involved and performance records, the chance of having well-structured and reliable outputs is significantly increased, removing risks.

Also another requirement of the Standard, the formation and training of a team to take care of the management, creates a critical mass within the organization, making it more capable in making decisions

C) "Lack of qualified personnel", "behavioral barriers" and "not prioritizing rational use" (CNI, 2009)

The EE is an engineering theme poorly covered in undergraduate courses, although this awareness is increasing. In some cases appears in the curriculum as an optional subject. It is still rare to have professionals who graduate with these characteristics, with specific knowledge and training actions directed towards energy efficient. Firms are therefore forced to have that form the professional.

The Standard describes about competence, training and awareness. Understanding that those working directly in operations that have a significant energy use are directly responsible for the success of the energy performance requires that such personnel be trained to better control this performance. The company must identify the need for training for their critical operations, those of significant energy use, and provide adequate training to them. As for the other employees, everyone should be at least aware of the energy performance and SGE. The company has a system of energy management established should qualify their staff according to specific needs.

D) "High initial costs," (CNI, 2009) and "The decisions by the upfront costs of energy systems, not the costs throughout the life cycle (lack of awareness with respect to losses)" (Goldemberg, Lucon, 2008) and yet on the acquisition: "Many building facilities are constructed, purchased or renovated facilities based on the lowest initial price and not the lowest cost with the desired characteristics as the" best buy ". *“Many businesses and public agencies acquire goods and services and select contractors for construction projects based on the lowest price bid (Loyins and Lovins, 1997). This kind of behavior discourages the inclusion of energy efficiency measures, even though they may offer a quick return. Energy efficiency is highly decentralized and diluted. Millions of consumers and businesses do not make the decisions considering energy efficiency when buying appliances, lighting or vehicles, build new buildings and expand manufacturing capacity. Energy efficiency is often ignored or given little priority when these decisions are made”* (Geller, 2003):

In fact, there is a mistaken opinion in decision to purchase products or services of energy. The initial cost may represent very little in the purchase of equipment or process as compared to the costs of their consumption over their lifetime. The Standard sets out what should be done to assess the lifetime planned or expected to purchase products or services that impact the significant energy use. This review aims to gain knowledge of the consumption potential of the asset acquired. It also establishes that the energy goals and action plans consider the financial condition of the company. As there aren’t set absolute requirements for energy performance, organization is allowed to schedule over time as investment in structural changes that require higher values.

E) "Lack of funding lines" (CNI, 2009) and "The lack of third party financing (and possible renegotiation of contracts) when the consumer does not have own resources to do so and when their own consultancies in efficiency do not take risks" (Goldemberg, Lucon, 2008)

Although the option of financing lines is a matter of market and public policy fleeing the scope of the Standard, their certification can facilitate a process of financial loan. In Brazil some funding lines have emerged today, both in public and in private banks. These financial agents, however, seek to ascertain the suitability of the candidate to credit. If the project is carried out by an ESCO, this likewise, seeks to be sure that the applicant company is pursuing its policy of investment in EE projects. Thus the Standard demonstrates the company's commitment to energy issues, both through its energy policy, signed by top management as the certification obtained by a third party, which certifies its effort to build an action plan with goals and objectives with well-established indicators and baseline resulting from a detailed energy review.

F) "The lack of priority for energy, considered fixed cost for companies focused on other activities" (Goldemberg, Lucon, 2008)

If a company proposes to adopt the Standard, as is evident in his concern address adequately their energy issue. The requirements of the Standard is intended to lead to reduced energy costs that may be being considered fixed until then. And these costs may be decreasing if new EE measures are made.

G) "The lack of credibility of energy consultancy in terms of quality, tracking results, lifting benefit-cost and confidential treatment of information obtained" (Goldemberg, Lucon, 2008)

The Standard proposes that a team is assembled, with people responsible for the effective implementation of the activities of the EnMS and by obtaining improvements in energy performance. A top management representative shall be the leader of this team. All these people shall be competent on the basis of appropriate education, training, skills or experience. With the formation of this team the company is better able to evaluate proposals for consulting and benefit-cost survey, monitor results and meet other needs that arise in the purchase of these services.

Commonly this difficulty in business is due to lack of qualified staff for such activity. Having a team and a detailed plan as proposed by the Standard, it may be possible to perform the activities or coordinate the hiring companies to do so satisfactorily.

H) "The economic and financial overview of short-term, especially in cultures with inflation or high interest rates" (Goldemberg, Lucon, 2008)

By deploying the Standard, the organization sets its goals within the time deemed necessary. Action plans should consider the data obtained in the energy review and baseline, determining the time and the values that are to be achieved which are objectives and energy targets. Therefore, there may be action plans for the short, medium and long term, given the current economic realities and planned.

In general it can be concluded that many of these barriers are outside of the companies and depend on market and on governmental actions. Inside the companies, it cannot be said that the Standard can solve all the problems, but there is no doubt that its implementation allows the organization to conduct EE activities in a systematic and planned way, with great possibilities to succeed. There is a good alignment between the requirements of the Standard and the requirements for energy management since it was developed by professionals who are active in this field and know the difficulties related to.

3 - Points to highlight

This topic develops briefly the most important points that make up the Standard. Many of these points are also recommended in the literature. Only the initiative to implement a permanent management system already provides significant gains and allows the continuity of actions that ensure the sustainability of results.

It also facilitates the acceptance of the fact that its construction has been based on standards already established in other countries, especially in Europe.

There are other strengths that are not detailed in this text, and among them are the ease of integration with other management standards ISO, the inclusion of mandatory baseline and its applicability to all types and sizes of organizations.

3.1 - Reduction of energy costs

When introducing the Standard for entrepreneurs and decision makers is necessary to emphasize that it is not getting new costs for the company, but in a system that can increase profit and improve competitiveness.

Companies need to generate profits to survive. The entrepreneur, when applying its funds in any investment seeks profit. It's good for the entrepreneur talk about reducing greenhouse gas emissions and other environmental impacts because it improves their image and demonstrates its commitment to sustainability. However, sustainability also has its economic pillar. The cost-benefit balance for the implementation of the Standard might be jeopardized if the benefits were only those related to the gain of image against to the burden of establishing a management system, obtaining a certification and keeping it. However, for the entrepreneur who, not without reason, has to guide the business on profitability, the importance should be given to the fact that the implementation of an energy management system provides economic gains. Yet, that the reduction in the energy bill does not only happen in the month of implementation, but in all sequent months, being incorporated into fixed costs and reducing continuously the extent that new investments are made.

Figure 1 shows the reduction of energy costs when an energy management system is established. It is seen how the energy costs decrease successively without increasing again, when continuous measures of improvement are taken. The decrease is gradual and steady, and the first decrease occurs only with simple measures of EE, later with investment in equipment and at last savings become part of the company structure.

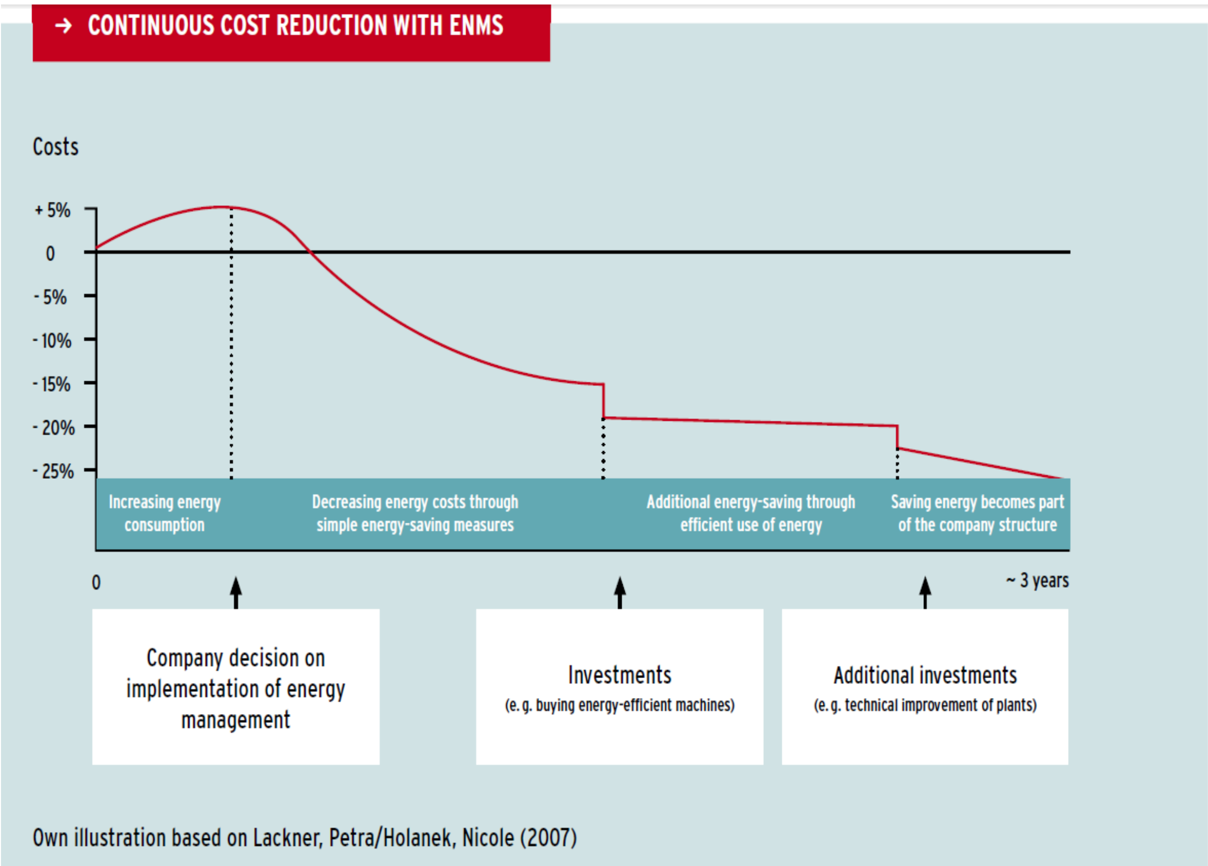

Figure 1: Continuous cost reduction with an Energy Management System

Source: Energy Management Systems in Practice – ISO 50001 - A Guide for Companies and Organizations www.umweltdaten.de/publikationen/fpdf-l/3959.pdf

3.2 - The involvement of top management and the energy policy

As is well known in management standards (ISO 9001 and 14001, for example) involving top management in the header of the management systems is a key factor for the success of the venture. Arguably the lack of this support and commitment, rather than a simple engagement, does not permit any successful implementation and maintenance of these systems.

Top management is what makes the PDCA wheel spins: sets policy, appoints a representative to drive the system, provides resources and incorporates actions that worked. It promotes the dissemination and communication and permeates all units so that all personnel involved becomes aware that a system of energy management works in the company and they must take this into account when performing their activities.

Energy policy is to formalize the support of top management to the management system. . The document expresses the company's motto, its judgment and its position giving a commitment to its official character in its dealings with the energy.

3.3 - Continuous improvement of the energy performance

By analyzing the requirements of this Standard and compare them to the requirements of the management standards ISO 9001 and ISO 14001 it is possible to observe a peculiarity. As if it would concentrate two standards, one of the energy management system and other of management system of energy performance. Similarly, it would be as if ISO 9001, beyond the requirements for the management system of quality, would establish requirements for product improvement and if ISO 14001, beyond the requirements for an environmental management system, would establish requirements to improve environmental performance, something like generate less waste or pollute less.

However it is known that the ISO 9001 setting out the requirements for the Quality Management System (QMS) and an organization that does not mean the quality assurance of the product. Its goal is to provide confidence that a certified supplier may provide consistent and repetitive, products and services according to what was specified.

Similarly, ISO 14001 specifies requirements for an environmental management system that enables an organization to develop and implement a policy and objectives which take into account legal requirements and information about the environmental aspects.

The ISO 50001 in turn, must be concerned with the proposed management system, composed of the elements common to these management standards cited and energy performance, ie, the product of this management. The EnMS in this case is not the end but a means to achieve improved energy performance and this continuously. There are therefore two performances to be managed and improved continuously: the management system itself and the energy one.

The term "continuous improvement" is likewise applied in the three standards referred to in the preceding paragraphs. In all is applied to the management system. In this Standard, however, refers not only to the management system, but also the energy performance, this should also showing continued improvement.

3.4 - The buying process

The process of acquiring goods and services presents important aspects. In procurement of energy services, products and equipment that have significant energy use, providers shall be aware that energy efficiency is part of the evaluation of purchase. It is not enough to have good price, quality and safety parameters, services, products and equipment shall be energy efficient.

To complete this intention and show that EE shall be treated with careful assessment of the future, the criteria for evaluation of purchase shall consider energy consumption and use and energy efficiency during the lifetime of planned or expected for these products, equipment and services. It is known that the initial cost can become negligible when compared to costs of energy of operating a process, plant or equipment, so buying decision shall not be based only on the initial cost of acquisition. Good practice in the literature also recommends this procedure. Finally, these practices also contribute to influence the supply chain supply in their ways of dealing with energy.

3.5 - Communication

The Standard states that the organizations must communicate internally about their energy performance and energy management system. External communication is optional. Good communication is the key to the integration of any working group and has extreme importance for business development. So, the organization shall establish a process by which any employee can make comments or suggestions for improvements.

This attitude, besides making employees aware of a policy adopted by the company, brings awareness of the importance of the work of each to achieve the goals and targets energy. Thus it acknowledges that many good ideas may arise from those who day to day use and consume energy in the company, either through labor as personal use.

This communication, however, is not the same given for those working with energy in an intense way, those whose activities are directly related to significant energy use. For these, there are requirements to determine that there is specific training, education and skills development.

3.6 - The focus in significant energy use

Usually where there is more energy consumption there is more opportunities to improve energy performance. The Standard defines what is significant energy use and over the entire text states that all actions shall fall with priority where there is significant use. Since the energy review that identifies where there is this meaningful use, the indicators, the action plan with goals and objectives, the training of personnel involved, all requirements shall consider that the activities occur where there is significant use of energy.

This definition of priority actions where there is significant energy use is reasonable, as demonstrated in Pareto's Law (the law states that for many phenomena, 80% of the consequences stem from 20% of causes). In the implementation of the Standard are involved planning, procedures, actions, resource investment, and these efforts should be maximized. It means invested where there is greater return.

3.7 - The fulfillment of legal requirements

To obtain a certification organization obviously needs to fulfill the requirements of the Standard. One of these requirements is that all legal requirements and other requirements to which the organization subscribes related to energy must be met. These can be international, national, regional, local or municipal government requirements and other examples can be voluntary agreements with customers, voluntary codes and principles, trade in emissions or public commitments to the unit matrix, etc.

Thus, on the one hand the certification has to be subject to compliance with all these requirements, and on the other hand, the certificate may bear evidence that the organization has fulfilled all its commitments with respect to energy.

4 - The environmental contribution

EE aims at saving energy in order to reduce costs and the exploitation of natural resources. So, should ultimately be seen as a means to achieve sustainability, since it addresses comprehensively economic and environmental aspects, without ignoring the social.

EE is the healthiest way to use energy. According to Wikipedia, "*Energy efficiency and renewable energy are said to be the twin pillars of sustainable energy policy and are high priorities in the sustainable energy hierarchy*". Indeed this partnership goes hand in hand in order to complement this mission, energy sustainability. EE in turn can be considered the cleanest, because their emission levels are precisely zero since nothing was consumed for a generation that did not happened.

It would be reasonable to say, therefore, that this is a Standard for sustainability. Your ultimate goal is composed of three factors two of which relate to environmental preservation. Its purpose is actually to enhance energy performance, but this is not its goal and not an end in itself. It seeks to improve the energy performance as a means of obtaining environmental preservation beyond financial gain due to the reduction of energy costs

In its introduction the Standard defines its purpose and goal:

"The purpose of this International Standard is to enable organizations to establish the systems and processes necessary to improve energy performance, including energy efficiency, use and consumption. Implementation of this International Standard is intended to lead to reductions in greenhouse gas emissions, energy cost and other related environmental impacts through systematic management of energy". As it turns out, it seeks to improve the energy performance as a means of obtaining environmental preservation and financial gain due to the reduction of costs. Figure 2 shows how the purpose of the improvement pass through the energy performance improvements in order to achieve what might be considered the goal. Once this goal is composed of two important actions of environmental preservation, we can say that is a Standard for sustainability.

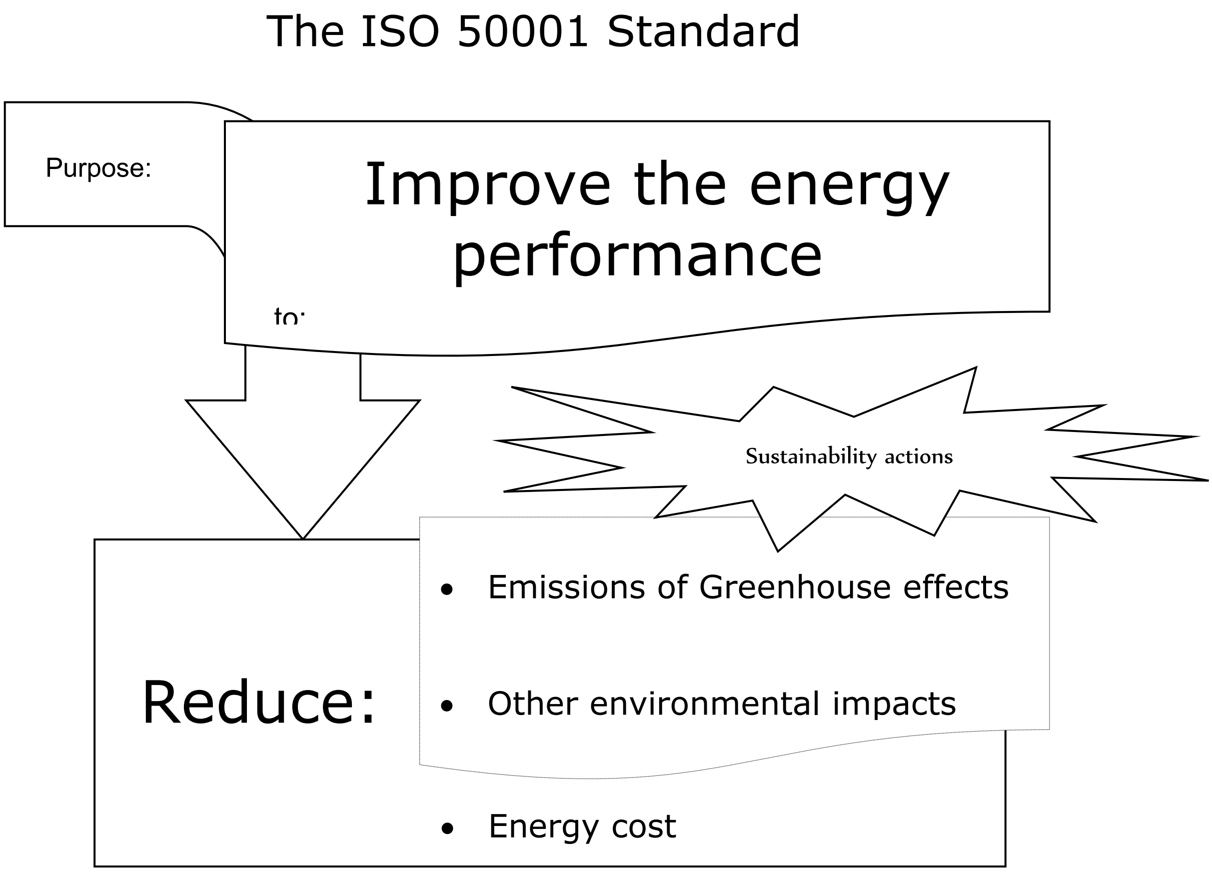

Figure 2: Environmental issues handled in the Standard

Source: Own elaboration

However, one cannot say that the company is been careful by buying or generating clean energy. The normative instrument cannot put impositions that require deeper changes such as the adoption of a cleaner energy matrix as this would affect the organization throughout its structure, engineering, economics and operation. On the other hand, external bodies, government and society in general must understand that the Standard is not a commitment to use clean energy, but to improve the energy performance and prioritize the use of alternative or renewable sources, taking the organization to reductions in emissions of greenhouse gases and other environmental impacts associated.

Should not be ignored that sustainability is inextricably linked to energy use and it sounds like void when an organization establishes goals and sustainability programs without dealing carefully with its energy management issue. Therefore, who has the certification of the Standard demonstrates, at least, that deals to its energy issue in a responsibly way. Finally, an engineering solution with an environmental preservation view.

Thus, environmentalists could have the Standard as an ally. Since society cannot give up the technology to meet the demands that the human need for its well-being, energy becomes essential and the use of fossil fuels is still needed. In this context, the Standard appears to make a contribution to energy to be used rationally, with its best performance.

CONCLUSION

The standard ISO 50001 - "Energy Management Systems - Requirements with guidance for use", may certainly contribute to the wider society, including government, business and citizens, paving the way for sustainable energy. Its progressive implementation can foster effective adoption of energy management systems in Brazil, filling in the gaps presented in this paper, and thereby achieve continual improvement of energy performance that includes permanent actions for energy efficiency.

As energy efficiency activities are quite dependent on human behavior, rules and procedures are necessary. A structure in turn, produces no effects by itself, but allows ordering and operational actions. This is the main function of this Standard, but their goals are more ambitious. It is not unnecessary formalities and requirements imposed by a document, but an useful methodology that using the recurring cycle of PDCA, enables continuous improvement and retention of earnings.

The Standard can bring good results, and even that will not provide all the solutions, introduces a systematic and structured way for organizations to conduct energy management and enhance efficiency. Nevertheless, it is too early to speak conclusively about its effectiveness, the document was recently released and the results could not be further analyzed with a representative database.

Families management standards ISO 9001 and ISO 14001 are very well accepted and disseminated worldwide. It is a highly visible action to adopt these standards for companies that wish to demonstrate suitability. The same is probably to happen with this energy Standard.

In Brazil, the Standard also contributes in forming the framework for compound existing EE activities by Law No. 10,295 which "Provides for the National Policy for Conservation and Rational Use of Energy" known as the Law of Energy Efficiency and programs of government agencies. However, its adoption by enterprises is still timid, yet that prepared this work only four companies had been certified, requiring it to make a broad outreach work highlighting their strengths and their benefits in order to catalyze interest in its implementation.

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The Colombian Strategic Program for Energy Management: Structure, Strategies, Advances, its relation with ISO 50001

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Abstract

This paper presents the structure, strategies and advance of the Colombian Strategic Program for Energy Management called "Programa Estratégico Nacional (PEN) - Sistema de Gestión Integral de la Energía (SGIE): PEN-SGIE". The PEN-SGIE is a joint initiative among government, university and industry and, its aim is to develop and broadcast the Integral Management System of Energy (SGIE) into the industrial sector in Colombia to increase the energy efficiency and reduce emissions. This program is structured in three projects: the first project is SGIE education and training (energy management) and consolidation of academic competences; the second project consists in implementation of SGIE in five regions of Colombia and, the third project is to propose strategies for consolidation and sustainability of the national productive sector.

The program began in 2010 and will end in late 2013. It is developed in five regions of Colombia and their representative cities: Bogotá, Barranquilla, Cali, Medellin and Bucaramanga. This program also works in partnership with the ICONTEC (Instituto Colombiano de Normas Técnicas) for training ISO 50001 internal auditors. The steering group of the PEN-SGIE participates in the Energy Management Colombian Committee ICONTEC 228 and the committee TC 242 ISO 50001.

1. Introduction

Fossil fuels account approximately 80% of global primary energy consumption, and its largest consumers are the transport and the industrial sector. Additionally, the use of fossil fuels (in systems that transform energy) produce CO2 emissions, CO2 is the most important greenhouse gas (GHG) because accounting for about 75% of the total concentrations of all GHG. Furthermore, a study published in 2007 by the IPCC shows that annual CO2 emissions have increased by approximately 80% between 1970 and 2004 [1].

This situation led to the search of alternatives that reduce GHG emissions and control climate change. Thus, several countries have developed actions for the implementation of energy management systems to reduce energetic consumption and emissions. In Colombia, the energy management system, called SGIE, was developed between 2005 and 2007 by Universidad Autónoma de Occidente and Universidad del Atlántico as part of a project founded by the Administrative Department of Science, Technology and Innovation of Colombia - Colciencias -, and the Unidad de Planeacion Minero Energetica (UPME) of Ministry of Mines and Energy in Colombia. The final product of this research was a model for the implementation of SGIE which utilizes stages and steps for its implementation as an integrated management system. The SGIE also provides a system that tracks the results and records the process used [2], [3].

The implementation of Energy Management Systems (EMSs) as a tool for increasing the energy efficiency of industrial processes was successfully applied since 1980 in many countries [4]. In this context, the high potential impact can exert implementation of EMSs in the increase of industrial energy efficiency, the reduction of GHG emissions, and climate change, made the UNIDO agree with ISO Standard the development of International standard on energy management systems. This gave rise to the ISO 50001 EMS, whose development began in 2008 and concluded in 2011. This standard specifies requirements for an EMS from which the organization can develop and implement an energy policy and set objectives, targets and action plans takes into account legal requirements of information related to the efficient use of energy [5]. In Colombia the ICONTEC adopted the ISO50001 Standard through the standard NTC - ISO 50001 "Sistemas de Gestión de la Energía. Requisitos con orientación para su uso" [6].

The PEN-SGIE has been developed from 2010 to 2013, in the framework of a strategy organized by the Colombian government through the Administrative Department of Science, Technology and Innovation of Colombia –Colciencias- and the Unidad de Planeacion Minero Energetica (UPME) of Ministry of Mines and Energy in Colombia to encourage energy efficiency. This strategic program was funded by the Colombian government and 5 energy companies and has been implemented by 15 Colombian universities. Then, this strategy has achieved a voluntary agreement of the sectors representing the State, Company and the University to promote the theme of energy efficiency and develop capabilities in Research-Development-Innovation (R+D+I) in the industrial sector.

This program is structured in three projects. The first project is on SGIE education and training and the academic competences consolidation. The second project consists in SGIE the implementation in the five regions of Colombia. Finally, the third project is to propose strategies for consolidation and sustainability of the national productive sector. The program began in 2010 and ended in late 2013. It is developed in five regions in Colombia whit 5 representative cities: Bogotá, Barranquilla, Cali, Medellin and Bucaramanga. The results of first the project was 600 engineers training in the SGIE methodology, as advanced energy managers and 250 ISO 50001 internal auditors. The second program result was the energy characterization of 65 industrial companies and the implementation of energy management system SGIE in 12 companies in the five regions of Colombia. The third project has been developed yet but this has allowed introduce to 400 business managers in the importance of implementing energy management systems in their companies. The PEN-SGIE program has given great impetus to the development of energy management in Colombia.

2. The Colombian Energy Management System: the SGIE

The Colombian Energy Management System, called SGIE, was developed between 2005 and 2007 by the Universidad Autónoma de Occidente and the Universidad del Atlántico as part of the Project UPME-COLCIENCIAS No. 1116-06-17871 "*Programa de Gestión Integral de la Energía para el Sector Productivo Nacional*". This project was founded by the Administrative Department of Science, Technology and Innovation of Colombia (Colciencias), and the Unidad de Planeacion Minero Energetica (UPME) of Ministry of Mines and Energy of Colombia. As a part of this project, the SGIE was implemented in 2007 with high success in 3 companies [2], [3], [7].

The SGIE utilizes 3 stages and 21 steps for its implementation. The 3 stages are: Strategic Decision, Implementation of the SGIE in the company and Operation of the System, Figure 1.

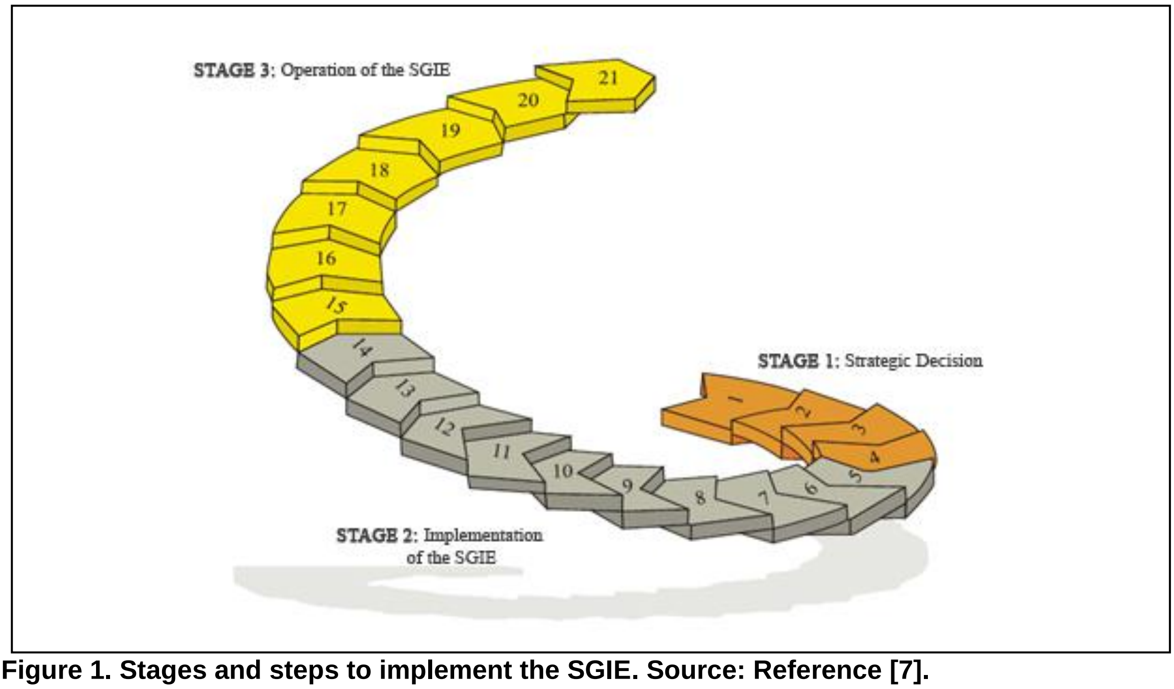

Figure 1. Stages and steps to implement the SGIE. Source: Reference [7].

The first stage, called Strategic Decision, is a preparatory stage in which the current state of energy management of the company is assessed, and the goals and achievable savings activities are defined. The second stage, Implementation of the SGIE, refers to the implementation of the energy management system SGIE within the company, taking into account indicators of management, control variables, definition of a monitoring system, energy assessment and a training plan. The final stage, operation of the SGIE, is about how to operate the system SGIE and make it sustainable, resulting in continuous improvement.

The SGIE was successfully applied in several Colombian companies between 2008 and 2012, achieving significant energy savings in companies where SGIE was implemented. For instance, between 2009 and 2010, the SGIE was applied to a cement company by Universidad Autónoma de Occidente [8], [9]. Between 2009 and 2013 the MGIE was applied in the oil company Ecopetrol by Universidad del Atlántico and Universidad Autónoma de Occidente [10]. Likewise, from 2010 the SGIE was used in the PEN-SGIE program. It is important say that the SGIE meets all the requirements of ISO 50001.

3. Structure of the Colombian Strategic Program for E M: PEN-SGIE

The PEN-SGIE program began in January 2010 and will end in late 2013 and it is a strategy organized by the Colombian government to joint to join efforts between the government, the university and the industry in order to improve the energy efficiency of the industrial sector in Colombia through the implementation of the SGIE.

3.1 PEN-SGIE structure: Member organizations.

There are three levels of participation in the PEN-SGIE: the funders, the executors and the co-executors, Figure 3. The funders are both the government and the private sector. The government is represented by the Administrative Department of Science, Technology and Innovation of Colombia (Colciencias), and the Unidad de Planeacion Minero Energetica (UPME) of Ministry of Mines and Energy of Colombia, while the private sector is represented by 5 energy companies. The executing universities are the entities responsible for the implementation of the program in each region and city (Bogota, Barranquilla, Cali, Medellin and Bucaramanga), while co-executors are the universities that accompany executors in the implementation of the program in each city.

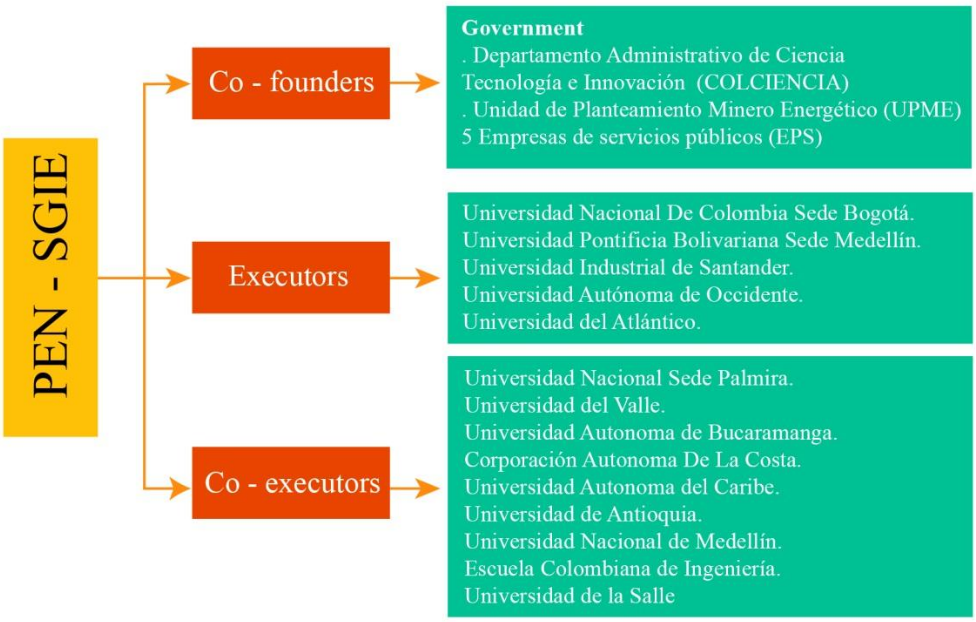

Figure 2. General scheme of the PEN-SGIE members. Source: Reference [11].

3.2 The Strategic Program PEN-SGIE Projects.

This program is structured in three projects. The first project is on education and training in the SGIE methodology of industrial and academic personal, and the academic competences consolidation held at participating universities. The second project consists in make both the energy characterization and the SGIE implementation in industries of the five cities in Colombia. Finally, the third project consists in proposing strategies to consolidate and maintain the energy management in the national productive sector, see Figure 3.

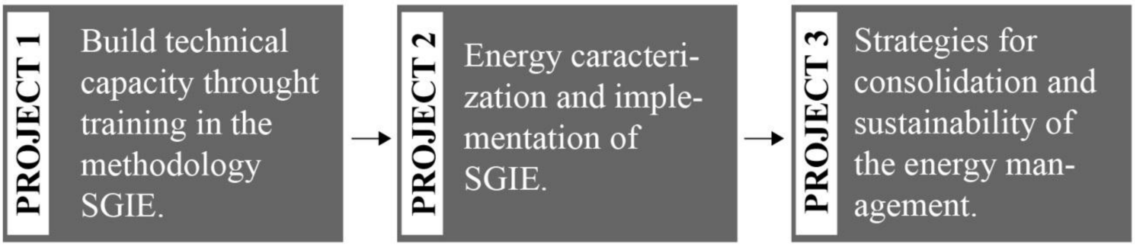

Figure 3. PEN-SGIE Projects. Source: Reference [12].

4. PEN-SGIE Strategies

Studies show that energy efficiency is the most effective alternative to prevent climate change currently. Thus, the IEA study affirms that energy efficiency in organizations can help to reduce 43% of GHG emissions required for climate change control plans to achieve by 2050 [13]. Consequently, actions to increase energy efficiency are urgently required, and experience shows that the application of energy management is an important tool for this purpose

The authors of this paper, are coauthors of the SGIE and belong to different research groups in energy efficiency. They have been working together since 2004 to promote the development of the energy management in Colombia. One of the first steps in the development of the strategy was the proposal for a competency model for improving energy efficiency through energy management [14]. The scheme proposed is shown in Figure 4.

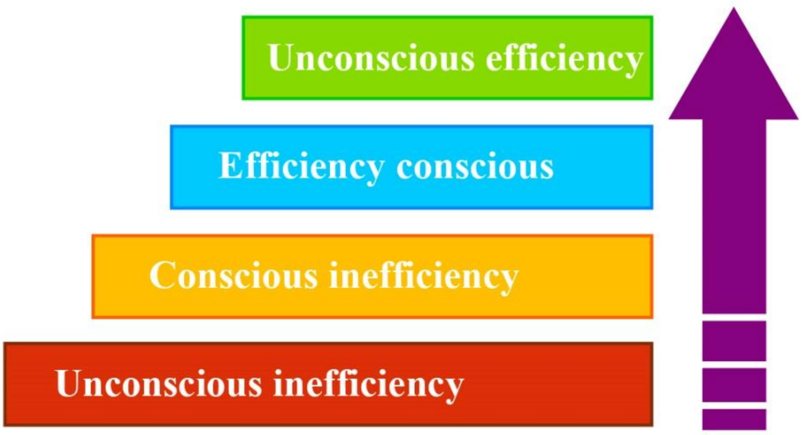

Figure 4. Competence levels in Energy Management. Source: Reference [14].

To move to the second competence level (conscious inefficiency), it is necessary to make the energy characterization of the company in order to know which are the potential energy savings that can be achieved by applying a management system. To move to the third level of competence (conscious efficiency) the company will require implement an EMS. The last level (unconscious efficiency) is reached when the EMS is part of the culture of the company. The authors believe that reaching this level of energy efficiency ISO 50001 should be a mandatory standard in the company.

4.1 Energy Management Training and Qualification Strategies.

This strategy seeks to build a critical mass of qualified personnel in energy management to increase the supply of services in the implementation of SGE, because it will be impossible reach the third level of competence without qualified personnel.

Following this strategy, the objective was to train about 500 people to be able to:

- Make energy characterization in a company according to ISO 50001.

- Develop an energy efficiency program in accordance with the current regulations.

- To implement, control and monitor an energy management program

- Evaluate compliance with ISO 50001.

- Identify the major energy transformation systems, used in enterprises.

For this purpose, a theoretical and practical course of 120 hours was organized. The topics are about energy management and efficient use of energy, where 40% of the course corresponded to energy management issues and ISO 50001. The course was aimed for academics, plant managers, maintenance managers and maintenance and operations personnel.

4.2 Strategies for SGE implementation in companies.

To carry out this strategy, it was required to have experiences that show success stories in companies, also actions to induce business managers in the benefits of implementing an EMS.

As a first step, the plan consisted in doing do the energy characterization in 50 Colombian companies with the aim of meeting the energy saving potential through energy management activities.

The second step of the plan was to implement the EMS called SGIE in 10 companies with the aim of evaluating the benefits of SGIE later on. It also sought to provide opportunity for energetic service companies and personnel trained in the full implementation of a EMS.

Also held seminars where invited national and international experts to spread the benefits of energetic management and recent advances in the world. Additionally, there were seminars to inform the general managers about the positive results of the PEN-SGIE.

4.3 ISO 50001 spreading strategies within companies.

Because the implementation of ISO 50001 standards is a guarantee for EMS implementation in the company, the increasing of energy efficiency and the reduction of GHG, the following activities were conducted:

- This program works in partnership with the ICONTEC (Instituto Colombiano de Normas Técnicas) for training ISO 50001 internal auditors.

- Conferences about ISO 50001 were held, where national and international experts in the ISO50001 talked about the benefits of adopting this standard in enterprises.

- Meetings and workshops were held with general managers in the five cities where the program developed.

- The topics that were discussed at the workshops are: Energy policy and its relationship with EMS, barriers imposed by problems in currently regulating energy, funding mechanisms and incentives for energy management projects, new strategies to consolidating the energy efficiency market, challenges for research, development and innovation for EMS consolidation of in the industry.

- An information system on energy management has been built. This information system will feed with the results of the two previous projects of PEN-SGIE, its completion is expected by the end of 2013. The PEN-SGIE awaits that the Information System will be a tool to help companies to take the decision to implement an EMS or adopt the ISO 50001 standard.

5. Some results of Program PEN-SGIE

Currently, the results of the program PEN-SGIE are:

- 600 people trained in the SGIE methodology, distributed in the 5 main cities of Colombia.
- 300 engineers trained as ISO 50001 internal auditors.
- The energy characterization was done in 65 companies in the 5 cities of Colombia, finding the energy-saving potential through energy management activities and giving them an energy efficiency program in accordance with the current regulations.
- The SGIE was implemented in 12 companies in the 5 Colombia cities. These implementations will be evaluated later on as part of the PEN-SGIE.
- The benefits of implementing an SGIE in companies were introduced to 400 business managers.
- It was verified that the SGIE implementation can give energy savings of 3 to 15% of enterprise total consumption.
- In the participating universities: the research laboratories and training programs in energy efficiency were improved and strengthened.

6. Conclusions

The SGIE is an EMS consistent with the ISO 50001 Energy Management Systems. Thus, the implementation of SGIE will allow the company to meet the standard, efficient manage available energy resources and contribute to environmental conservation. Therefore, the SGIE methodology will be an effective support to implement EMS in Colombia.

The results show that the SGIE implementations produce energy savings between 3% and 15% of consumption through energy management activities, without investing in new machines. This saving means CO2 emissions reduction and contributes to sustainable development.

The personnel trained in the PEN-SGIE will contribute to build a critical mass of specialists in energy management and allow the creation of a market for energy efficiency services in Colombia.

Investments in research and development carried out by the Colombian government have contributed to the development of energy management and leadership of Colombia in this issue.

For an EMS implementation and sustainability in a company, in accord to ISO 50001, it requires the commitment of the company's top management to achieve institutional changes for the efficient use of the energy. Therefore it is important that the company adopts ISO 50001.

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Implementing Standardized Energy Management Systems, compatible with ISO 50001: case study of UNIDO's EnMS Program in Latin America

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Abstract

The purpose of ISO 50001 Energy management systems (EnMS) standard is to enable organizations establishing systems and processes to improve energy performance. This standard is expected to achieve long-term increases in energy efficiency (20% or more) in several sectors and to reduce greenhouse gas (GHG) emissions worldwide. The United Nations Industrial Development Organization (UNIDO) has developed a program for the promotion of EnMS in 12 developing countries to support national institutions in adopting an integrated approach for industrial energy efficiency measures, including the adoption of standards. Despite the increasing use of standardized EnMS (mainly in Europe) and the certified organizations in several countries, the number is still very timid.

The paper first presents a review of the literature which establishes the major reasons for, and the benefits of, the introduction of ISO 50001. It also details the principles of the UNIDO's program for implementation of EnMS. The purpose of this empirical study is to examine the various barriers and misconceptions that impede ISO 50001 implementation in the industrial sectors, using a sample of organizations participating of UNIDO's EnMS program in Ecuador. The study suggests the need to formulate local strategies to meet the emerging ISO requirements which will enable industry organizations to achieve benefits by maximizing the use of its energy sources and assets, thus reducing energy cost and consumption. This study contributes to the knowledge in the area of EnMS, promoting the development of policies for increasing the energy efficiency of systems (including motors) and their uptake in industry. The findings of this work are limited to the sample surveyed and its geographical limits, however, they draw important conclusions for policy-makers around world.

Introduction

Energy is critical to the operation of enterprises or organization and can represent a significant operational, whatever their economic or activity sector is. An idea can be gained by considering the use of energy through the supply chain of a business, from raw materials through to recycling. In addition to the economic costs of energy to an enterprise, energy has associated environmental and societal costs by depleting resources and contributing to climate change. Improved energy performance can provide rapid benefits for an enterprise by maximizing the use of its energy sources and energy-related assets, thus reducing both energy cost and consumption [1].

The ISO 50001 Energy Management System is based on the management system model that is already understood and implemented by enterprises worldwide. It can make a positive difference for enterprises of all types, while supporting longer term efforts for improved energy technologies and providing strategies to increase energy efficiency, reduce costs and improve energy performance. The standard is intended to accomplish the following:

- Assist organizations in making better use of their existing energy consuming assets;
- Create transparency and facilitate communication on the management of energy resources;
- Promote energy management best practices and reinforce good energy management behaviors;
- Assist facilities in evaluating and prioritizing the implementation of new energy-efficient technologies;
- Provide a framework for promoting energy efficiency throughout the supply chain;
- Facilitate energy management improvements for greenhouse gas emission reduction projects;
- Allow integration with other organizational management systems such as environmental, and health and safety.

ISO 50001 is based on the ISO management system model familiar to more than a million organizations worldwide who implement standards such as ISO 9001 (quality management), ISO 14001 (environmental management), ISO 22000 (food safety), ISO/IEC 27001 (information security). In particular, ISO 50001 follows the Plan-Do-Check-Act process for continual improvement of the energy management system and the energy performance. Figure 1 presents an EnMS model.

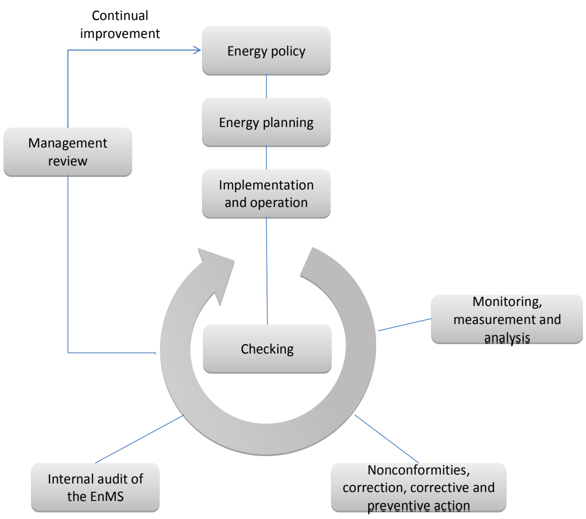

Figure 1 – Energy Management Systems Model for ISO 50001

These characteristics enable organizations to integrate energy management with their overall efforts to improve quality, environmental management and other challenges addressed by their management systems. ISO 50001 provides a framework of requirements enabling organizations to:

- Develop a policy for more efficient use of energy;
- Fix targets and objectives to meet the policy;
- Use data to better understand and make decisions concerning energy use, efficiency and consumption;
- Measure the energy results and review the effectiveness of the policy;
- Continually improve energy management and energy performance.

ISO 50001 does not fix targets for improving energy performance [2]. Target setting is up to the user organization, or to regulatory authorities. This means than any organization, regardless of its current mastery of energy management, can implement ISO 50001 to establish a baseline and then improve on this at a rhythm appropriate to its context and capacities.

Since its introduction in 2011, the ISO 50001 standards have received wide acceptance; the number of organizations certified has grown. According to a survey [3] conducted by ISO in 2011, the total number of certifications at the end of 2011 exceeded 450. Table (1) presents the worldwide total of ISO 50001:2011 certification and other management systems.

Table 1 - Survey of Management Systems Standards Certification - 2011

Name of standard	Number of certificates in 2011	Number of certificates in 2010	Evolution	Evolution in %
ISO 9001	1.111.698	1.118.510	-6.812	-1%
ISO 14001	267.457	251.548	15.909	6%
ISO 50001	461	0	-	-
ISO/IEC 27001	17.509	15.626	1.883	12%
ISO 22000	19.980	18.580	1.400	8%
ISO/TS 16949	47.512	43.946	3.566	8%
ISO 13485	20.034	18.834	1.200	6%
TOTAL	1.484.651	1.467.044	17.607	1%

The number of ISO certificates in Latin America was 0 in 2011. Based on this facts and due to lack of research information about this field in Latin America, there is a strong need exists to conduct this proposed study to comprehend and explain the implementation issues and misconceptions about standardizes management systems at regional level. The purpose of this empirical study is to investigate the phenomenon pilot program to facilitate the adoption of standardized EnMS, and to report results to policy-makers in the Latin America organizations. It is expected that the findings of this work will help the non-ISO certified organization to consider investing resources in the adoption and the deployment of EnMS which will, finally, lead to certification under the ISO 50001 standard. With respect to theoretical contribution, this work shall augment the knowledge in the domain of energy management within the context of developing countries with particular focus on Latin America organizations. Although this study has a limited scope, it is the first one of its kind, by addressing energy management adoption in Latin America.

Benefits of the adoption of standardized energy management systems

ISO 50001 standard background

The United Nations Industrial Development Organization (UNIDO) initiated a dialogue on the development of an international energy management system standard at an expert group meeting (EGM) on industrial system optimization and energy management standards in industry, in March 2007. The meeting included representation from developing countries, the ISO Central Secretariat, and countries using national energy management standards. As a result, a request was submitted to the ISO Central Secretariat to work on an international energy management standard.

As of March 2007, four countries Denmark, Ireland, Sweden and United States had national energy management standards. In addition, China had a draft standard, the Netherlands had an energy management specification, and the European Committee for Standardization (CEN) and the

European Committee for Electrotechnical Standardization (CENELEC) had formed a task force to develop a common standard for the European Union. As of June 2008, Republic of Korea, Spain and Thailand completed work on a draft national standards; Brazil and South Africa initiated this process.

In view of international interest in the subject and its potential impact on industrial energy efficiency, UNIDO launched a new initiative to support the development of an international ISO energy management standard in July 2007. As part of the initiative, a regional workshop was held in Thailand, in September 2007, and an international working group meeting was held in China, in April 2008 discussing about concept of energy management.

In February 2008, the Technical Management Board of ISO approved the establishment of a new project committee, PC 242 – Energy Management (changed to technical committee TC242 in 2011), to develop the new ISO management system standard for energy, ISO 50001. The Secretariat of ISO/TC 242 is shared by the American National Standards Institute (ANSI), which chairs ISO/TC 242, and the Brazilian Association for Standardization (ABNT). The Standardization Administration of China (SAC) provides the Vice-Chairman. As of December 2008, UNIDO workshops and awareness-raising initiatives had been held for more than 30 developing countries and emerging economies, with many of them currently members of ISO TC 242.

Benefits of ISO 50001 implementation

The ISO 50001 was launched in 2011 [4]. Energy management seeks to apply to energy use the same culture of continual improvement that has been successfully used by organizations to improve quality, environmental and safety practices. An energy management standard can influence how energy is managed in an organization facility, thus realizing reductions in the energy use through changes in operational practices, as well creating a favorable environment for adoption of more capital-intensive energy-efficiency measures and technologies.

An energy management standard requires a facility to develop an energy management plan. In organizations without a plan in place, opportunities for improvement may be known but may not be promoted or implemented because energy management is not part of the organizational culture and the normal planning process. This failure to plan reinforces traditional barriers, which include lack of communication among sites, poor understanding of how to create support for an energy efficiency project, limited finances and financial data, poor accountability for measures and perceived risk from changing the status quo. In addition, business metrics such as energy performance indicators that relate energy use to production output are typically not utilized, thus making it difficult to document improvements in energy performance. Companies who have voluntarily adopted an energy management plan have achieved major energy intensity improvements [4]. Some examples include:

- Dow Chemical achieved 22% improvement ($4B savings) between 1994 and 2005, and is now seeking another 25% from 2005 to 2015;
- United Technologies Corporation reduced global GHG emissions by 46% per revenue dollar from 2001 to 2006,: an additional 12% reduction is sought from 2006 to 2010;
- Toyota's North American (NA) Energy Management Organization has reduced energy use per unit by 23% since 2002; company-wide energy efficiency improvements have saved $9.2 million in NA since 1999;
- Interface FLOR, a carpet manufacturer, is a world leader in sustainable manufacturing and has reduced its energy intensity for manufactured carpet by 35% from 1994 to 2004 through a systematic continual improvement program in energy efficiency.

Evidence of ISO 50001 implementation benefits were presented by ISO when discussing about five early adopters of the standard [5]. The organizations are power and thermal management solutions enterprises. They report numerous early gains from implementing ISO 50001, including significant reductions in power consumption, carbon emissions and energy costs, and benefits to manufacturing plants, communities and the environment. The following quotes are taken from the article:

- Delta Electronics (China) have reduced power consumption by 10.51 million kWh in 2011 as compared to the same period in 2010. This is equivalent to a reduction of 10.2 thousand tons of carbon emissions and a saving of CNY 8 million.

- Schneider Electric (France) is implementing ISO 50001 in all facilities around the world, integrating with other ISO standards such as ISO 14001. About 90% of facilities are ISO 14001 certified.
- Dahanu Power Station (India) has conducted a series of targeted investments since March 2010 which, aided by the organization's new ISO 50001 based energy management system, are expected to yield annual savings of about INR 96.4 million form raised energy efficiency and management.
- AU Optronics (Taiwan) was expected to help achieve 10% energy conservation at the plan in 2011, save an estimated 55 million kWh of electricity and reduce carbon emissions by 35.000 tons.
- Municipality of Bad Eisenkappel (Austria) expected to decrease by nearly 25% whit the main savings achieved by updating the waste plant and reducing energy consumption by 86.000 kWh, equivalent to EUR 16.000.

ISO identifies energy management as one of its the top five priorities based on its enormous potential to save energy, increase profitability, and reduce greenhouse gas (GHG) emissions worldwide [4].

The challenge in implementing EnMS

A successful program in energy management begins with a strong commitment to continual improvement of energy performance, related to energy use, efficiency and consumption. A first step once the organizational structure (management representative and cross-divisional/functional team) has been established involves assessing the major energy uses in the facility to develop a baseline of energy use and set targets for improvement. The selection of energy performance indicators and objectives help to shape the development and implementation of an action plan. The effectiveness of an action plan depends on the involvement of personnel throughout the organization, who need to be aware of energy use and performance objectives. Staff and those who work on behalf of the organization need training in both skills and day-to-day practices to improve energy performance. The results should be regularly evaluated and communicated to all personnel, recognizing high achievement. The emergence over the past decade of better integrated and more robust control systems can play an important role in energy management and in reducing energy consumption.

Experience in countries with energy management standards has shown that the appropriate application of these standards requires significant training and skill. Implementation of an energy management standard within an organization requires a change in existing institutional practices toward energy, a process that may benefit from technical assistance from experts outside the organization. There is a need to build not only internal capacity within the organizations seeking to apply the standard, but also external capacity from knowledgeable experts to help establish an effective implementation structure.

Development of an internationally recognized energy management standard would be particularly helpful to developing countries and economies in transition that lack national EnMS as well as policies and mechanisms for improved efficiency in the industrial sector. Experience with environmental management standards shows that ISO standards have provided stimulus and a framework for development of national environmental standards, regulations and laws. The promotion of and support for the adoption and implementation of standardized energy management systems, compatible with ISO 50001**,** is a core element of UNIDO's program to strengthen policy- making and technical capacities of developing countries and emerging economies to improve energy efficiency in industry.

UNIDO's program in Ecuador to facilitate the implementation of Energy Management Systems

Ecuadorian context

According to reports by the Latin American Energy Organization (OLADE), the energy consumption in Ecuador in 2011 was of 81,389 Million barrels of oil equivalent (Mboe). The annual electricity consumption was of 15,248 GWh in 2011 and the sector with highest consumption were residential with 29.9% and industrial with 26.8% (CONELEC) [6]. The energy intensity in Ecuador is higher than in other Latin American countries; in 2009 it was 3.23 barrels of oil equivalent (boe) per USD 1,000, in two to three times higher than in Argentina (0.94 boe/USD 1000), Brazil (1.65) or Colombia (1.32).

The total consumption of fuels by the industry sector in 2009 was 233.5 million gallons of diesel (11.10 million GJ). Electricity demand in industry was of 4,798 GWh (6.8% of national consumption) and the average power price for the industrial sector was USD 0.0487 per kWh in 2011. The energy consumption resulted in greenhouse gas emissions of 7,009 KtCO2e in 2011.

Around 68% of industrial activity is located in only two provinces, namely Guayas (with capital Guayaquil, 35%) and Pichincha (with capital Quito, 33%) with minor activity in Manabí (9%) and Azuay (5%).SMEs (known as *PyMES - pequeñas y medianas empresas* in Ecuador) provide 15% of the manufacturing sector contribution to the GDP in Ecuador, but encompass 86% of the industrial companies (13% are characterized as large companies), consisting of medium enterprises (20%), small enterprises (43%) and micro industries (24%).

In reality, energy efficiency has always been a low priority of the industry due to relative low energy prices (supported by subsidies), and preference for second-hand equipment. An local analysis concluded that the avoided electricity costs realized from the investment in energy efficiency and renewable energy technologies by 1% of the country GDP, amounting to over USD 5 billion by 2025, could contribute significantly to poverty alleviation, job creation and to the improvement of social services [7]. The Government of Ecuador is committed to increase energy efficiency (EE) in the country. Given this culture of lack of regard for energy conservation, there exist numerous related barriers that stand in the way of financing and implementing energy efficiency options.

An overview of these barriers, related to industrial energy management, are the following:

- Energy efficiency is not a core interest for most industries and company strategies tend to focus on output growth rather than cost management. Most industries have a budgetary disconnect between capital projects (equipment purchases) and operating expenses (energy and maintenance), therefore, purchasing decisions are based normally on initial capital investment consideration, rather than on operating costs;
- Technology aims to support production, and production practices can have a significant impact on operational efficiency. These practices, however, are usually outside the control of the facility engineers;
- Industries lacks a culture of energy and resource management.

Other barriers can be related to technical knowledge and dissemination, as following:

- Facility engineers tend to focus on components, not on systems. When processes and equipment change over time, inefficiencies in term of energy use compound and reoccur. Even were systems optimization is available, knowledge resides with the individual who has been trained and is often not institutionalized;
- SMEs are not familiar with system optimization and energy efficient;

UNIDO’s project seeks to address some of the existing barriers to industrial energy efficiency in the Ecuadorian industrial sector, to deliver measurable results and to make an impact on how Ecuadorian industries manage energy through an integrated approach that combines capacity building and technical assistance interventions at the policy and energy efficiency project level. Primary target groups of the project are industrial decision-makers (managers), engineers, vendors and other professionals and industrial energy efficiency (IEE) policy-making and/or implementing institutions. With regard to social beneficiaries, the project includes the improvement of industrial competitiveness and the development of national technical capabilities. The main aspect for the improvement of technological knowledge will take place during the training and accreditation of 75 national experts (25 in energy management and 50 in systems optimization).

Latin America EnMS program

The proposed project in Ecuador focuses on building national capacities in two technical fields: Systems Optimization and Energy Management Systems.

The reason to integrate these two ethnical measures is related to the benefits archived, by addressing the software (managerial) and hardware (equipment replacement) actions. The presence of energy-efficient components in industrial systems, while important, provides no assurance that energy savings will be attained if the system of which the components are part is not properly designed and operated. Evidence from implemented national and international programs shows that, while efficient components may bring about gains in the range of 2 to 5 percent, systems optimization measures can attain average efficiency gains of 20 to 30 percent with a payback period of less than 2 years. The implementation of system optimization measures requires specific technical knowledge and consistent monitoring and remedy action by the industry.

The program focuses on four main areas of actions:

- Analysis of industrial EE institutional and regulatory arrangements and development of tools to facilitate EE measures adoption
- National program to implement ISO -compatible energy management standard
- Capacity building for personnel involved in EE from the public and private sectors in the areas of energy management and system optimization and energy efficiency promotion. UNIDO's has developed targeted programs to train different stakeholders at different levels or tiers of training for both technical fields. National programs include an awareness raising training for enterprise manager, an introductory training fro plant staff, technical training for equipment vendors and extensive expert for national training
- Demonstrated and measured energy savings in industrial entities through application of system assessment techniques by trained experts, leveraging additional energy savings as more industrial facilities will seek the implementation of systems optimization

The adoption and promotion of national energy management standards, along with capacity building of enterprises and institutions intends to be effective in transforming the national industrial energy efficiency market condition. Experiences in national and international Industrial Energy Efficiency projects have shown that maintaining energy efficient practices is a challenge in industry: most optimized systems lose their initial efficiency gains over time due to personnel and production changes.

The research problem

The first review of companies who have voluntarily adopted an energy management and expected results from early adopters of the standard provides opinions about the benefits in adopting and implementing standardized EnMS. The literature revision presents some barriers in adopting and working with the concept of energy efficiency, mainly in industry sectors. Although the developing countries have attempted, for long time, to implement other management systems (ISO 9001, ISO 14001) to compete in domestic and international markets, we observed that the ISO 50001 implementation in developing countries is still very limited. The implementation issues standardized EnMS has been explored in some developed countries, but no research work has been conducted on Latin America in this field.

The importance of combing technical and managerial measures

Implementation activities of EnMS Program in Ecuador

Since May 2012, the project has focused on the development of key activities, sustained in:

- User training for national Industry staff through introductory (user training) workshops;
- Awareness seminar for top management;
- Expert training for Industrial companies in order to promote implementation of EnMS.

The user training has been designed with the aim of raising awareness of the energy efficiency benefits. This training aims to present the global reality on the energy issues, the sources and their energy trends for reducing consumption and environmental impacts, including a complete revision of the standardized EnMS, implications, requirements, results and experiences of implementation in other countries.

Four user training rounds have been implemented to date at national level in relevant locations in which industry is concentrated: two in Quito, one in Guayaquil and other in Cuenca. More than 200 experts and private consultants attended the meetings.

The awareness workshops for managers and executives of the industries were made, one in each city, Quito, Guayaquil and Cuenca. Almost 150 people have been registered representing 85 industries nationwide. These events have allowed to define the interest of industrial companies that currently implement the EnMS.

The development of training of experts is being accomplished through the following activities:

- Selecting 25 national technical professionals from industrial plants and consultants, which are being trained as national EnMS (ISO 50001) experts;
- Identifying related industries in order to facilitate the training of the 25 technicians in implementing ISO 50001. These industries are from the following sectors: metals, textiles, finishes and home accessories, automotive accessories, cosmetics, timber and food. Figure 1 shows the distribution of these companies.
- Conducting the “train-the trainers “program with theoretical and practical training, undertaken international experts selected by UNIDO.

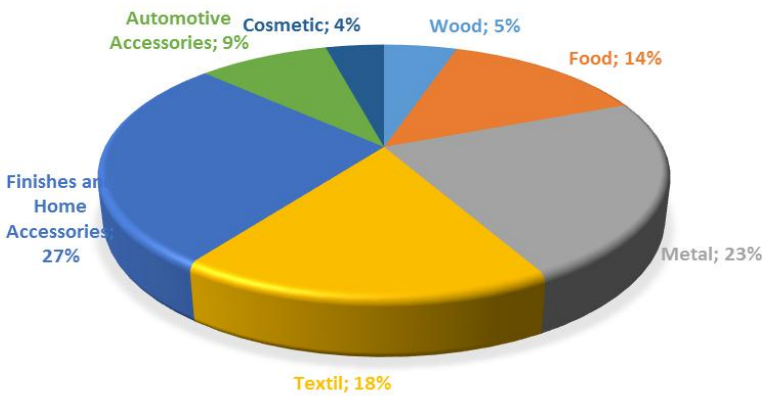

Figure 1 – Distribution of industrial sub sectors in the industries implementing EnMS

Implementation activities of System Optimization Program in Ecuador

Electric motors are responsible for 73% of all electricity consumed in the industry. This consumption was 22% distributed in pumping systems, 18% in compression systems and 16% related to ventilation systems. These are precisely the objectives in the field of System Optimization training program in Ecuador.

In Ecuador, the initial step to build national technical capacities have been taken forward.

The experience gained so far in the early stage of the Motor System Optimization Programme implemented by UNIDO in Ecuador, highlighted the importance of combining both technical and managerial measures to achieve greater energy, carbon and economic savings.

Motor systems are often very complex systems and its efficiency depends on various factors which include: motor efficiency; motor controls (such as soft-starters and variable speed drives); the distribution network that feeds the motor (attention to power factor and distribution losses); power supply quality (high-quality power supply), with careful attention to harmonics; system oversizing (proper equipment sizing); the transmission and mechanical components (optimized transmission systems); maintenance practices (careful maintenance of the entire drive power system) and the match between the load and the motor (good load management practice). Figure 2 present a general motor system highlighting the relevant components which may influence the system performance and efficiency.

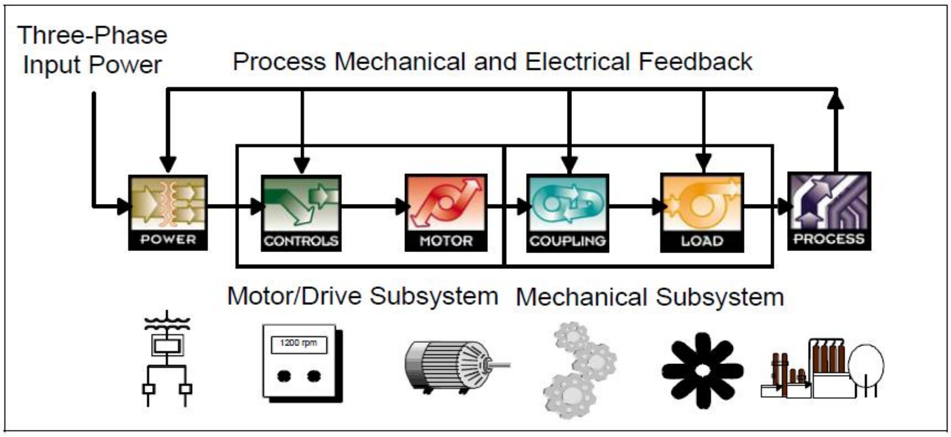

Figure 2 – General configuration of a motor system

It must be emphasized that the design of the process itself can also influence to a large extent the global efficiency (units produced/kWh). However, technical solutions alone are not able to realize the full savings potential available. An organization that has a right approach towards energy-efficiency, both by having the technical expertise and by having an energy management system that works, is in a much better position to implement a successful energy saving campaign, and the created synergies potentiate the obtained environmental and economic saving. Furthermore, the combination between managerial and technical solutions increases the reliability of the equipment and processes, reducing maintenance and costly plant downtime.

Therefore, technical solutions should not be considered as circumstantial measures but included in a broader management plan that takes into account operational and maintenance practices, also in the long-term. Talking to other staff, such as maintenance and production personnel, who are also familiar with the items of the plant, is a very good way of identifying other benefits. Additionally, by making them to feel involved and being able to identify the different type of benefits, they will be more likely to support actions towards energy-efficiency.

The integration between the production and maintenance teams, and the energy manager is key to optimizing resources and achieving sustainable, long term goals. For example, a list of all key equipment should be at the heart of a maintenance management program, and is an excellent basis for the development of an energy management program; routine checks on equipment such as checking for leaks, verifying lubrication, monitoring bearing vibration, temperatures/pressures etc. are core elements of both maintenance and energy saving campaigns. The implication is that the person doing these measurements should be aware of both reasons for undertaking them, and where appropriate modify the details of the procedure to maximize all energy saving and maintenance benefits; on equipment that runs for weeks or months between scheduled stoppages, the cost in lost production means that shutting down plant to fit and commission energy saving equipment can only be done if planned ahead as part of a scheduled shutdown; expansion or contraction of plant output can quickly lead to a mismatch between the provision of site services and the actual demand, and is a common cause of inefficiency. A better match of those services minimizes the costs of maintenance both through better use of existing plant resources, and through the avoided costs of plant maintenance to supply capacity that is no longer needed. The periodic re-appraisal of what site services are actually needed should therefore be part of maintenance and energy saving best practice.

The support of the plant management is also of fundamental importance, particularly of the energy management plan which will often determine its success or failure. Therefore, the clear definition of goals, assignments, training needs; an assessment of the costs and benefits (energy savings, demand reduction, productivity gains) associated with conservation opportunities; the implementation of time-lines, and a description of feedback and reporting mechanisms is essential to secure the management commitment to energy-efficiency which will, in turn, help secure the involvement of all plant staff.

Research design and data collection

The present study is similar to other studies conducted in foreign several countries, mainly related to implementing management systems. Although the similarity is found in the objective of determining the important factors which impede the adoption and implementation of management systems and other related activities. The difference between this study and the prior research work reviewed is found in investigating the misconceptions about ISO standards which could reveal some possible indicators for factors behind the adoption of ISO 50001. No attempt is made here to test any hypothesis or to verify any relationships between variables. Our interest in this work is pure explorative. To achieve the objective of this research, an instrument was designed to obtain evidence about the barriers and the misconceptions of adopting ISO 50001. The instrument was derived from the research literature and was adjusted to add more clarity to the questions. The research instrument included a data collection during user and experts training activities. The direct interviews with experts during training were intended to investigate the barriers of ISO 50001 adoption, while the analyses of EnMS implementation procedures were concerned with exploring the misconceptions about ISO 50001. The group analyses comprises the observations from the 25 national trainees who aspire to become experts participating of the EnMS program in Ecuador.

Barriers which prevent the industry from becoming more energy efficient

Barriers to ISO 50001 implementation

According to research performed the most important barriers to ISO 50001 implementation are:

- Absence or difficult of measuring gains;
- Absence of government incentives;
- Insufficient knowledge about energy systems and programs;
- Employee resistance;
- Lack of human resources;
- Absence or difficult of consulting energy data;
- Difficulty of performing energy measurements;
- Difficulty of defining energy baselines and performance indicators;
- Financial resources.

The major quoted factors that impedes the standardized EnMS implementation are absence or difficult of measuring gains and absence of government incentives. In fact, all of barriers are strong related. Insufficient knowledge about energy systems, absence of energy data and difficult of performing energy measurements contribute to define a clear figure for energy performance target. Also the difficulty of defining energy baselines and energy performance indicators can influence any construction of energy performance situation.

Lack of staff dedicated to managing energy performance is common in industrial organizations. The implementation of a standardized EnMS can affect the whole organization, and if technical management is able to shows total dedication to energy programs, it leads to an atmosphere of continuous improvement. If not, it is almost impossible to implement an EnMS. Top management must be convinced that the implementation shall enable the organization to obtain advantages like energy savings, improvement in efficiency or reduction in energy consumption. It should understand that an EnMS shall improve the business efficiency by optimizing energy systems improving energy performance of processes. Some suggested actions that may be taken by organization are: participating in energy improvement projects creating an atmosphere to encourage people participation in energy management initiatives. The employee resistance is always founded in energy management research. The employee resistance may come from the fear caused by a lack of information about standardized EnMS requirements, and from the belief that it will be difficult to change the mindset of employee regarding energy programs. Therefore, employee understanding and support to standardized EnMS are critical to its success. Another important barrier reported by the sample surveyed is the difficulty of performing energy measurement. Measurement procedures are as a mean of improvement energy performance and to confirm compliance with other requirements of the standards. Lack of equipment is attributed to lack of understanding the importance of monitoring energy aspects inside processes. Funds are needed to institute training programs, provide quality resources, payments for external consultants, payment for auditors, and payment for certification. With respect to human resources, the experts thought that lack of human resources was essential factor acting against the implementation of ISO 50001. A range of issues may comprise this factor such as: inadequate level of education, misinterpretation of the standards, low worker moral, and high worker turnover.

Misconceptions about standardized EnMS

Since the adoption of standardized EnMS is voluntary in most important countries, and the limited dissemination of the ISO standard to date, it is expected that many misconception exist about such systems. The most important misconceptions are:

- Standardized EnMS requires to measurement of all equipment and processes of organization;
- Standardized EnMS requires great financial resources in order to control energy processes;
- Standardized EnMS define values for energy performance to be attended;
- All activities of organization must be certified for ISO 50001;
- Standardized EnMS is not simple in mixing with existent management systems;
- The certificate is awarded to industrial sector only;
- Standardized EnMS decreases productivity;
- ISO 50001 certification requires a long time.

The first and second misconception delineated by respondents was related to the great funds required for equipment and/or control of energy processes. It is true that implementation can requires financial resources, but these resources are not inhibitive. There are cases where no investments are necessary in implementation activities. A significant part of sample believe that EnMS establish values for energy performance. The intention of Standardized EnMS, particularly ISO 50001, is to lead the organization in defining own objectives and targets, according to own intention. Part of the respondents believed that all the levels in the organization must be certified. This belief comes from little education on Management Systems. In fact, the whole organization, or one of its departments, or one process can be qualified to obtain the ISO 50001 certification. This is one important misconception of why organizations hesitate in taking the initiative to qualify for the Standardized EnMS. The ISO 50001 was designed to be align with other management systems in order to promote adoption in case of existent system in the organization. Many respondents agreed that ISO 50001 is awarded to private organizations only. Actually, any organization (manufacturing or service) public, private, mixed, for profit, and non-profit can be ISO certified upon compliance with the requirements. In addition, part of the sample surveyed believed that ISO 50001 results in decreased productivity. Many companies that have implemented an energy management system reported cost savings through improved process, effectiveness, and efficiency. Standardized EnMS like ISO 50001 can lead to improved management and operational processes related to energy, resulting in less waste in energy, increased energy efficiency, and cost saving. The last misconception about ISO 50001 is that the certification process takes long time. Depending on the size of the organization, the nature of its operations, and the maturity of its energy system, the certification process may take between 6 months to two years.

Conclusions and recommendations

Interested countries in implementing EnMS, mainly developing countries, are facing a shortage of formal researches to reflect the barriers and misconceptions about Standardized EnMS. To enable the Ecuador's organizations in competing locally and abroad, the Government of Ecuador are encouraging local organizations to adopt EnMS as a way to achieve efficiency in using energy, but so far none organizations are ISO 50001 certified.

The observations made are qualitative, due to the fact that the adoption of ISO 50001 in the case study is still ongoing. Further investigations shall be made when the implementation of the national program is completed and evaluated. This explorative study has attempted to uncover the barriers and misconceptions surrounding the implementation of ISO 50001 through a sample of 25 organizations at the cities of Quito and Guayaquil.

This study recognize the importance of combining both technical and managerial measures to achieve greater energy, carbon and economic savings. The present research identified nine important barriers which impede the adoption of ISO 50001; absence of measuring gains and government incentives comes at the head of the list. This study has also addressed the misconceptions about ISO 50001 and has evidenced eight misconceptions; the belief that ISO 50001 requires great financial resources was top ranked. Combining the barriers with the misconceptions leads us to conclude that ISO 50001 is not a subject of significant interest in the Ecuador organizations, and its implementation is still very limited.

To meet the growing demand for compliance with the Standardized EnMS like ISO 50001, the Government of Ecuador should formulate national strategies to comply with these emerging requirements. These strategies should include the creation of agencies to register organizations complying with ISO 50001, encourage certifying bodies to work in Ecuador, lay down guidelines for training and registering auditors, educate top management and employees about ISO 50001 benefits and requirements, encourage teamwork and continuous energy performance improvement, and push towards integrated coordination within the organization. National standards board, trade and industry associations, and universities have an important role in establishing viable, independent, and credible national systems that will be recognized worldwide. Certain countries do not have a culture of certification. Nevertheless, adopting the principles of a standardized EnMS provided equivalent benefits. We stress again that top management and competent leadership are the backbone for implementing ISO 50001.

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RESEARCH IN AUSTRALIA AND SWITZERLAND ON MEASURING ENERGY EFFICIENCY OF ELECTRIC MOTORS AND MOTOR-DRIVE COMBINATIONS

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Paper structure:

1 The Australian-Swiss collaborative research project

1.1 Introduction

There is increasing interest throughout the world in motor energy efficiency, and the potential for (electrical) energy savings which result from the use of power electronic converters with conventional motors, and the introduction of new motor technologies. Consequently, there is a corresponding interest in updating existing motor standards, and the production of new standards, particularly in relation to new motor technologies and energy efficiency considerations applicable to electronic power conversion equipment and the behaviour of electrical machines which they supply.

Standards development work raises significant questions around measurement procedures applicable to the above equipment. Thus, in 2012, a collaborative research project was established, involving the *Electrical Machines Laboratory at the Ecole Polytechnique Federale de Lausanne (EPFL)* in Switzerland, and the commercial laboratory *CalTest*, in South Australia.

The objective was to establish motor and drive testing and measurement facilities in both locations, employing ‘state of the art’ instrumentation, which would serve for the investigation of some of the many questions which arise from the standards development process.

It was decided that the two laboratories should be designed and built independently, with a careful and detailed comparison at the end of that process, in order that the best aspects of the two facilities could then be identified.

This paper outlines the way in which the Australian laboratory has been designed and constructed, and provides information about some of the technical topics which have so far been investigated using that facility. It is expected that the Swiss laboratory, EPFL will be fully set up and have test results available at the end of 2013.

The central objective of this project has been to develop a ‘state-of-the-art’ dynamometer system for the evaluation of those high efficiency motors and driven systems in which it is not possible to determine losses or efficiency by separation of losses methods. The project has sought to identify the most precise instruments and test methodologies for making high precision efficiency measurements, and to quantify the associated uncertainties. This has included the provision of controlled laboratory ambient temperature conditions, since it is not possible, in general, to determine the way in which the losses and efficiency of motor-drive systems vary with temperature. Without control of ambient temperature, it is difficult to compare test and measurement results obtained in different laboratories.

When suitable test and measurement facilities have been developed in both Australia and Switzerland, ‘round-robin‘-type tests will be undertaken by exchanging test objects, including ‘new technology’ motors and motor-drive systems. Comparison of the test results obtained in both facilities should provide useful information which will aid the generation of new measurement standards and technical specifications.

1.2 The South Australian laboratory

In order to demonstrate the feasibility of maintaining controlled laboratory ambient air-temperature conditions, a special purpose laboratory environment has been established: A window-less, heavily insulated room with approximate dimensions 12 m x 6 m x 2.2 m has been equipped with an unmodified ‘inverter-type’ reverse-cycle domestic split-system air-conditioner. A large (800 mm diameter) multi-blade fan, driven very slowly (at approximately 100 r.p.m.), is used to stir the air in the laboratory, breaking up any tendency for the air-conditioner indoor unit to form local air circulation loops, but does so without creating any appreciable draught. This system maintains the laboratory ambient air temperature at the desired value of 25 ± 0.5°C, and with a high degree of spatial uniformity.

Electrical supply is provided by a precisely speed controlled alternator whose 50 (or 60) Hz very low distortion three phase output has a frequency stability of better than ±0.01%, and voltage stability and balance better than 0.1%.

Loading of a motor under test is achieved using a 30 kW shunt wound d.c. machine which forms part of a Ward-Leonard-type drive system. Highly stable loading of the test machine is achieved by varying the field excitation to both the Ward-Leonard machines.

Electrical input power to a motor or drive-system under test is measured using a precision power analyser made by Yokogawa (Model WT 3000 - Motor Version) having a claimed basic power accuracy of ±0.02%.

Voltage signals are obtained directly from the terminals of the motor under test.

Mechanical output power is calculated by the power analyser, as above, from speed and torque pulse-trains supplied by the torque transducer.

The power analyser displays all measured electrical and mechanical data in real time, including calculated efficiency, and logs that data for later analysis.

Mechanical output power is measured using an HBM model T12 'ultra precision' torque transducer, ('class 0.03'), with a full scale rating of 100 Nm. (This full-scale torque value represents the most sensitive transducer available at the time, and with 'flange'-type construction). That transducer also supplies shaft speed information generated by an optical chopper, producing 360 pulses per revolution.

A flange-type transducer was chosen because it has no bearings or slip-rings, with power supply and signals to and from the moving part transferred electromagnetically. No correction is therefore required to account for bearing or slip-ring frictional losses. The mechanical connection between the motor and torque transducer is by means of a carefully aligned Cardan shaft, incorporating two universal joints.

Laboratory ambient air temperature is measured using a T-type thermocouple in a radiation screen, located one metre from the air-intake of the motor along the axis of the motor shaft.

Motor temperature, for the purpose of determining temperature stability, is measured using a thermocouple either secured with self-adhesive aluminium tape to the outer surface of the motor casing, or placed into the lifting-eye socket, from which the eye has been removed and replaced with a small quantity of light oil.

Temperatures are continuously monitored and logged.

Following construction and commissioning, the laboratory has been used for a number of tests and investigations associated with international standards development work, examples are below.

2 Efficiency measurements on Line Start Permanent Magnet (LSPM) motors

2.1 Introduction

In these motors, synchronous operation is achieved by embedding high strength rare-earth permanent magnets in the rotors of what would otherwise be induction machines. When energized, induction torque rapidly accelerates the rotor from stand-still, and synchronization occurs as the rotor approaches synchronous speed, as a result of the permanent magnets.

Even with a light load, LSPM motors do not start smoothly, however, exhibiting significant oscillatory torque and large line-current transients prior to synchronisation. Such behaviour has the capacity to overload or even damage precision torque and power analysis equipment with which the mechanical and electrical measurements are to be made.

Manufacturers also warn that LSPM motors may experience difficulty in pulling into synchronism with the supply if the driven load has high inertia. Another possible problem is that the permanent magnets in the LSPM rotor represent full rotor excitation at all times, and significant a.c. voltage is produced at the motor terminals when the rotor is driven externally.

A procedure is therefore required to start an LSPM in a controlled manner. The technique employed in this project is that which is commonly used for the synchronisation of a.c. generators: With its terminals open-circuit, the LSPM motor is driven up to approximately synchronous speed using the (active) d.c. dynamometer machine and its associated speed control system. The LSPM motor terminal voltage is then phase-synchronised with its supply, whose value had been adjusted to match the open-circuit voltage generated by the test motor, at which point the motor terminals are switched on to the supply. The motor supply voltage is then raised to its rated value and maintained for the whole of the subsequent testing and measurement process. The dynamometer machine then reverts to its normal role as a mechanical load for the motor under test.

In addition to possible starting problems, as above, synchronous motors represent unusual loads, since their torque-speed characteristics are vertical straight lines, and excessive load torque may cause loss of synchronism. Many conventional dynamometers are essentially *speed*-controlled and as such are quite unsuitable for loading synchronous machines. In such circumstances, stable loading is achieved by operating the dynamometer loading system in controlled-*torque* mode. In this project, such a characteristic is obtained by the introduction of significant resistance into the armature circuit of the d.c. Ward-Leonard system which controls the dynamometer machine.

2.2 Test results

The LSPM under test was allowed to run under each of several loaded conditions until the temperature rise of the motor case was 2 K per hour or less. Direct efficiency measurements were then made using the WT3000 analyser. Since testing took place in controlled ambient temperature equal to the reference temperature in the standard (25°C), no further corrections were necessary.

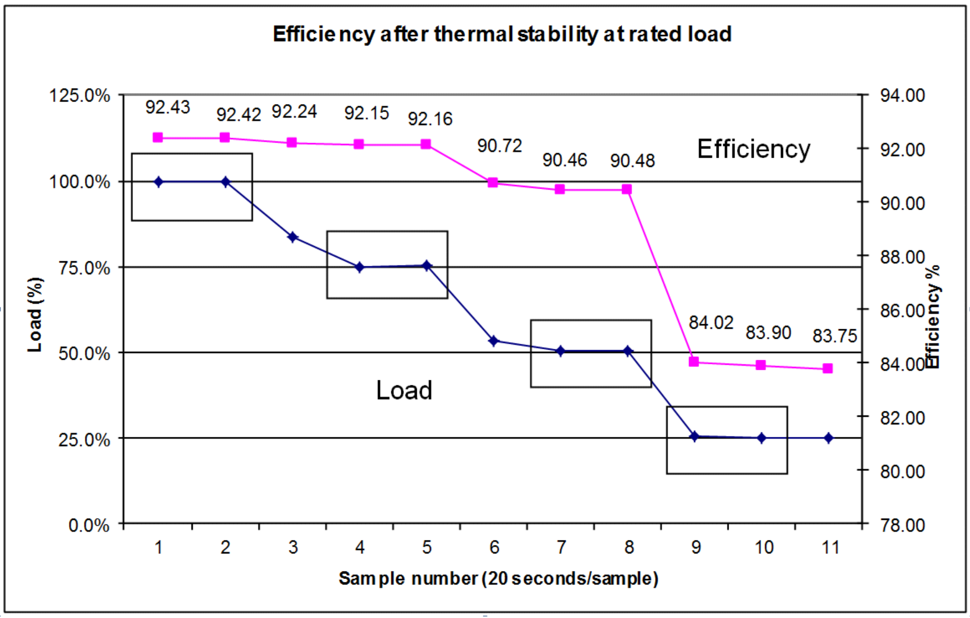

Figure 1: Test results after motor temperature stability at rated load. Samples at 20 second intervals match the averaging time of the analyser.

Load (%)	Efficiency with thermal stability at each load point (%)	Efficiency with thermal stability only at 100% (%)	Difference (percentage Points)
100	92.4	92.4	–
75	92.3	92.2	0.1
50	90.7	90.5	0.2
25	84.1	83.9	0.2

Table 1: Measured efficiency with and without thermal stability at each load point

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2.3 Summary

The laboratory and its equipment provided a precisely ambient temperature-controlled environment for making measurements on an as yet uncommon motor type. The resulting efficiency values indicate that attainment, or otherwise, of thermal stability in the motor under test leads to an additional uncertainty in the measured efficiency value of up to 0.2 percentage points.

3 Efficiency measurements on motor-drive systems

3.1 Introduction and test method

Using the output/input method, a series of measurements on a motor-drive system were undertaken to determine overall efficiency at a range of loads with motor temperature stability at different load points in controlled ambient air-temperature conditions.

Those tests and measurements were undertaken in order to trial the suggested "Draft standard for determination of efficiency of new technology motors and motor-drive systems using output/input measurements" developed by the South Australian laboratory in March 2013. That document is available on the 4E[1] Electric Motor Systems Annex website, at www.motorsystems.org/testing. Two complete sets of efficiency measurements were made on consecutive days in order to check the reproducibility of the test results.

The motor drive system under test comprised an SEW-Eurodrive 1.1 kW 'Movitrac' single phase variable speed drive and an SEW-Eurodrive 3-phase, 1.1 kW, 4 pole cage-rotor induction motor.

Physically, the VSD was mounted 2 m behind the motor under test, and in line with the axis of the motor shaft, with the ambient temperature monitoring sensor and associated radiation screen again on the above axis, and mid-way between the converter and motor. The VSD was arranged such that its cooling fan blew its exhaust air in the opposite direction from the motor under test.

[1] 4E is the Efficient Electrical End-Use Equipment Implementing Agreement of the International Energy Agency: www.iea-4e.org.

For each of the load points shown in bold type in Table 2, measurements were made after the rate of change of motor case temperature-rise (above laboratory ambient temperature) became less than 2K per hour. The remaining load points for that speed were then measured as quickly as possible, down from 100% load.

Test runs were made on two consecutive days to confirm repeatability of the measurements. In all cases, the laboratory ambient temperature was maintained, by the air-conditioning system described above, at 25 ± 0.5°C.

3.2 Results:

Day 1			Speed			
			25%	**50%**	**75%**	**100%**
			375 rpm	**750 rpm**	**1125 rpm**	**1500 rpm**
Load	**100%**	1100 W	58.5%	71.2%	76.5%	**73.6%**
	75%	825 W	58.9%	70.8%	**76.3%**	77.1%
	50%	550 W	55.9%	**68.1%**	73.5%	77.1%
	25%	275 W	**45.1%**	57.7%	63.4%	69.4%

Day 2			Speed			
			25%	**50%**	**75%**	**100%**
			375 rpm	**750 rpm**	**1125 rpm**	**1500 rpm**
Load	**100%**	1100 W	58.7%	71.4%	76.4%	**73.7%**
	75%	825 W	59.4%	70.9%	**76.3%**	77.0%
	50%	550 W	56.8%	**68.6%**	73.1%	77.0%
	25%	275 W	**45.9%**	57.5%	63.5%	69.6%

Table 2: Efficiency values at the different load and speed points for the two test runs on consecutive days.

Figures in bold are the speed-load points at which (motor) thermal conditions were allowed to stabilise

3.3 Conclusion

The objective of the draft standard has been to provide a test and measurement procedure for the determination, by the output/input method, of drive efficiency which balances the conflicting requirements of accurate and realistic measurements over a wide range of operating conditions versus a reasonable time taken in which to make those measurements.

Two complete sets of measurements were made in two working days, and it is clear that a working day is more than sufficient time for all the necessary measurements to be made and for motor temperature stability to be achieved at the number of points specified.

The repeatability of the measured efficiency values was good. Efficiencies measured in the two experimental runs agree within 0.4 percentage points or better at the higher load - speed points. Agreement at the lowest speed and power points is not quite so good, and this was attributed to slight loading instability at very low torque values, a problem which has now been corrected.

It has been demonstrated that closely-controlled laboratory ambient air temperature may be achieved using unmodified domestic-type air-conditioning equipment which is readily available, and that a requirement in a published standard for closely controlled ambient temperature conditions should not therefore be difficult to achieve in laboratories around the world.

4 Efficiency measurements on small motors

Work on the measurement of energy efficiency in small motors was prompted by the extension, by IEC TC2 Working Group 31, of the range of motor ratings covered in the draft second edition of IEC 60034-30-1 (IE-code) from a lower output power rating of 0.75 kW downwards to 0.12 kW.

Meanwhile, IEC TC2 Working Group 28, which is responsible for the efficiency tests and measurement standard IEC 60034-2-1, has identified the method of separation of losses with additional losses determined by smoothing of residual losses (‘Method B’) as the preferred method for efficiency measurements on *all* three phase machines.

Measurement of efficiency of rotating machines with rated outputs as low as 120 W poses special problems, however, and a survey has indicated that many laboratories do not have facilities for testing motors with this rating. Rated output torque for a 120 W, 2 pole motor is only 0.38 Nm at synchronous speed when operated from a 50 Hz supply, and even lower (0.32 Nm) at 60 Hz. An uncertainty in the measurement of output mechanical power of only 1 W thus causes an error in the final efficiency figure of almost one percentage point.

Measurement of output shaft torque in such machines is by no means straight-forward: ‘Torque flanges’, with the advantage of having no bearing between the motor under test and the torque sensitive element, appear to be an obvious instrumentation choice. Such flanges tend, however, to be available only with comparatively high full scale ratings, with the most sensitive having full scale ratings of 50 or 100 Nm.

Other types of ‘in-line’ transducers suffer from the great disadvantage of having bearings at each end, and although the power required to drive the bearing at the loading end is easily accounted-for, the bearing between the motor and the torque sensitive element has losses which are not measurable by the transducer.

A possible means of measuring the mechanical losses in that bearing could be to use an electrically operated clutch between the motor under test and the torque transducer, and to note the difference in the electrical input power to the motor when the clutch is operated. That difference would, however, give information about *both* bearings, and assumptions would need to be made about the way in which the mechanical power losses were distributed between the two. Further, the loss characteristics of such bearings tend to be temperature dependent, adding further uncertainty to the measurement process.

Work is currently underway to investigate means by which efficiency measurements may be made on very small motors with minimum uncertainty, and to verify (or otherwise) that the 'preferred method', as specified in the current draft edition of IEC 60034-2-1 is, in fact, readily applicable to such machines.

That work involves the comparison of different ways in which very small torques may be measured and traced to international standards of measurement. These involve the use of mechanical coupling systems with very low windage and other losses, the use of currently available 'torque flanges' operating at very small fractions of their ratings, and the use of ultra-low friction 'pendulum' mounting arrangements for motors under test, involving the use of porous air-bearings, and the subsequent measurement of (test motor) stator reaction torque by means of lever arms and precision load cells.

This experimental work is currently being carried out as part of the Australian-Swiss collaborative research project, with results and experience to be compared with the Swiss researchers at the end of the process.

5 Converter-fed motor terminal voltage measurements

5.1 The need for a 'flux voltmeter'

Draft Technical Specification IEC 60034-2-3 seeks to quantify the additional losses suffered by rotating electrical machines when converter-fed. This Specification was initially based on the idea that the principal additional losses produced in converter-fed motors were iron losses, and that these could be identified by finding the ratio of the no-load losses produced in a given machine by a converter and an essentially sinusoidal supply respectively. The ratio between the two measured power values would then be called the 'harmonic loss ratio'.

A problem arose, however, with what constitutes an 'equivalent' voltage applied to a motor for the above purpose, given the very different waveforms generated by the two supplies, as above.

The measurement of voltage derived from a (nominally) sinusoidal supply to a motor is straight-forward, and requires the use of a voltmeter responsive to the mean value of the rectified voltage, but scaled to read the r.m.s. voltage of a sinusoidal wave having the same mean value.

(This is recognized by international standards relating, for example, to the measurement of power transformer core losses: See, for example, IEC 60076-1).

If a moving-coil voltmeter is connected to the terminals of a motor or transformer winding via a full-wave rectifier, then that instrument will respond in direct proportion to the peak flux value established by that supply voltage. This will always be the case, providing the magnetic flux contains no d.c. components or even harmonics, and that there are no subsidiary flux minima.

Thus a rectified-average responding instrument is always the best way to measure the voltage applied to the terminals of a motor (or transformer) under test, when the supply is essentially, but not perfectly, sinusoidal.

If the supply *is* purely sinusoidal, then the readings on average rectified- and r.m.s. responding instruments will be identical.

Measurement of voltage supplied to rotating machines from electronic converters poses additional problems, as the magnetic flux produced in those machines does not meet the above criteria, since it contains an alternating component at the converter switching frequency, and is not, therefore, without subsidiary minima which prevent accurate averaging by a simple rectifier-type voltmeter.

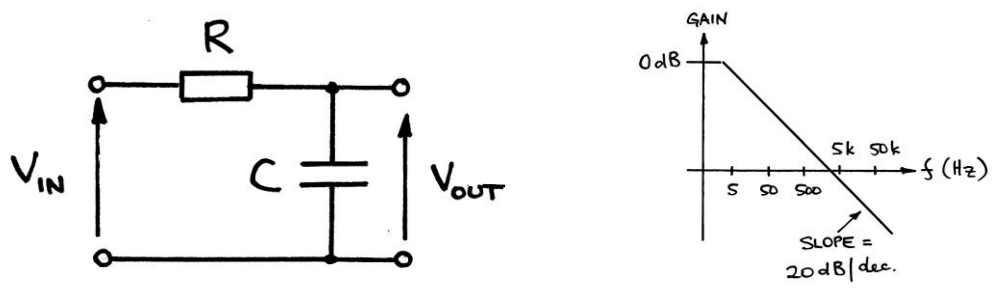
Various commercially available digital multimeters are claimed, by their manufacturers, (e.g. Fluke, Yokogawa) to be suitable for such measurements, and such instruments generally include filters of various types. There is apparently no agreement, however, as to the ideal characteristics of such filters.

Consider, now, the problem of comparing the performance of a given motor when fed with an essentially sinusoidal supply, with the performance under converter supply conditions, as above. What instrument should be used to ensure that the motor has comparable voltages at its terminals in each case?

A measurement system which responds essentially to the fundamental frequency magnetic flux excursions in the motor under consideration provides the required information.

Motor flux is closely related to the terminal voltage and frequency, the flux approximated by the time integral of the terminal voltage. A measuring system capable of measuring this integral would thus provide the necessary reference measurement method.

Such a measurement is very simple to make: A single ‘L-section’ RC network (see Figure 2) with a ‘corner frequency’ which is very much lower than the lowest frequency component in the motor supply voltage provides such a time integral.



(a) (b)

Figure 2: (a): A single pole passive R-C network accurately integrates signals whose frequency components are significantly greater than the cut-off or corner frequency. (b): Passive integrator frequency response characteristic

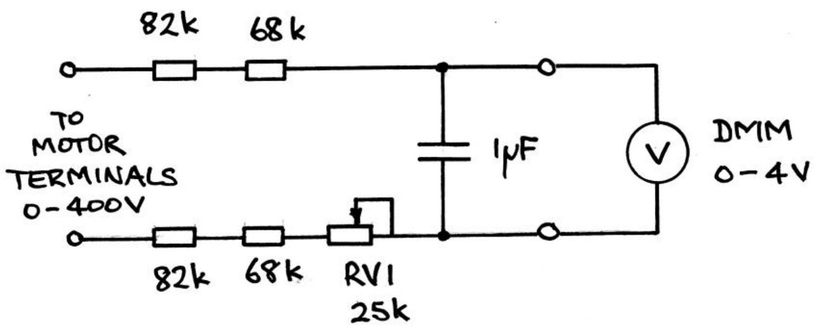


Figure 3: Practical (balanced) flux voltmeter according to the above design.
The variable resistor allows adjustment.

Because of the low-pass filter characteristics of the above network, the output voltage waveform is nearly sinusoidal, but with a small amount of super-imposed ripple at the converter PWM 'carrier' frequency. Its output may therefore be read with a rectified-averaging responding meter without significant error.

A flux voltmeter of the above type has been used to compare the (total) no-load losses of a number of 2, 4 and 6 pole 1.1 kW cage-rotor induction machines, with the results shown graphically in Figure 4. The increase in no-load losses is shown as the portion at the top of each of the bars, but that figure also shows that motors are not re-ranked according to the nature of the supply.

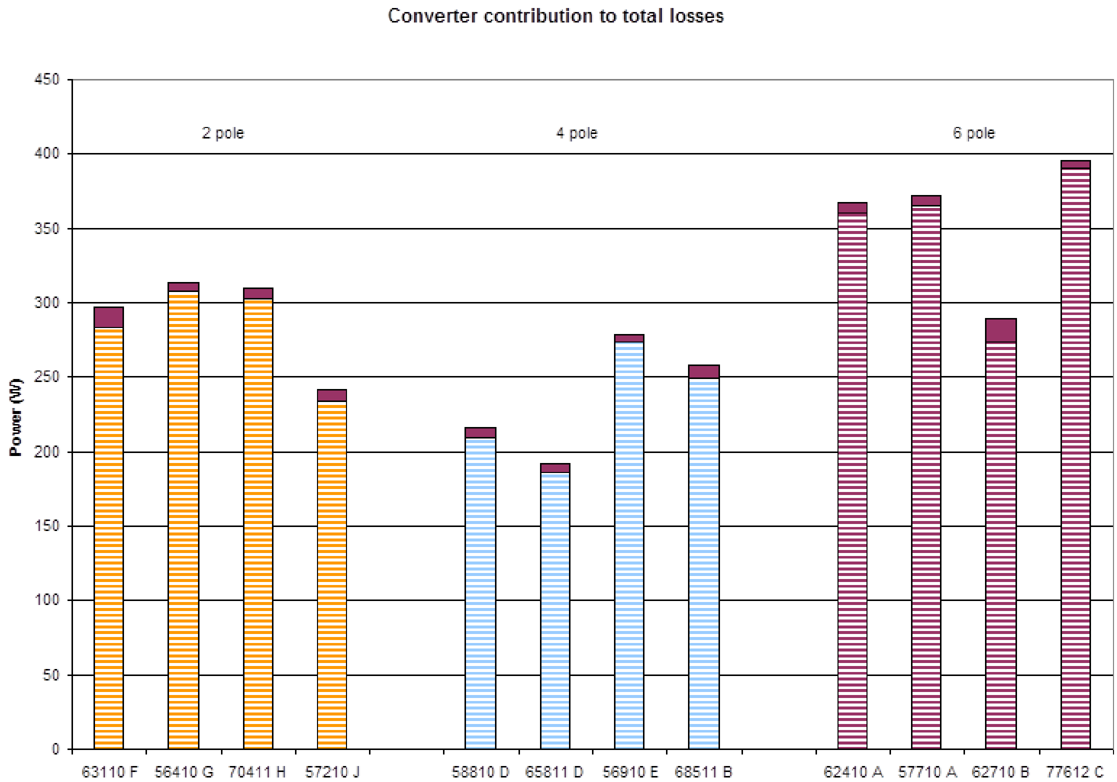


Figure 4: No-load loss measurements on 2, 4 and 6 pole motors with essentially sinusoidal and converter supply, the sections at the tops of the bars representing the additional losses under converter supply. These measurements were facilitated by the use of a flux voltmeter to adjust the motor supply voltages to comparable values

5.2 Other uses for the flux voltmeter

The curve in Figure 8 was produced by connecting a ‘flux voltmeter’ to the terminals of a small motor fed from a converter which had been set up to produce (as closely as possible) a ‘reference converter’ output waveform (as defined in Draft TS IEC60034-2-3) at 50 Hz.

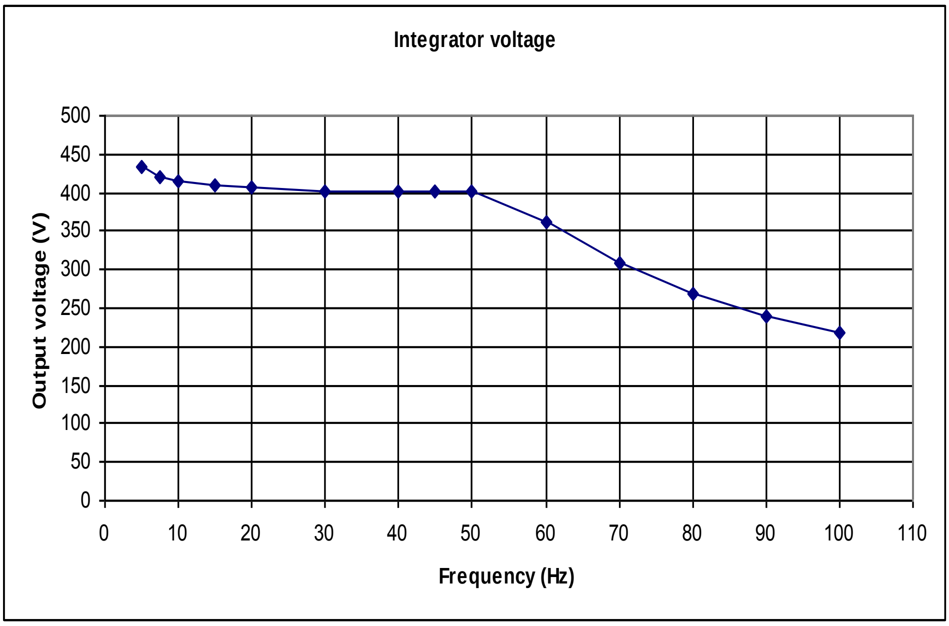


Figure 5: Flux voltmeter (‘Integrator voltage’) readings vs. frequency for a converter set to produce a ‘reference converter’ waveform at a fundamental output frequency of 50 Hz

The ‘flux voltage’ readings in Figure 5 clearly show:

1. constant motor flux as the frequency drops below 50 Hz
2. the effects of ‘voltage boost’ at low frequencies, a technique which is used to compensate for resistive voltage drop at those frequencies
3. the way in which flux drops at converter output frequencies above 50 Hz and
4. that the transition between (1) and (3) occurs at 50 Hz, indicating that the converter set-up is correct

The flux voltmeter is thus a useful tool for setting-up and adjusting variable speed drive equipment, since it clearly shows the transition between the various operating modes. The actual voltage applied to the motor terminals may be calculated from the flux voltmeter reading by multiplying the latter by the fundamental converter output frequency divided by the frequency at which the voltmeter was set up (50 Hz in the above case).

6 Methods for determining the efficiency of totally enclosed air-over (TEAO) motors

6.1 Background

Totally enclosed air-over (TEAO) motors are a type of rotating electrical machine designed specifically for driving axial-flow fans, and which are mounted in the resulting air-stream. Such machines are not equipped with their own external cooling fans, and rely, therefore, on the air-stream in which they are mounted to transfer heat away from the external surface of the motor. Enquiries directed to manufacturers show that TEAO motors are sold in significant quantities, and that this type of machine is widely used for ventilation of mines, traffic and other tunnels, and for cooling associated with high-density indoor livestock farming.

Because such motors are reliant on their driven loads for cooling, the usual methods for determining motor efficiency are not applicable, and TEAO motors have therefore been exempt from MEPS requirements as set out, for example, in draft revisions of IEC60034-30-1, the IE-Code.

Such a situation is unsatisfactory, however, as the availability of copious quantities of cooling air presents an opportunity for an unscrupulous manufacturer to supply high-loss motors for this type of duty.

The problem of measuring the efficiency of such motors has formed part of the present project, and the following outlines possible solutions to the problem of making efficiency measurements on such machines.

A motor without a means of self-cooling is likely to overheat if subjected to a conventional dynamometer test for the measurement of efficiency. A cooling air stream is therefore required, but the amount of cooling air provided from an external source must be carefully adjusted in order to neither under- or over-estimate the motor's efficiency. There are several ways in which the problem of providing the correct amount of cooling air may be overcome.

6.2 On-line resistance measurements

One possibility is the use of 'on-line' resistance measurement techniques which allow stator winding resistance, and therefore stator winding average temperature, to be measured while the machine is running. Measurements of this type are described in the (now withdrawn) IEC standard 60279 (First edition – 1969-01): '*Measurement of the winding resistance of an a.c. machine during operation at alternating voltage*'. That standard describes a number of ways in which the resistance of the winding of (for example) an electric motor, may be measured in real time whilst the motor is energised under rated a.c. supply conditions. As can be seen from the date of issue, that standard was written well prior to the present digital instrumentation era, and some of the methods described are quite cumbersome, and difficult to carry out. The current availability of high quality and very accurate digital instrumentation has changed that situation, however, and the principles of 'on-line', 'hot-line' or 'energised' winding resistance measurement are well worth revisiting, especially in the electric motor measurements context.

Instruments which offer 'energised' winding resistance measurements are now commercially available. Figure 6 shows a circuit which allows direct current to be injected into motor terminals and the resulting d.c. voltage drop to be measured, from which winding resistance may be determined continuously, and in real-time. Such a technique facilitates the 'rated load thermal test' which forms part of the preferred (separation of losses) method for the determination of induction machine efficiency, allowing the velocity of cooling air blown over external motor surfaces to be adjusted in order, for example, to produce winding temperatures corresponding to the insulation class, or to a maximum value specified by the manufacturer.

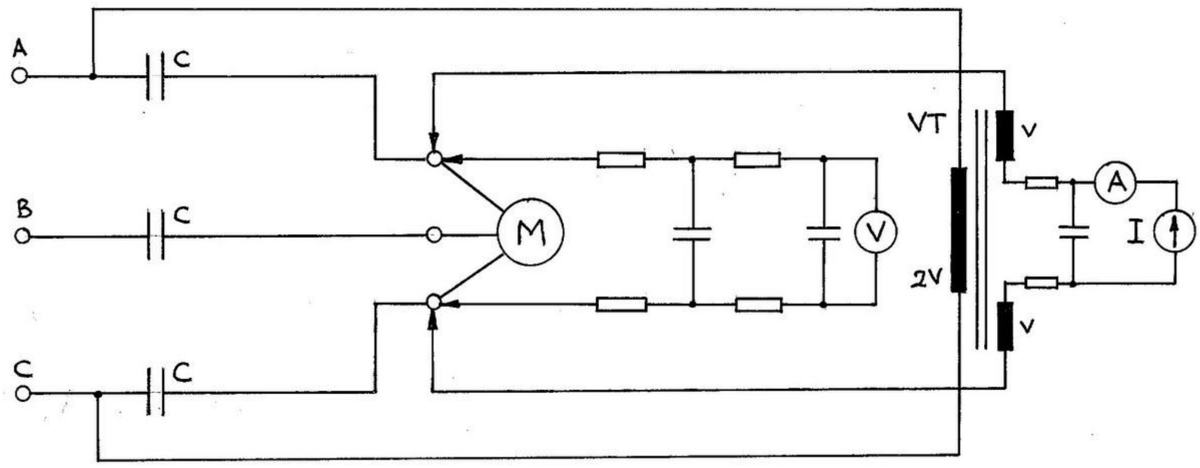


Figure 6: On-line resistance d.c. resistance measurement principle

In the above figure, the motor under test is energised from its normal a.c. supply via three d.c. blocking capacitors, C. The motor's stator winding d.c. resistance may be measured, even in the presence of the normal a.c. supply, by introducing a small direct current via a simple low pass filter and a voltage transformer, 'VT', connected so as to remove the motor a.c. supply voltage from the current injection circuit. The resulting d.c. voltage drop across the motor stator winding is measured using a low pass filter (to reduce the a.c. voltage component) and a digital voltmeter.

Note that such a technique could very usefully be used in measurements made on conventional machines, obviating the need to make stator resistance measurements within the time intervals after switch-off specified in IEC 60034-1, or back-extrapolation of resistance values. It is hoped to generate interest in revisiting IEC 60279 and to rewrite it in order to update these very useful on-line techniques.

6.3 Methods for making TEAO motor efficiency measurements

The ability to measure the d.c. resistance of energised machine windings facilitates the determination of efficiency of TEAO motors.

One proposed method is based on the provision of external motor cooling arrangements, and the use of 'energised' d.c. winding resistance measurements to allow a specified winding temperature to be reached and maintained.

The following sketch (Figure 7) shows a suggested test set-up, in which the motor under test is connected to a conventional dynamometer, and cooling is provided by means of a cylindrical sleeve fitted around the motor, through which air, initially at laboratory ambient temperature, is blown at a controllable rate. The instrumentation includes an energised d.c. resistance measurement system for the real-time indication of average stator winding temperature.

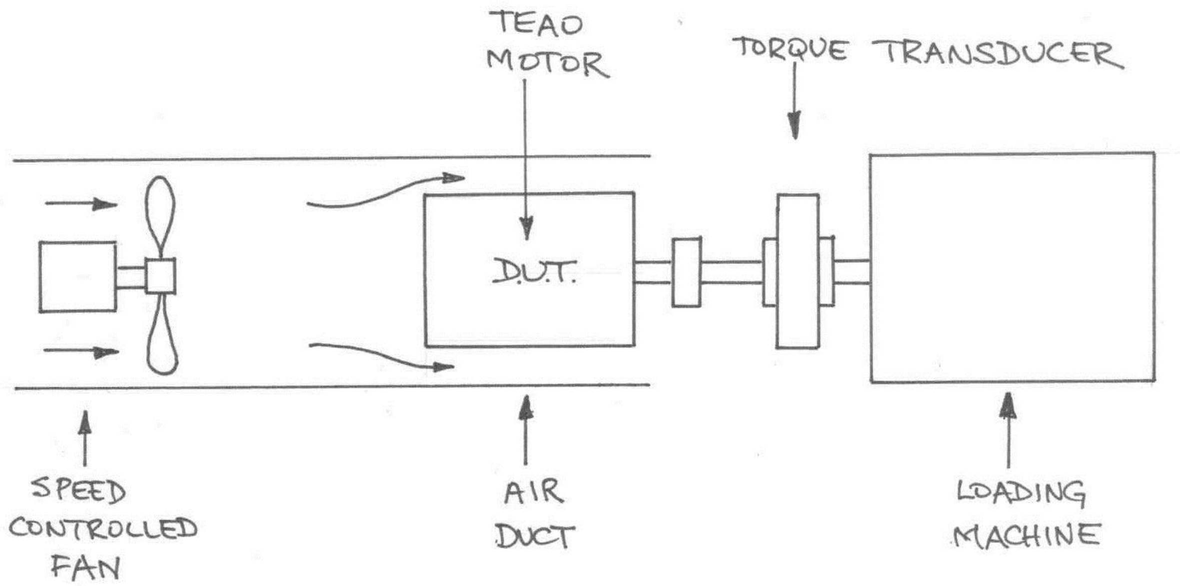


Figure 7: Suggested TEAO efficiency measurement set-up

The test and measurement procedure is carried out according to the requirements of IEC 60034-2-1 (Method B (see draft edition) – separation of losses, with additional load losses determined by the residual loss method).

The rated load thermal test proceeds with the motor loaded mechanically to its rated output, and with the flow of cooling air adjusted until the average stator winding temperature (inferred from stator winding d.c. resistance) stabilises at a predetermined value.

The required temperature may be selected from the following possibilities:

- The temperature corresponding to the stator winding insulation class, as in IEC 60034-2-1, Table 4 ('Reference temperature'), with Class B insulation corresponding to: 95˚C, class F: 115˚C, class H: 135˚C etc.
- A temperature-rise designated by the manufacturer

Note that the external cooling air-stream may be adjusted by a number of means, including a variable-speed blower or fan, or the provision of an adjustable input-air damper system.

The load-curve test would then be carried out maintaining the same cooling air system settings as were determined during the rated load thermal test.

The cooling air system would run whenever the motor under test runs, and is stopped when the motor is de-energised.

6.4 An alternative TEAO motor efficiency measurement test method

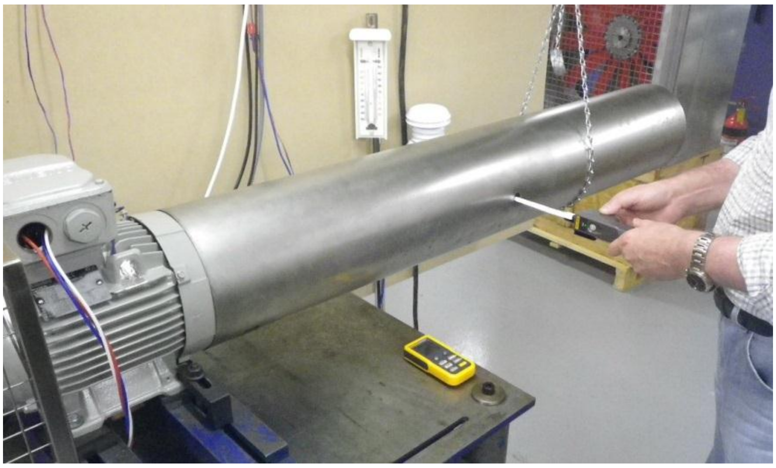
Another way in which the efficiency of TEAO motors might be treated is for manufacturers to be required to state, on the nameplate of such machines, the minimum air velocity (at full load) which is required to pass over the body of the motor.

As part of this study, air velocity over the bodies of conventionally cooled TEFC motors which might be considered ‘parents’ of corresponding TEAO motors, has been investigated, and comparisons made between efficiency figures obtained from a given TEFC motor which was then modified by removal of the fan cowling and fan. The resulting TEAO motor was then cooled by external means, with air velocities over the motor body matched as closely as possible.

<u>Experimental Method:</u>

A normal, TEFC 2.2 kW 2 pole induction motor was randomly chosen for testing as the ‘parent’ motor. Using the Precision Dynamometer laboratory as previously described above, efficiency, determined using both the separation of losses and direct output/input methods, was measured at a controlled ambient temperature of 23 ± 0.5 °C.

Using methods developed by the HVAC industry, the air inlet flow velocity to the cooling fan of the (TEFC) motor was measured using a hot-wire anemometer probe inserted into in a long sheet-metal circular duct fitted over the motor’s fan cowling, having previously determined that the presence of the duct had minimal effect on motor temperature rise.



Photograph 1: measuring the air velocity in the duct: TEFC motor

By removing the integral fan and cowling, the motor was then converted to TEAO construction. An external speed-controlled centrifugal blower was then used to supply air through the same sheet-metal duct at the same average velocity as measured for the TEFC motor. Since the diameter of the duct was the same as the internal diameter of the original fan cowling, it was reasoned that the same air flow velocity at the same temperature would have the same cooling effect.

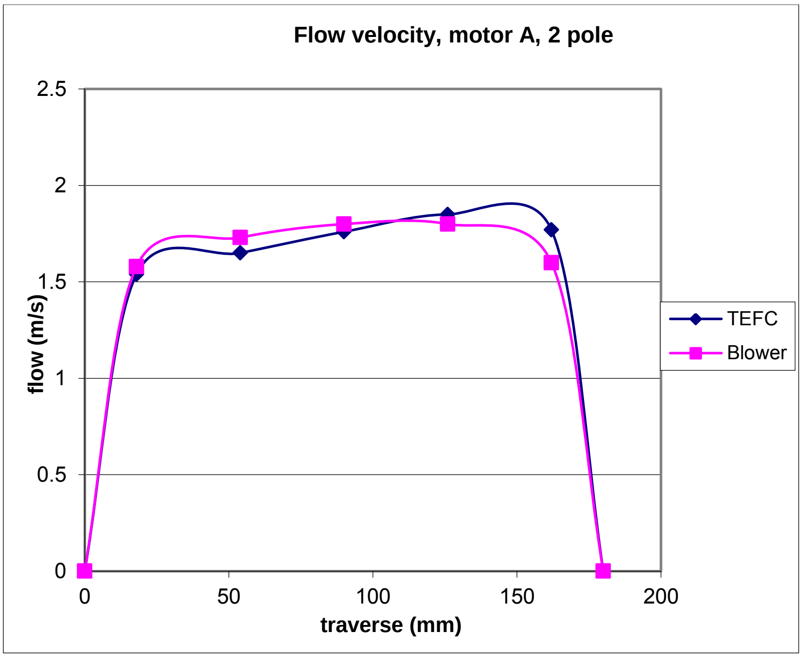


Figure 8: Air velocity in the duct, 2 pole motor. Velocity profile is flat in both modes, indicating low turbulence.

Measurements of motor efficiency were then repeated.

The above procedure was then repeated using a 2.2 kW 4 pole motor.

Results:

Condition	Mode	Efficiency (separation of losses)	Constant loss	Efficiency (output/input)	Intercept, B	Stator rise
Normal cooling	TEFC	86.2 %	87.2 W	86.3 %	-1 W	42.2 K
External air flow, speed matched	TEAO (no fan or cowling fitted)	86.4 %	70.9 W	86.7 %	-5.7 W	52.4 K
External air flow, speed matched	TEAO (fan cowling refitted)	86.3 %	70.9 W	86.3 %	1.47 W	51.3 K

Figure 9: Results, 2.2 kW 2 pole motor, TEFC and TEAO mode

An increase of efficiency of 0.4 % was measured in TEAO mode. The constant loss is reduced due to the removal of the cooling fan. However, the stator temperature rise was 10 K greater despite the air flow replication. Thus the measured efficiency was slightly lower due to the temperature.

Refitting the original fan cowling (but without fan) inside the duct in TEAO mode, and with the airflow velocity matched as before, had no significant effect on the stator rise or efficiency.

Condition	Mode	Efficiency (separation of losses)	Constant loss	Efficiency (output/input)	Intercept, B	Stator rise
Normal cooling	TEFC	84.7 %	102.7 W	84.9 %	-3.5 W	68.1 K
External air flow, speed matched	TEAO (no fan or cowling fitted)	84.2 %	98.8 W	84.6 %	-8.6 W	76.6 K

Figure 10: Results, 2.2 kW 4 pole motor, TEFC and TEAO mode

In the above table, the efficiency (measured by separation of losses) is 0.5 % lower for TEAO operation, compared with TEFC. Again, the constant loss shows a small decrease due to the removal of the fan, but the stator temperature is higher, reducing the efficiency slightly.

Conclusion: Air flow velocity can be accurately measured and replicated. Efficiency measurements, with good agreement between separation of losses and output/input methods, show a change in constant loss and efficiency when changing a TEFC motor to a TEAO. However the increase in stator temperature with the same cooling-air velocity is not yet understood.

Experience with efficiency measurement of VSD fed induction motors using calorimetric loss measurement technique

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Abstract

Accurate measurement of the motor and/or motor drive system losses is very important in view of upcoming stringent standard requirements. The EU eco-design directives 2005/32/EC through Commission Regulation (EC) No 640/2009 is pushing for use of higher efficiency class motors for industrial applications through the upcoming efficiency standards for motors and drive systems. For motors of higher efficiency classes, the measurement of efficiency becomes more critical since small errors introduced by measurement system have large effect of estimated efficiency. There are well known established procedures to measure the efficiency of motors fed from sinusoidal supply as outlined by IEC 60034-2-1 standard. The efforts are made in to draft a new technical specification IEC 60034-2-3[1] to address the methods to measure the additional losses incurred associated with Variable Speed Drives (VSD) supplied motors [10] [21]. Similarly, the work is ongoing to describe methods for measuring the system efficiency of complete motor-drive system for VSD fed motor drives [7][6]. This draft specification describes either electrical input-output or calorimetric loss measurement as preferred methods to measure efficiency of motor drive system.

This paper addresses our experience with measuring the VSD fed motor efficiency using calorimetric loss measurement technique and comparing the measurements with other preferred efficiency measurement methods. A calorimetric loss measurement system is built for measuring the losses of motor supplied from a sinusoidal supply mains or VSD. The calorimeter is an open type two phase system. The thermal equilibrium is established by running the test motor inside the calorimetric chamber, and then the same thermal equilibrium is re-established using a heating resistor element supplied from a DC power source. The power fed to the heating resistor at the thermal equilibrium is subsequently interpreted as the motor losses. A series of tests were performed using calorimeter to measure the motor losses at different load conditions. The measured losses are then compared with losses measured with the direct input-output efficiency measurement method. The uncertainties of calorimetric loss measurements are also established by considering all possible heat leakage points and instrumentation error sources. Finally both electrical and calorimetric loss measurement results are compared.

Keywords:- IEC60034-2-1, IEC 60034-2-3, Direct input-output efficiency measurement, calorimetric loss measurement technique

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[1] The technical specification is still in draft stage, the publishing date is scheduled to be in late 2013. http://www.iec.ch

Introduction

The motor efficiency can be measured in a number of ways, IEC 60034-2-1 standard describes methods for testing induction motors and also suggests the accuracy requirements of different equipment used for measurements. The direct method (Method 2-1-1A) is the most common and straightforward way of measuring motor efficiency; it involves testing the motor by coupling it to a separate load machine together with a torque measurement device on the shaft. The test motor input and output power is thus directly measured for several load points. The accuracy of the direct efficiency measurements have been discussed extensively in literature and general observation is that the method can lead to large measurement errors since it involves measurement of two large quantities. A slight error in any of the quantity will result into large error in the efficiency. The other popular and more accurate technique- called the summation of loss method, in fact measures different loss components like no load losses and load losses separately using no load and load tests. The additional stray load losses are either estimated by linear regression analysis on measured load loss (Method 2-1-1B) or by using an "assigned value" as described by the standard (Method 2-1-1C). The applicability of which method should be used is also described by the standard. Accordingly, the stray load loss shall be determined from residual loss for motors up to 2 MW and it is to be calculated from assigned value for higher than 2 MW machines.

Even with the use of a consistent and accurate efficiency measurement method, variations in the results for the same motor do occur. This is primarily due to test equipment and instrument characteristics, and in the case of non-automated testing, due to personnel factors. The situation is very different when the motor is supplied from Variable Speed Drives (VSD), as the existing standard is no longer applicable. The effect of PWM voltages applied by the VSD is increase in motor losses- these are mainly the additional harmonic losses. A new draft specification IEC 60034-2-3[2] is under preparation which describes the methods to measure motor efficiency under VSD supply [10][21].

Motor efficiency measurement methods involve use of standard equipment like power meters which have higher measurement error margins under PWM supply voltages as compared to sinusoidal voltage condition [23]. Both IEC 60034-2-1 and 60034-2-3 specify the necessary accuracy requirements for different instrumentation used in the electrical loss measurements. Mainly the instrumentation used for the electrical loss measurements shall have an accuracy class of 0.2 in accordance with IEC 60051 and the instrumentation used for measuring mechanical quantities should have accuracy range of 0.2% of full scale [3]. It has been reported that even when the same motor has been tested in different laboratories, it was not possible to reproduce the same efficiency values [6] [9]. This topic has been under review in the standards committee and efforts are being made in to improve the accuracy of electrical test methods. As of now, more precise loss measurement under these situations can be done using calorimetric loss measurements. The uncertainty associated with calorimetric loss measurement is much lower than input-output method while measuring the higher efficiency systems/components as reported in [22].

Calorimetric system measures actual loss in terms of generated heat of the machine, which is very much different in principle from other methods described in the above standard specifications. The heat dissipated in the test objects results in the temperature rise of the cooling medium. The temperature rise is measured together with the coolant flow inside the calorimetric chamber. By knowing the relative humidity, absolute pressure and temperature rise, the actual heat loss can be calculated. This approach is termed as closed cycle calorimetric loss measurement.

In another approach, referred to as an open type calorimetric system, the measurements are carried out in two stages. In the first stage- calibration phase, the induction motor is driven with specific load and the respective temperature rise at known coolant flow rate is established. Then in the second stage- balance phase, the DC power is fed to a known resistor network placed inside the box. This power fed to the resistor is adjusted until the same thermal equilibrium as calibration phase is achieved, which is then taken as the motor loss during the calibration phase. The open type calorimetric loss measurement is simpler, mostly uses air as cooling medium and with proper care for considering heat leakages, accurate results can be obtained.

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[2] The technical specification is still in draft stage, the publishing date is scheduled to be in late 2013. http://www.iec.ch

Still calorimetric loss measurements often involve more complex and time consuming tasks and thus this method cannot be used for routine testing but rather should be used as an evaluation tool for confirming the accuracy of efficiency measured by other methods. This is the main motivation for this paper. The paper presents construction of a test setup which is capable of performing both calorimetric loss measurements and electrical efficiency measurements simultaneously. The paper addresses some common issues with calorimetric loss measurement systems involving electric motors as test objects. The paper is organized as follows. First a literature overview of the calorimetric loss measurement method is presented, with more focus on application to measurements involving the electric motor as test object. Then the common issues, and difficulties associated with loss measurements are discussed, and solutions are proposed. The main cause of heat leakage which deteriorates the accuracy of measurements, and methods to account for these losses is described. Then the actual measurement results by calorimetric loss measurement method performed on a test motor at different load conditions are presented and compared with the losses measured by electrical direct input-output power measurement method.

Overview of calorimetric loss measurement

The calorimetric loss measurement technique has been in use for loss measurements for many years. The initial usage can be found for chemical engineering processes. In recent years, its applications have been reported for measuring losses on electrical machines and power electronic systems. A good overview about earlier calorimeters and subsequent attempts for measuring losses in electric machine can be found in [14]. The calorimeters can be classified into different categories based on the principle of their operation and cooling medium used. Direct calorimeters measure the heat produced by the test object directly, whereas indirect calorimeters uses an auxiliary resistor and create a similar heat generation. Thus indirect calorimeters may perform two tests-first using the test object for heat generation and second for mimicking the similar thermal condition using a resistance heating element. Double chamber calorimeters are also reported in literature- one chamber for housing the test object while a second chamber is used for heating the resistor element. The cooling medium also differs, open type generally uses air as heat transfer medium. When liquid or gas coolants are used, the calorimeter also consists of a heat exchanger to take out the heat from coolant. The reference [14] provides an overview of different calorimeter types and also presents advantages and dis-advantages of the same. The accuracy of calorimetric system is of prime importance to justify investments in such a complex system and the time required for testing.

Important requirements for calorimetric loss measurement

The main challenges in calorimetric loss measurements for measuring motor efficiency can be described as below-

- Minimize and estimate the heat loss from the walls and other sealing places
- Temperature control and precise measurement
- Mounting of motor inside calorimeter and arrangement for shaft opening and sealing arrangement.
- Accurately control and measure the air (or other mass) flow rate, minimize disturbance by motor fan

The last two requirements is very specific to the measuring motor losses. Since the heavy motor mass has to be securely mounted inside the calorimeter and the shaft has to be brought out. It is very important to contain any heat leakage either from shaft opening or through the motor mounting bolts in such situation. This heat leakage from different sources has to be calculated and used to readjust the measured motor losses through dissipated heat loss. The next section of the paper presents construction of the calorimetric measurement system and describes novel solutions to minimize the heat leakages from both of the above mentioned points.

Calorimetric loss measurement system

The calorimetric loss measurement system is based on an open type calorimeter. The main control function during **calibration phase** is to attain a steady temperature rise between air inlet to outlet by controlling the blower fan speed. This is followed by the **balance phase** during which the blower fan speed is kept constant, equal to the blower speed recorded during calibration phase and then the power to the heating resistor is controlled until the same temperature rise is obtained.

The main assumption for power balance during calibration and balance phase is that the room ambient conditions remain unchanged; else the results will have significant errors. In past, some calorimeters have been reported which use a preheater stage to control air inlet temperature. In our case, the room temperature is controlled by a separate air conditioning system, thus there is no need for a separate preheater stage. Although utilizing a separate preheater does reduce the risks of errors due to room temperature variation.

Mechanical construction-

The schematic diagram of the calorimeter is shown in the Figure 1. The calorimeter chambers inside dimensions are 1000 x 1000 x 1000 mm, designed to handle power losses up to 3 kW. The calorimeter walls consist of 150 mm of polyurethane sandwiched in between two fiberglass plates. The box houses the test motor, heating resistor and an array of temperature sensors.

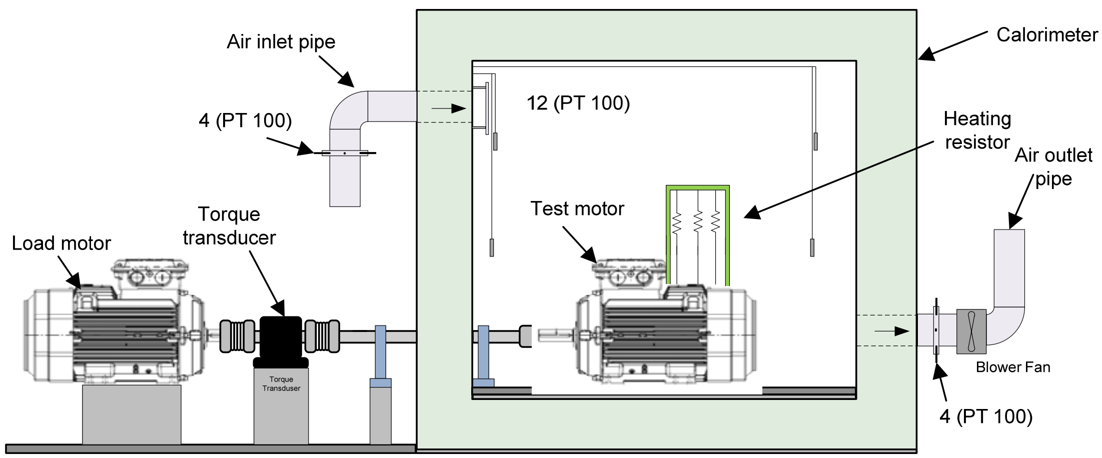

Figure 1: A schematic of the calorimetric loss measurement system

The motor is supported on a metal plate which is bolted to the metal table structure on which the calorimeter is placed. Heating resistor is mounted on the aluminum plate and the PT100 sensor elements are supported on the ceiling. There are 6 sensors on top level and 6 sensors at middle of the chamber. The chamber has openings for motor shaft, inlet and outlet air pipes. The calorimeter can be opened from two sides for easy mounting and dismounting of the test motor. The inlet and outlet air pipes houses four PT100 temperature sensors for accurately measuring the air temperature.

Motor and chamber mounting

The schematic of motor mounting is shown in Figure 2(b). A 5 mm thick aluminum baseplate is used below the chamber and inside on the chamber floor. The aluminum plates help in reducing risks of damage to the calorimeter chamber due to uneven weights and uneven pressures by mounting bolts. The heating resistor is secured to the inside aluminum plate. The motor is mounted on a 20 mm thick steel plate placed on top of aluminum plate using normal steel bolts as shown in Figure 2(b). The mounting arrangement for the steel plate is critical since any mismatch will result into shaft misalignment causing extra stress on the shaft assembly.

The motor shaft assembly

The mechanical assembly of the calorimeter should minimize the heat leakage from the box. The possible leakage points are the motor shaft hole and the chamber (motor) mountings which must be designed carefully to minimize any heat leakage. Motor shaft assembly consists of a long shaft supported by two elevated bearings, one inside the calorimeter and one outside the calorimeter. This shaft is coupled to the motor shaft through a flexible backlash free compact elastomer coupling which minimizes any heat conduction through the motor shaft to connecting shaft. The other end of the shaft is connected to torque transducer through a flexible bellow coupling. The load machine is connected to the torque transducer at the other end.

To avoid any heat leakage through the shaft hole, special rubber sealing are inserted in the shaft hole as shown in Figure 2(a). The calorimeters reported in literature, as in [12], mount the test motor first and then place the calorimeter on top of it, which causes large unsealed portions around the shaft opening and thus are major source of heat leakage. The steel plate is secured to the mounting table using **four fiber glass bolts** as shown in Figure 2. The holes are reinforced with fiber glass tube to avoid any heat leakage and hard fiber bolts are used instead of metal bolts. The use of fiber glass bolts as described above also minimizes any heat flow through motor baseplate.

The shaft height is maintained such that 160 frame size motor can be coupled directly to the interconnecting shaft. Any lower frame motor can also be connected by using additional baseplate, but a larger than 160 frame size motor cannot be tested on existing setup.

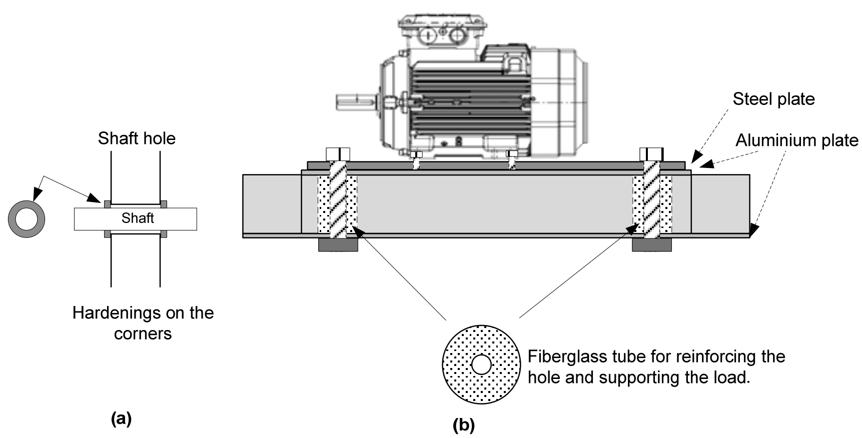

Figure 2: (a) Details of shaft hole, (b) Chamber support arrangement

Air inlet and outlet pipes

The air enters the calorimeter chamber from the top on one side and leaves from the bottom on the opposite side. The blower fan is connected at the outlet pipe which draws the air from inside the chamber. The blower fan is controlled by a separate VSD which runs at the reference speed determined by the control system. Four temperature sensors are mounted on the inlet and outlet pipes to measure the air temperature. The long inlet pipe ensures that the air is thoroughly mixed before entering the chamber.

Electrical cable connections and motor control

The electrical wiring schematic is shown in Figure 3. The load machine is connected to a variable speed drive (ABB ACS800 drive) which is configured in torque control mode. The drive controls the load motor to apply a constant torque to the motor shaft. The test object (motor) can be connected directly to the supply mains for performing loss measurements under sinusoidal supply conditions or alternately it can be connected to a test drive (ABB ACS850) which can rotate the test motor at variable speeds. Two power meters are utilized to measure test converter input and output powers respectively. The current sensors are used to provide current interface to the power meters whereas the voltage inputs are directly connected. A torque sensor and associated acquisition system provides measurement of the mechanical speed and torque at the motor shaft. Both test and load motor converters can be controlled from the central control system.

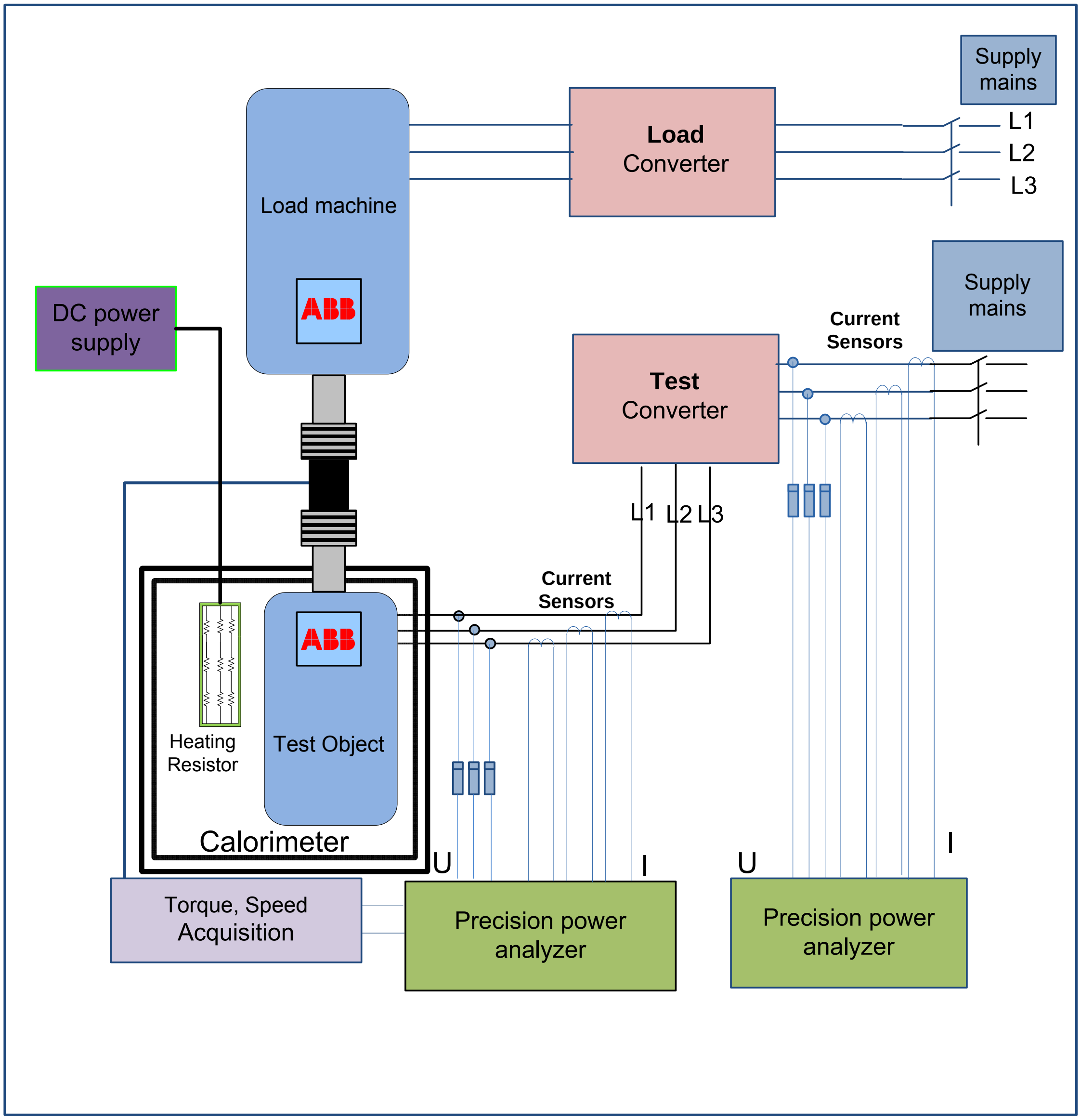

Figure 3: Electrical wiring schematic

Communication interface

The overall instrumentation system is as shown in Figure 4. All the peripheral instruments, as well as power converters are connected to standard Ethernet network. 4 wire PT 100 elements are used to measure temperature at various places of interest like, various points inside calorimeter, air inlet-outlet pipe, motor housing and motor winding temperatures and ambient temperature. The temperature sensing elements are connected to temperature data acquisition instrument, which send the temperature data to main 'data acquisition and control computer' over Ethernet network. Blower fan is driven by a separate variable speed drive (ABB ACS355). The drive receives the command signals from main data acquisition and control system over Ethernet network and also sends the drive data for control and monitoring purposes. The test motor drive also configured to communicate with the main control system computer over Ethernet. The load motor drive receives the command in terms of analog signals from test motor drive.

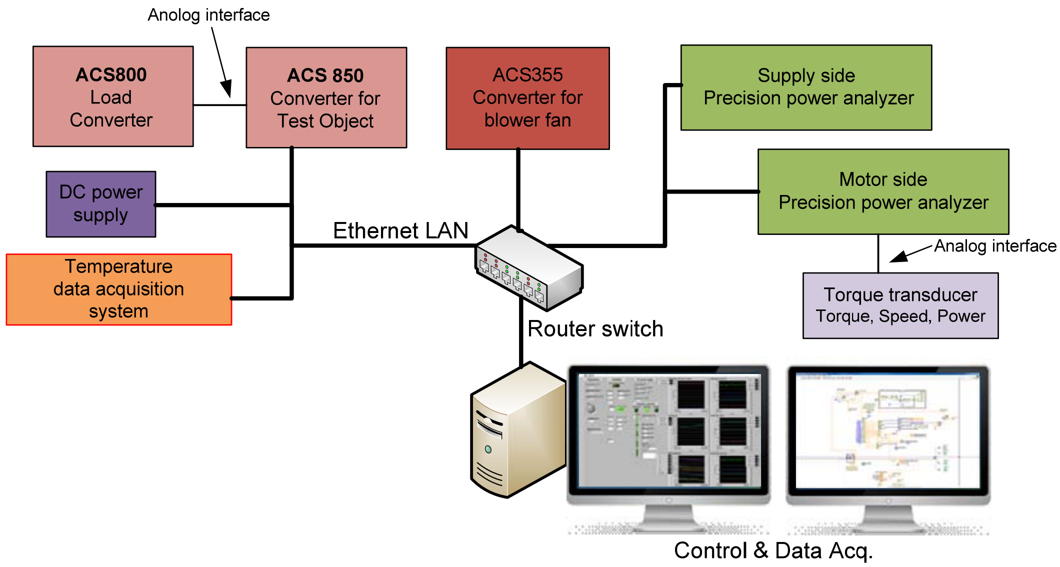

Figure 4: Communication interface between different instruments and control computer

The power meters used in the calorimeter system are Precision power analyzers [23], which are connected to Ethernet network. The speed and torque signals from torque transducer are fed to one of the power meter as analog and digital signals respectively. The DC power supply which is used to provide power to heating resistor elements is also connected to Ethernet network and receives commands from main computer through Ethernet network.

Control system

The control system is designed on LabVIEW platform which runs on a control and data logging computer. The LabVIEW comes with basic library function to establish interface with wide variety of sensing, data acquisition and monitoring equipments and instruments. The interface to temperature data logger, DC power supply, power analyzer is designed using these standard functions. The interface with the test, load and blower fan drive is build using standard Modbus over Ethernet IP protocol. The main tasks of the control system are described as below-

- Data acquisition from peripheral sensors, instruments drives.
- Data logging at specified interval
- PID control for controlling speed of blower during calibration phase
- PID control for controlling heating resistor power during balance phase
- Basic protection functions for chamber, motor over temperature and motor over speed

Experimental tests on an induction motor

The calorimetric measurement system is used to measure the losses of the test induction motor at different load conditions. The induction motor used in the experimental study is a 15 kW, IE2 efficiency class (400 V, 50 Hz, 1500 rpm) induction motor. The motor is tested for efficiency under sinusoidal supply conditions. The motor efficiency is measured as per test methods specified in IEC60034-2-1. First the heat run test performed at different loading conditions and the efficiency is measured as per direct input-output method. This is followed by indirect efficiency measurement as described in method 2- summation of losses, residual losses estimated from stray losses.

Electrical efficiency measurement

Table 1 summarizes the results from direct and indirect efficiency measurement tests with sinusoidal supply. As per IEC 60034-2-1, the motor efficiency from indirect loss measurement can be expressed in two ways- first as function of input power (P_{in}) and losses (P_L) and secondly as a function of losses (P_L) and output power (P_{out}). The efficiency calculation using both methods is shown in Table 1.This is followed by calorimetric loss measurements at rated load point.

Table 1: Summary of motor efficiency measurement using electrical methods

	Load Torque [%]	115	100	75	50	25
Efficiency (%)						
Indirect method	$(P_{in} - P_L)/P_{in}$	90.5	91.2	91.9	91.6	88.1
	$P_{out}/(P_{out} + P_L)$	90.4	91.2	91.9	91.6	88.0
Direct input-output power measurement		90.2	90.2	90.9	91.6	91.2

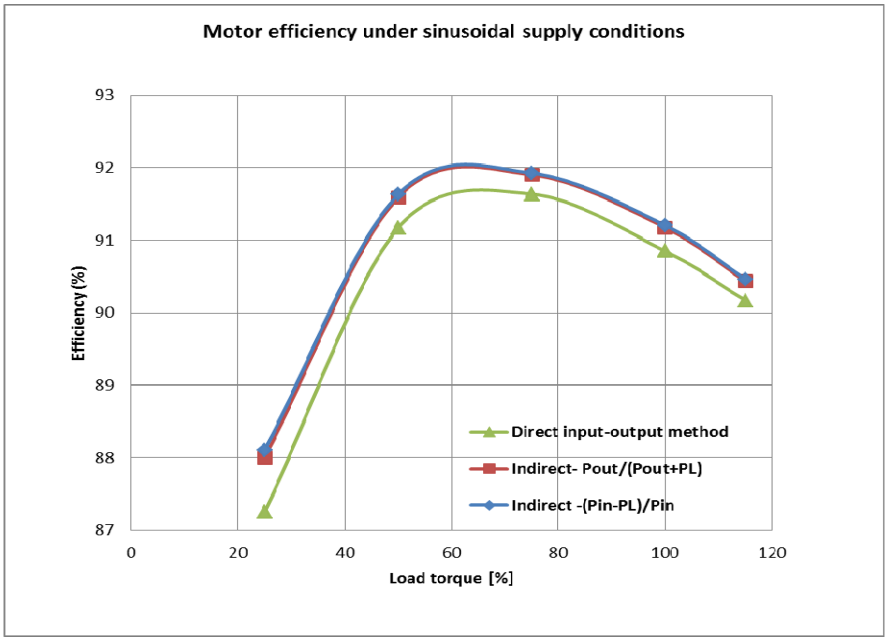

Figure 5: Efficiency of induction motor measured from standard measurement methods

Calorimetric loss measurement tests

The motor is started by directly connecting to line supply and nominal load is applied from the load motor. The reference temperature gradient of 30^0 C is set between inlet and outlet air. The calibration phase is continued until the air blower fan speed is stabilized at a constant value. The room ambient conditions are maintained constant during the test. Since the test object is iron mass, it takes long time to bring it to a constant temperature. In order to speed up the process, the power is also fed to the heating resistor during the initial time to rapidly increase the chamber and motor temperature. The electrical power to the motor during calibration phase is also logged using the data logging system. The P_L* in Table 2 denotes the motor loss (1598.2 W) obtained by subtracting output power P_m measured by torque transducer from electrical input power P_{e_in} during calibration phase.

The balance phase is carried out right after calibration phase. As the motor is already at thermal equilibrium, it helps to speed up the balance test. The DC power is supplied to heating resistor and the blower fan is set to run at the speed recorded during the calibration phase. A PID controller controls the power to the heating resistor in such a manner that the temperature rise between inlet and outlet is equal to the temperature gradient during calibration phase. The recorded power P_{res} at the thermal equilibrium is be equal to 1651 watts as show in Table 2.

Table 2: results summary of calorimetric loss measurement at rated load

		Calibration phase	Balance phase 1 (motor standstill)	Balance phase 2 (motor running at nominal speed)
Temp Diff, ΔT	^{0}C	30.0	30.0	30.0
Blower speed, N_{blower}	RPM	3199.6	3198.1	3198.1
Blower freq	Hz	53.30	53.30	53.30
P_L* (P_{e_in}-P_m)	W	1598.2		
Heating res. Current, $I_{res.}$	A	-	17.8	17.1
Heating res. Voltage, $V_{res.}$	V	-	92.9	89.7
Heating res. Power, $P_{res.}$	W	-	1651	1534.8

Air circulation inside calorimeter during calibration and balance phase

There is one fundamental difference between the air circulation inside calorimetric chamber during calibration phase and balance phase. During calibration phase, there is very good air circulation because of the test motor fan inside the calorimetric chamber. But during balance phase, there is no air circulation inside the calorimetric chamber. This results in the large temperature gradient inside the chamber.

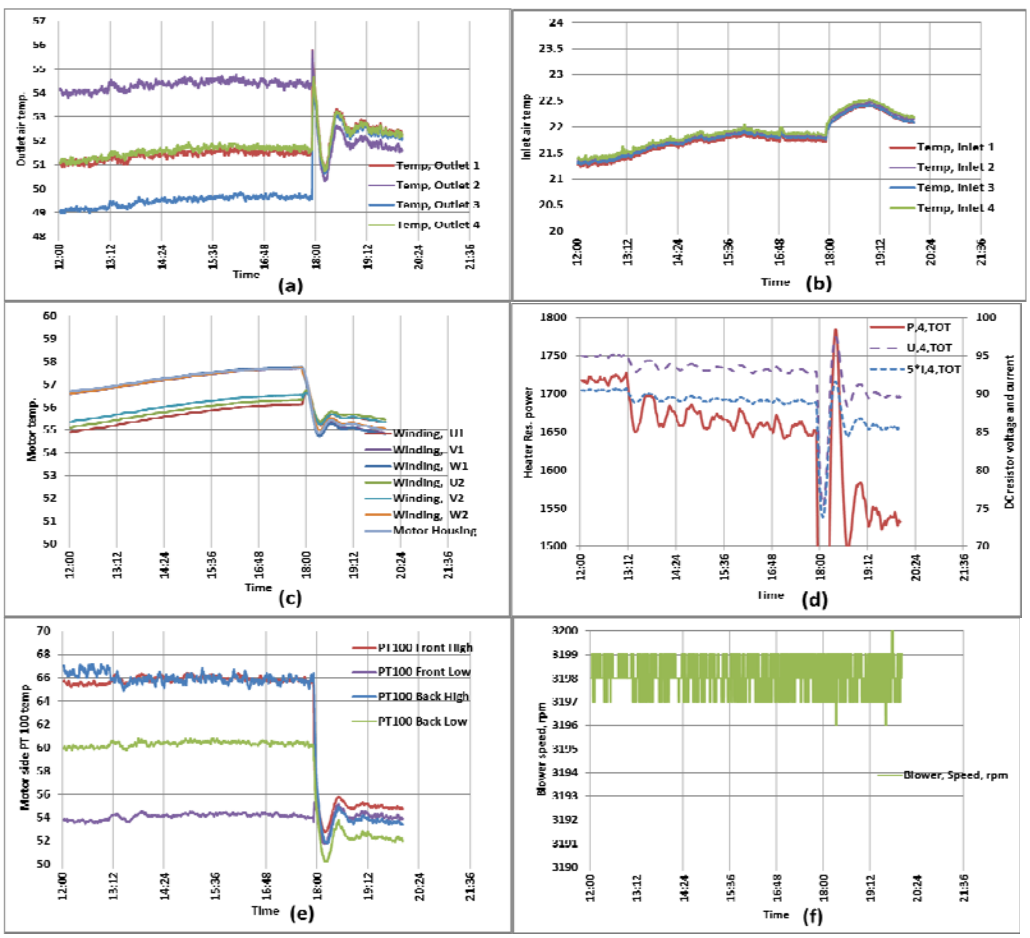

Figure 6: Temperature profile at various points during balance phase (a) outlet pipe, (b) input pipe, (c) motor, (d) heating resistor power, (e) motor side temperature inside calorimeter, (f) air blower speed

This is shown in Figure 6 (e), the motor side temperature sensors show around 12 degrees difference between the top and middle temperature sensor. This even creates a temperature gradient inside motor body which is evident from Figure 6(c). The temperature sensors mounted inside motor at different locations show different temperatures. One option to create similar air circulation during balance phase is to rotate test motor with the help of load motor in the same direction. The load motor drive is now configured in speed control mode and controls the speed of the motor equal to the speed during calibration phase. The temperature gradient diminishes as the test motor is started (at 18:00 hr as shown in Figure 6). The balance phase after this point is referred as “balance phase 2”. The heating resistor power during both balance test phases was found to be equal to 1651 W and 1552 W, the different between these two readings is ~100 W.

The main reason for this variation is that the thermal equilibrium (and air circulation) under both balance phase conditions is very different to each other. When the test motor is driven from load machine, the friction losses in the test motor are supplied by load machine through motor shaft. This causes reduction in the power in the heating resistor. Thus the friction losses supplied by load machine plus heating resistor power shall be considered as total losses during balance phase 2. The shaft power recorded by torque transducer is equal to 107 watts in balance phase 2. As mentioned above, the difference in the heating resistor power during balance phase 1 and balance phase 2 is ~100 W. Thus it can be concluded that when the test motor is rotated using the load drive to avoid temperature gradients, part of the losses (which are mainly friction and windage losses inside test motor) are supplied by load motor. This power should be considered together with heating resistor power is determine total power loss inside calorimeter during balance phase.

Still the mechanical power measured by torque transducer (as described above) can be very erroneous as the torque value in above case is a few percent of the rated torque for the transducer. This can lead to significant errors in torque or power measurements under this condition.

Determination of friction and windage loss

It is possible to estimate the power input through shaft during the balance test 2 using the calorimetric loss measurement system. A separate set of calibration and balance test are performed for this as described below

- During the calibration phase, the test motor is rotated using load machine but no power is fed to the heating resistor. During this phase, the losses inside the calorimetric chamber are only friction and windage losses inside test motor. The temperature rise and blower fan speed is recorded when the thermal equilibrium is reached. It should be noted that in this phase, since the power losses inside the chamber are very small, the temperature gradient is set to very low value, to achieve reasonable blower speed. Otherwise the blower fan may run at very low speed. For better accuracy, the calibration phase is first performed with temperature gradient setting of 4 ^{0}C and then again with 2.7 ^{0}C to obtain two different blower fan speeds for thermal equilibrium. The recoded blower speed at thermal equilibrium is both cases were 1440 rpm and 2170 rpm respectively.
- This is followed by a balance phase in which the temperature gradient and blower speed obtained from calibration phase are set as reference and the DC power to heating resistor elements is controlled to obtain desired temperature gradient. The resulting heating power, blower speed and temperature gradient for two independent temperature gradients of 4 ^{0}C and 2.7 ^{0}C (i.e. the friction losses) are equal to 94 watts and 113 watts. Again this closely matches with the 100 W power difference recorded during balance phase 1 and 2 described in previous section.

The main conclusions from above tests are summarized as below

- The test motor can be rotated using load machine during the balance test to maintain the homogeneous temperature distribution inside calorimeter. This avoids large temperature gradients which otherwise can be generated inside the box because of no air circulation during balance phase.
- In this condition, the total power loss in the balance test is the sum of power input to heating resistor and motor friction and windage losses which are fed by the load motor through motor shaft.

- This part of loss i.e. motor friction and windage loss, fed by load motor can be measured from torque transducer or a separate set of calibration and balance test can be performed. The results from this balance test closely match with the power recorded by torque transducer.

Summary and comparison of motor efficiency measurement at rated power

Table 3 shows the summary of the determined efficiency using electrical and calorimetric loss measurements at rated load under sinusoidal supply conditions. The motor efficiency in case of calorimetric loss measurement is determined assuming the electrical input power during calibration phase. It can be seen that the results are in very close agreement using both type of balance tests. The real advantages with Balance test 2 is that the possibility of large temperature gradients inside calorimeter is eliminated by utilizing motor fan for air circulation.

Table 3: Summary of efficiency measurements at nominal operating condition

Test	Input power, [W]	Measured loss, [W]	Motor efficiency [%]
Electrical measurements (Calibration phase)	16715	1598.2	90.4
Balance phase 1 (test motor standstill)	---	1651	90.1
Balance phase 2 (test motor rotated at nominal speed)	----	1647.8(1534.8 heating resistor + 113 friction loss from load motor)	90.1

Separate fans for air circulation

An alternate way to maintain good air circulation inside the calorimeter chamber is using separate fans mounted at suitable location on the calorimeter chamber ceiling, as shown in Figure 7. In such situation, power fed to the air circulation fans also result in additional losses inside chamber and thus shall be subtracted from losses measured in balance phase.

A balance test is performed wherein the air circulation fans were used for air circulation both during calibration and balance phase. The motor is loaded with nominal torque and speed as before. In this situation, the power measured by calorimeter is approximately 1670 watts, thus measuring approximately 20 watts more than the previous results shown in Table 3. The power to the auxiliary fans is measured using power meter during the test, which was equal to 22 watts. This additional 22 watts gets reflected in the total power loss measured during balance test.

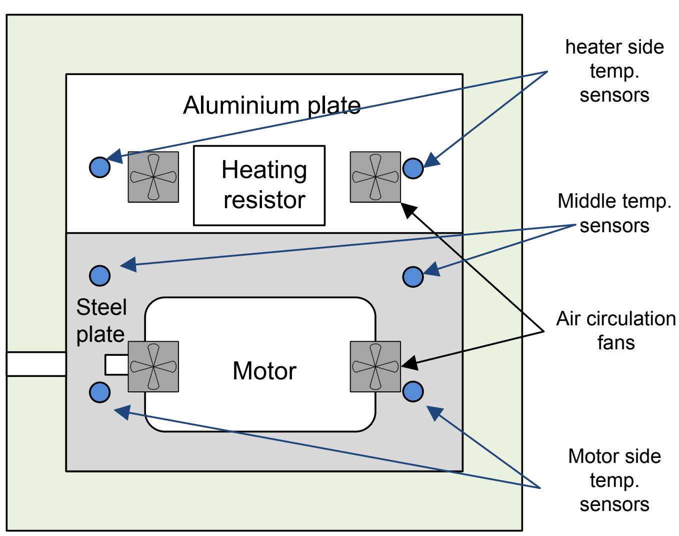

Figure 7: Use of separate fans on calorimeter ceiling for air circulation inside the calorimeter

The difference in temperature between upper and lower temperature sensors during balance tests with use of auxiliary fans is compared with “balance test 1” described in pervious section. Figure 8 shows the temperature gradient between top and bottom temperature sensors at three different locations shown in Figure 7; "motor side" refers to the temperature sensors towards motor side, "heater side" towards heater side, and "middle" is in between heater and motor. The reduction in the temperature gradient is clearly evident. The largest reduction in temperature gradient is obtained directly under the circulating fan (for ex. Heater side temperature difference is reduced from 22.3 ^{0}C to 1.8 ^{0}C. On the other hand, the reduction in temperature is only 6.1^0 (from 17.5 ^{0}C to 11.4 ^{0}C) in the central part. Thus placement of the circulation fans is very important. It is recommended that more number of small fans shall be used rather than using one big fan.

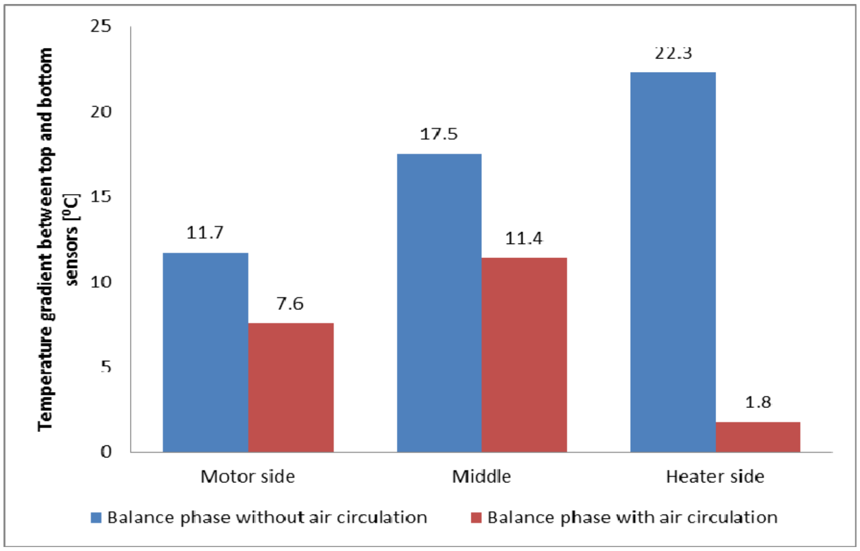

Figure 8: Effect of air circulation fans on temperature gradient inside the calorimeter at three locations

Motor efficiency measurement under VSD supply

The similar procedure is followed to measure the motor efficiency under VSD supply conditions. This section summarizes the results obtained from direct input-output power measurement and calorimetric loss measurement for different four load conditions.

Calibration phase

First calibration test is performed for four different load conditions at rated speed with suitable temperature gradient. The results are summarized in Table 4. A higher value of temperature gradient "ΔT" is required for nominal load conditions to handle higher loss inside calorimeter and it is gradually decreased for partial load conditions. Thus the motor ambient temperature for all load conditions is not similar. The blower speed N_{blower} at thermal equilibrium is summarized in Table 4 for different load conditions. The electrical measurements like motor input power P_{e_in}, output (mechanical) power P_{out}, and so the motor loss $P_{Loss,\ motor}$ is also recorded during the test so that the motor efficiency as per direct input-output methods is known instantaneously.

Balance phase 1

The balance phase 1 is performed right after calibration phase and the test motor is rotated using load motor in this phase to maintain the air circulation. The temperature gradient "ΔT" and blower speeds N_{blower} obtained in calibration phase are used as input variables and the calorimeter is allowed to settle at thermal equilibrium by controlling the DC power fed to heating resistor elements. The heating resistor power $P_{res.}$ at thermal equilibrium condition is taken as the heat loss inside the calorimeter. As the motor is rotated using load motor, the mechanical power from torque transducer is also recorded which indicates the friction and windage losses for the test motor. Instead the second approach (as described in previous section) is followed to estimate this power flow into the calorimeter through motor shaft (i.e. the friction and windage loss supplied by load motor) by performing a separate set of calibration and balance phase experiment. During the calibration phase, the tests motor is driven by load motor and thermal equilibrium is established. As the friction and windage loss is a small percentage of the total loss handling capacity of the calorimeter, the errors in the measurement are anticipated. To increase the measurement accuracy, a constant power of 500 W is fed to heating resistor as a bias power. The thermal equilibrium at temperature gradient of 5 ^{0}C is established at 1800 rpm. The blower speed value obtained at thermal equilibrium is used as reference value during balance phase. The corresponding DC resistor power was found to be equal to 613 W under thermal equilibrium. Thus the friction and windage loss power supplied from load motor is equal to the 113 W (500 W being the bias power). This is used as mechanical power input "P_{mech}" during calculation of total losses during balance phase 1.

Balance phase 2

A second set of balance tests is performed in which the air circulation inside calorimeter is maintained using separate fans. The DC power fed to these auxiliary fans "P_{fan}" is also measured with power meters, and kept constant around 22 W. The resulting heating resistor power "$P_{res.}$" at thermal equilibrium for blower speed "N_{blower}" and temperature gradient "ΔT" values obtained from calibration phase for different load conditions is summarized in Table 4.

Table 4: Summary of calorimetric loss measurement tests with PWM supply conditions

	Load Torque	[%]	100	75	50	25
Calibration phase	$P_{e\ in}$	kW	16.8	12.6	8.6	4.3
	P_{out}	kW	15.0	11.4	7.8	3.7
	$\mathbf{P_{Loss,\ motor}}$	**W**	**1837.3**	**1156.0**	**812.4**	**608.7**
	ΔT	^{0}C	20.0	9.0	5.0	5.0
	N_{blower}	RPM	1447.7	2008.4	2516.9	1628.0
Balance Phase 1	ΔT	^{0}C	20.0	9.0	5.0	5.0
	N_{blower}	RPM	1444.9	2006.9	2507.9	1614.0
	$P_{res.}$	W	1729.9	1069.6	691.0	434.7
	P_{mech}	W	113.0	113.0	113.0	113.0
	$\mathbf{P_{total\_1}}$	**W**	**1842.9**	**1182.6**	**804.0**	**547.7**
Balance Phase 2	ΔT	^{0}C	20.0	9.0	5.0	5.0
	N_{blower}	RPM	1445.8	2010.3	2501.8	1614.0
	$P_{res.}$	W	1793.3	1163.4	804.4	515.7
	P_{fan}	W	22.0	22.1	22.1	22.3
	$\mathbf{P_{total\_2}}$	**W**	**1815.3**	**1185.5**	**826.5**	**538.0**
Motor loss						
Direct input-output	$\mathbf{P_{Loss,\ motor}}$	W	1837.3	1156.0	812.4	608.7
Calorimetric- Balance phase 1	$\mathbf{P_{total\_1}}$	W	1842.9	1182.6	804.0	547.7
Calorimetric- Balance phase 2	$\mathbf{P_{total\_2}}$	W	1815.3	1185.5	826.5	538.0
Efficiency						
Direct input-output		%	89.1	90.8	90.6	85.9
Calorimetric- Balance phase 1		%	89.0	90.6	90.7	87.3
Calorimetric- Balance phase 2		%	89.2	90.6	90.4	87.5

The summary of motor loss and motor efficiency values determined based on above calibration and balance phase tests are also given in Table 4. The results obtained with direct input-output and calorimetric loss measurement system are in close agreement with each other. The only exception is at 25% load torque where the electrical measurements deviate from calorimetric loss measurements by approximately 50 W. The power loss inside calorimeter in this situation is small, thus small errors in loss measurement leads to large variation in efficiency value.

Estimation of heat leakage from the calorimeter

The accuracy of calorimetric loss measurement greatly depends upon the minimizing any heat leakage from the calorimeter. The main source of heat leakage is through the motor shaft and mounting bolts along with the heat dissipated through the calorimeter surface. It should be noted that the accuracy of calorimetric loss measurement is independent of actual value of heat leakage. But it is dependent upon the difference between heat leakage during calibration and balance phase. The heat leakage through the above three locations is determined as described below

Motor shaft

The heat flow through the motor shaft occurs due to different surface temperature inside and outside the calorimeter. Two temperature sensors are mounted at these locations and used to monitor the temperatures during the tests. Then the actual heat conduction through motor shaft is determined based upon the temperature gradient, cross section area, and length of shaft between the temperature sensors as

$$p_{shaft} = kA\frac{\Delta T_{shaft}}{x} \qquad \textbf{(1)}$$

Where p_{shaft} is heat conduction through shaft, *k* is the thermal conductivity ($Wm^{-1}K^{-1}$), A is the area of cross section (m^2), ΔT_{shaft} is the temperature difference (K), and *x* is the distance of heat flow (m) [12]. For steel shaft, the diameter is 42 mm, the thermal conductivity of the steel is 50 ($Wm^{-1}K^{-1}$) [20], and the distance between the inner and outer temperature sensor 150 mm (insulation width). The corresponding values of heat flow through shaft are given in Table 5 for both calibration and balance phase (the analysis is only performed for balance phase 1 described in previous section). It should be noted that the temperature gradient across the shaft is a negative value for 20%, 50% and 75% load condition. This is due to the local heat produced by the supporting bearing on the interconnecting shaft. It is found that the outer bearing is producing more heat than the bearing inside calorimeter and thus the actual heat flow is in reverse direction.

Mounting bolts

The motor baseplate is secured to the foundation using four glass fiber bolts. Two temperature sensors are mounted on top and bottom of the one of the bolts to measure the heat conduction through these bolts and the temperature measurements at these points are recorded during calorimetric tests. Since the glass fiber bolts are good resistors of heat (thermal conductivity of glass fiber is 0.04 ($Wm^{-1}K^{-1}$)), the heat flow through the bolts is very small. Thus the temperature recorded by temperature sensors mounted on outer side of bolt does not show any influence from the temperature inside calorimeter (although it is changing with respect to change in ambient room temperature, this is indicated by $\Delta_{Bolt\_ambient}$ in Table 5). It can be concluded that the heat leakage through the mounting bolts can be neglected.

Calorimeter surface

The heat flow through calorimeter surface can be expressed as,

$$p_{surface} = U_{surface}.S_{surface}.\Delta T_{surface} \qquad \textbf{(2)}$$

where $U_{surface}$ is heat transfer coefficient of calorimeter wall material, $S_{surface}$ is the surface area and $\Delta T_{surface}$ is the temperature gradient between inner and outer surface of the calorimeter [12]. The temperature of the inner surface is very difficult to measure. Even though the proper heat circulation inside the calorimeter chamber is maintained, the inner surface temperature at different points is not constant due to local vertical temperature gradients. Therefore average of the temperature measured by sensors inside calorimeter is considered as inner surface temperature. The total heat leakage $p_{leakage}$ from calorimeter is determined as below

$$p_{leakage} = p_{surface} + p_{shaft} \tag{3}$$

The estimated value of heat dissipation according to the above described procedure is summarized in Table 5 for calibration and balance phases.

Table 5: Estimation of heat leakage through different points

	Load Torque	[%]	100	75	50	25
Calibration phase	Temp, Shaft inside	^{0}C	55.8	46.1	41.3	39.2
	Temp, Shaft outside	^{0}C	49.2	47.0	44.8	46.8
	ΔT_{shaft}	^{0}C	6.6	-1.0	-3.5	-7.6
	p_{shaft}	**W**	**3.1**	**-0.4**	**-1.6**	**-3.5**
	Temp, Bolt inside	^{0}C	42.4	31.7	26.8	24.5
	Temp, Bolt outside	^{0}C	20.6	21.3	21.0	19.9
	Temp, inlet	^{0}C	21.5	22.6	21.7	21.1
	Δ_{Bolt}	^{0}C	21.8	10.4	5.9	4.6
	$\Delta_{Bolt\_ambient}$	^{0}C	1.0	1.3	0.8	1.2
	Surface					
	$\Delta T_{surface}$	^{0}C	20.3	9.2	5.4	5.1
	$p_{surface}$	**W**	**50.2**	**22.9**	**13.4**	**12.6**
Balance phase 1	Temp, Shaft inside	^{0}C	51.6	40.6	36.5	37.4
	Temp, Shaft outside	^{0}C	51.2	46.8	45.9	46.9
	ΔT	^{0}C	0.4	-6.2	-9.4	-9.5
	p_{shaft}	**W**	**0.2**	**-2.9**	**-4.4**	**-4.4**
	Temp, Bolt inside	^{0}C	43.4	29.0	22.8	23.6
	Temp, Bolt outside	^{0}C	21.4	20.6	20.4	20.2
	Temp, inlet	^{0}C	22.7	22.2	21.1	21.1
	Δ_{Bolt}		22.0	8.4	2.3	3.4
	$\Delta_{Bolt\_ambient}$	^{0}C	1.3	1.6	0.7	1.0
	Surface					
	$\Delta T_{surface}$	^{0}C	20.8	7.4	3.6	4.9
	$p_{surface}$	**W**	**51.6**	**18.4**	**9.0**	**12.1**
$p_{leakage}$	Calibration phase	W	53.3	22.4	11.8	9.0
	Balance phase 1	W	51.8	15.5	4.7	7.7
	Difference		**1.5**	**6.9**	**7.1**	**1.3**

It can be seen from Table 5 that the biggest portion of the heat leakage is from the calorimeter surface whereas the heat leakage from motor shaft and mounting bolts is comparatively small. As mentioned earlier, the accuracy of the calorimetric loss measurement is dependent upon the difference between the heat leakage during calibration and balance phase. This difference is very small compared to the actual loss measured during the tests as shown in Table 5. Thus its addition to the actual measured loss will not result into big variation in the efficiency values which are presented in Table 4. This also confirms the superior construction of the calorimeter.

Conclusions

The main purpose of the work is to validate the electrical (direct input-output) efficiency measurements procedures being used extensively in ABB using alternate efficiency measurement methods like calorimetric loss measurement. A calorimetric loss measurement system is built for this purpose and series of the tests were performed to measure the efficiency of the induction motor at different load conditions. The special construction methods are followed to avoid any heat leakage through motor shaft and motor mountings. These are the main concerns (points of heat leakage) when measurements on electric motor are performed inside calorimeter. The electrical efficiency is determined as per direct input-output method and this was followed by calorimetric loss measurement on rated load condition under converter supply. Because of the cooling fan of the motor, the air circulation inside calorimeter is gets affected during calibration phase. To maintain the similar conditions as calibration phase, the test motor is rotated with the help of load machine during balance phase. The additional power flows inside calorimeter through motor shaft during this condition which is the friction and windage losses inside test motor and this power should be accounted in the total losses during calibration phase. A separate set of calibration and balance phase is performed to measure this power flow from motor shaft. The measured friction and windage loss is then considered together with heat resistor power to determine the total loss under different load conditions. The resulting loss and efficiency values are in close agreement with the direct input-output method.

The heat leakage by conduction through shaft is calculated based on measured shaft temperature inside and outside of calorimeter. Similarly, the non-variation of temperature recorded by temperature sensor at outer side of mounting bolt indicates that there is no heat leakage through the mounting bolt. It is seen that the estimated value of leakage loss is smaller as compared to the power loss measured by calorimeter and thus considering the leakage value in total loss will not change the estimated efficiencies considerably.

It is also observed that the calorimeter accuracy can be further enhanced by controlling the temperature of the inlet air to the calorimeter. Since the calorimeter stability is based on temperature gradient between inlet to outlet temperature, any slight variation in inlet temperature will cause the whole motor mass inside the calorimeter either to absorb or dissipate the heat. This introduces errors in the loss measurement. Clearly, the situation can be avoided by use of external inlet temperature controller. Another source of error is the friction loss produced by the supporting bearing used for interconnecting shaft. One of the support bearing is inside the calorimeter. The heat produced by this bearing also contributes to the heat inside calorimeter. Thus the losses measured by calorimeter are higher than the actual motor losses. Suitable methods to measure and compensate for these bearing losses are the next steps towards accurate loss measurements using calorimetric method.

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Current developments in IEC standards for energy efficiency of electric motors and for the IECEE global motor energy efficiency (GMEE) program

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Abstract

Following the mandates M/470 for standardization in the field of electric motors (June 2010) and M/476 for standardization in the field of variable speed drives and/or power drive systems (November 2010) a number of projects were launched at IEC ([4], [5], [6]) and CENELEC ([1], [2], [3]) level. Furthermore, a new IECEE initiative has been started to develop a global motor energy efficiency label ([7], [8]) including procedures for laboratory accreditation, certification and compliance testing. This paper provides an update on the current status and further development of these projects.

Introduction

The European Commission has established the first directive to save energy already in 2005 (Energy Using Products (EuP) Directive [10]). The directive allows the European Commission to develop measures to reduce the eco-impact of energy using products within the EC. One of the focal points were industrial electrical motors as they convert the largest part of the generated electrical energy in Europe.

Based on that directive a study was commenced to assess the impact of energy efficiency regulations of electric motors (Lot 11 Study [12]). The outcome of the study led to Commission Regulation 640/2009 ([13]) implementing measures to improve the energy efficiency of electric motors.

Similar implementing measures have been introduced for a number of other products as well, for example circulators (641/2009), fans (327/2011) and water pumps (547/2011).

Measures are introduced in three timely steps: From 16 June 2011, all electric motors in the power range between 0,75 kW and 375 kW must comply with the IE2 (High efficiency) class. From 1 January 2015, all motors with a rated output of 7,5 kW up to 375 kW running directly on-line must furthermore comply with the efficiency class IE3 (Premium-Efficiency). Finally, from 1 January 2017, all motors with a rated output of 0,75 up to 375 kW that are operated direct on-line must comply with the efficiency class IE3 (Premium-Efficiency).

To acknowledge the energy saving benefit of variable speed and variable torque operation it was agreed that motors fed by power electronics with variable voltage and frequency can remain on the IE2 level.

In the meantime, the EuP directive was succeeded by the Energy Related Products directive (ErP-Directive [11]), which has a broader scope.

Several measures were started by the European Commission to prepare for a future Regulation of electric motors and other energy using products. In particular, two standardization mandates and several new preparatory studies were initiated.

Four of the new studies are related to electric motors. They deal with motors outside the range of regulation 640/2009 including special purpose motors (Lot 30), waste water pumps (Lot 28), pumps for swimming pools (Lot 29) and compressors (Lot 31).

The studies are expected to conclude in 2014. The European Commission will then commence an impact assessment and draft for new implementing measures. It is expected that the adoption phase needs at least one to two years. A successor to the Commission Regulation 640/2009 can therefore be expected in 2015 … 2016 at the earliest.

Mandate M/470 EN

The aim of the mandate is to create harmonized standards for measurement procedures for establishing energy consumption and other parameters of motors, which are reliable, accurate and reproducible. Furthermore, the range of motors was broadened significantly. Variable speed motors shall be covered as well as all other types of motors, such as single phase induction motors, permanent magnet synchronous motors and reluctance motors. The output power range was increased starting from 0,2…0,5 kW up to at minimum 500 kW. Part load efficiencies at 50% and 75% are requested as well as a future efficiency class IE5. Finally, testing tolerances shall be redefined and reduced and a template for a test report is required.

The mandate was issued to CENELEC TC2, which decided in good tradition to pass it on to IEC TC2. At IEC level, three activities were started.

IEC 60034-2-1

A document for comments (2/1538/DC) was issued already in December of 2008 to request proposals for the revision of IEC 60034-2-1 Ed 1 (2007-09), the standard for determining losses and efficiency from test. In subsequent meetings of IEC TC2 working group 28, a first committee draft of the new standard was prepared and published in December of 2011 (2/1648/CD). After further revisions and meetings a committee draft for vote (CDV) was issued in January of 2013 (2/1687/CDV). The voting result (2/1704/RVC) was very successful with 26 positive votes and 3 abstain. At their last meeting in May 2013 in Istanbul, Turkey, WG28 therefore prepared the final draft for the next edition of this international standard. The FDIS paper is expected by summer of this year.

Compared to the first edition of IEC 60034-2-1, a number of changes will be introduced.

The whole document structure has been revised to make it more readable and user friendly. Furthermore, flow charts have been introduced to demonstrate the individual tests and their sequence in the testing procedure clearly. Figure 1 gives an example.

All test procedures are now associated with unambiguous names to simplify referencing. Preferred testing methods are given for all motor types, see Figure 2.

The accuracy requirements for testing equipment have been revised and adapted to modern laboratory standards.

Finally, a new annex will be included in the FDIS giving a test report template.

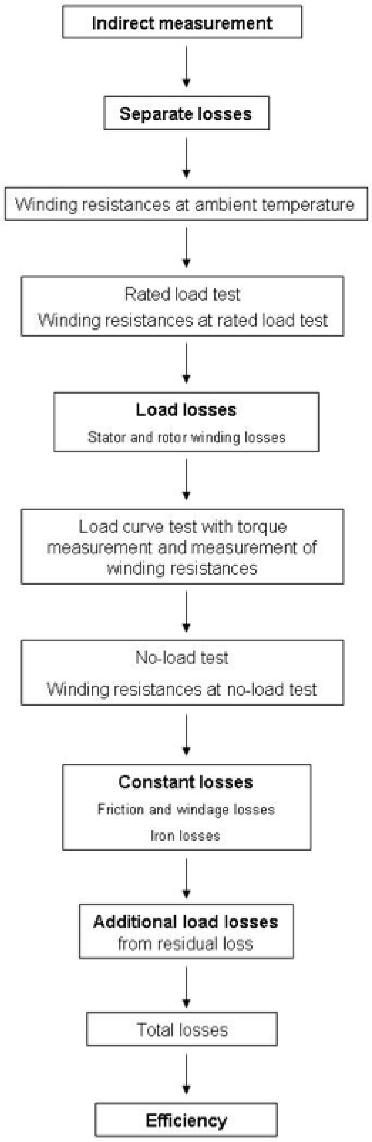

Figure 1: Flow chart to visualize the sequence of testing (from [4])

Ref	Method	Description	Clause	Application	Required facility
2-1-1A	**Direct measurement: Input-Output**	Torque measurement	6.1.1	All single phase machines	Dynamometer for full-load
2-1-1B	**Summation of losses: Residual losses**	P_{LL} determined from residual loss	6.1.2	Three phase machines with rated output power up to 2 MW	Dynamometer for 1,25 x full-load
2-1-1C	**Summation of losses: Assigned value**	P_{LL} from assigned value	6.1.3	Three phase machines with rated output power greater 2 MW.	

Figure 2: Preferred testing methods for induction machines (from [4])

IEC 60034-2-3

IEC TC2 WG 28 started the new project IEC 60034-2-3 with the document 2/1570/CD in August of 2009. It is an extension of the testing standard IEC 60034-2-1. While the latter is limited to motors that are operated direct on-line, the new project will deal with motors being operated on variable voltage and variable frequency, i.e. being fed from an electronic power converter.

A committee draft for vote (2/1626/CDV) was issued in April 2011. It received a mixed response with 12 positive and 8 negative votes out of a total of 26 total votes cast. WG28 decided to reduce the status of the project from International Standard (IS) to Technical Specification (TS) due to the lack of experience with the new test procedures. A new draft of the technical specification (2/1696/DTS) was published in January 2013. Unfortunately, the voting results and comments (2/1696/DTS) were not yet available at the last meeting of WG28 in May in Istanbul. The voting was positive with 18 of 24 countries voting in favor and so the publication of the TS is envisaged for October 2013.

For the time being, IEC 60034-2-3 is limited to AC induction motors. The objective of the technical specification is to define test methods for determining the additional harmonic motor losses associated with converter feeding. They appear in addition to the losses on sinusoidal power supply as determined by the methods of IEC 60034-2-1.

Naturally, the type and operation mode of the frequency converter (in particular switching frequency and type of modulation) will have a large impact on the associated motor losses. In order to make motors comparable and to allow for the testing of motors that are not intended for just one specific frequency converter, IEC 60034-2-3 defines a test converter, which has a very typical behavior of current day industrial converter products.

When it is required to test the combined losses of motor and frequency converter (power drive system PDS) or just the losses of the frequency converter alone, this technical specification does not apply. The activities regarding mandate M/476 EN will provide a solution to this task (see below).

IEC 60034-2-3 will give four different methods to determine the harmonic losses, see figure 3.

Ref	Method	Description	Clause	Required facility
2-3-A	**Summation of losses:** **Test-converter supply**	Harmonic loss determination with test-converter according to Annex A	6.1	Sinusoidal supply and test-converter supply for full-load operation
2-3-B	**Summation of losses:** **Supply with specific converter for final application**	Harmonic loss determination with converter for final application	6.2	Sinusoidal supply and specific converter supply for full-load operation
2-3-C	**Input-Output**	Torque measurement	6.3	Dynamometer for full-load; Specific converter supply
2-3-D	**Calorimetric**	Loss determination from coolant temperature rise	6.4	Specific converter supply. Measurement according to IEC 60034-2-2

Figure 3: Test methods for the determination of the efficiency of converter-fed motors (from [5])

In essence, the two summation of losses methods of IEC 60034-2-3 are related to the well-established procedures of IEC 60034-2-1. However, the no load losses and the residual losses (additional load losses) are determined twice: Once with sinusoidal power supply and once with frequency converter supply.

The difference between the no-load losses with a sinusoidal power supply and converter supply is the constant part of the additional harmonic motor losses. The difference between the additional load losses with a sinusoidal power supply and converter supply is the additional harmonic motor losses.

The third procedure, input-output, is straightforward. However, due to the nature of this method it can only be used with good accuracy when the efficiency level of the motor under test is not too high (below some 90%).

The fourth method, calorimetric, is limited to very special applications, in particular to motors that are equipped with a primary and/or secondary water-cooling circuit.

It should be added that there is currently some debate among experts regarding the liability of the tests procedures and the accuracy, which can be expected. A working group has been established on CENELEC level (CLC/TC2/WG1) with the target to gain more experience with the testing procedures of IEC 60034-2-3. It is expected that the results of this working group will lead to an improved version of the TS within the next years.

IEC 60034-30

This standard is about energy efficiency classification; in particular it defines the efficiency limits of the efficiency classes IE1 (low efficiency), IE2 (high efficiency), IE3 (premium efficiency) and IE4 (super-premium efficiency). The first edition was established by IEC working group 31 already in October 2008.

The revision of this standard based on the new requirements of mandate M/470 EN was started with the publication of a committee draft (2/1632/CD) in May 2011. It was followed by a second committee draft (2/1652/CD) in December 2011.

At that time it was decided to split the standard in two parts. IEC 60034-30-1 would cover energy efficiency classes of line operated AC motors and IEC 60034-30-2 would deal with motors operated on variable voltage and frequency.

The first project was developed further by issuing a committee draft for voting (2/1679/CDV) in September of 2012. The voting result was very positive with just one negative vote out of 31 total votes cast. Therefore, IEC WG31 decided at their last meeting in Istanbul, Turkey in May 2013 to continue the project by issuing a final draft international standard (FDIS). Publication is expected by October 2013.

IEC 60034-30-1 widens the product range covered in IEC 60034-30 ed. 1 significantly. The power range has been expanded (starting at 0,12 kW and ending at 1000 kW). All technical constructions of electric motors are now covered as long as they are rated for on-line operation and not just three-phase, cage-induction motors as in the first edition. That includes, for example, line-start permanent-magnet motors (LSPM), which have become increasingly popular in recent years.

The IE4 classification will be newly included in the standard. The informative definition of IE4, which was previously included in IEC/TS 60034-31, will become obsolete.

The new class IE5 is not yet defined in detail but is envisaged for potential products in a future edition of the standard.

New limits for 8-pole motors have been introduced at special request.

A number of loopholes, that enabled clever manufacturers and customers to circumvent energy efficiency regulations with little or no effort, have been closed. For example, all motors that are rated for an operating temperature within the range of -20 °C to +60 °C are now covered. All motors rated for an operating altitude up to 4 000 m above sea level are covered as well.

Still there are a number of motors that cannot be rated, for example motors completely integrated into a machine. Brake motors are only excluded when the brake is an integral part of the inner motor construction and can neither be removed nor supplied by a separate power source during the testing of motor efficiency. This definition will include more than 99% of all brake motors in the efficiency classification and leave an exception only for a very tiny part of the market.

Fortunately, many of these loopholes, which were also present in the Commission Regulation 640/2009, will be closed by the European Commission as well in due time.

The standard now includes a table with different motor technologies and their energy-efficiency potential as seen by the group of experts, see figure 4. This table is particularly aiming at regulators. It shall create awareness that an overly strict energy efficiency regulation may hurt motor technologies that are still common in the market place and their special applications.

Motor type		IE1	IE2	IE3	IE4	IE5
Three-phase cage-rotor induction motors (ASM)	Random wound windings (all enclosures, all ratings)	Yes	Yes	Yes	Difficult	No
	Form wound windings; IP2x (open motors)	Yes	Yes	Difficult	No	No
	Form wound windings; IP4x and above	Yes	Yes	Yes	Difficult	No
Three-phase wound-rotor induction motors		Yes	Yes	Yes	Difficult	No
Single-phase induction motors	Start capacitor	Difficult	No	No	No	No
	Run capacitor	Yes	Difficult	No	No	No
	Start/run capacitor	Yes	Difficult	No	No	No
	Split-phase	Difficult	No	No	No	No
Synchronous motors	Line-start permanent-magnet (LSPM[a])	Yes	Yes	Yes	Difficult	No

[a] Line-start permanent-magnet motors have limitations on their line-start capabilities with respect to torque and external inertia and may not be suitable for all types of applications.

Figure 4: Motor technologies and their energy-efficiency potential (from [6])

The first draft of the second project, IEC 60034-30-2 for rating of energy efficiency of motors fed by frequency converters, was prepared by WG31 at their Istanbul meeting. The FDIS (2/1709/NP) has been accepted and so the project will continue.

The testing of efficiency will be related to IEC 60034-2-3. Unfortunately that standard is, for the time being, limited to AC induction motors. However procedure 2-3-C (input-output) is applicable to all kinds of variable speed motors and will therefore be preferred for the classification of IEC 60034-30-2.

It is obvious that any rating of variable speed motors cannot be based on full speed and full load performance only. The whole purpose of variable speed drives is to provide different operating points at different speeds and loadings.

There are two basic types of applications most often used: Constant torque (as in elevators, belt drives etc.) and square torque (as in pumps, fans etc.). The new standard will acknowledge this by introducing an average efficiency over a number of characteristic load points for these basic applications. The procedure is somewhat similar to the well-known driving cycles that are used to determine the fuel consumption of cars.

The individual efficiencies will be determined at seven characteristic load points along the two torque/speed curves, see figures 5 and 6. The average will be calculated taking a weighting factor into account that represents a typical operating time in the particular points. At the end, just one single value of average efficiency is created. This value is then classified according to the already known IE classes. In order to take the extra harmonic losses into account, new efficiency tables for variable speed motors will be created.

It is known that some motors are operated at speeds above their rated speed with constant power (reduced torque). This operation is also called “field weakening”. Such conditions are rarely used in industrial applications (it is common for traction drives) and will therefore not be assessed by the classification procedure.

Constant torque applications		
Speed	Torque	Weighting Factor (WF)
100	75	0,20
75	75	0,30
50	75	0,30
25	75	0,20

Figure 5: Proposed load points of constant torque applications (from [16])

Square torque applications		
Speed	Torque	Weighting Factor (WF)
100	100	0,33
75	50	0,33
50	25	0,33

Figure 6: Proposed load points of square torque applications (from [16])

Mandate M/476 EN

This mandate was also given to CENELEC and passed on to working group 6 of CENELEC TC22X for further processing. Subsequently, three projects were started.

Project prEN 50598-1 will give basic procedures how to assess efficiency of power drive systems including their driven applications by means of an extended product approach (EPA) and a semi analytic model (SAM)-

Project prEN 50598-2 deals with the energy efficiency of power drive systems, motor starters, power electronics and their drive applications. This is certainly the most interesting project for motor and power electronics manufacturers and their users as it handles the efficiency determination and classification of frequency converters and power drive systems (PDS).

Finally, project prEN 50598-3 handles environmental aspects and and the product declaration for power drive systems and motor starters.

Committee drafts for voting have been published for all three projects in September 2013.

It is planned to bring the second standard (EN 50598-2) to IEC level by using the Unified Acceptance Procedure (UAP). That means, the relevant working group (IEC/SC22G/AG15) will publish the original CENELEC standard for voting by IEC by the end of 2014. If all goes well, an IEC approved standard can be published in 2015.

IECEE GMEE

Already in June of 2012, IEC TC2 WG31 issued a document for comments that raised three questions with regards to the further steps necessary for implementing energy efficiency regulations not currently addressed by IEC standards.

These are, for example, questions regarding the certification of test laboratories, the number of samples of motors to be tested, the frequency of re-certification, statistical procedures to demonstrate compliance based of a number of test results etc.

In particular, the following questions were given to the IEC national committees:

1. Should IEC/TC 2 develop a standardized procedure for the determination of energy efficiency classification of electric motors by the manufacturer as an IS or TS?

2. Should there be an accreditation procedure for testing laboratories (similar to the IEC Ex scheme)? "IEC System for Certification to Standards relating to Equipment for use in Explosive Atmospheres (IECEx System)", see: http://www.iecex.com/about.htm

3. Do national committees envisage support for solutions in 1 or 2 above by the legal bodies in their countries?

The outcome of the questionnaire was published in 2/1686/INF in October 2012. It can be summarized as follows: 10 out of 14 NCs supported question 1, 8 out of 14 NCs supported question 2 and 8 out of 12 NCs supported question 3.

In parallel to this questionnaire, IECEE has started the E3 Global Energy Efficiency (GMEE) Program addressing similar issues. For that reason WG31 decided at their last meeting to leave all future actions in this field to IECEE.

IECEE is a sister organization to IEC. It establishes worldwide systems for conformity testing and certification of electrotechnical equipment and components. On request by the Motor and Generator Section of NEMA (the Association of the North American electrical equipment manufacturers) IECEE is exploring the opportunity to design and operate a program on energy efficient electric motors. The program was effectively launched on September 5, 2012. It is based on the existing NEMA Premium Efficiency electric motor program but tailored for global use.

Two task forces have been established to work out future action plans. Task force 1 is about Policies and Procedures, task force 2 about technical requirements. The action plans will be presented to the IECEE Steering Committee in October of 2013, which will then decide how to proceed. If the plan is accepted, the GMEE program can start as early as 2014.

For the time being, the European motor manufacturers (CEMEP) do not support the GMEE project.

Summary

On request of the European Commission numerous standardization projects on energy efficient electric motors have been started on IEC level. IEC 60034-2-1 is improving testing procedures for motors operated direct on-line. IEC 60034-2-3 is a new project on testing frequency converter fed motors. IEC 60034-30-1 is an update of the energy efficiency classification standard IEC 60034-30 and IEC 60034-30-2 is a new classification standard for variable speed motors. All projects are well under way and should be finalized in the next 1-2 years.

Glossary

IEC	International Electrotechnical Commission; http://www.iec.ch
CEN	European Committee for Standardization; http://www.cen.eu
CENELEC	European Committee for Electrotechnical Standardization; http://www.cenelec.eu
ETSI	European Telecommunications Standards Institute; http://www.etsi.org
NEMA	National Electrical Manufacturers Association; http://www.nema.org
TC	Technical Committee

SC	Sub Committee
WG	Working Group
CD	Committee Draft
CDV	Committee Draft for voting
FDIS	Final Draft International Standard
IS	International Standard

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[4] IEC Project 60034-2-1 Ed. 2.0. *Standard methods for determining losses and efficiency from tests.* 2/1687/CDV, January 2013.

[5] IEC Project 60034-2-3 Ed. 1.0. *Specific methods for determining losses and efficiency of converter-fed AC machines.* 2/1696/DTS, January 2013.

[6] IEC Project 60034-30-1 Ed. 1.0. *Efficiency classes of line operated AC motors (IE-Code).* 2/1679/CDV, September 2012.

[7] IEC Document for Comments 2/1673/DC. *Energy efficiency determination procedures.* June 2012.

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[10] Directive 2005/32/EC of the European Parliament and of the Council of 6 July 2005 establishing a framework for the setting of ecodesign requirements for energy-using products and amending Coucil Directive 92/42/EEC and Directives 96/57/EC and 2000/55/EC of the European Parliament and of the Council

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[12] *EUP Lot 11 Motors Final Report February 2008*; A. Almeida, F. Ferreira, J. Fong, P. Fonseca

[13] Commission Regulation (EC) No 640/2009 of 22 July 2009 implementing Directive 2005/32/EC of the European Parliament and of the Council with regard to ecodesign requirements for electric motors

[14] M/470 EN; Mandate to CEN, CENELEC and ETSI for Standardisation in the field of electric motors; European Commission Directorate-General for Energy; Brussels, 23rd June 2010

[15] M/476 EN; Mandate to CEN, CENELEC and ETSI for Standardisation in the field of variable speed drives and/or Power Drive System products; European Commission Directorate-General for Energy; Brussels, 30th November 2010

[16] IEC Project 60034-30-2; *Efficiency classes of variable speed AC motors (IE-code)*; unpublished

An energy efficiency measurement test bench for gearboxes

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Abstract

Over the last decade, forced regulations and a growing social awareness with respect to energy efficiency have resulted in a renewed interest in the research for high efficient electrical machines. When an electrical motor is coupled to a machine, in many cases a gear or belt is used. Research shows a lack of information on energy efficiency of these components. In comparison to electrical motors and drives, there is very few regulation and if efficiency values can be found in catalogues, there's no regulated test procedure available to validate the data. As a result, the reliability of these efficiency values is low and comparison between manufacturers and technologies is impossible.

Regulation on energy efficiency on the other hand evolves to a total system approach such as the new European fan directive 327/2011. Information on the efficiency of mechanical transmission components such as gearboxes and belt drives will be required to invest on which drive train part it is most recommended to invest in order to optimize the overall system efficiency.

Due to the lack of reliable information on energy efficiency of these components, the need for a test bench emerged. This paper discusses the test bench build for testing gearboxes up to 15kW in their entire working area. In the first part of the paper the technical set-up and influence factors on measurements are discussed. Secondly a test procedure will be proposed to ensure reliable and reproducible results. Finally the first results obtained by this procedure are presented and discussed.

Technical description and construction test bench

The purpose of the test bench is to measure gearbox efficiency at different loads and speeds within the allowed working area of the gearbox. Industrial gearboxes come in various types and power ranges. With the gearbox test bench it is possible to test a large scope of these types for a power range until 15kW.

Test benches for tests on gear sets are fairly common. In such cases it is just one gear wheel pair that is being tested (Figure 1). Wear, load capacity, oil level, seal friction and efficiency are subjects which can be tested with these test rigs.

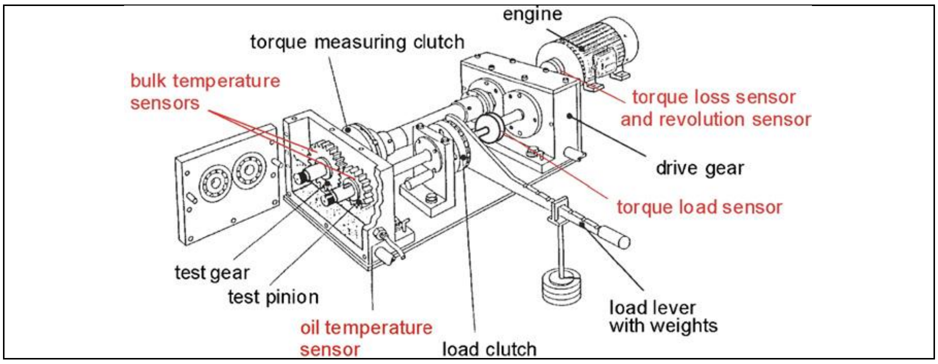

Figure 1: FZG back-to-back test rig with add-ons for efficiency tests [1]

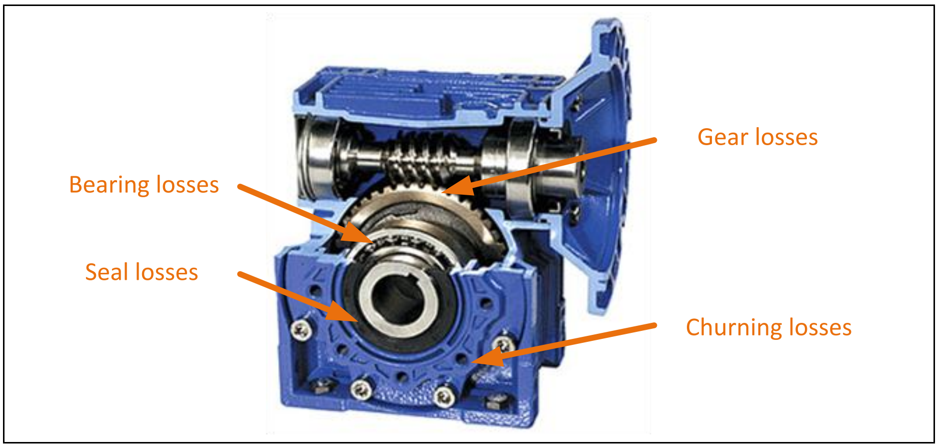

Figure 2: Typical gearbox losses

An industrial gearbox however usually contains more than one gear wheel pair. As can be seen in figure 2, the typical gearbox losses are located at some specific locations.

The gears are fixed in their right position by means of bearings, which have friction losses. While transmitting power, losses occur in the gear pairs as gear losses. The lubrication oil is transported via the gears which result in churning losses. To prevent the oil from leaking out of the gearbox, seals are implemented and they also result in some friction losses. To measure the efficiency of a complete gearbox a few different principles can be applied.

Back-to-back mechanical

An equal setup as in figure 1 could be used to test a complete gearbox. To do so two identical gearboxes with same ratio should be connected to each other at the input axes and respectively at output axes as shown in figure 3.

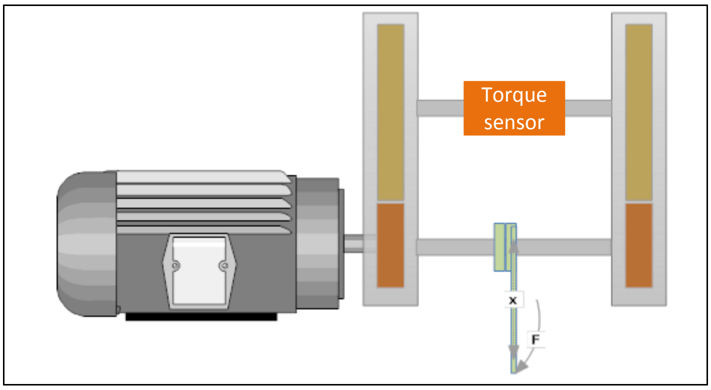

Figure 3: Back-to-back test bench complete gearbox

To load the transmissions a preload has to be set at ‘X’ and by applying a speed, different work points can be reached. The efficiency is determined by measuring the mechanical power from the motor which is equal to the losses from the two gearboxes together. This method could work for gearboxes with parallel axes but in many cases it’s not possible to connect in- and output axes to each other. The rotation of both gearboxes is also opposite. Losses of gearboxes can be rotation dependent and gear boxes of the worm wheel type can sometimes only be run in one rotation sense. As a result, the back-to-back mechanical setup is not universally applicable.

Calorimetric method

This is a test method in which the losses in a machine are deduced from the heat produced by them. With the right equipment this would be possible to do and it can result in a very high accuracy, but reminding that the purpose is to test at a large set of different loads and speeds, the measuring time would be very large because at every working point the whole test set up has to be thermally stabilized which would take too much time.

Back to back electrical

Another way to measure the efficiency of a gearbox is to drive it with an electrical motor on one side and load the gearbox with a motor on the other side (figure 4). The drive motor sets the speed, the load motor sets the torque and works as a generator. The generated energy can be used for the drive motor or can be send back into the grid. In this case two torque and speed measurements are necessary to determine the efficiency.

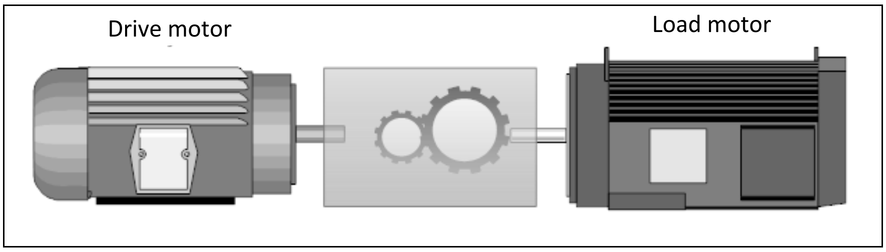

Figure 4: Back-to-back electrical

Usually a gearbox reduces the speed and enlarges the input torque. This means the load motor has to be able to deliver a large torque, which generally means a motor with higher power range. To solve this problem a second gearbox can be implemented to reduce the torque so the load and drive motor can be equally sized. This is shown in figure 5.

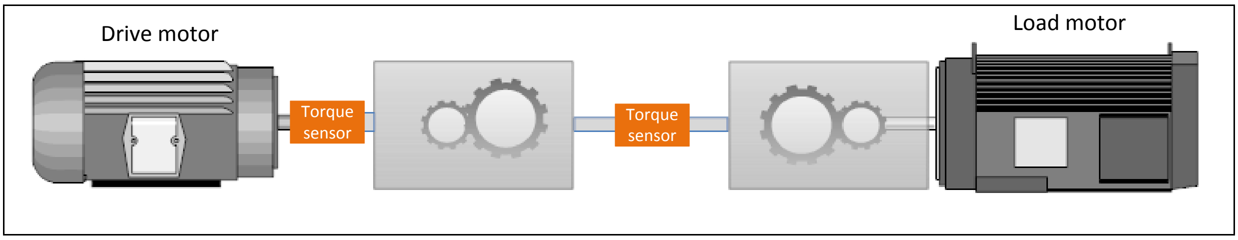

Figure 5: Back-to-back electrical with reducer

This test method is used for the test bench discussed in the paper. The method allows a large range in types and power for gearboxes to be tested. Also it will be possible to measure the efficiency at different speed and load points in a flexible way. The accuracy of the efficiency determination depends on the speed and mainly on the torque measurement, so selection of these sensors will be important.

Actual test bench

sizing

A lot of industrial gearboxes are used for conveyors and other applications in the lower power range. Therefore a 15kW, 4 pole induction motor was selected at drive and load side. 4-pole because in gearbox catalogs a speed of 1400rpm is very common. Usually double speed is also allowed for gearboxes and with the 4 pole drive motor this can easily be reached with the help of a frequency converter. To ensure that the chassis doesn't become too complex and heavy and therefore expensive, a maximum permissible torque of 1000Nm is chosen. To be able to load the gearbox at 1000Nm a torque reducer with a ratio of 10:1 is selected. Taking into account these parameters the range of gearboxes that can be tested is defined and presented in table 1.

Table 1: Measuring range test bench (limiting values in red)

	Input Power	Input Torque	Input speed	Max. ratio gearbox	Output torque gearbox	Output speed gearbox	Load torque	Load speed
Max P	15 kW	100 Nm	1460 rpm	10	1000 Nm	140 rpm	100 Nm	1460 rpm
	15 kW	50 Nm	2920 rpm	10	500 Nm	292 rpm	50 Nm	2920 rpm
Min P	0,12 kW	0,78 Nm	1460 rpm	1282	1000 Nm	1,14 rpm	0,78 Nm	11,4 rpm
	0,12 kW	0,39 Nm	2920 rpm	2564	1000 Nm	1,14 rpm	0,39 Nm	11,4 rpm

The nominal torque of a 15kW, 4 pole induction motor is about 100Nm. Given the maximum torque for the test bench of 1000Nm the ratio of a 15 kW gearbox cannot be higher than 10. When the input speed doubles the limiting factor is no longer the torque but the speed of the load motor.

Measurement principle

The aim is to conduct steady state measurements, i.e. constant speed and constant load torque. The loading of the gearbox is realized by means of the reducer gearbox via an induction machine with regenerative VSD in field oriented torque control mode and speed feedback. The drive side VSD, also with speed feedback, drives the gearbox at desired speed. By connecting both VSD’s via DC-bus the energy flows from generator to drive side and only the losses of the system have to be added from the grid.

The direct method is used to determine the overall efficiency. It requires accurate measurement of the mechanical in- and output power. The torque is measured by means of dedicated ‘dual range’ torque sensors with an accuracy of 0.1% full scale. At input side the torque range is 10Nm/100Nm and at output 100Nm/1000Nm. The speed is measured using an incremental encoder of 1024 pulses/rev. at input side and at output side a 360 pulses/rev. encoder embedded in the torque sensor. The ambient and gearbox temperature are measured and logged with calibrated thermocouples type K. Also the temperatures of the torque sensors are logged. The impact of temperature is explained further on in this paper.

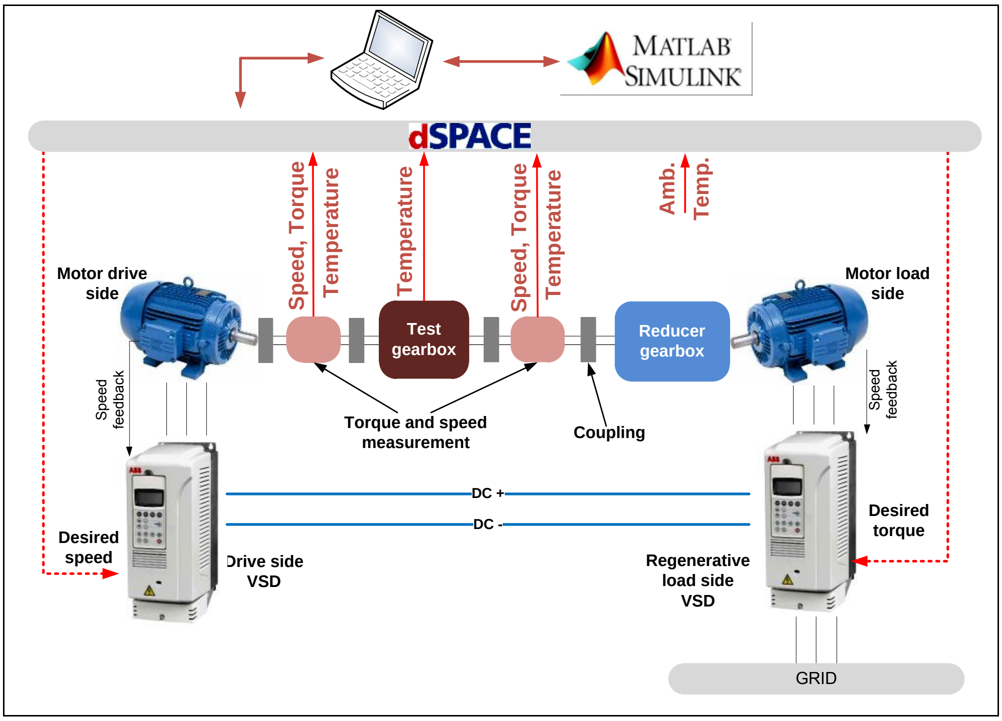

Figure 6: measurement principle gearbox test bench

The control of the test bench is done with an embedded dSPACE 1103 acquisition board in combination with Matlab Simulink and dSPACE ControlDesk. With this system the desired torque and speed set points are regulated and all the measurement data is synchronized captured and logged.

Mechanical design

Industrial gearboxes come in many sizes and types. In contradiction to electrical motors there is no standardization in terms of shaft height, shaft diameter, foot connection, etc… . Consequently the design of the test bench has to be very flexible in order to test all types of gearboxes. As can be seen in figure 7 the height of the drive motor, load motor and test gearbox can be adjusted independently. The base plate of the gearbox under test is adjustable so all the different dimensions for fixation can be handled. In figure 7 the setup is made for an angled gearbox but the drive motor can rotate 90° so a straight gearbox can be tested too.

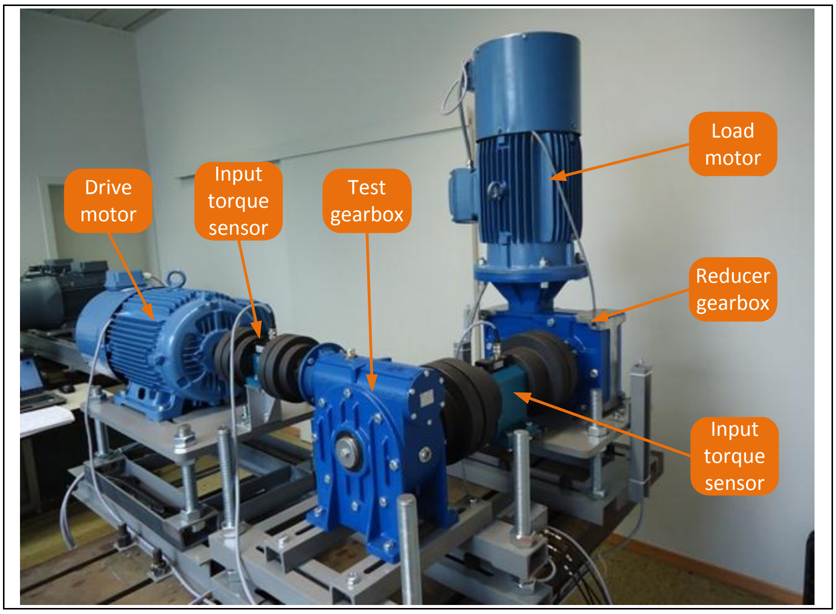

Figure 7: Mechanical design gearbox test bench

Measurement accuracy

Test bench accuracy

The efficiency is determined by direct measurement of the mechanical in- and output power and can be calculated as follows:

$$\eta_{gearbox} = \frac{P_{out}}{P_{in}} = \frac{M_{out}\ x\ \omega_{out}}{M_{in}\ x\ \omega_{in}} \qquad (1)$$

$\eta_{gearbox}$	*gearbox efficiency*	*[%]*
P_{out}	*output power*	*[W]*
P_{in}	*input power*	*[W]*
M_{out}	*output torque*	*[Nm]*
M_{in}	*input torque*	*[NM]*
ω_{out}	*output speed*	*[rpm]*
ω_{in}	*input speed*	*[rpm]*
i	*ratio*	*[/]*

Because of the mechanical design of the gears the speed ratio can be considered as constant [2]. If the ratio is brought into the calculation, formula (1) evolves to:

$$i = \frac{\omega_{in}}{\omega_{out}} \qquad \eta_{gearbox} = \frac{M_{out}}{M_{in}\ x\ i} \qquad (2)$$

In this way the fault on the speed measurement doesn't affect the efficiency value if the exact ratio can be determined. The accuracy of the efficiency determination is then solely depending on the torque measurement at in- and output. The two selected torque sensors are equipped with strain gauges and have a contactless signal transmission from rotor to stator. The sensors have a dual torque range to benefit the accuracy at low torque measurement points. The torque sensor specs are listed in table 2.

Table 2: Specifications torque sensors

	Input torque M_{in}	Output torque M_{out}
Type	DR-2531	DR-2531
Range	10Nm / 100Nm	100Nm / 1000Nm
Accuracy	0,1% f.s.	0,1% f.s.
Speed measurement	No	360 Impulse, 2 x TTL
Output	± 10V DC	± 10V DC

The relative fault (RF) on the efficiency can be calculated by summing up the relative faults on the torque measurements (formula 3).

$$\eta = \frac{M_{out}}{M_{in}.\, i} \qquad RF_{\eta}(tot) = RF(M_{in}) + RF(M_{out}) = \frac{AF(M_{in})}{|M_{in}|} + \frac{AF(M_{out})}{|M_{out}|} \qquad (3)$$

The fault on the torque consists of three different parts. The torque signal itself has a fault of 0,1% full scale. The analog voltage output signal which represents the torque is captured via an analog digital converter of the dSPACE acquisition board. Due to the 16 bits resolution of the AD converter over a bandwidth of 20V (±10V) this absolute fault (AF) is:

$$AF_{resolution} = \frac{20V}{2^{16}} = 0{,}3mV \qquad (4)$$

The fault given by the manufacturer on the AD conversion is 0,25%. This fault together with faults due to the cables and signal isolation are compensated by calibrating the acquisition system. A constant voltage is put on the system input and precisely measured with a voltage meter with an accuracy of 0,1%. The measured calibration values are compared and used to correct the output signal. Because of this calibration the fault is reduced from 0,25% to 0,1%.

The fault calculation can be illustrated by following example. Measured input torque is 95Nm and output torque is 920Nm for a gearbox with ratio 10.

Fault input torque sensor: Range 100Nm; 0,1% full scale

$$AF_{M\,in} = 100Nm\ x\ \frac{0{,}1}{100} = \pm 0{,}1Nm$$

Fault A/D converter input signal: Range 10V; 0,1% full scale

$$AF_{AD\,in} = 10\,.\frac{0{,}1}{100} = \pm 0{,}01V = \pm 10mV$$

$$100Nm \asymp 10V$$

$$AF_{AD\,in} = \pm 0{,}10Nm$$

Fault resolution converter input signal: $100Nm \asymp 10V;$

$$AF_{R\,out} = 0{,}0003V\ x\ 10Nm/V = 0{,}003Nm$$

Fault output torque sensor: $Range\ 1000Nm;\ 0{,}1\%\ full\ scale$

$$AF_{M\,out} = 1000Nm\,.\frac{0{,}1}{100} = \pm 1Nm$$

Fault A/D converter input signal: Range tot 10V; 0,25% full scale

$$AF_{AD\,out} = 10\,.\frac{0{,}1}{100} = \pm 0{,}01V = \pm 10mV$$

$$1000Nm \asymp 10V$$

$$AF_{AD\,out} = \pm 1Nm$$

Fault resolution converter output signal: $1000Nm \asymp 10V;$

$$AF_{R\,out} = 0{,}0003V\ x\ 100Nm/V = 0{,}03Nm$$

Fault on efficiency:

$$RF(tot) = \frac{AF(M_{in}) + AF(AD_{in}) + AF(R_{in})}{|M_{in}|} + \frac{AF(M_{out}) + AF(AD_{out}) + AF(R_{out})}{|M_{out}|}$$

$$= \frac{0{,}1 + 0{,}1 + 0{,}003}{95} + \frac{1 + 1 + 0{,}03}{920} = 0{,}00434$$

$$\eta = \frac{M_{out}}{i\ x\ M_{in}} = \frac{920Nm}{95Nm\,.10} = 0{,}968$$

$$AF(tot) = |\,\eta\,|.RF(tot) = 0{,}968\,.\,0{,}00434 = 0{,}00420$$

$$\boldsymbol{\eta = 96{,}8\,\% \pm 0{,}4\%}$$

An absolute error of ±0,4% is reached with a measurement point close to full range of the sensors. If the torque sensors only would have a single range and a point at low load would be taken, the fault will be much larger. This is shown in table 3 were an example is given for two different load points.

Table 3: fault comparison one range - dual range sensor

M_{in} = 8Nm **M_{out} = 76Nm**	**Single range sensors**	**Dual range sensors**
Total RF	5,2086%	0,5209%
Total AF	95% ±4,9%	95% ±0,5%
M_{in} = 12Nm **M_{out} = 115Nm**	**Worst case**	
Total RF	3,5%	3,5%
Total AF	95,8 ±3,3%	95,8 ±3,3%

If the measured torques lie just beneath the first torque range the fault gets high when only one range would be available. With the dual range sensor this is avoided. When a point just above the first range (10Nm resp. 100Nm) is taken, the fault will be at its highest. In table 3 one can see in worst case the absolute error on the test bench is about 3,3%.

Temperature dependency measurements

An important parameter which influences the efficiency measurements is the temperature. Figure 8 shows a graph where an efficiency measurement is performed at different ambient temperatures on a reference gearbox.

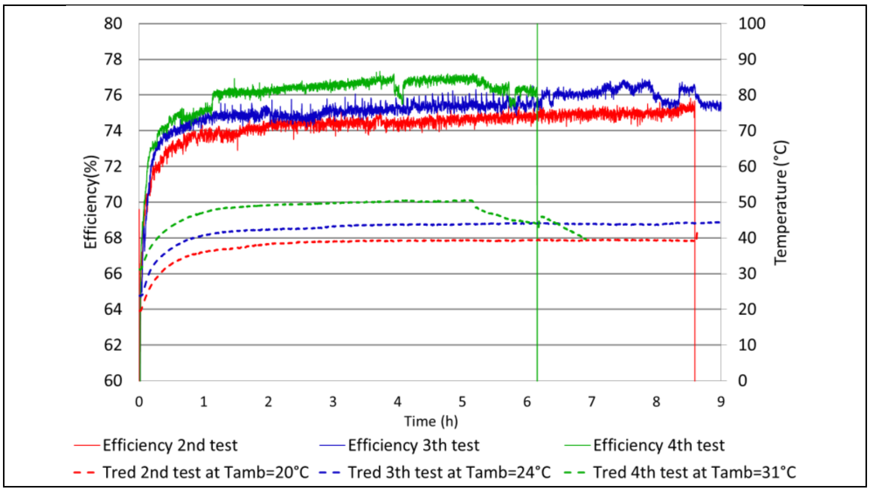

Figure 8: Efficiency comparison at different ambient temperature

The gearbox is loaded with a constant nominal torque and runs at nominal speed. The tests show a significant efficiency difference when the ambient temperature varies. A temperature rise of 10°C results in an efficiency rise of ±2%. The causes of the temperature dependency can be found partly in the temperature sensitivity of the torque sensor. To counteract these effects a thermal model was made up for the torque sensor. By measuring the temperature of the sensors at every measuring point, the model can be used to compensate this error. Other causes are the gearbox depended parameters such as oil temperature, mounting position, oil level and mechanical properties. The oil temperature influences the viscosity of the oil which influences o.a. the friction losses and thus the efficiency of the gearbox [3]. To make sure the test bench gives reproducible measurements it is important to stabilize the ambient temperature. Therefore the complete test setup was placed in a temperature controlled room.

Measurement procedure (Flowchart) gearbox efficiency tests

In order to guarantee reproducibility and obtain accurate measurements, a measurement protocol has been setup. The gearbox under test first is fixed on the test bench and the gearbox in- and output shaft are precisely aligned with respectively the shaft of the drive and load motor. The oil level has to be checked with the prescribed level in accordance with is installation position.

Running-in test

Before starting the actual efficiency measurements, the gearbox is subjected to a running-in test. In the first operating hours a gearbox doesn't work at its nominal efficiency. First the gears will run in and in this way 'polish themselves'. In the most gearbox catalogs this running-in is also stated and a running-in period of 24 to 48 hours is mentioned before nominal values are reached. To start up the running-in test the gearbox is driven and loaded at rated values for a minimum of 48 hours. After this period the measurement values, especially efficiency and gearbox temperature, are checked until they stabilize.

Start-up test

This second test is carried out to confirm the gearbox has run in and reproducible measurements can be obtained. After cooling down from the running-in test until ambient temperature it is started up again at nominal load and speed. If the same gearbox temperature and efficiency are being reached the next step in the procedure can be taken. Otherwise, the start-up test is performed again from ambient temperature until reproducible results are obtained. Usually this start-up test takes about 1 to 2 hours depending on the size of the gearbox. The stabilized gearbox temperature will be used as reference temperature for the next experiments.

ISO efficiency map measurement

Before starting the tests a measuring grid has to be defined. Using the catalog data the maximum speed and corresponding maximum load are specified. The determination of the minimum number of measurement points required to obtain an accurate ISO efficiency map for a gearbox is important. With the experience gathered out of a previous project [4] concerning ISO efficiency maps of VSD's and electrical motors a measuring grid (figure 8) of 16 different torque values and 19 speed measurement points is defined.

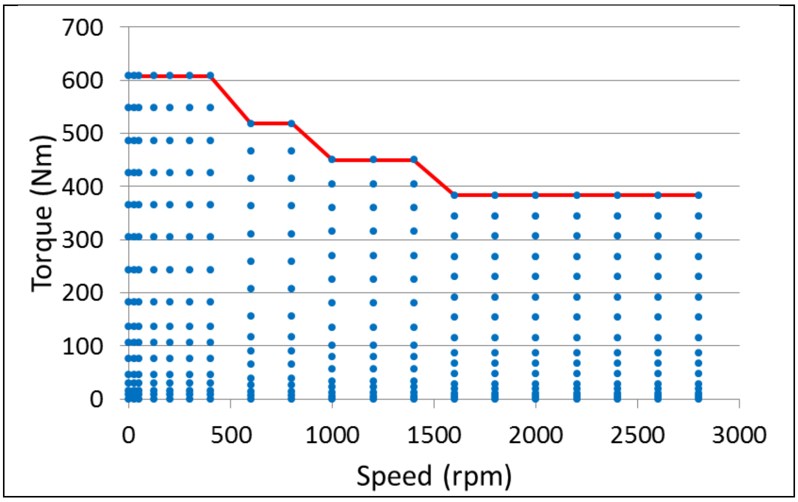

Figure 9: Example of a 16x19 measuring grid for a gearbox

As can be seen from figure 9, the measurement points are not evenly distributed over the entire operating area of the gearbox. A higher concentration is required in the regions near zero torque and zero speed because it is expected that the efficiency in those regions varies more.

The measurements start directly after the start-up test when the gearbox runs at operating temperature. During the measurements at different torques and speeds, a temperature window of 3°C is allowed. After measuring all the points the measurement data is organized in matrices which can be handled in Matlab to construct ISO efficiency maps.

First test results

The first measurements with the test bench have been done for a comparison of a worm gearbox and a bevel gearbox. Both types are right angle transmissions which have a similar scope. The specifications of the gearboxes are presented in table 4.

Table 4: Specifications worm and bevel gearbox

	Worm gearbox	Bevel gearbox
ω_{in} (rpm)	1400	1400
i	80	77,76
ω_{out} (rpm)	17,5	18
M_{out} (Nm)	450	505
P (kW)	0,82	1
$\eta_{catalog}$ (%)	62	95
Gear stages	1	2
Oil viscosity (mm²/s)	220	320
Ambient temperature (°C)	23	23

The worm gear unit reached a stable efficiency of ±74% at nominal load after about 70 hours. This means a 12% higher efficiency compared to the catalog value. After about 90 hours the bevel gear reached a stable efficiency of ±84% resulting in a 11% lower efficiency than specified in the catalog. These differences show that catalog efficiency doesn't give a good view on the performance of the gearbox. A reason could be, in comparison to electric motors, that there is no standardized test procedure by which the efficiency of gear units can be determined. Each manufacturer probably has its own methods and therefore catalog efficiencies of different manufactures are not comparable.

Next the measurements for the ISO efficiency map where carried out and the results are shown in figure 10 and 11. For the worm gearbox, at rated speed and torque the efficiency is maximum. The efficiency decreases both with decreasing speed as torque.

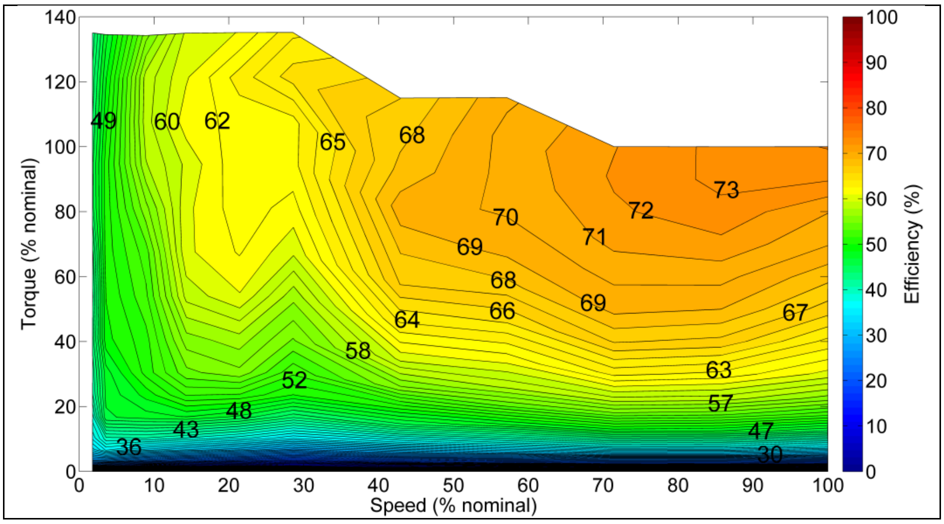

Figure 10: ISO efficiency map worm gearbox

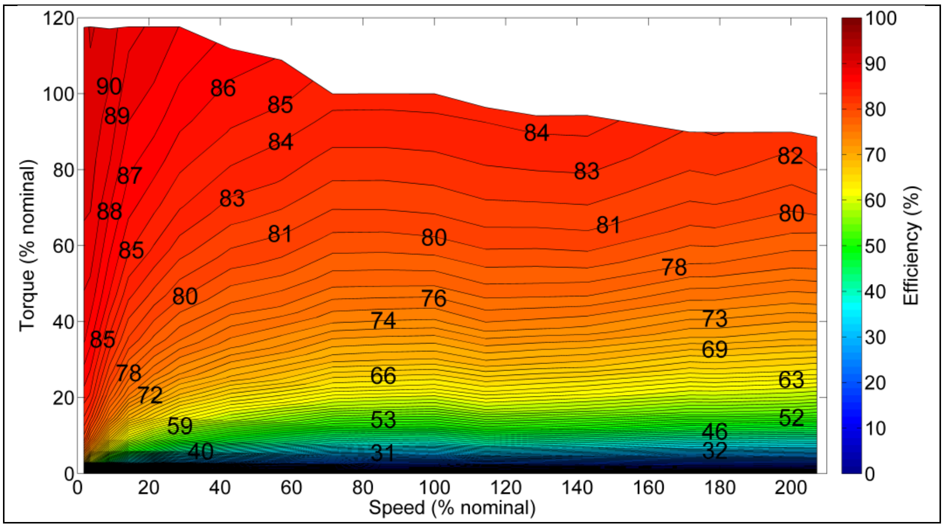

Figure 11: ISO efficiency map bevel gearbox

For the bevel gearbox, the highest efficiency is achieved at low speed and rated torque. It is also noticeable that a speed variation has a much smaller effect on the efficiency compared to a torque variation. Only when the speed falls below 60% of the nominal speed, with torque kept constant, it has a positive impact on the efficiency. A torque reduction always leads to a lower efficiency.

In order to easily compare the two measurements with each other, a difference contour map is generated and presented in figure 12. At rated speed and load the efficiency of the bevel gear unit is about 10% higher compared to the worm gearbox. When the speed decreases and torque remains stable, this efficiency gain increases up to 38%. For low torque, the efficiency gain is lower.

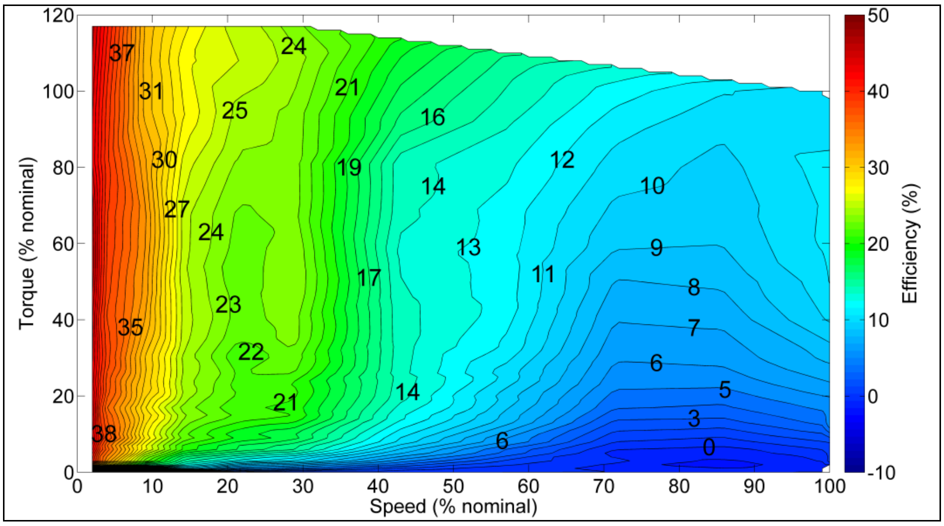

Figure 12: Difference contour map: bevel versus worm gearbox

Conclusions

This paper discusses the methods, design and measurement principles of a test bench to measure the efficiency of a large range of types of gearboxes. Also typical influences on gearbox efficiency measurements are discussed. A flowchart to perform the measurements is designed to ensure reproducible and trustworthy measurements. At last the first measurements on a worm- and bevel gearbox are presented and shortly discussed.

The accuracy of the efficiency measurement mainly dependents on the torque sensors. Therefore two dual range sensors were selected with a high accuracy. Temperature has a large impact on the determination of the efficiency. When the ambient temperature varies, it affects the torque sensors and the gearbox temperature thus the gearbox oil temperature, and so also the efficiency varies. Not only oil temperature but also oil level and mounting position, which also influences the oil immersion depth of the gears, influences the gearbox efficiency. All these influence factors show the need for some standardization in the field of efficiency testing for gearboxes.

With the first measurements a large difference is noticed between measured efficiencies and catalogue values. Here it would also be helpful to have standardization. Manufacturers now determine the efficiency in different ways, with different ambient temperatures, based on theoretical calculations, etc. As a result, the catalogue values can not be compared.

The ISO efficiency maps of the worm and bevel gear also show that the maximum efficiency is not reached at the same working point. If the gearbox runs at a lower torque the efficiency drops. Especially with worm gears this is also the case when speed drops. At this time such information isn't available for customers and machine builders causing them to make a selection for a particular machine which is not optimal in terms of energy efficiency.

Further research is still needed and is being done at the moment to enlarge the scope of measurements for different types, ratios and powers. This will help to inform gearbox users on how to select the best gear for their application.

Usage of a more efficient gearbox requires less power from the electric motor to produce the same output torque. Downsizing the motor rating can add to system efficiency and cost.

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Review of Energy Efficiency Measurement Standards for Induction Motors in the Context of the IECEE Global Efficiency Labeling Initiative

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Abstract

As part of The International Electrotechnical Commission (IEC) System for Conformity testing and Certification of Electrotechnical Equipment and Components (IECEE) initiative, a new Certification Body (CB) Scheme is proposed for global labeling of the efficiency classes of electric motors. A CB scheme is intended to reduce obstacles to international trade which arise from having to meet different national certification or approval criteria. Where national standards are not yet based on IEC standards, declared national differences will be taken into account; however, successful operation of the Scheme presupposes that national standards are reasonably harmonized with the corresponding IEC standards.

For the determination of electric motor efficiency, IEC 60034-2-1 (2007) is currently under revision. Two testing standards from the Institute of Electrical and Electronics Engineers, IEEE Standard 112 and from the Canadian Standards Association, CSA C390, are also applied globally and are either under revision or have recently been published. Recently, much effort has been undertaken to harmonize these and other countries efficiency standards but differences in the procedures and specifications still exist. This paper reviews the latest editions of these standards, published or with the modifications likely to be accepted in the current revisions, and presents the outcomes in relation to the global labeling initiative.

1 Introduction

As part of the International Electrotechnical Commission (IEC) System for Conformity testing and Certification of Electrotechnical Equipment and Components (IECEE) initiative, a new Certification Body (CB) Scheme is proposed for a global labeling for the efficiency classes of electric motors. A CB scheme is intended to reduce obstacles to international trade, which arise from having to meet different national certification or approval criteria. Where national standards are not yet completely based on IEC standards, declared national differences would be taken into account; however, successful operation of the Scheme presupposes that national standards are reasonably harmonized with the corresponding IEC standards.

The IEC testing standard 60034-2-1 (2007): "Rotating Electrical Machines – Part 2-1: Standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles)" is actually used by many country members for the determination of electric motor efficiency. This edition is currently under revision (FDIS stage) and a new edition should be published by the end of 2013. Among other standards in use, one from the Institute of Electrical Engineers: "IEEE 112 Standard Test Procedure for Polyphase Induction Motors and Generators", Method B (ed. 2004, currently under revision) and one from the Canadian Standards Association, CSA C390 (2010): "Test methods, marking requirements, and energy efficiency levels for three-phase induction motors" are well recognized and also applied globally. National standards from other countries also exist. In recent years, much effort has been done to harmonize these energy efficiency standards but still differences in the procedure or in the specifications exist.

2 Review of Energy Efficiency Electric Motor Standards in Use around the World

Tables 1 and 2 show energy efficiency determination standards of different countries, the organizations that publish them and the regulations in place. Two types of standards are currently specified for electric motors. A *testing standard* is a method or procedure with specifications, requirements and instrumentation of how to determine the electric motor efficiency. The second standard type is related to the classification of motors based on energy efficiency. Individual regulations from country to country use this classification to specify *Minimum Energy Performance Standards or MEPS*.

Table 1: Motor Energy Efficiency MEPS around the World

	MEPS				
Country	**MEPS Table**	**Level**	**Organization / Regulation**	**Type**	**Year**
USA	NEMA MG 1	IE3	Department of Energy / EISA 2007	Mandatory	Dec. 2010
Canada	CSA390	IE3	Natural Resources Canada /Office of Energy Efiiciency	Mandatory	Apr. 2012
China	GB 18613 (IEC 60034-30)	IE2	Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China (AQSIQ)	Mandatory	2012
Mexico	NOM-016-ENER-2010	IE3	National Commission for Energy Efficiency (CONUEE)	Mandatory	Jan. 2011
India	IS 12615 (IEC 60034-30)	IE2	Bureau of Energy Efficiency (BEE)	Mandatory	2011
Malaysia	11S027R0 (IEC 60034-30)		Standard and Industrial Research Institute of Malaysia (SIRIM)	Mandatory	Public Comments
Turkey	IEC 60034-30	IE2	SMG-2012/2	Mandatory	June 2012
EU	IEC 60034-30	IE2	EuP / EC 640/2009	Mandatory	June 2011
Taiwan	CNS14400	IE2	Bureau of Standards, Metrology and Inspection	Mandatory	
South Korea	KEMCO	IE2	MOCIE	Mandatory	2010
Australia / NZ	AS/NZS 1359.5:2004	IE2	Department of Resources, Energy and Tourism	Mandatory	2001
Brazil	NBR 17094-1 (similar to IEC 60034-30?)	IE2	National Institute of Metrology, Quality and Technology (INMETRO)	Mandatory	2009
Chile	NCH 3086	IE2	National Institute of Metrology, Standardization and Industrial Quality	Mandatory	Jan. 2011
Japan	JIS C 4212 IEC 60034-30	IE2?	Japanese Standards Association	Mandatory	2010
Switzerland	IEC 60034-30	IE2	EuP / EC 640/2009	Mandatory	July 2011
Russia	GOST R 51677-2000	IE1?	???	???	???

Depending of the standard and the country, a standard may include testing and classification in the same document or in two separate ones. For example, IEC 60034-2-1 is the measurement procedure and IEC 60034-30-1 specifies the classification. In the U.S, IEEE 112B includes the measurement standard and is referred by NEMA MG 1 in which the classification and MEPS are specified (Table 12-11 to 12-14) for 50 and 60 Hz motors. In another case, CSA C390 includes a testing procedure and MEPS tables.

Since each country has different MEPS and applies them in a different way (mandatory or voluntary), it is essential to know what differentiates one *standard* from another in order to reach a global approach of using one unique standard.

From Table 2, it can be seen that many countries use the International Standard IEC 60034-2-1 as reference. Others have national standards that are considered to be similar to IEC 60034-2-1. IEEE 112 and CSA 390 are also used in several countries.

Table 2: Motor Energy Efficiency Measurement Standards around the World

	Measurement Standard		
Country	Measurement Standard Provider	Measurement Standard	Year
USA	Institute of Electrical and Electronic Engineers (IEEE)	IEEE 112B	2004 (2013)
Canada	Canadian Standards Association (CSA)	CSA390	2010
China	Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China (AQSIQ)	GB/T1032 (IEC 60034-2-1)	2006 (2011)
Mexico	National Commission for Energy Efficiency (CONUEE)	NOM-016-ENER-2010	2004 (2013)
India	Bureau of Energy Efficiency (BEE)	IS15999 (IEC 60034-2-1)	2011
Malaysia	Standard and Industrial Research Institute of Malaysia (SIRIM)	11S031R0 (IEC 60034-2-1)	Public Comments
Turkey	International Electrotechnical Commission (IEC)	IEC 60034-2-1	2007 (2013)
EU	International Electrotechnical Commission (IEC)	IEC 60034-2-1	2007 (2013)
Taiwan	Institute of Electrical and Electronic Engineers (IEEE)	IEEE 112B	2004 (2013)
South Korea	Korean Agency for Technology and Standards (KATS)	KSC 4202 - IEC 60034-2-1 or IEEE 112	2007 (2013)
Australia / NZ	Standards Australia/Standards New Zealand	AS/NZS 1359.102.3	2000
Brazil	National Institute of Metrology, Quality and Technology (INMETRO)	NBR 5383-1 (similar to IEC 60034-2-1?)	2002
Chile	International Electrotechnical Commission (IEC)	IEC 60034-2-1	2007 (2013)
Japan	Japanese Electrotechnical Committee	JEC 2137	2000
Switzerland	International Electrotechnical Commission (IEC)	IEC 60034-2-1	2007 (2013)
Russia	International Electrotechnical Commission (IEC)	IEC 60034-2-1	2007 (2013)

It can be seen from Table 2 that most European and Asian countries except Taiwan use the IEC standard. Others, mostly in North America (U.S.A., Canada and Mexico), Brazil and Australia have their own testing standard. These are the known testing standards. Many other countries do not have or use standards at all and it is believed that if they want to use one, they will select one from the above list. So the comparison of measurement standards was thus limited to those in Table 2.

3 Nomenclature of Measurement Standards Reviewed

3.1 IEC 60034-2-1 (FDIS 2013)

The latest edition of International standard IEC 60034-2-1 was issued in 2007 as a revision of IEC 34-2 published, in 1972 with amendments in 1995-1996. This standard also applies to DC and synchronous motors and contains several methods for the determination of a motor's efficiency by back-to-back, calorimetric and summation of losses techniques. The 2007 revision has closed a long debate by now including provision for evaluating stray load losses by measurement of torque resulting in low uncertainty in motor efficiency determination based on the summation of losses as the preferred method (2-1-1B) to use in the standard for motors in the range of 1-150 kW. The next edition of the standard, scheduled to be published by the end of 2013, extends the scope to motors with ratings up to 2 MW and also down to 0,12 kW and incorporates changes in the testing method and specifications from edition 2007.

3.2 IEEE 112 Method B (latest draft revision 2013)

The first version of the IEEE Standard Test Procedure for Polyphase Induction Motors and Generators IEEE112 was first issued in 1964 with revisions in 1991, 1996 and 2004. This standard contains methods for the determination of efficiency of motors and generators and specific tests for speed-torque and lock-rotor evaluation. Among the methods related to motor efficiency, the summation of losses (Method B) is used for efficiency verification and compliance with regulations for motors in the range 1 to 500 hp (0,75 to 375 kW). This standard is currently under revision and should be published in 2013 /2014 with modifications from the edition of 2004.

3.3 CSA C390 (2010)

CSA C390 Standard: "Test methods, marking requirements, and energy efficiency levels for three-phase induction motors" applies to three-phase induction motors rated 0.746 kW at 1800 rpm (or equivalent) and greater. The method of determining and marking the nominal efficiency values is also specified. The standard was first published in 1985 with revisions in 1993, 1998 and 2010. CSA C390 deals specifically with three-phase induction motors and only with the summation of losses method.

3.4 NOM-016-ENERGY (2010)

The Mexican standard "NOM-016-ENERGY-2010" concerns testing and marking of three-phase squirrel-cage induction motors rated 0.746 to 375 kW. It includes a summation of losses method similar to the other standards but with some variations in the calculations.

3.5 NBR 5383-1 (2002)

This standard: "Rotating electrical machines Part 1: Polyphase induction motors – Tests" has been used in Brazil for determining efficiency of three-phase induction motors from 0.746 kW since 2002. It includes two testing methods based on the summation of losses depending on whether the efficiency determination is for the local national labeling program or for export.

3.6 AS/NZS 1359 102.3 (2000)

The testing standard used in Australia and New Zealand is AS/NZS 1359.102.3: "Methods for determining losses and efficiency—Three-phase cage induction motors". This standard covers any cage motors and includes two methods and among them the summation of losses method with the greatest accuracy. The standard has been in effect since year 2000 and is based on a draft of IEC 60034-2-1.

4 Comparison of Testing Standards

Although the above standards use similar summation of losses methods, differences in the test conditions, specifications for instrumentation, order of the individual testing procedures and the computation of the results still exist and may have an impact on determined motor efficiency.

4.1 Test Conditions

To test a motor for efficiency, specifications should be made for the condition of the power supply feeding the motor and the test set-up required.

4.1.1 Power supply

Table 3 gives the specifications of each standard for power supply, total harmonic distortion (THD), voltage unbalance and variation from nominal voltage and frequency.

Table 3: Specifications of the power supply

Parameter	IEC	IEEE	CSA	NOM	NBR	AS/NZS
Max. THD (%)	1.5[1]	5	5	5	5	-
Max. Voltage Unbalance (%)	0.5[2]	0.5	0.5	0.5	0.5	-
Max. Deviation from Rated Voltage (%)	-	-	0.5	0.5	-	0.5
Max. Deviation from Rated Frequency (%)	0.1	0.1	0.1	0.1	0.1	0.3

[1]: IEC 60034-1 specifies this factor as Harmonic Voltage Factor (HVF) and considers the computation of the sum of the harmonics over the rated voltage instead of the fundamental as with IEEE and CSA.

[2]: IEC 60034-1 specifies this factor as the negative sequence divided by the positive sequence voltage instead of the NEMA voltage unbalance factor definition. It is recognized that below a value of 2%, both factors are considered similar.

From Table 3, it can be seen that IEC 60034-1 specifies a THD (HVF) maximum of only 1.5 % compared with IEEE and CSA. According to many manufacturers and testing laboratories, this value may be difficult to achieve during testing. Many studies have attempted to study the relationship between power supply, THD and motor efficiency but this is difficult to quantify since the rank of the harmonics have varying effects on motor efficiency. There is a consensus that a lower power supply voltage THD produces a higher motor efficiency, but the THD limit should be achievable for testing, so IEEE and CSA give some allowance by specifying 5 %.

4.1.2 Test set-up

The test set-up required for determining motor efficiency based on the summation of losses method depends mainly on how additional load losses are to be evaluated. If these losses are computed by the residual loss method, a torque measurement is required, requiring the use of a calibrated dynamometer. For all standards as above, this is the preferred method.

4.2 Instrumentation

Table 4 presents a comparison of the specifications for accuracy of the instrumentation.

Table 4: Specifications of the instrumentation

Parameter	IEC	IEEE	CSA	NOM	NBR	AS/NZS
Instrument transformer (%)	± 0.3	± 0.3	± 0.3	± 0.5	± 0.3	± 0.3
Power (%)	± 0.2 FS	± 0.2 FS - ± 1.0 R	± 0.2 FS - ± 1.0 R	± 0.2 FS	± 0.2 FS	± 0.2 FS
Voltage (%)	± 0.2 FS	± 0.2 FS - ± 0.5 R	± 0.2 FS - ± 0.5 R	± 0.2 FS	± 0.2 FS	± 0.2 FS
Current (%)	± 0.2 FS	± 0.2 FS - ± 0.5 R	± 0.2 FS - ± 0.5 R	± 0.2 FS	± 0.2 FS	± 0.2 FS
Torque (%)	± 0.2 FS	± 0.2 FS - ± 0.7 R	± 0.2 FS - ± 0.7 R	± 0.2 FS	± 0.2 FS	± 0.2 FS
Speed (rpm)	± 1	± 1	± 1	± 1	± 1	± 1
Frequency (%)	± 0.1 FS	± 0.1 FS	± 0.1 FS	± 0.1 FS	± 0.1 FS	± 0.1 FS
Resistance (%)	± 0.2 FS	± 0.2 FS	± 0.2 FS - ± 1.0 R	± 0.2 FS	± 0.2 FS	± 0.2 FS
Temperature (°C)	± 1	± 1	± 1.5	± 1	± 1	± 1

FS: Full scale R: Reading

Table 4 shows that the standards provide similar specifications for the instrumentation to be used for testing, with accuracy in the range of ± 0.1 – 0.2 %, a high level of accuracy but considered easily obtainable with instruments that are readily available. One particularity with CSA and IEEE is the addition of the measurement uncertainty based on the reading. This is a new approach compared with the others. The purpose of this is to ensure that the instrument is operated in the right portion of its range. CSA feels that it is not enough to specify instrumentation with good accuracy; it has to be used in the right way. However, using new digital instruments with automatic scale adjustments also helps to solve this issue.

4.3 Test Procedure

The method of summation of losses is applied differently, depending on re individual standard. Table 5 gives the steps for each standard test procedure.

Table 5: Test procedure

Step	IEC	IEEE	CSA	NOM	NBR	AS/ NZS
Motor Temperature by detector	Optional	Yes	Yes	Yes	No	No
Measurement of motor resistance value	All 3	Any of 3	Any of 3	Median of 3	Median of 3	All 3
Temperature test at rated load	Yes	Yes	Yes	Yes	Yes	Yes
Measurement of motor temperature during load test	$R_{stator\ before}$ $R_{stator\ after}$	$T_{detector}$	$T_{detector}$ and R_{stator}	$T_{detector}$	$R_{stator\ before}$ $R_{stator\ after}$	$R_{stator\ before}$ $R_{stator\ after}$
Load test	Yes	Yes	Yes	Yes	Yes	Yes
Bearing loss stabilization	No	Yes	Yes	Yes	Yes	Yes
No-load test points	8 Fixed values	Min. 6 Variable values	Min. 6 Variable values	Min. 6 Variable values	Min. 6 Variable values	Min. 6 Variable values
Measurement of motor temperature during no-load test	$R_{stator\ before}$ $R_{stator\ after}$	$T_{detector}$	$T_{detector}$ and R_{stator}	$T_{detector}$	$R_{stator\ before}$ $R_{stator\ after}$	$R_{stator\ before}$ $R_{stator\ after}$

Table 5 shows some differences between standards. One major difference between the standards is the option to omit installing a temperature detector on or in the motor. This approach is certainly interesting with no obligation to dismantle the motor to install the temperature detector on the stator winding. However, the drawback is without a temperature measurement, it is difficult to know when the motor reaches its temperature stabilization as specified in the standard. IEEE 112 still requires having a temperature detector in the motor.

CSA has taken a different approach: it is still required to install a temperature detector but not necessarily inside the motor. The preferred place is always on the stator winding but the detector may also be on the core or even externally on the frame. The temperature detector measurement is then corrected based on the temperature by resistance method.

Another discrepancy relates to the measurement of motor winding resistance. Here all standards diverge: IEC and AS/NZS require measurement of all three combinations of line-to-line resistance, IEEE and CSA: any of the three combinations and NOM and NBR: the median of the three. The method used by IEC and AS/NZS gives the resistance of each winding (balanced or not) but is less practical when measurement of three values is undertaken in the time interval allowed after the temperature test, unless it is done automatically. The IEEE and CSA methods are more practical (one resistance value) but do not give the information about the two other winding resistances unless they are verified when the motor is cold. The method proposed by NOM and NBR seems to be the most practical (one resistance) giving the *average* temperature based on the temperature rise by *median* resistance. Nevertheless, with the today's manufacturing capabilities, winding resistances are rarely unbalanced and if the resistance measurement is performed correctly, all methods will give relatively the same results.

One last point to mention concerns bearing loss stabilization before performing the no-load test. Contrary to other standards, IEC does not require bearing stabilization but requires that the no-load test be run immediately after the load test. This approach has the advantage of reduced test time and is valuable since the motor has run for a minimum of a few hours and bearing loss due to grease has normally stabilized at that point. It is assumed that the differences in the determined efficiency between the standards related to bearing losses are in general negligible.

4.4 Computation of the results

Comparison of the computation of the results from each standard is presented in Table 6.

Table 6: Computation of the results

Step	IEC	IEEE	CSA	NOM	NBR	AS/NZS
Calculation of motor rated load resistance	$t = t_0$	$t \le t_{table}$	$t = t_{table}$	$t \le t_{table}$	$t \le t_{table}$	$t \le t_{table}$
Calculation of motor load points resistance	$R_{stator\ before}$ $R_{stator\ after}$ $R_{stator\ linear}$	Based on $T_{detector}$	Based on $T_{detector}$ and R_{stator}	Based on $T_{detector}$	R_{stator} average	$R_{stator\ before}$ $R_{stator\ after}$ R_{stator} average
Core losses computation considering voltage drop in the stator	Yes	Yes	Yes	No	No	Yes
Correlation coefficient of the residual losses	0.95	0.90	0.95	0.90	0.90	0.95
Correction of windage / friction losses	Yes	No	No	No	No	No
Correction of input power	Yes	No	No	No	No	No
Coefficient for temperature correction	235	234.5	234.5	234.5	234.5	235

Here again, the fact that IEC, NBR and AS/NZS evaluate the temperature of the motor and the losses during the load and the no-load tests based on winding resistance only, without any temperature detector, makes the computation of the results different compared with the other standards.

IEC 60034-1 specifies that the resistance for 100 % load and higher loads shall be the value determined before the highest load reading. The resistance used for loads less than 100 % shall then be determined as varying linearly with load, using the reading before the test for the highest load and after the lowest reading for 25 % load. NBR and AS/NZS do some averaging of the resistances.These approaches may lead to variation in the determination of the stator losses between the standards since no time or specifications is mentioned between the measurement of the resistance and the actual measurements during the load test. All depend of the motor temperature variation during the load points in one case (IEC, NBR and AS/NZS) and the difference between the temperature by the detector and the temperature based on the winding resistance (IEEE, CSA and NOM) in the other case. This also applies to the no-load test but with less, effect since the motor temperature does not normally vary lot during this test.

Calculation of motor winding resistance at rated load is different between the standards: IEEE, NOM, NBR and AS/NZS accept the resistance measurement if determined within the time interval allowed. CSA takes the value at exactly the time interval (by interpolation or extrapolation) since when the time interval is passed, it is mandatory that the final value has to be computed back to this time interval (ex. 30, 90 or 120 sec) according to the motor size. IEC changed its resistance calculation back to time of power off in all occasions. There have been many debates on the subject in the standards committees (IEEE, IEC, CSA) on the subject of what is the most appropriate approach. Unfortunately, at the time of this publication, no investigation has been made to determine the impact on the final efficiency figures.

Core losses: all standards except NOM and NBR calculate the actual voltage drop in the stator winding giving variable core losses during the load test. This approach gives a different evaluation of the core losses from those, which have been considered constant in the past. From recent investigation on a series of motors, it is clear that core losses calculated considering voltage drop produce higher motor efficiency, particularly for small motors. However, the impact remains relatively small for motors with ratings greater than 5 kW.

Another point of difference is the correlation coefficient associated with the residual losses that varies from 0.90 to 0.95 depending of the standard used. This coefficient is an indicator of the quality of the test. An informal survey of laboratories indicates that most obtain a minimum coefficient of 0.95 and to reach 0.99 is not difficult. Coefficient of 0.95 has been proposed for inclusion in the IEEE 112 standard but it was not accepted yet at the time of this publication. NOM and NBR are in the process of revising their standards in this respect area.

Two more points of difference: the correction made in the IEC standard to the windage / friction losses based on the change in motor's speed (from synchronous) during the load test. Calculations demonstrated that if this correction is realistic, the difference with other standards is marginal; the other point being the temperature correction of input power. On this point, if one considers that all losses are temperature corrected, there is no reason not to do the same with the input power. As with the other correction, this is the right approach and other standards should consider it but calculations showed negligible impact.

Finally a very minor difference relates to the coefficient for temperature correction for copper. IEC and AS/NZS use a value of 235 and the others 234.5. A review of the literature did not give a consensus value. It is more a manner of usage and consistency with other published standards (especially IEC and IEEE). It would be logical to have the same value in all standards but in practice, efficiency values are unaffected.

5 Conclusion

The main conclusion of this review is that after modifications incorporated in the most recent standards such as CSA, IEC and IEEE, and despite minor differences with other testing standards reviewed, these standards may be considered as equivalent. Thus the use of the new edition of IEC 60034-2-1, to be published by the end of 2013, will not place any burden on countries that do not necessarily use it as reference and shall be considered a "*Global Testing Standard*" for global labeling of efficiency classes of electric motors.

Efficiency Measurement of a Squirrel-Cage Induction Motor fed by a Frequency Inverter within its Range of Operation

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I. Abstract:

This paper presents a procedure to measure the efficiency on an induction motor fed by a frequency inverter by the all operation range to speed and torque. The article describes the procedure, and accuracy requirements of the instrumentation required by international standards and research results to ensure the measurement of real efficiency of induction motors and drives. Also, describes the basic measurement requirements of the variables, accurate data measurement, information processing, power and efficiency calculations. The paper describes and analyzes the different power calculations implemented and researched, which correspond to algorithms used by the commercial instrumentation. The losses on the induction motor–frequency inverter system are shown and analyzed. Finally, the procedure for efficiency measurement is implemented through lab tests.

Index Terms— *Efficiency, Harmonics, Induction Motor (IM), Variable Speed Drive (VSD), losses, PWM, THD*

II. Introduction

Nowadays, electrical motors are widely used in industry. This is why they are the main source of energy consumption in the world, with 40% and can be responsible of worldwide 13% CO2 emissions. Within this sector, squirrel-cage induction motor (IM) dominates the use of motors in industry, with 90%. Thus, it is important to improve the operation efficiency in the IM, because this improves energy consumption and reduces polluting emissions [1].

To improve productivity and energy saving on IM, the use of a variable speed drive (VSD) has been implemented, as these regulate speed or torque in the motor. However, it must be emphasized that the use of VSD with motors is viable for large and medium motors, or for applications when we have variable load [3]. Hence, measurement and classification of energy efficiency are important to reduce energy consumption and polluting emissions. However, test procedures for appropriate efficiency measurement must be developed to establish such classification, which can be incorporated into a standard or universal procedure, for the usefulness of globalized markets and for industrial clients [2].

The International Electrotechnical Commission (IEC) sets the 60034-2-3 Standard in order to determine losses and efficiency in alternating current (AC) motors fed by a power converter. However, the test method is defined for fundamental frequency and rated motor speed. The standard does not characterize all of the losses due to harmonics in the IM - VSD system, and does not detail the steps of the procedure for the measurement of efficiency [1]. Several researchers have worked on the development of methods, models, measuring stations, testing three-phase and double-three phase induction motors, tests with different control signals and instruments for determining the IM – VSD overall efficiency. [2, 3, 4, 5, 6, 7].

This paper presents the procedure to measure efficiency in the system IM-VSD, and a comparison of methods for efficiency calculations, next to the behavior analysis of the IM within its range of operation

III. Motor - Drive system losses

The motor drive system (IM – VSD system) voltage source inverter (VSI) type is presented in Figure 1. Each module of the system presents different types of mechanical and electrical losses which affect the efficiency of the system and produce undesired effects in performance [8]. The development and availability of power electronic devices such as FETs, BJTs, IGBTs and GTOs have allowed the commercialization of indirect VSD drives by pulse width modulation (PWM) and by consequence to be widely implemented in addition to offer a high performance.

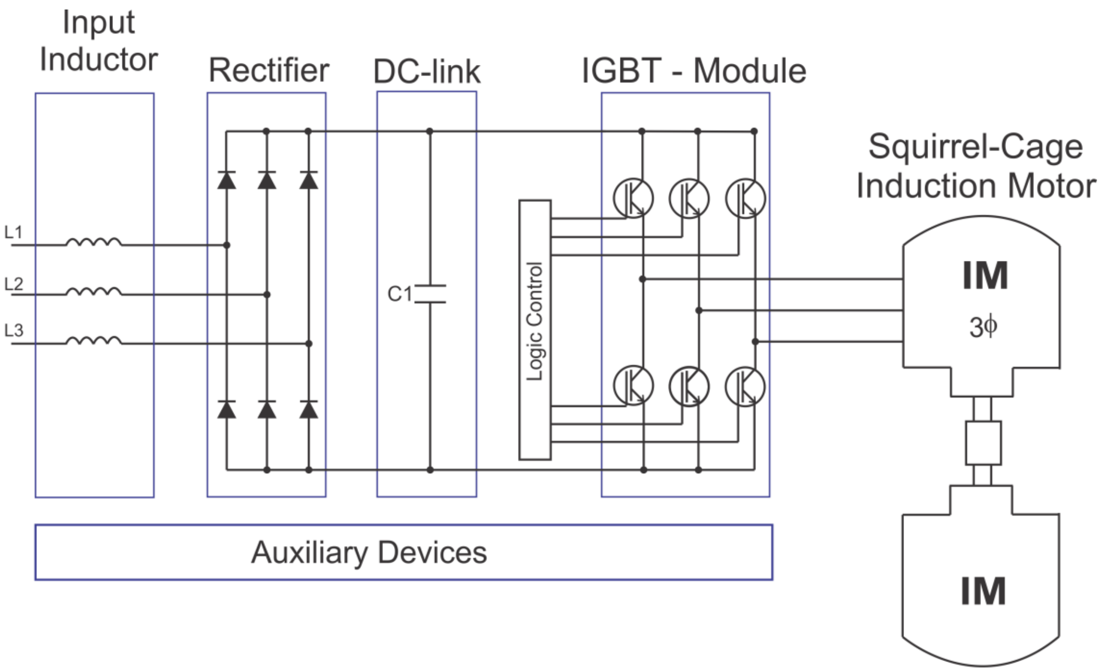

Figure 1. Motor Drive System

a. Variable Speed Drive (VSD) losses

The variable speed drive is composed of the following elements, which present different losses:

Inductor losses: The inductor is at the entrance of the VSD and is implemented as an AC harmonic filter. This element has power losses in the core and windings. The most used model to determine the losses is by a resistive-inductive impedance in series as shown in equation (1).

$$P_{choke}(t) = 3i_L^2(t)ESR_L \qquad (1)$$

Where $\mathrm{i_L}$ is the instantaneous current line of the inductor, $\mathrm{ESR_L}$ is the equivalent series resistance. $\mathrm{ESR_L}$ is calculated from the current measurements and losses at the entrance [9].

Diode bridge losses: Losses in the diode bridge can be represented as a function of small leaks that occur in the diode when this works in direct or inverse polarization. Equation (2) models these losses.

$$P_{diode,on}(t) = U_F i_{diode}(t) + R_F i_{diode}^2(t) \qquad (2)$$

Where $\mathrm{i_{diode}(t)}$ is the instantaneous current that flows through the diode, $\mathrm{U_F}$ is the voltage drop when diode is forward biased while $\mathrm{R_F}$ is the internal diode resistance [9].

DC Bus losses: drives have a DC bus capacitor to avoid the ripple in the signal. Because of the DC bus interconnects the diode bridge with IGBT bridge; the current will be the sum of a DC component and the harmonics produced by the bridge rectifier and the inverter bridge. Therefore, the DC voltage produced by the rectifier has a large number of harmonics. Equation (3) represents the losses in the capacitor.

$$P_C = \sum_n I_{C(6n)}^2 ESR_{C(6n)} \qquad (3)$$

Where $\mathrm{I_C(n)}$ is the RMS value of the capacitors nth order current and $\mathrm{ESR_{C(n)}}$ is the equivalent series resistance of the capacitor for a particular frequency [9].

IGBT module losses: The losses in the IGBT module can be divided between conduction losses and switching losses. Furthermore, there are additional losses by the diode that generally accompanies the IGBT in parallel. Both for the IGBT and for the diode, the instant conduction losses are expressed in the equation (4) and (5).

$$P_{IGBT,cond} = U_{CE_0} i_m^2(t) + R_{CE_0} i_m^2(t) \qquad (4)$$

$$P_{diode,cond} = U_{F0} i_m(t) + R_{F0} i_m^2(t) \qquad (5)$$

Where $\mathrm{i_m}$ is the phase current of the induction motor, $\mathrm{U_{CE_0}}$ is the threshold voltage of the IGBT, $\mathrm{R_{CE_0}}$ is the resistance of the IGBT turn-on mode. Moreover, the variables for the diode losses correspond to the diode voltage and the internal resistance of the element ($\mathrm{U_{F0}}$ and $\mathrm{R_{F0}}$ respectively). The losses in the IGBT and in the diode due to switching can be expressed by equation (6) and (7).

$$P_{IGBT,sw} = \frac{U_{DC}}{U_{rated}} \frac{I_m}{I_{rated}} E_{sw,IGBT} N_{sw,change} \qquad (6)$$

$$P_{fw-diode,sw} = \frac{U_{DC}}{U_{rated}} \frac{I_m}{I_{rated}} E_{sw,fw-diode} N_{sw,change} \qquad (7)$$

Where $\mathrm{N_{sw,change}}$ is the number of switches in a specific period of time, $\mathrm{E_{sw}}$ is the switching energy losses in the respective element, and $\mathrm{U_{Dc}}$ and $\mathrm{I_m}$ are switching voltages and currents [9].

Auxiliary devices Losses: The losses that are presented in this drive controller module are constant and do not significantly affect the induction motor and VSD overall efficiency. Items that present losses are the micro variable speed controller, the display, the communication bus, the control system, control panel [9].

b. Squirrel-Cage Induction Motor

The losses in the IM due to supply and control of the VSD are evaluated at steady state. Their losses mainly increase in the iron and on the stator and rotor windings due to voltage and current harmonics. Currently there is no a circuit model to determine the motor losses due to the different frequency spectrums of the current and voltage generated by the VSD [10]. The IEC 610034-17 Standard [11] states that "There is no a simple method to calculate the additional losses and cannot be established any general rule about its value. Its dependency in relation to different physical characteristics is extremely complex, also exists a large variety of converters both as motors and the quality of manufacture of the core is an important feature. "In the IEC 60034-31 standard [12] is commented the determination of motor efficiency fed by the frequency converter from the IEC 60034-2-3 where according to the European Committee for Electrotechnical Standardization this last will be distributed by November 2012 according to the Committee Draft for VOTE (CDV) established at 2011-10-14 [13].

The losses in the induction motor fed by a current converter in the iron are essentially the same but the losses in the stator and rotor can significantly increase the product of the IGBT switching. In the case of IM fed by voltage converter additional losses in the iron cannot be ignored, losses in the windings are limited by the dispersion reactance and there are no switching losses, due to the switching currents do not flow through the motor windings. The IEC 610034-17 Standard verifies through testing the total value of the additional losses caused by harmonics and note that is not dependent on the load. These losses are reduced when the switching frequency increases as illustrated in Figure 2.

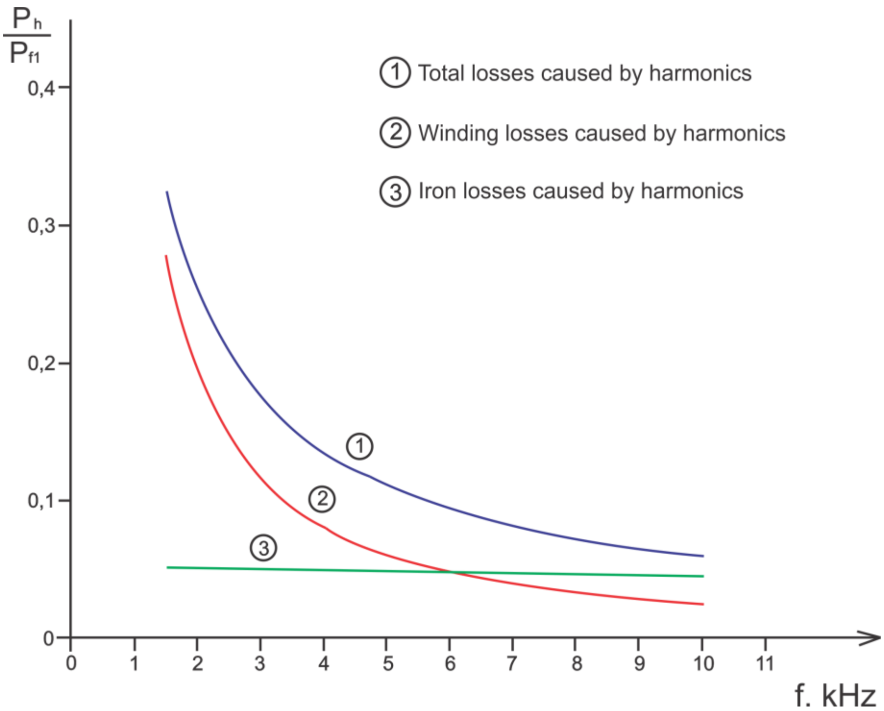

Figure 2. Example of motor losses due to harmonics

In the procedure for determining experimentally the motor efficiency, the instruments and its accuracy are important. The IEC 60034-2-3 Standard establishes an instrument bandwidth from 5 Hz up to 10 times the switching frequency of the drive. The requirements of the measurement instruments are defined by the IEEE 112 and IEC 60034-2-1 [14] as shown in Table 1.

Table 1. Instrumentation accuracy [15]

Variable	IEEE 112	IEC 34-2-1
Instrument transformer	0.5	0.3
Voltage	0.2	0.2
Current	0.2	0.2
Power	0.2	0.2
Torque	0.2	0.2
Speed	1 rpm	1 rpm
Frequency	0.1	0.1
Resistance	0.1	0.1
Temperature	1°C	1°C
Efficiency by WCE	0.31 %	0.33%
Efficiency by RPBE	0.17 %	0.18 %

The previous requirements consider the current and voltage harmonics generated by VSD. Furthermore the signals may contain components or inter-harmonic sub-harmonic signal modifying periodic [16] and can increase the measurement error. The maximum error of measurement is lowered if the number of cycles of the inter-harmonic measured increases, for example contemplating cycles 20 at the measurement it would represent a ± 0.2 % error as shown in Figure 3.

The current electric power measurement devices show an increase at the measurement error due to the existence of the high harmonic content of the voltage and current signals further by the lack of synchronization between the fundamental frequency and the sampling frequency. The wattmeters are mainly classified as Regularly Asynchronous Sampling Digital Wattmeter (RASDW) and Regularly Spaced Sampling Digital Wattmeter. The RSSDW present advantages as they are devices easier to implement, low cost and low risk of failure, however they have low bandwidth. The RASDW have good accuracy and a wide bandwidth, however are difficult to implement and require complex and costly measuring instruments [17]. The implementation of the device is mainly characterized by the degree of precision and the types of the algorithms architecture of the meter.

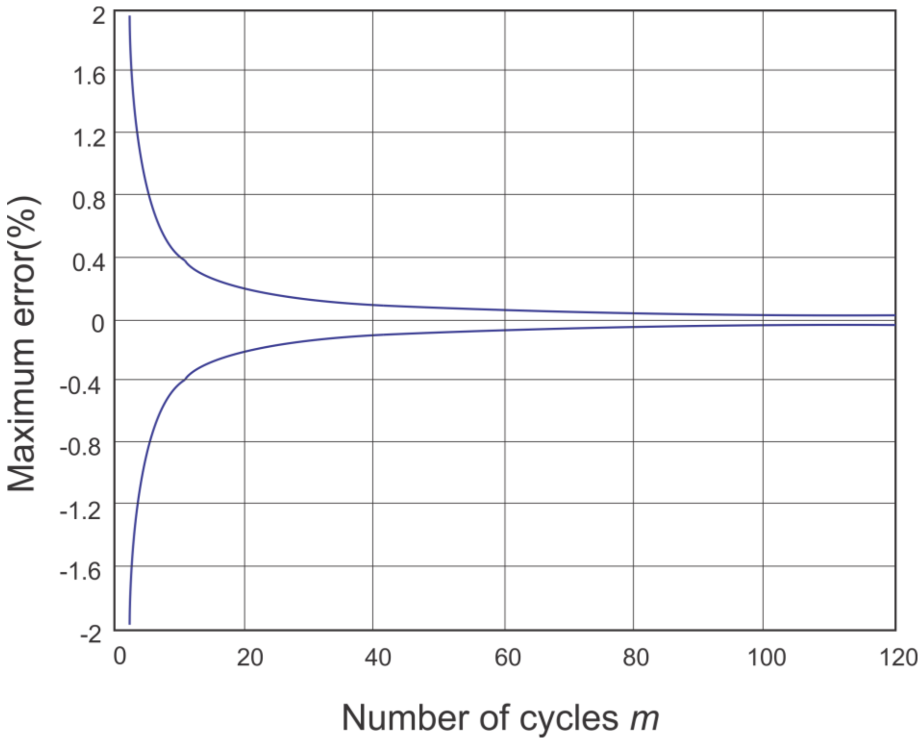

Figure 3. Error vs. number of cycles [18]

The current architecture of the modern power meter is shown in Figure 4 where the Sample & Hold (S/H) and Phase-Locked Loop (PLL) blocks are responsible for a correct and accurate sampling. The Digital Signal Processing (DSP) handles the computation of the respective acquired signals and it's computing through different algorithms to calculate voltage, current, power, among others [16]. The Analog-to-Digital Converter (ADC) and the voltage and current conditioning blocks to attenuate or amplify the input signals.

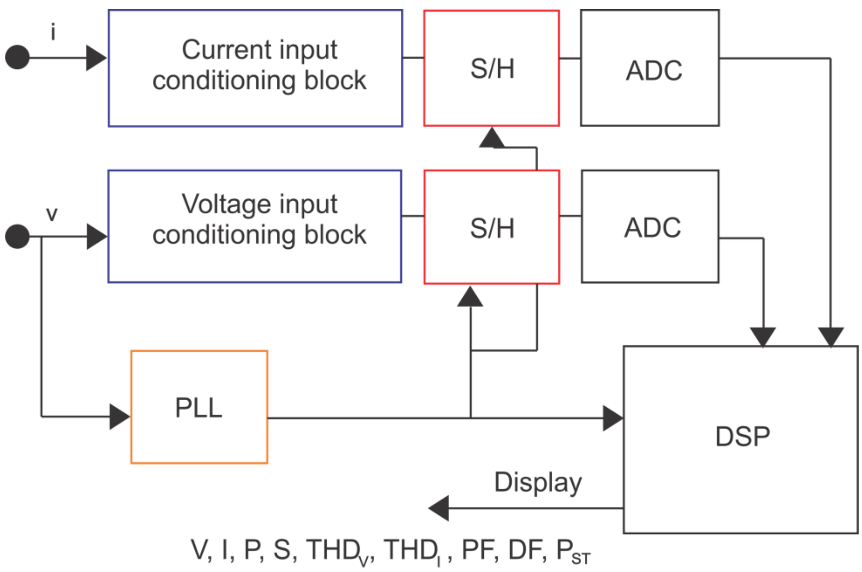

Figure 4. Block diagram of a power meter

IV. Calculation methods of electric power

The three calculation methods of power developed below are used to determine the efficiency of the squirrel-cage motor induction and VSD.

a. Fourier decomposition method

The Fourier series are used widely to describe non-sinusoidal periodic waveforms in terms of a sinusoidal series. The power relations for electrical and electronic circuits with non-sinusoidal periodic voltages and / or currents can be expressed in terms of the components of the Fourier series. The Fourier series can express a periodic function $\mathrm{f(t)}$ as trigonometric, as presented in equation (8) and (9).

$$f(t) = a_0 + \sum_{n=1}^{\infty}[a_n cos(n\omega_0 t) + b_n sen(n\omega_0 t)] \qquad (8)$$

$$a_0 = \frac{1}{T}\int_{-T/2}^{T/2} f(t)dt \qquad a_n = \frac{2}{T}\int_{-T/2}^{T/2} f(t)\cos(n\omega_0 t)\,dt \quad b_n = \frac{2}{T}\int_{-T/2}^{T/2} f(t)\,\mathrm{sen}(n\omega_0 t)\,dt \qquad (9)$$

Alternatively, equations (10) and (11) combine $\mathrm{a_n}$ and $\mathrm{b_n}$ factors into a single sinusoid.

$$f(t) = a_0 + \sum_{n=1}^{\infty} C_n \cos(n\omega_0 t + \theta_n) \qquad (10)$$

$$C_n = \sqrt[2]{a_n^2 + b_n^2} \qquad \theta_n = \tan^{-1}\left(\frac{-b_n}{a_n}\right) \qquad (11)$$

The term $\mathrm{a_0}$ is a constant, which corresponds to the root mean square (RMS) value of $\mathrm{f(t)}$, and represents a voltage or current (DC). Furthermore, the coefficient C1 is the amplitude of the fundamental frequency term ω_0, while the coefficients C2, C3... are the amplitudes of the harmonics [19]. The RMS value can be calculated by the equation (12).

$$F_{rms} = \sqrt{\sum_{n=0}^{\infty} F_{n,rms}^2} = \sqrt{a_0^2 + \sum_{n=1}^{\infty}\left(\frac{C_n}{\sqrt{2}}\right)^2} \qquad (12)$$

Finally, based on the periodic waveform of voltage and current represented by the Fourier series, the electric power is calculated by the equation (13).

$$v(t) = V_0 + \sum_{n=1}^{\infty} V_n \cos(n\omega_0 t + \theta_n) \quad i(t) = I_0 + \sum_{n=1}^{\infty} I_n \cos(n\omega_0 t + \phi_n) \quad P = \frac{1}{T}\int_0^T v(t)i(t)dt \qquad (13)$$

The electric power for non-sinusoidal periodic voltage and current waveforms is calculated by the equation (14):

$$P = V_0 I_0 + \sum_{n=1}^{\infty} V_{n,rms} I_{n,rms} \cos(\theta_n - \phi_n) \quad \text{ó} \quad P = V_0 I_0 + \sum_{n=1}^{\infty}\left(\frac{V_{n,máx} I_{n,máx}}{2}\right)\cos(\theta_n - \phi_n) \qquad (14)$$

b. VI Power calculation method

This power calculation method is based on the analysis of voltages and currents in the discrete domain. Because of the voltage and current signals are sampled over time and stored in digital records. In applying the laws of electrical circuits is obtained the expression of equation (15) for the time domain and for a number N discrete samples [20]:

$$P = \frac{1}{T}\int_0^T v(t)i(t)dt \qquad P = \frac{1}{N}\sum_{0}^{n=N-1} V[n] * I[n] \qquad (15)$$

c. Orthogonal Method

This method is based on Parks transformation that represents the three-phase system in a new reference framework whose components are the direct axis component, quadrature and zero sequence. Considering the three-phase voltage and current signals, the Parks transformation Equation (16) must be applied to make the change of reference and the calculation of power in Equation (17)

$$\begin{bmatrix} w_d \\ w_q \\ w_0 \end{bmatrix} = [T]\begin{bmatrix} w_a \\ w_b \\ w_c \end{bmatrix} \qquad [T] = 2/3\begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \sin\theta & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \qquad (16)$$

$$P_{dq0} = P_{abc} = \frac{3}{2}\left(v_q i_q + v_d i_d + 2v_0 i_0\right) \qquad (17)$$

Where the 3/2 factor depends on the matrix used for transformation. This change of reference framework is commonly used in the analysis of AC machines, as in the measurement of components of the power systems and some control systems associated with electrical systems [21].

V. Analysis of Results

Some results obtained from testing according to efficiency measurement procedure are shown in figure No 6. The figure shows the software developed for the determination of overall efficiency IM - VSD. The program allows visualizing voltage and current signals, harmonic magnitude of each signal, harmonic angles of each signal in respect with its fundamental component and system efficiency for different load values. In addition, the program calculates power using the three methods outlined above. It is noted that for the experimental test at 1800 rpm (input frequency: 60 Hz), the efficiency calculated under the three power methods is similar. The measurement instruments that are used for the power calculation by the VI method, do not present major problems for data obtaining. However, when the testing is made in other frequency ranges powers methods deliver different results, because the methods include the harmonics that are present in the electrical signals of the system.

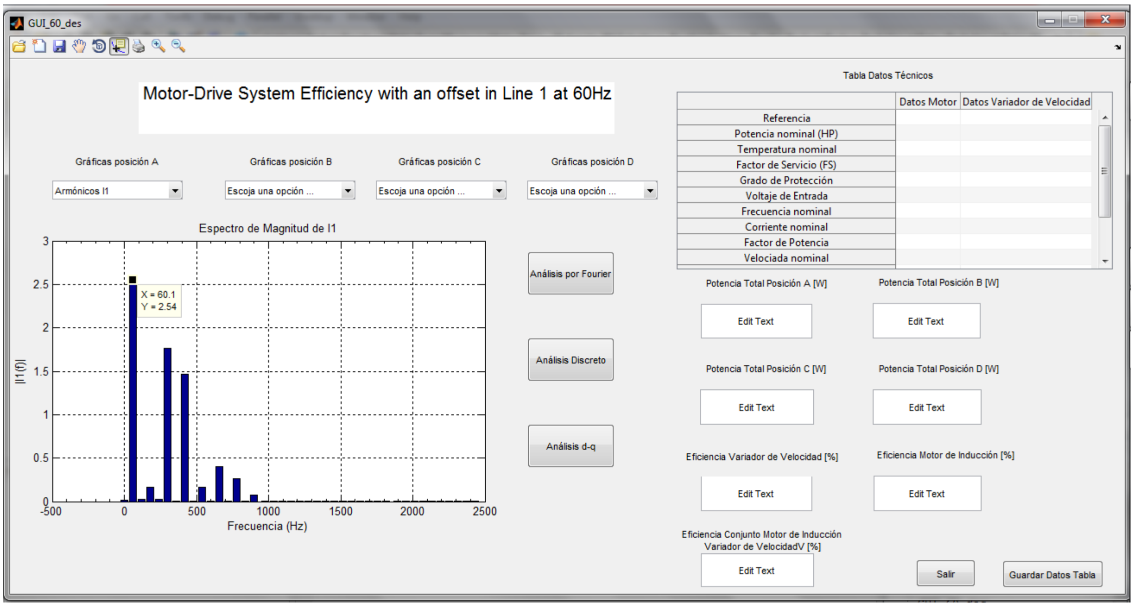

Figure 5. GUI Application for the power and efficiency calculation

The comparison of the power calculation methods by the three methods with different test conditions in which differences above 3% for low speeds become evident are shown in table 2.

Table 2. Efficiency measurements by different methods

Input Frequency (Hz)	Synchronous Motor speed (rpm)	VI Method [%]	Fourier Method[%]	Orthogonal Method [%]
60	1800	95.3	95.6	95.4
50	1500	94.1	95.0	94.3
40	1200	89.3	90.8	89.5
30	900	85.0	86.9	85.3
20	600	81.5	84.7	82.6

Although the power calculation method based on the decomposition of the signal by Fourier takes into account the different harmonics that may occur in the voltage and current signals of periodic non-sinusoidal waves, this method presents higher efficiency values at low operation speed. The orthogonal method presents greater capacity for calculating the efficiency within the operating range for the motor speed.

VI. Conclusions

The results point that the algorithm implemented in the instrument to take no lower than 40 cycles of samples in order to obtain a 0.1% error in the power calculation. This demonstrates the influence of the inter-harmonics in the power calculation by the instrument and is recommended to increase the number of sampling cycles. The measurement instrument used to test the procedure took only 4 cycles of samples, where the figure 3 indicated that the maximum error in the measurement is ±1%. The results have been illustrated by means of simple examples.

The proposed procedure for determining the efficiency of the squirrel cage induction motor powered by a variable speed drive allows obtaining the efficiency curves of all the equipment under test and the overall system in a simple and practical way, in order to make a future efficiency rating of the whole IM - VSD.

The results of the measurement can be affected by the instrument uncertainty and error. On one hand, the instrument uncertainty is related with external sources such as noises and test numbers. While the error, is concerned with the instrument characteristics. Most of the measurement instruments use the “Regulary spaced sampling digital wattmeter” which implements a PLL (Phase Locked Loop) block. This subsystem does not take the exactly multiple frequency of the fundamental signal. Therefore, the significant values of the different power calculation methods will be affected. In order to reduce this error, we suggest a Random asynchronus sampling digital wattmeter. (for example the 8650B Series Universal Power Meters of Giga-tronics).

The efficiency determination methods are under investigation to identify the relationship of the harmonics, PWM, variable speed losses over the final efficiency the whole IM-VSD.

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Losses determination in induction motors using infrared thermography techniques

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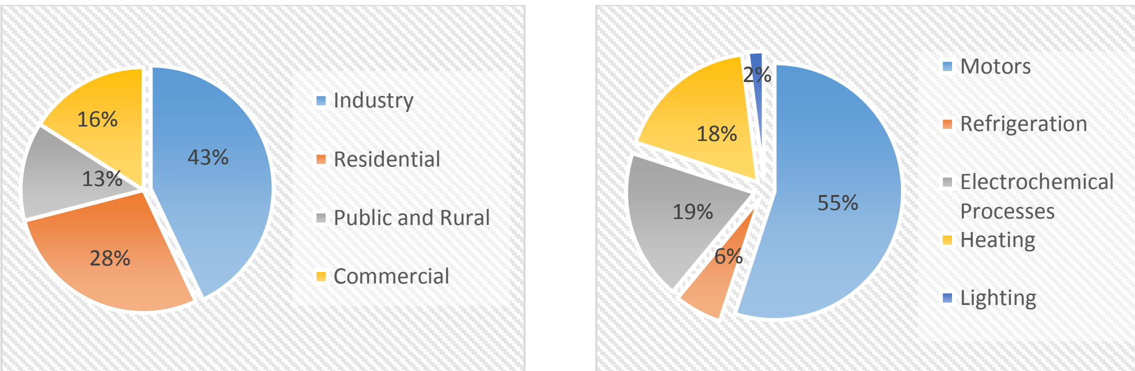
Abstract

This work aims at obtaining the losses of a three-phase induction motor using the thermography techniques, which assumes that all the losses of the motor are dissipated as heat. The proposed technique is compared to the traditional method of losses segregation with direct measurement of the electric and mechanical power. Results statistically treated are also presented.

Introduction

Three-phase induction motors are the most used machines in the industry due, among other reasons, to their high reliability and efficiency. Such equipment presents great potential for energy conservation because of the large number of installed units and the common occurrence of inefficient application. Therefore, it is very common to find the so-called oversized motors, i.e. motors driving loads much smaller than rated capacity, resulting in low operational efficiency and power factor [1].

Induction motors are very important energy end-use in Brazil as they are responsible for the consumption of about 25% of total generated electricity. Figure 1 (a) shows the share of industrial sector energy consumption in Brazil, while figure 1 (b) shows the percentage of industrial energy consumption attributable to motor force.



(a) (b)

Figure 1 – Energy consumption distribution in Brazil (a) and in the industry (b).

Basically, the induction motor is an electromechanical energy converter that, based on electromagnetic principles, converts electrical energy into mechanical energy. Unfortunately this conversion is not complete due to the inevitable losses that occur in the machine during this conversion process. Such losses can be grouped as follows: stator and rotor losses, iron losses, stray load losses and losses due to friction and windage [2].

Stator and rotor losses result from the passage of electric current through their windings (I^2R). Iron losses consist of hysteresis and eddy current losses. The hysteresis loss results from the constant reorientation of the magnetic field on the package of silicon-steel sheets and the eddy current losses are basically I^2R losses due to the induced current within the magnetic material. Friction and windage occur due to friction in the bearings of the machine and the aerodynamic drag caused by the irregular geometry of the rotor and the fan itself installed at the shaft end. Stray load or dispersion includes all losses not previously classified. Figure 3 shows the average distribution of losses in a motor operating at rated conditions.

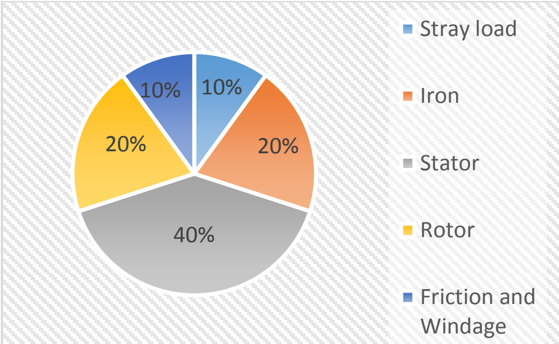


Figure 3 - Losses distribution in a three phase induction motor [2].

If one considers that all the losses of a motor are converted into heat and released to the surrounding environment, they could be measured using the thermodynamic method. Thermodynamic methods imply the construction of a special environment surrounding the machine, the so-called volume of control, where air flow, inlet, and outlet temperatures are of easy measurement [3].

As long as induction machines are intrinsically efficient machines [1], for energy saving analysis, knowing the operating efficiency is not as important as knowing its loading. Nevertheless, for economic analysis, the knowledge of the efficiency is of utmost importance, as long as the difference in the electricity consumption of motors being compared is inversely proportional to their efficiencies.

For those cases where it is important to know the motor losses or efficiency, this paper proposes a thermodynamic method based on measuring the heat released into the surrounding environment by convection, conduction and radiation, using a thermography method along with temperature and air flow measurements. The thermography method has the advantage of not requiring contact with any energized or rotating parts of the machine. The motor can be in its regular operation while the data is being gathered.

The thermography method for losses determination

During the process of energy conversion, the losses occur mostly in the form of heat and are released into the surrounding environment by convection, conduction and radiation. The parcels of conduction and radiation can be neglected, and the parcel of convection can be divided into natural and forced ones. Natural convection refers to the heat on the surface that goes naturally to the environment, while forced convection is related to the loss absorbed by the air flow pushed by the motor fan, described as follows.

Natural convection

These losses comprise the heat transfer from the machine surface to the environment, heat transfer to the concrete case, and heat transfer through the machine shaft. The general equation of the radiation and convection losses is:

$$P_N = h\, A\, \Delta\theta \qquad (1)$$

Where h is the heat transfer coefficient (W/m²·K), A is the area of the radiant surface (m²) and $\Delta\theta$ is the temperature difference between the surface and the environment (K).

While IEEE std-115 suggests 12.4 as the value for *h* [6], the IEC 60034-2 standard considers a value of 15 in the absence of fluid flow. Otherwise, a heat transfer coefficient dependent on the coolant fluid speed is specified, as follows, for external surfaces [7], where v is the coolant fluid velocity (m/s).

$$h = 11 + 3v \qquad (2)$$

The proposed method suggests the fragmentation of the motor surface area into isotherms, i.e. regions of same temperature. By applying the isotherms process the natural convection loss formula must also be fragmented into a summation of the areas.

$$P_N = h \sum_{1=\mathrm{i}}^{\mathrm{n}} A_i \, \Delta\theta_i \qquad (3)$$

Where *n* is the number of considered isotherms, A_i is the area corresponding to the *i-th* isotherm, and $\Delta\theta$ is the temperature difference between the *i-th* isotherm and the environment.

Forced convection

Forced convection is a heat transfer type in which fluid movement is due to an external force. In electric motors, it has great importance due to the fan fixed at the end of the shaft that blows air in the axial direction. The machine losses absorbed by the coolant fluids can be determined using:

$$P_F = c\, \rho\, Q\, \Delta\theta \qquad (4)$$

Where Q is the air flow (m³/s), ρ is the specific mass of air (kg/m³), c is the specific heat of the air (kJ/kg·K) and $\Delta\theta$ is the coolant fluid temperature difference between the inlet and outlet.

Thermal image processing

It is possible to calculate the area of each part of a motor from drawings provided by the manufacturer, as showed in figure 4. Therefore, the area of each pixel of a thermal image can be obtained by dividing the total area of the motor surface by the number of pixels of the focal plane array.

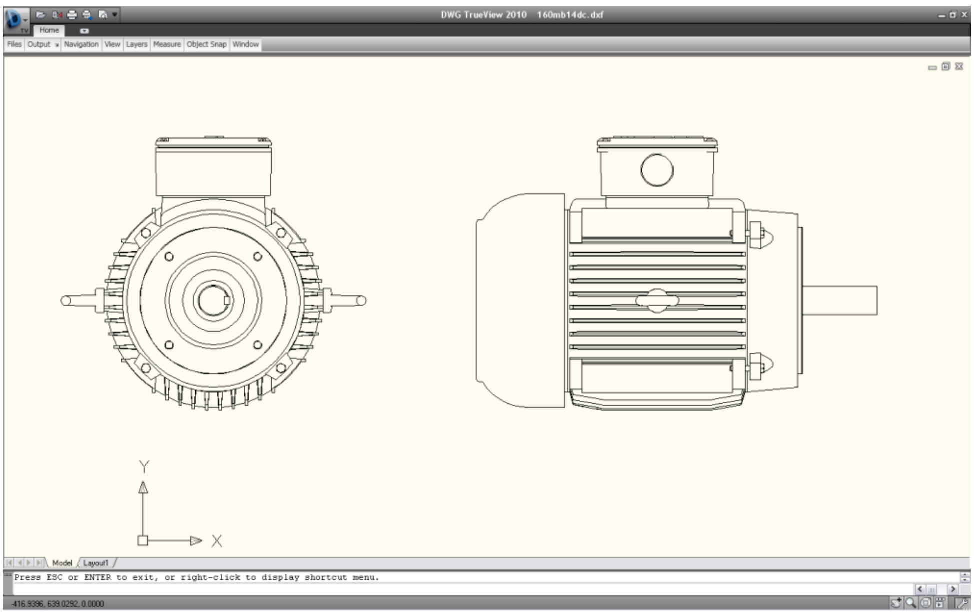
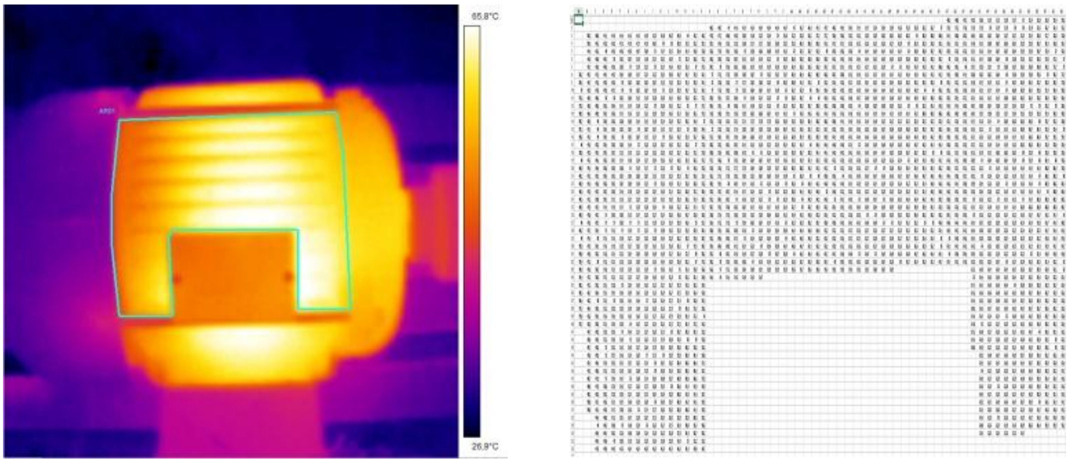


Figure 4 – Drawing of the motor frame provided by the manufacturer.

Using proper software, supplied along with the camera, it is possible to process thermal images, in order to obtain the temperature profile of a surface. This temperature profile can be exported as a spreadsheet file where each cell represents the temperature of each pixel of the entire picture or of a selected area of the picture, as showed in figure 5. Therefore, equation (3) can be applied with great accuracy.



(a) (b)

Figure 5 –Thermography image (a) and pixel spreadsheet (b).

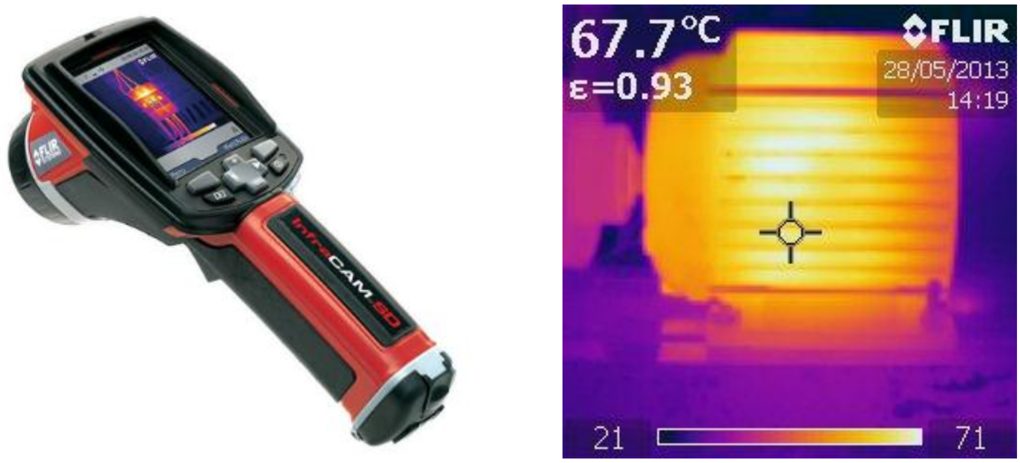
Experimental application

Energy efficiency tests were applied to three motors of different rated power in an appropriate test bench showed in figure 6. The motors were coupled to a DC-Generator through a torque transducer, allowing for mechanical power measurement, and tested at no-load, 50%, 75%, and 100% of full load.

Figure 6 – Motor test bench

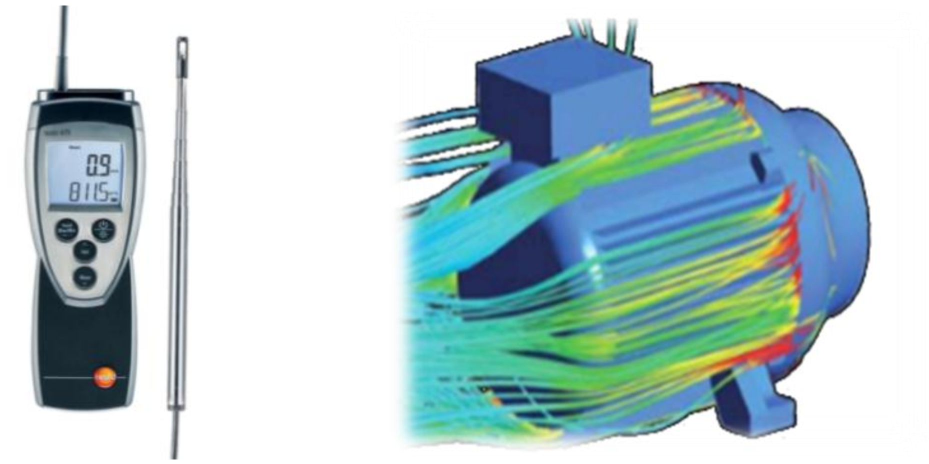
The losses segregation method was used, based on IEEE Standard 112-1991 with direct measurement of input and output power and indirect measurement for stray-load loss [6].

In accordance with IEC 60034-2 after reaching steady-state temperature images were taken until its whole surface is covered for each load. Figure 7 shows the used camera (a) and one of the several pictures taken during the tests (b). Figure 8 shows the hot-wire anemometer used to measure the air velocity (a) and the temperature and air flow at the inlet and outlet of the motor (b).



(a) (b)

Figure 7 – Infrared camera (a) and thermal image (b).



(a) (b)

Figure 8 – Anemometer (a) and air current profile in a motor (b).

For the thermography image process analysis, isotherms with 2°C steps were determined to produce the best accuracy. Tables 2 to 3 present the obtained results. Calculations were made according to IEC 60034-2 [7]. All calculations are presented assuming errors of type A and B, with a 95.45% confidence interval, taking into account statistical Student distributions [8].

Table 1 – Results summary – 1 HP Motor, 78.00% Efficiency, 0.84 Power factor, 4 pole, 60 Hz, 220 V

Losses Segregation	**100 % load**	**75 % load**	**50 % load**
Stator (W)	89.96 ± 4.85	62.15 ± 3.35	42.94 ± 3.35
Rotor (W)	31.73 ± 1.22	17.07 ± 0.88	8.10 ± 0.88
Iron (W)	97.25 ± 2.43	97.17 ± 2.44	97.02 ± 2.44
Friction and Windage (W)	9.14 ± 4.77	9.14 ± 4.77	9.14 ± 4.77
Stray-Load (W)	5.25 ± 11.37	2.70 ± 5.73	1.31 ± 5.73
Total losses (W)	233.34 ± 12.65	188.24 ± 7.20	158.51 ± 4.53
Efficiency (%)	74.79 ± 1.38	72.95 ± 1.05	67.52 ± 0.95
Thermography	**100 % load**	**75 % load**	**50 % load**
Natural Convection (W)	82.32 ± 11.01	67.54 ± 2.72	51.38 ± 2.67
Forced Convection (W)	83.92 ± 28.05	71.28 ± 35.81	50.37 ± 26.02
Total losses (W)	166.24 ± 29.10	138.82 ± 35.95	101.74 ± 26.19
Efficiency (%)	82.04 ± 3.15	80.05 ± 5.17	79.15% ± 5.37

Table 2 – Results summary – 2 HP Motor, 81.50% Efficiency, 0.80 Power factor, 4 pole, 60 Hz, 220 V

Losses Segregation	**100 % load**	**75 % load**	**50 % load**
Stator (W)	161.59 ± 8.68	106.23 ± 5.70	72.65 ± 5.70
Rotor (W)	78.88 ± 2.48	37.79 ± 1.79	15.32 ± 1.79
Iron (W)	117.83 ± 5.83	117.67 ± 5.84	117.58 ± 5.84
Friction and Windage (W)	19.73 ± 4.77	19.70 ± 4.77	19.70 ± 4.77
Stray-Load (W)	35.49 ± 12.55	19.70 ± 7.00	8.64 ± 7.00
Total losses (W)	413.51 ± 17.19	301.09 ± 11.91	233.89 ± 9.17
Efficiency (%)	76.29 ± 1.00	76.11 ± 0.97	72.20 ± 1.10
Thermography	**100 % load**	**75 % load**	**50 % load**
Natural Convection (W)	198.05 ± 19.72	158.26 ± 4.28	127.52 ± 3.88
Forced Convection (W)	172.47 ± 28.00	112.33 ± 35.43	91.63 ± 23.26
Total losses (W)	370.52 ± 32.75	270.59 ± 35.22	219.15 ± 23.38
Efficiency (%)	78.75 ± 1.88	78.53 ± 2.80	73.95 ± 2.79

Table 3 – Results summary – 5 HP Motor, 85.00% Efficiency, 0.81 Power factor, 4 pole, 60 Hz, 220 V

Losses Segregation	**100 % load**	**75 % load**	**50 % load**
Stator (W)	295.46 ± 15.56	187.94 ± 9.87	120.89 ± 9.87
Rotor (W)	160.08 ± 6.36	90.22 ± 4.73	40.56 ± 4.73
Iron (W)	283.48 ± 13.55	292.69 ± 13.55	292.43 ± 13.55
Friction and Windage (W)	13.63 ± 4.77	4.27 ± 4.77	4.27 ± 4.77
Stray-Load (W)	53.53 ± 21.42	29.06 ± 11.61	12.82 ± 11.61
Total losses (W)	806.18 ± 33.30	604.18 ± 25.47	470.97 ± 22.28
Efficiency (%)	81.85 ± 0.76	81.61 ± 0.75	78.96 ± 0.92
Thermography	**100 % load**	**75 % load**	**50 % load**
Natural Convection (W)	307.93 ± 51.15	266.45 ± 8.76	198.77 ± 5.54
Forced Convection (W)	386.92 ± 65.74	336.91 ± 63.39	239.90 ± 77.98
Total losses (W)	694.85 ± 79.23	603.36 ± 63.90	438.66 ± 78.22
Efficiency (%)	84.35 ± 1.79	81.64 ± 1.95	80.40 ± 3.50

Conclusions

The work presented a thermodynamic methodology to obtain the total loss of a motor employing a thermography technique, which allows its application in field rather than applying standard methods and expensive equipment in laboratory. The methodology employs an image processing technique that divides a thermal image in several isotherms, calculating the natural convection in each one. The forced convection is obtained using a thermo-anemometer sensor that measures the air flow and its temperatures at motor's inlet and outlet. Comparing the results of the proposed methodology with the standard ones, it was found that there is a very good agreement when considering the errors imposed by each methodology.

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Abstract:
This book contains the papers presented at the eighth international conference on Energy Efficiency in Motor Driven Systems EEMODS 2013
EEMODS 2013 was organised in Rio de Janeiro, Brasil from 28 to 30 October 2013. This major international conference, which was previously been staged in Lisbon (1996), London (1999), Treviso (2002), Heidelberg (2005), Beijing (2007), Nantes (2009) and Washington DC (2011) has been very successful in attracting an international and distinguished audience, representing a wide variety of stakeholders in policy implementation and development, manufacturing and promotion of energy-efficient motor systems, including key policy makers, equipment manufacturers, academia and end-users.
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