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## Premium Efficiency Motors

M. Benhaddadi<sup>1</sup>, G. Olivier<sup>1</sup>, R. Ibtouen<sup>2</sup>, J. Yelle<sup>3</sup>, and J-F Tremblay<sup>3</sup>

<sup>1</sup>*École Polytechnique de Montréal, dépt. de génie électrique, C.P. 6079*

*Succursale Centre-ville, Montréal, Québec, H3C 3A7*

<sup>2</sup>*École Nationale Polytechnique d'Alger, dépt. de génie électrique, Avenue Pasteur*

*BP 182, El Harrach, 16200 Alger*

<sup>3</sup>*Cégep du Vieux Montréal, dépt. Technologie de génie électrique, 255 Ontario-Est*

*Montréal, Québec, Canada H2X 1X6*

<sup>1,3</sup>*Canada*

<sup>2</sup>*Algérie*

### 1. Introduction

Despite its considerable potential for energy savings, energy efficiency is still far from realizing this potential. This is particularly true in the electrical sector (IEA, 2010). Why? There is no probably just one single answer to this question. A consequential response requires major multiform research and an analytical effort. No doubt that analysis of the interaction between energy efficiency policies and energy efficiency performance of economies accounts for a significant part of the effort.

In the future sustainable energy mix, a key role will be reserved for electricity, as GHG emissions reduction in this sector has to be drastically reduced. In this option, obvious conclusion is that large market penetration Premium motors needs a complex approach with a combination of financial incentives and mandatory legal actions, as industry doesn't invest according to least life cycle costs (DOE, 2010).

This present work illustrates the induced enormous energy saving potential, permitted by using high-efficiency motors. Furthermore, the most important barriers to larger high-efficiency motors utilization are identified, and some incentives recommendations are given to overcome identified impediments.

In the present work, experimental comparison of the performance characteristics of 3 hp Premium efficiency motors from three different manufacturers has been presented. The motors were tested according to Standard IEEE 112-B.

### 2. Energy, climate change and electricity

According to last report Intergovernmental Panel on Climate Change IPCC report (IPCC, 2007), the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations. Moreover, there is no doubt that discernible human influences now extend to other aspects of climate, including ocean warming, continental-average temperatures, temperature extremes and wind patterns. Stabilizing atmospheric carbon dioxide concentrations at twice

the level of pre-industrial times is likely to require emissions reductions up to 90 % below current levels by 2100. Clearly, reductions of this magnitude can be achieved only by taking action globally and across all sectors of the economy. The electricity sector will undoubtedly need to assume a major share of the weight, according to its contribution to overall emissions estimated to be more 10 000 Mt (million tone) CO<sub>2eq</sub> per year.

As can be seen in fig.1, the electricity generation is dominantly produced from fossil fuels (coal, oil, and gas), and today's situation is the same as forty years ago (DOE, 2010). In the last XXI world energy congress, it is highlighted that electricity generation will still depend on fossil sources. In the meantime, according to (IEA, 2010), industry accounts for more 40 % of the world 20 000 TWh (terawatt hours, or so called billion kilowatt hours) electricity consumption, weighting more 4 000 Mt CO<sub>2eq</sub> per year. Within the industrial sector, motor driven systems account for approximately 60% to 65% of the electricity consumed by North American (RNC 2004, DOE 2010) and European Union industries. Implementing high efficiency motor driven systems, or improving existing ones just by 1 to 2 %, could save up to 100-200 TWh of electricity per year. This would significantly reduce the need for new power plants. It would also reduce the production of greenhouse gases by more 100 million CO<sub>2eq</sub> per year and push down the total environmental cost of electricity generation.

The worldwide electric motors above 1 hp can be estimated to be nowadays more 300 million units, with the annual sales of 34 million pieces. Typically, one-third of the electrical energy use in the commercial sector and two-thirds of the industrial sector feed the electrical motors (DOE, 2010). Moreover, the low voltage squirrel cage induction motor constitutes the industry workhorse. In particular industrial sector such as the Canadian petroleum and paper industry, the share of the energy used by electrical motors can reach 90% (RNC 2004). Since induction motors are the largest electrical energy user, even small efficiency improvements will result in very large energy savings and contribute to reduce greenhouse gas emissions GHG. Furthermore, the declining resources combined environmental global warming concerns and with increasing energy prices make energy efficiency an imperative objective.

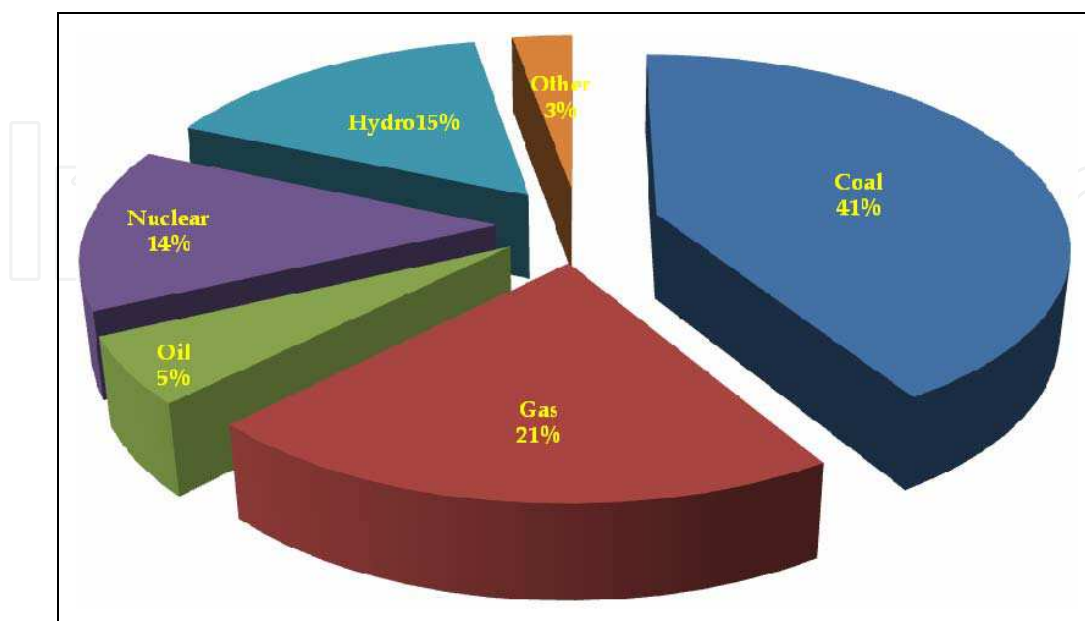


Fig. 1. Electricity generation by fuel

### 3. Motor losses segregation and efficiency

The impact of a motor in terms of energy and economical costs depends on its performance during its lifetime. The motor performances are characterized by the efficiency with which it converts electrical energy into mechanical energy.

In Standard IEEE 112-B the losses are segregated and the efficiency is estimated by the following formula:

$$\Delta P_{\text{str}} = P_{\text{in}} - P_{\text{out}} - (\Delta P_{\text{el1}} + \Delta P_{\text{el2}} + \Delta P_{\text{core}} + \Delta P_{\text{mech}}) \quad (1)$$

Where the electric input power,  $P_{\text{in}}$ , is measured with a power analyser and the output power,  $P_{\text{out}}$ , with a torque meter. The overall precision of efficiency assessment mainly depends on the torque estimation, and with the improved accuracy of recent power analysers and torque meters, this method can be considered accurate and reliable.

Motor efficiency is defined as a ratio motor mechanical output power and electrical input power. Hence in order to have a motor perform better, it is important to reduce its losses. The major motor losses are resistive losses in the stator and the rotor windings, and magnetic losses (hysteresis and eddy current losses) in the cores. Other losses include mechanical (bearing friction and ventilation), and stray load losses. High efficiency motor losses relative distribution is not so different at low efficiency one's; it's more dependent on the power. Their general distribution is illustrated in fig.2.

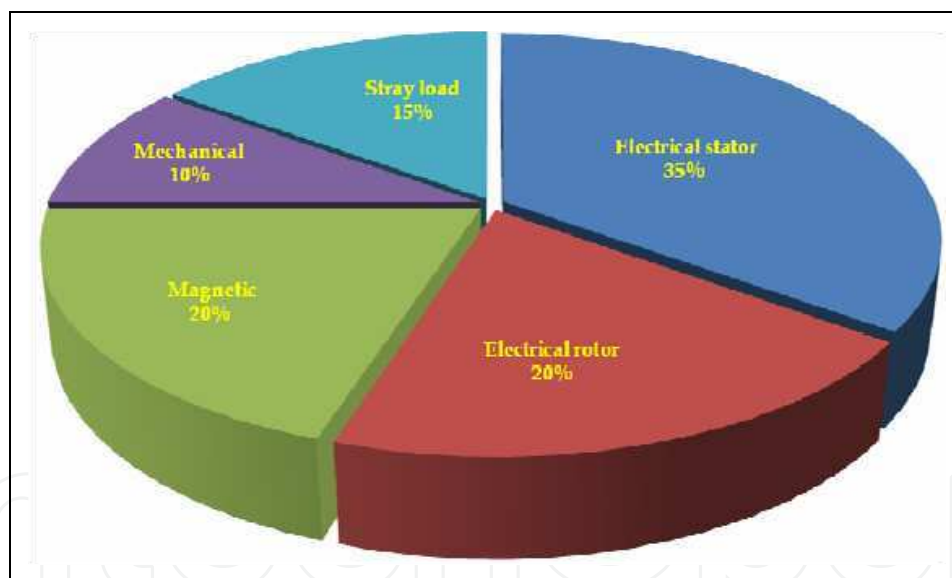


Fig. 2. Induction motor losses distribution

There are many ways to improve electric motor efficiency; the majority of them make the motor larger in diameter or overall sizes and, of course, more expensive.

- Winding stator ( $\Delta P_{\text{el1}}$ ) and rotor ( $\Delta P_{\text{el2}}$ ) losses are due to currents flowing through the stator windings and rotor bars. These losses can be reduced by decreasing the conductor current density in the stator windings, in the rotor bars and in the end rings. Using larger conductors lowers stator resistance, while the use of copper instead of aluminum reduces rotor losses (Parasiliti et al. 2002). Another way of decreasing stator losses is by reducing the number of turns. Unfortunately, this increases the starting current and maximum torque, as worsen the power factor.

- Magnetic losses  $\Delta P_m$  occurring in the stator and rotor laminations are caused by the hysteresis and eddy current phenomena. These losses can be decreased by using better grade magnetic steel, thinner laminations and by lowering the flux density (i.e larger magnetic cores). The better grade of laminations steel are still relatively very expensive. Cheaper manufacturing methods other than stamping are expected to become available in the near future.
- Mechanical losses  $\Delta P_{mec}$  are due to bearing friction and cooling fan air resistance. Improving the fan efficiency, the air flow and using low friction bearings result in a more efficient design. As these losses are relatively small, the efficiency gain is small too, but every improvement is welcome.
- Stray load losses  $\Delta P_{st}$  are due to leakage fluxes induced by load current, non-uniform current distribution, mechanical air-gap imperfection... These losses can be reduced by design optimisation and manufacturing method improvements.

As can be deduced, one of the most established methods of increasing motor efficiency is to use higher quality materials, inexorably increasing the motor cost, as most high performance materials are expensive materials. In a recurrent manner, the same problem of increased cost holds true for better construction techniques, such as smaller air gaps, copper rather than aluminum in the rotor construction, higher conductor slot fill, and segmented core stator construction. The resulting increase in motor cost is evaluated to be between 15 % and 30 %.

#### 4. Testing standards

In North America, the prevailing testing method is based on direct efficiency measurement method, as described in the Institute of Electrical and Electronics Engineers (IEEE) "*Standard Test Procedure for Polyphase Induction Motors and Generators*" IEEE 112-B and in its Canadian CSA 390 adaptation. The standard first introduced in 1984 and updated in 2004, requires the measurement of the mechanical power output and the electric input, and provide a value for the motor losses, where the additional stray load losses are extrapolated from their total by the following formula (1). So, the efficiency is extrapolated by:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{P_{out} + \Delta P_{el1} + \Delta P_{el2} + \Delta P_m + \Delta P_{mec} + \Delta P_{st}} \quad (2)$$

In Europe, the prevailing testing method is based on an indirect efficiency measurement as defined in IEC 34-2 standard "*Rotating electrical machines - Part 2: Methods for determining losses and efficiency of rotating electrical machinery from tests*". The standard first introduced in 1972 and updated in 1997, attribute a fixed value, equal to 0.5 % of input power to the additional stray load losses.

These standards differ mainly by the method used to take into account the additional load losses (Aoukadi & Binder, 2008, Boglietti et al 2004, Nagorny et al. 2004, Elmeida et al. 2002...). Many papers have been published and some authors have illustrated, that IEC 34 - 2 has drawback with a noticeable influence on the testing of high efficiency motors, as the efficiency of this motor type is overestimated, particularly in the small motor size cases. Ultimately, standard IEC 34 - 2 was found to be unrealistic with its 0.5 %  $P_{in}$  value for stray losses (Aoukadi & Binder, 2008, Renier et al. 1999, Boglietti et al 2004...). That is why, in 2007, IEC published a revised standard for efficiency classification no. 60034-2-1 which includes a test procedure largely comparable to IEEE 112-B or CSA C390. Newly

harmonized standards for energy efficiency testing IEC 60034-2-1 can contribute to lowering barriers in global trade for energy efficient motor systems.

## **5. Minimum energy performance standard MEPS and efficiency motor classification**

There are many different worldwide definitions for energy efficient motors, as until these last years, there was no consensus on what really represents an energy efficient motor. Technical barriers include non harmonized testing standards and efficiency classification. In reality, the key mandatory instrument is minimum energy performance standards (MEPS).

### **5.1 MEPS in North America**

On October 1992, US Congress voted law, Energy Policy Act EPAct, which mandates strict energy efficiency standards for electrical appliances and equipment, including electric motors. Motor MEPS were for the first time introduced in 1992 when all partners were finally persuaded that voluntary measures are too slow, and no significant market transformation towards more efficient motors was possible otherwise.

EPAct requires that the general purpose electric motors meet the higher nominal efficiency requirements defined in the table of National manufacturer association NEMA Standard, and the implementation of the motor MEPS went into effect in 1997.

The Canadian Standard association developed a Canadian standard in 1993, and updated it in 1998. CAN/CSA C-390 set the requirement for minimum efficiency for new motors made or sold in Canada at the same value as the NEMA energy-efficient level.

The Energy Policy Act EPAct-92 motors covered are:

- General purpose
- Definite or special purpose in a general purpose application
- Continuous duty
- 2, 4 & 6 Pole
- 1-200 HP
- 230/460/, 60 Hz

The Canadian standard was furthermore extended to 575 V and IEC motors, and included 75 % full load to reach maximum efficiency.

Some motors were not covered:

- Definite or special purpose in a non-general purpose application
- Slower speeds
- Inverter duty
- Multi-speed
- Totally enclosed air over TEAO, and totally enclosed not ventilated TENV

As a result of the mandatory standard that was endorsed as part of the EPAct-92, North America had a motor standard foundation that leads the new century world.

In 2002, NEMA and Consortium for energy efficiency CEE established a voluntary NEMA Premium level of efficiency, and the manufacturers began the next step in evolution with the implementation on voluntary basis MEPS NEMA Premium efficiency motors. NEMA premium efficiency standards (CEE 2007) have remained voluntary for a long period of 10 years. In spite of this, NEMA premium motors have been progressively gaining market share, as the overall benefits of Premium motors is incommensurable (more reliable, last

longer, have longer warranties, run more quietly and cooler and produce less waste heat than their less-efficient counterparts). The trend is particularly well depicted in the work, illustrated in fig. 3.

The evolution of MEPS based on NEMA Premium is now moving from voluntary basis to legislated regulation, as the law implementation is awaited for December 2010. So, 1 -200 HP general purpose motors already covered by EPAct will change from NEMA MG-1, Table 12-11 Energy Efficient (Annex 1) to Table 12-12 NEMA Premium efficiencies levels (Annex 2), except for fire pump motors which remain at EPAct-92 level.

Moreover, the proposal expands the scope of enclosed 1-200 Hp motors, as several motor types not previously covered by EPAct-92 must meet EPAct efficiency levels. The added motors are:

- U-frame
- Design C
- Footless
- Close-coupled pump
- Vertical solid shaft normal thrust
- 8 poles
- All low voltages  $\leq 600$  V not previously covered, including IEC Metric frame motors from 90 frames and up.
- 201 to 500 HP low voltage 2-8 pole general purpose motors, where Design B represent something like  $\frac{3}{4}$  of total range.

It's appropriate to highlight that this additional coverage means that MEPS is extended to more 90 % of the motors in the 1 to 200 Hp range, despite the fact that some manufacturers expressed technical skepticism about meeting premium efficiency levels design C and 900 rpm motors.

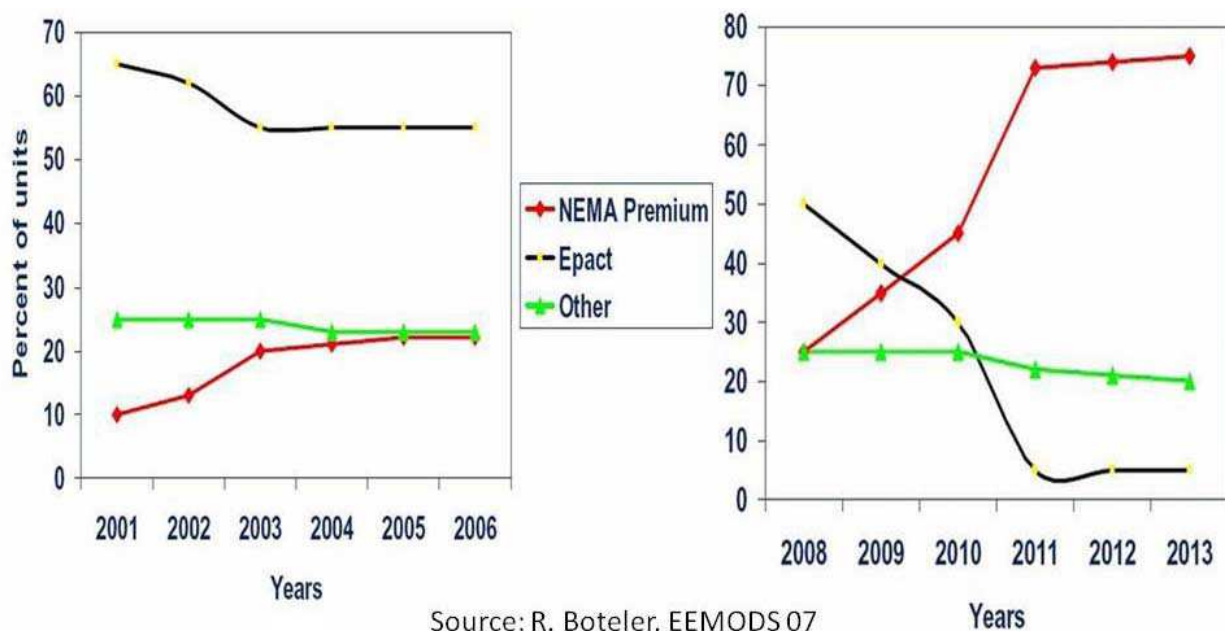


Fig. 3. Efficiency trend 2001-2006 and efficiency expected 2008-2013

On the other hand, EISA does not apply to motors exported outside North America, as well as EISA doesn't contain any requirement to replace electric motors in use. In addition, the

law applies only to motors manufactured after December 19, 2010 and motors in inventory on that date can be sold or used without any additional constraints, but some customers may not probably want them.

Some Motor configurations are not covered by EISA law. These are:

- Design D with high slip
- Inverter duty with optimized windings for adjustable speed drives ASD use
- Customized OEM mounting
- Intermittent duty
- Integral with gearing or brake where motor cannot be used separately
- Submersible motors
- Single Phase motors
- DC motors
- Two-digit frames (48-56)
- Multi-speed
- Medium voltage motors
- Repaired motors
- TENV and TEAO enclosures

It's relevant to notice that regulation concerning single phase and three-phase small (42/48 and 56 frame) motors is ready, as Department of energy (DOE 2010) published in 2010 its final rule giving efficiency limits that must be met by small general purpose electric motors, starting from 2015. Nevertheless, NEMA doesn't support regulation of this product, as many questions are still not solved while small induction motor is continually losing market part to switched reluctance and permanent magnet types.

## 5.2 New IEC standard

In 2007, IEC published a revised standard for efficiency testing no. 60034-2-1 which includes a test procedure largely comparable to IEEE 112-B or CSA C390, and in September 2008 a new standard no. 60034-30 for efficiency classification of electric motors.

New standard for efficiency classification is applicable to single speed, three-phase induction motors with the following parameters:

- Power from 0.75 to 375 kW
- Voltage under 1000 V
- 50 and 60 Hz frequency
- 2, 4 and 6 poles
- Duty S1 or S3
- All IP1x to 6x and IC0x to 4x
- Networked
- All types of fixing, shaft extension, accessories

Some Motor configurations are not covered by IEC 60034-30. These are:

- Motors with reinforced isolation specifically designed for variable speed drives applications
- Motors which are fully integrated in a machine and cannot be tested separately

Newly 2008 harmonized standard for energy efficiency class 60034-30-2008 follow International Electrotechnical Commission (IEC) protocol and defines four induction motor efficiency classes:



- Super Premium efficiency level IE4
- Premium efficiency level IE3
- High efficiency level IE2
- Standard efficiency level IE1

It's noticeable that, nowadays, Premium efficiency IE3 is the most efficient motor. Super Premium efficiency IE4 is a future new generation motor. It is awaited that in average, the losses reduction of IE4 should be 15 % compared to IE3. So, IE4 is not a standard in fact, but just a level.

### 5.3 MEPS in EU and BRIC countries

In Europe, the European committee of manufacturers of electrical machines and power electronics CEMEP has classified 2 & 4 pole 1-90 kW motors into three levels:

- High (EFF1),
- Improved (EFF2), and
- Standard efficiency (EFF3).

The CEMEP classification has induced substantial EFF3 motors reduction and EFF2 market share promotion. Nevertheless, EFF1 market part is still modest. Meanwhile, European Union is considering prohibiting the sale of motors that don't meet EFF2 criteria in the near 2011 future.

The new EU MEPS system is based on the latest IEC standard, and it represents a significant step towards worldwide harmonization of efficiency regulations.

The challenges that EU countries facing are:

- From June 16, 2011, motors shall not be less efficient than IE1 (i.e. EFF2) and EFF3 motors will be banned
- From January 1, 2015, motors with rated output of 7.5 to 375 kW shall not be less efficient than IE2
- From January 1, 2017, motors with rated output of 7.5 to 375 kW shall not be less efficient than IE3
- From January 1, 2017, all motors with rated 0.75 to 375 kW shall not be less efficient than IE2 if equipped with adjustable speed drive (ASD).

BRIC countries (Brazil-Russia-India-China) motors and motor driven equipment are still relatively less efficient. For example, the efficiency of over 80 % Chinese motors is 2-5 % lower than international advanced ones. Chinese scientists consider that if efficiency of motor systems could be raised to the North American level, then 150 TWh of electricity would be saved each year. But China is making progress, by formulating a number of policies, laws and regulations on energy conservation. Beginning this 2010 year, the MEPS efficiency of newly added motors should reach international first-rate level Class 2, which is equivalent to IE1, or EFF2.

At the present time, 10 countries with a half of global electricity demand have motor MEPS endorsement. In the next two years, 15 new countries targeted for a next round until 2012 to reach around 80% of global electricity demand.

As earlier mentioned, the International Electrotechnical Commission (IEC), a worldwide organization for standardization comprising all national standards committees, defined in IEC 60034-30 (2009) four efficiency classes for single-speed cage-induction motors, and specified test procedures. It's important to notice that the so-called IE4 Super Premium Efficiency products are not commercially available yet, while lower efficiency motors in use

now Eff3 disappears in the new classification. This new classification will be probably soon adopted worldwide in place of regional or local classification, as illustrated in table 1. This new standard defines efficiency classes and their containing minimum values (conditions).

Efficiency Class	IEC	USA/Canada	CEMEP	China
Super Premium efficiency	IE4	-	-	-
Premium efficiency	IE3	NEMA Premium	-	-
High efficiency	IE2	EPAct	EFF1	Class 1
Standard efficiency	IE1	-	EFF2	Class 2
Below standard efficiency	-	-	EFF3	Class 2

Table 1. International motor efficiency classification

## 6. Life cycle cost Premium motors

An electric motor is somewhat cheap to buy, but expensive to run. For example, a 3 hp Premium efficiency motor functioning 6 000 hours per year consumes about 1000 \$ of electricity at \$0.07/kWh. The purchase price for such a motor is about 500 \$ and over the motor's 15-year life, the acquisition price represents only 3 % of the lifetime costs, while the cost of electricity accounts for 97 %. Finally, a 2 % increase in Premium motor efficiency over EFF1 translates in energy savings over that time nearly twice the cost difference. In addition, with a larger motor, the saving potential will be larger, and therefore payback periods would be shortened. For the 100 Hp motor, the acquisition price represents only 1 % of the lifetime costs, while the cost of electricity accounts for 99 %!!! Fig. 4 depicts typical lifetime cycle cost motor in the conservative case (Benhaddadi & Olivier, 2010a).

The average life cycle of the small power motors is of the order of 15 years, i.e. the equivalent of the average car range. The fundamental difference is in the fact that during this period, the cost of the electricity will represent 97 % of the cost of useful life cycle of the electric motor, while for the car motor, it represents only 10 %. Moreover, the car's internal combustion motors can rarely overcome 50 % efficiency, with an enormous negative impact to be paid in environmental pollution. We can deduct from this fact that the improvement of 1 % of the electrical motor efficiency will have the same impact as the reduction of the 10 % gas consumption car.

Moreover, the Canadian electricity costs are presently up to two times cheaper than elsewhere and high electricity prices reduce payback period. In addition, some Canadian utility companies and public agencies like Hydro Québec in Québec offer rebate programs to encourage customers to upgrade their standard motors to Premium efficiency (Benhaddadi & Olivier, 2010b). For motors from 1 to 75 hp, this program allows 600 \$/hp to the customer and 150 \$/hp to the distributor for each saved hp. Unfortunately, as a consequence of the lack of energy saving importance, the purchase of a new motor, as well as the rewinding of defective standard-efficiency motors, the choice of the motor is often driven by short term investment considerations, not on the cost of the electricity which can be saved.

The first law for energy efficient motors is the Energy Policy Act (EPAct) which mandates strict energy efficiency standards for electrical appliances and equipment. This law was first adopted in USA and became effective in Canada with the adoption of Standard CAN/CSA-

C390-98. Today more than 75 % of the motors sold in North America are Premium efficiency and EPart machines. This clearly indicates the positive effect of the energy law. In light of the above, and taking into consideration the very slow market transformation with just voluntary and incentive measures, there's no doubt that Premium motors will monopolize the dominant part of the market in the near 2013 future. This is well illustrated in fig. 3. There is no doubt that the appropriate legislation is the best way of achieving that goal (Benhaddadi & Olivier, 2009b). Only the latest energy efficient motor technologies should be manufactured and used. In general terms, North America is not on the leading edge for energy saving and conservation. Motor efficiency is an exception that should be at least maintained by EISA law implementation.

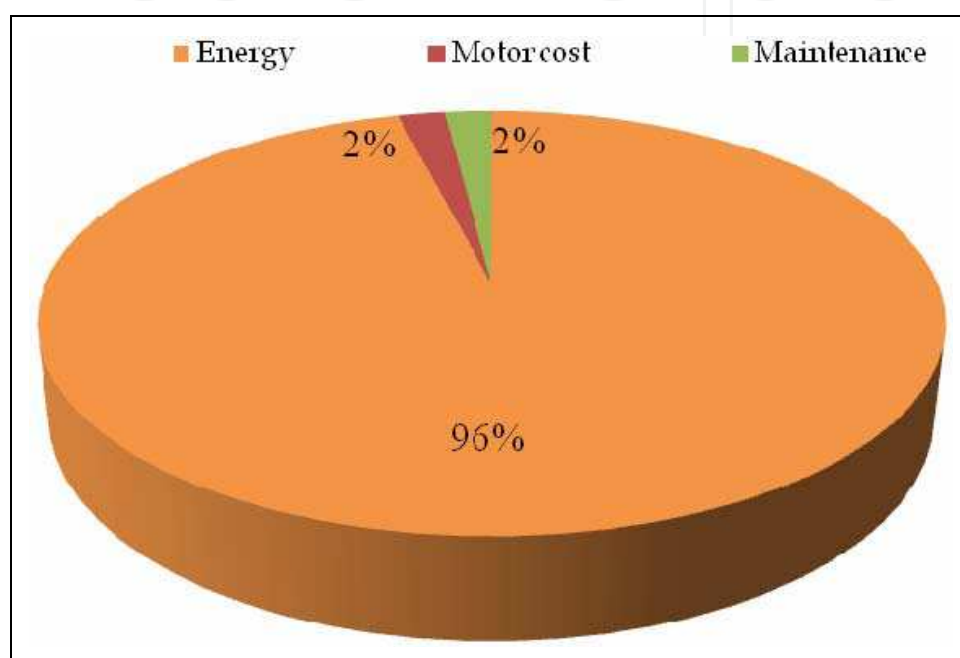


Fig. 4. Lifetime motor cost

## 7. Barriers to high efficiency motors market penetration

Despite the colossal energy saving potential and financial incentives programs, many companies are still reticent to invest in energy-efficiency motors. The reasons why the well-known potential for energy saving energy is not exploited have been investigated, and the authors have identified several reasons why this potential is not yet fully exploited. The Grand paradox is that cost effective measures are not taken because of several illogical barriers. So, the most important barriers to high efficiency motors promotion are (Benhaddadi & Olivier, 2008a):

- The energy costs are relatively so small that energy efficiency improvement isn't taken into consideration,
- Lower priority of energy savings importance, when other factors such as availability service, reliability, and first costs are of premium importance,
- Industry reluctance to change what is, a priori, a good functioning system,
- Doubt about success of energy efficiency programs, or the discount rates used to justify energy efficiency programs are too low,

- Downtime replacement cost look like peanuts, but shutdown time to install new equipment is expensive and many companies don't accept this inconvenient,
- Reduced budget often makes reducing energy consumption as « poor parent », inducing a lack of encouragement to make a decision,
- Implementing making-decision responsibility is often shared with many internal conflicting pressures and divergence and ultimate choice don't always belong to electrician engineers, who are energy savings conscious,
- Distributors regularly represent two or more motor manufacturers and they can advantage products from the manufacturer that offers the highest discount rather than high-efficiency ones,
- Usual predisposition to use stocked old motors rather than purchase high efficiency ones,
- It is not economically pragmatic to change a motor until it fails,
- Penchant to have the failed motor repaired rather than replaced by high efficiency ones,
- Degradation efficiency of repaired motor cannot be simply illustrated,
- Annual running hours are not sufficiently high to induce satisfactory payback.

## 8. Incentive policies to overcome barriers

Experience derived from many energy saving initiatives around the world showed that the most successful programs are based on a combination of technical and promotional information, educational tools and financial incentives. If technicians and engineers would be trained in system design integration and least lifecycle cost as a goal, no doubt that the problem of inefficient industrial equipment should be solved (Benhaddadi & Olivier, 2008a). Consequently, to overcome the identified obstacles need a combination of the following measures:

- Premium priority: For the companies, the energy saving status has to arrive at legislative endorsement, like is the case for safety and quality insurance,
- Incentive programs: to reinforce energy savings promotion politics, much higher discount rates should be used to evaluate the cost-effectiveness of energy efficiency policies, programs or measures,
- Highlighted information and diffusion: this information must be of practical value, and sufficiently demonstrative with real pilot projects,
- Environmental concern: It's necessary to reinforce ecological policy criteria and support environmental friendly companies. This follows the principle that the saved energy is the most environmentally friendly one. A particularly promising concept is the emissions trading scheme, which could be enable companies to claim emissions credits for investments that reduce energy consumption,
- Legislation: to legislate against recalcitrant and to impose to market the gradual approach of the « carrot and the stick », where the carrot represents the incentives and the stick stands for refractory.

The authors strongly believed in the need to enhance policy measures aimed at reducing the demand for energy and the resultant environmental impact. We therefore welcome the increased interest in energy conservation in Canada. But, the accumulated experience clearly show that putting in place incentives and voluntary measures for the energy efficiency of electric motors is not sufficient, as it is prerequisite to implement mandatory measures for

larger market penetration (fig. 5). The carbon savings from this measure have the potential to make a significant contribution to emissions target reduction.



Fig. 5. Incentives, voluntary and mandatory measures impact

## 9. Experimental setup and results

Figure 6 depicts the experimental laboratory set-up. The motors are fed by three single phase autotransformers and direct torque control, DTC drives. The motors are mechanically loaded by dc machine connected through a precision torque-speed transducer. A motor/harmonic power meter is used for measuring real and reactive power, currents, voltages and power factor. The motors are mechanically loaded by dc machine connected through a high precision torque-speed transducer.

The measurements were taken in similar conditions and each motor was loaded until thermal equilibrium was reached, while each of the two benches can be used to determine the efficiency.

The two benches are sufficiently flexible and require minimum adjustments when different Premium motors are tested (Benhaddadi et al. 2010b). Several 3 hp Premium motors from different 3 manufacturers were tested. Figures 7 and 8 show the stators and rotors of the three different motors.

The measurements were taken in similar conditions and each motor was loaded until thermal equilibrium was reached.

For each of the motors B & C, Fig. 9 shows the variation of the efficiency versus the mechanical torque in the case of direct 60 Hz feeding, without drive. The results for motor A are not provided, as they are the same as for the motor B. One can deduce that when the motors are fed from the rated 230 V grid, the difference between the measured efficiency at rated load and the nameplate value is less than 0.2 %. But, most electric motors are designed to function at 50 % to 100 % of rated value. Fig. 9 also shows that maximum Premium motor



Fig. 6. Measurement setup with instrumentation

efficiency is near 75 % of rated load, and tends to decrease substantially below about 50 % load. Moreover, experienced overloaded motors don't significantly lose efficiency, as they are designed with a 1.15 factor service. It's also relevant to notice that the two motors give the same efficiency value just for the rated regime, as this efficiency difference is significant (1.5 %) when the motor is under loaded (Benhaddadi et al. 2010b).

Next step is to analyze the feeding voltage impact. The voltages choice are made taking into account practical considerations: 230V, and 200.

- The first one is the motor nameplate indication, which is in accordance with an industrial available 240 V feeding voltage,
- The second one is the real full-time laboratory available voltage. These two voltages were obtained with three one-phase transformers.

The experimental results obtained in the grid feeding case (without drive) and illustrated in fig. 10 show that feeding voltage has an important impact on efficiency value. With rated 230 V voltage and load values, efficiency is 89.3 %, i.e. 0.2 % less than nameplate value. When the feeding voltage is decreased to 208 V and 200 V values, the efficiency decrease up to 2 %. So, additional losses occur when a 230 V motor is operated at or below 208 volts. The motor show lower full-load efficiency, slips more, and produces less torque.

In another hand, the ASD (adjustable speed drive) deployment to control motor can substantially reduce energy consumption. The ASD advantages and energy consumption reduction are nowadays well documented (Benhaddadi & Olivier, 2007). But, at the present

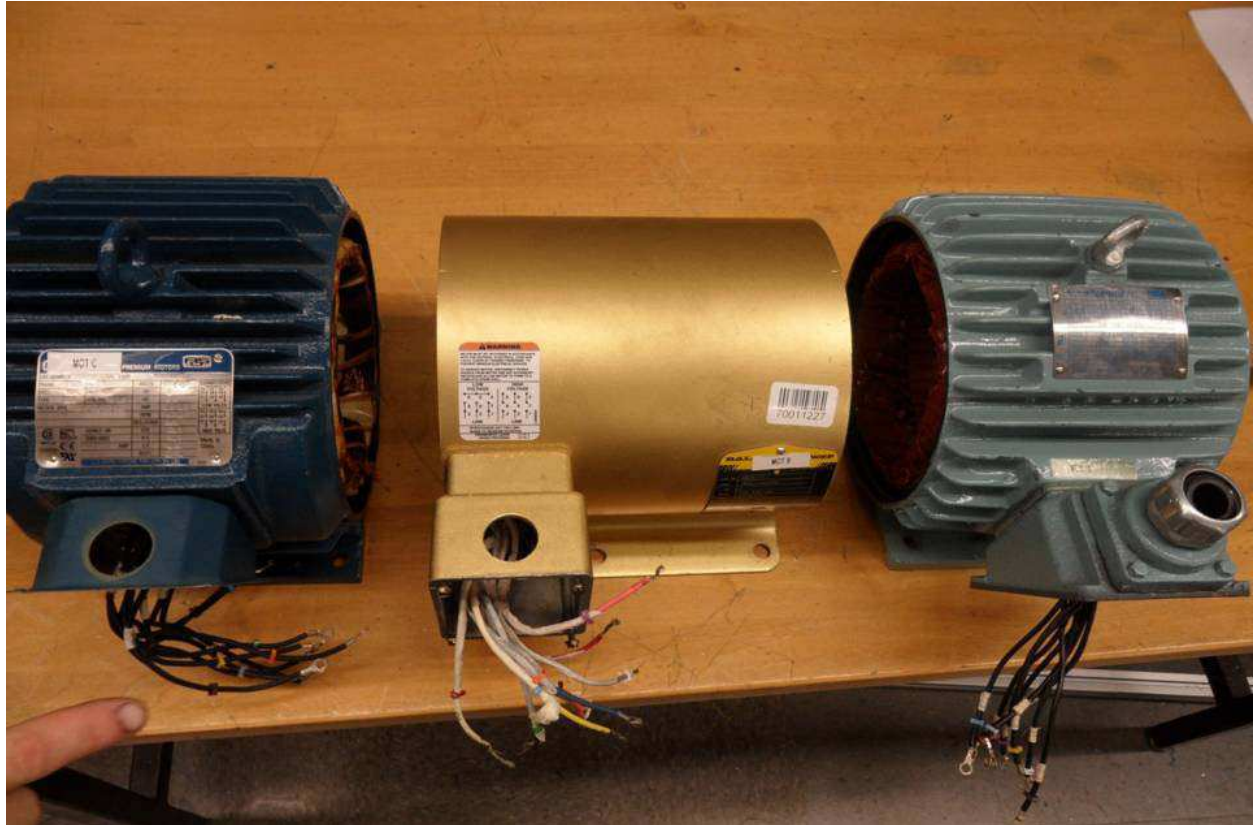


Fig. 7. Stator Premium motors



Fig. 8. Rotor Premium motors

time, many companies use ASD to feed their motors, whenever they don't need speed regulation. In the energy saving point of view, we must be careful with this making-decision, as ASD introduces supplementary losses in the motor and the drive. As can be seen in fig. 11 and 12, the drive introduces a noticeable reduction of the motor system efficiency. This decrease reaches approximately 4 % in the rated regime, withdrawing totally energy savings induced by Premium efficiency motor use. Further investigations to correctly understand the extents of the losses introduced by the controller for all frequencies are under consideration.

The other problem is that if Premium motors are misapplied, they may not achieve predicted energy savings and may result in diminished performance efficiency. For centrifugal pumps, an increase in operating speed will increase the required power by the third power of the speed ratio. For example, by substituting Premium 1760 rpm motor to EPAct 1740 rpm one, a 20 rpm increase in the speed induce 3.5 % increase in the load, as  $(1760 \div 1740)^3 = (1.014)^3 = 1.035$ . So, when replacing a standard efficiency motor, one must be careful, as a Premium motor with lower or equal full-load speed must be selected to avoid the energy increase that may negate the predicted energy savings resulting from a higher efficiency.

It's important to notice that to date, there is no agreement that allows the determination of ASD system efficiency at any given frequency. The ideal situation is to obtain a family of efficiency curves for diverse torques and frequencies, including overrated values, as experimentally illustrated in fig. 13.

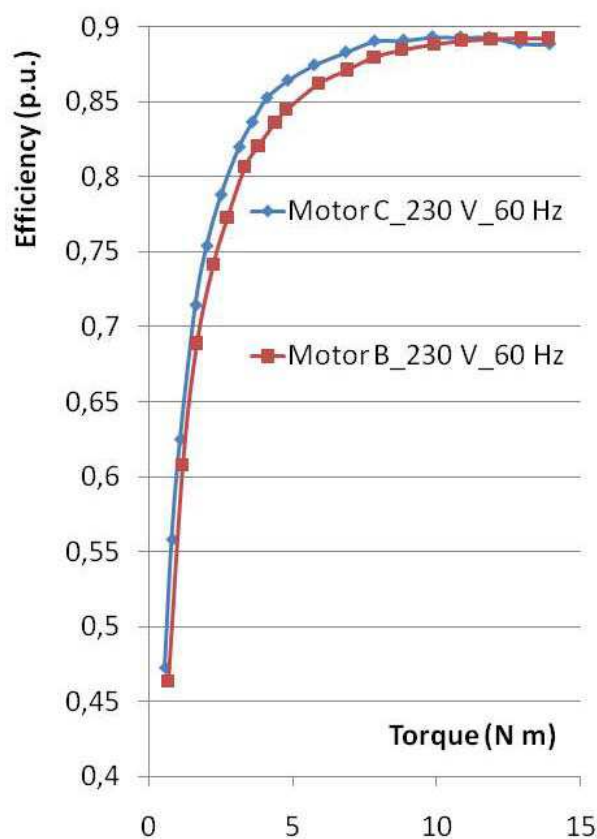


Fig. 9. Manufacturing technology impact

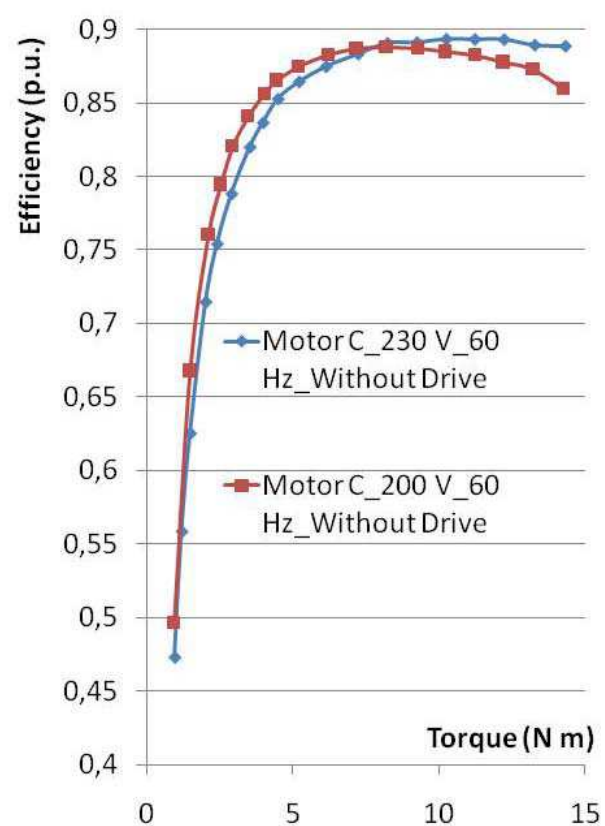


Fig. 10. Voltage feeding impact



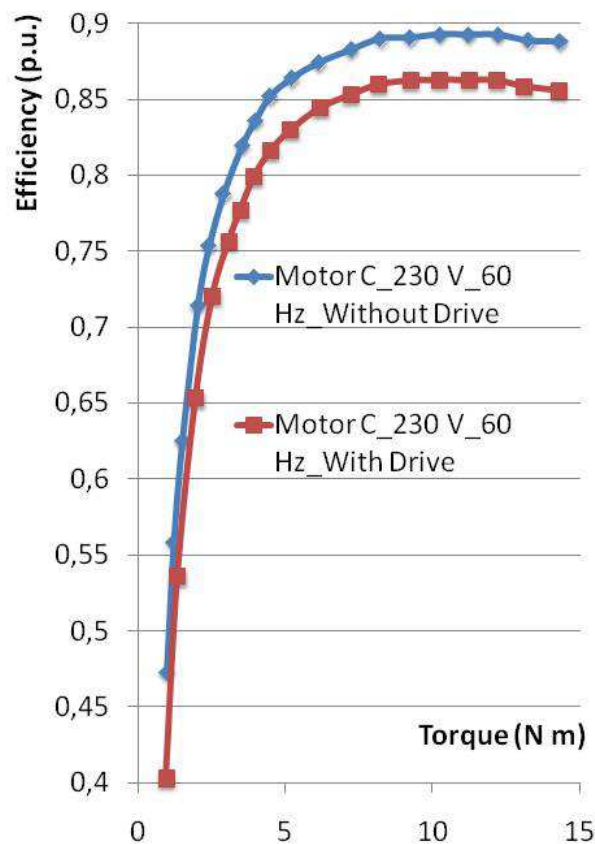


Fig. 11. Drive impact

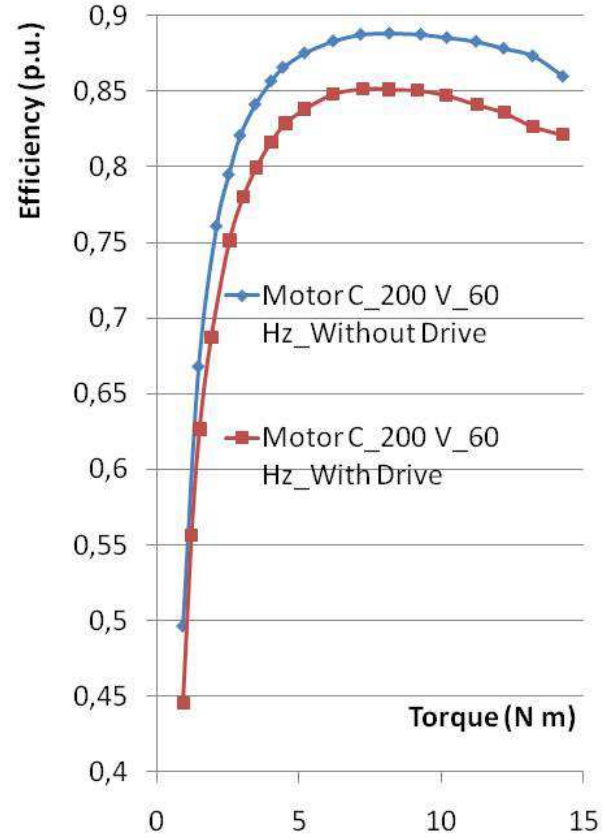


Fig. 12. Drive impact

But, to generalize results, there are two difficulties: the first one can be illustrated by the results presented in fig.14, where we can see that the same 3 Hp motors issued from two different manufacturers can have the same efficiency for 60 Hz frequency feeding voltage, but different efficiency for another 30 Hz frequency (fig. 14). For each of these two motors B & C, Fig. 14 shows the variation of the efficiency versus the mechanical torque. In the 60 Hz case, the difference between the measured efficiency at rated load is negligible, while it reaches 2 % in the 30 Hz feeding frequency.

The second difficulty is about 50-60 Hz feeding frequency dilemma. As earlier illustrated, 50 Hz frequency gives better efficiency beginning from 2/3 load, while 60 Hz is better for low loads. It's noticeable that the same results were obtained for Motor B.

Considering that for the same frequency, two Premium motors issued from two different manufacturers can show significantly different efficiency in low frequencies, one must be careful in generalizing the conclusions of this research. Moreover, the same motor tested for different frequencies can yield to different losses repartitions. So, before claiming that the obtained results are, or are not in agreement with findings of other authors, several other Premium efficiency motors from different constructors should be tested. The mentioned work is under consideration.

## 10. Conclusions

In the future sustainable energy mix, a key role will be reserved for electricity, as GHG emissions reduction in this sector has to be drastically reduced. In this option, obvious

conclusion is that large market penetration Premium motors needs a complex approach with a combination of financial incentives and mandatory legal actions, as industry doesn't invest according to least life cycle costs.

The US Energy Policy Act and the Canadian Energy Efficient Act, along with the implementation of NEMA Premium efficiency levels, have lead to North American leadership on motor efficiency implementation. In general terms, North America is not on the leading edge for energy saving and conservation. Motor efficiency is an exception that should be at least maintained. Next step is to get Tax incentives to promote early retirement of older inefficient pre-EPAAct motors by replacing instead of repairing

Experimental comparison of the performance characteristics of 3 hp Premium efficiency induction motors has been presented. The motors were tested according to Standard IEEE 112-B. In the rated frequency and voltage case, the experimental results are in good agreement with nameplate manufacturer's information. Particularly, a comparison of the rated operating point shows that, the discrepancy is approximately 0.2 %.

However, in low voltage/frequency applications, the use of a variable speed drive introduces extra losses and the overall efficiency can be noticeably reduced. The experimental results show that feeding voltage has an important impact on efficiency value, while efficiency at low frequencies depends on a certain level at manufacturer technology. From a global energy saving point of view, the ASD application to Premium efficiency motors should be promoted just when adjustable speed is needed.

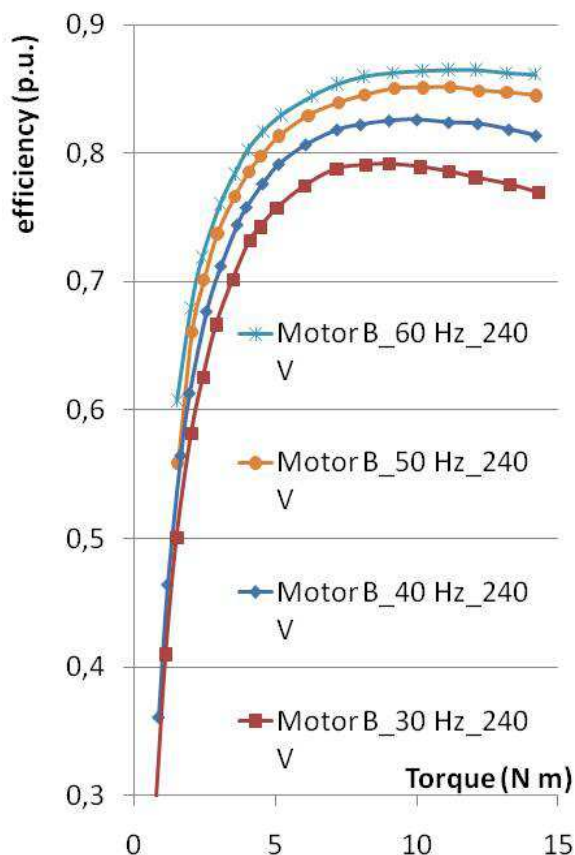


Fig. 13. Frequency impact

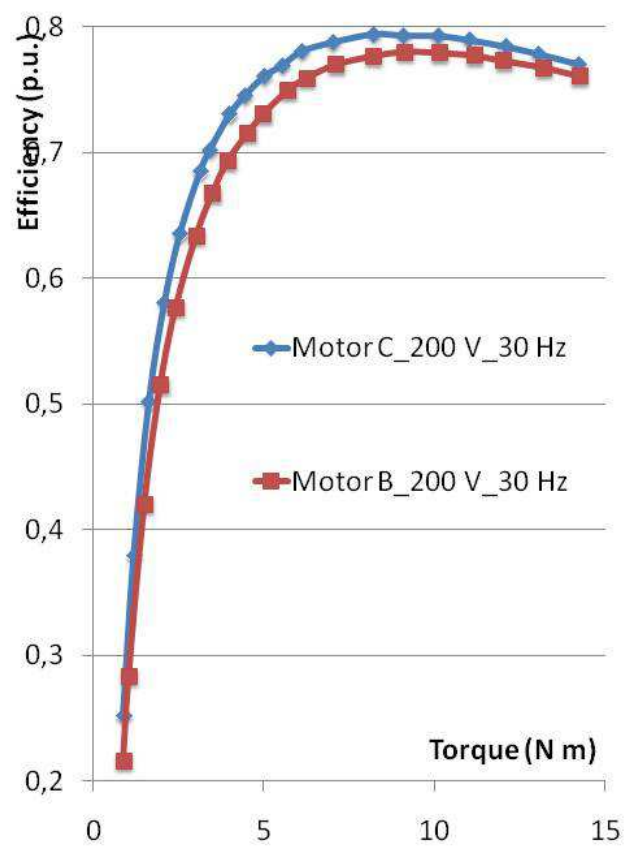


Fig. 12. Frequency & manufacturing technology impact

HP	ODP				TEFC			
	2 Pole	4 Pole	6 Pole	8 Pole	2 Pole	4 Pole	6 Pole	8 Pole
1.0	0.0	82.5	80.0	74.0	75.5	82.5	80	74
1.5	82.5	84.0	84.0	75.5	82.5	84	85.5	77
2.0	84.0	84.0	85.5	85.5	84	84	86.5	82.5
3.0	84.0	86.5	86.5	86.5	85.5	87.5	87.5	84
5.0	85.5	87.5	87.5	87.5	87.5	87.5	87.5	85.5
7.5	87.5	88.5	88.5	88.5	88.5	89.5	89.5	85.5
10.0	88.5	89.5	90.2	89.5	89.5	89.5	89.5	88.5
15.0	89.5	91.0	90.2	89.5	90.2	91	90.2	88.5
20.0	90.2	91.0	91.0	90.2	90.2	91	90.2	89.5
25.0	91.0	91.7	91.7	90.2	91	92.4	91.7	89.5
30.0	91.0	92.4	92.4	91.0	91	92.4	91.7	91
40.0	91.7	93.0	93.0	91.0	91.7	93	93	91
50.0	92.4	93.0	93.0	91.7	92.4	93	93	91.7
60.0	93.0	93.6	93.6	92.4	93	93.6	93.6	91.7
75.0	93.0	94.1	93.6	93.6	93	94.1	93.6	93
100.0	93.0	94.1	94.1	93.6	93.6	94.5	94.1	93
125.0	93.6	94.5	94.1	93.6	94.5	94.5	94.1	93.6
150.0	93.6	95.0	94.5	93.6	94.5	95	95	93.6
200.0	94.5	95.0	94.5	93.6	95	95	95	94.1
250.0	94.5	95.4	95.4	94.5	95.4	95	95	94.5
300.0	95.0	95.4	95.4	94.5	95.4	95.4	95	0
350.0	95.0	95.4	95.4	94.5	95.4	95.4	95	0
400.0	95.4	95.4	0.0	0.0	95.4	95.4	0	0
450.0	95.8	95.8	0.0	0.0	95.4	95.4	0	0
500.0	95.8	95.8	0.0	0.0	95.4	95.8	0	0

Annex 1. NEMA MG-1 Table 12-11 Full-Load Efficiencies of Energy Efficient Motors (EPAct)

HP	ODP			TEFC		
	2 Pole	4 Pole	6 Pole	2 Pole	4 Pole	6 Pole
1	77	85.5	82.5	77	85.5	82.5
1.5	84	86.5	86.5	84	86.5	87.5
2	85.5	86.5	87.5	85.5	86.5	88.5
3	85.5	89.5	88.5	86.5	89.5	89.5
5	86.5	89.5	89.5	88.5	89.5	89.5
7.5	88.5	91	90.2	89.5	91.7	91
10	89.5	91.7	91.7	90.2	91.7	91
15	90.2	93	91.7	91	92.4	91.7
20	91	93	92.4	91	93	91.7
25	91.7	93.6	93	91.7	93.6	93
30	91.7	94.1	93.6	91.7	93.6	93
40	92.4	94.1	94.1	92.4	94.1	94.1
50	93	94.5	94.1	93	94.5	94.1
60	93.6	95	94.5	93.6	95	94.5
75	93.6	95	94.5	93.6	95.4	94.5
100	93.6	95.4	95	94.1	95.4	95
125	94.1	95.4	95	95	95.4	95
150	94.1	95.8	95.4	95	95.8	95.8
200	95	95.8	95.4	95.4	96.2	95.8
250	95	95.8	95.4	95.8	96.2	95.8
300	95.4	95.8	95.4	95.8	96.2	95.8
350	95.4	95.8	95.4	95.8	96.2	95.8
400	95.8	95.8	95.8	95.8	96.2	95.8
450	95.8	96.2	96.2	95.8	96.2	95.8
500	95.8	96.2	96.2	95.8	96.2	95.8

Annex 2. NEMA MG-1 Table 12-12 Full-Load Efficiencies for 60 Hz NEMA Premium Efficient Electric Motors Rated 600 Volts or less

Rating (kW)	Rating (hp)	Poles		
		2	4	6
0.75	1	72.1	72.1	70.0
1.1	1.5	75.0	75.0	72.9
1.5	2	77.2	77.2	75.2
2.2	3	79.7	79.7	77.7
3	4	81.5	81.5	79.7
4	5.5	83.1	83.1	81.4
5.5	7.5	84.7	84.7	83.1
7.5	10	86.0	86.0	84.7
11	15	87.6	87.6	86.4
15	20	88.7	88.7	87.7
18.5	25	89.3	89.3	88.6
22	30	89.9	89.9	89.2
30	40	90.7	90.7	90.2
37	50	91.2	91.2	90.8
45	60	91.7	91.7	91.4
55	75	92.1	92.1	91.9
75	75	92.1	92.1	91.9
90	125	92.7	92.7	92.6
110	150	93.0	93.0	92.9
132	175	93.3	93.3	93.3
160	215	93.5	93.5	93.5
200	270	93.8	93.8	93.8
260	350	94.0	94.0	94.0
300	400	94.0	94.0	94.0
335	450	94.0	94.0	94.0
375	500	94.0	94.0	94.0

Table 3. Standard Efficiency IE1 50Hz

Rating (kW)	Rating (hp)	Poles		
		2	4	6
0.75	1	77.0	78.0	73.0
1.1	1.5	78.5	79.0	75.0
1.5	2	81.0	81.5	77.0
2.2	3	81.5	83.0	78.5
3	4	84.5	85.0	83.5
4	5.5	86.0	87.0	85.0
5.5	7.5	87.5	87.5	86.0
7.5	10	87.5	88.5	89.0
11	15	88.5	89.5	89.5
15	20	89.5	90.5	90.2
18.5	25	89.5	91.0	91.0
22	30	90.2	91.7	91.7
30	40	91.5	92.4	91.7
37	50	91.7	93.0	91.7
45	60	92.4	93.0	92.1
55	75	93.0	93.2	93.0
75	75	93.0	93.2	93.0
90	125	93.0	93.5	94.1
110	150	94.1	94.5	94.1
150	200	94.1	94.5	94.1
185	250	94.1	94.5	94.1
200	270	94.1	94.5	94.1
260	350	94.1	94.5	94.1
300	400	94.1	94.5	94.1
335	450	94.1	94.5	94.1
375	500	94.1	94.5	94.1

Table 4. Standard Efficiency IE1 60Hz

## Annex 3. CEI efficiencies

Rating (kW)	Rating (hp)	Poles		
		2	4	6
0.75	1	77.4	79.6	75.9
1.1	1.5	79.6	81.4	78.1
1.5	2	81.3	82.8	79.8
2.2	3	83.2	84.3	81.8
3	4	84.6	85.5	83.3
4	5.5	85.8	86.6	84.6
5.5	7.5	87.0	87.7	86.0
7.5	10	88.1	88.7	87.2
11	15	89.4	89.8	88.7
15	20	90.3	90.6	89.7
18.5	25	90.9	91.2	90.4
22	30	91.3	91.6	90.9
30	40	92.0	92.3	91.7
37	50	92.5	92.7	92.2
45	60	92.9	93.1	92.7
55	75	93.2	93.5	93.1
75	75	93.8	94.0	93.7
90	125	94.1	94.2	94.0
110	150	94.3	94.5	94.3
132	175	94.6	94.7	94.6
160	215	94.8	94.9	94.8
200	270	95.0	95.1	95.0
260	350	95.0	95.1	95.0
300	400	95.0	95.1	95.0
335	450	95.0	95.1	95.0
375	500	95.0	95.1	95.0

Table 5. High Efficiency IE2 50Hz

Rating (kW)	Rating (hp)	Poles		
		2	4	6
0.75	1	75.5	82.5	80.0
1.1	1.5	82.5	84.0	85.5
1.5	2	84.0	84.0	86.5
2.2	3	85.5	87.5	87.5
3.7	5	87.5	87.5	87.5
5.5	7.5	88.5	89.5	89.5
7.5	10	89.5	89.5	89.5
11	15	90.2	91.0	90.2
15	20	90.2	91.0	90.2
18.5	25	91.0	92.4	91.7
22	30	91.0	92.4	91.7
30	40	91.7	93.0	93.0
37	50	92.4	93.0	93.0
45	60	93.0	93.6	93.6
55	75	93.0	94.1	93.6
75	75	93.6	94.5	94.1
90	125	94.5	94.5	94.1
110	150	94.5	95.0	95.0
150	200	95.0	95.0	95.0
185	250	95.4	95.4	95.0
200	270	95.4	95.4	95.0
260	350	95.4	95.4	95.0
300	400	95.4	95.4	95.0
335	450	95.4	95.4	95.0
375	500	95.4	95.4	95.0

Table 6. High Efficiency IE2 60Hz (EPACT)

Annex 3. CEI efficiencies

Rating (kW)	Rating (hp)	Poles		
		2	4	6
0.75	1	80.7	82.5	78.9
1.1	1.5	82.7	84.1	81.0
1.5	2	84.2	85.3	82.5
2.2	3	85.9	86.7	84.3
3	4	87.1	87.7	85.6
4	5.5	88.7	88.6	86.8
5.5	7.5	89.2	89.6	88.0
7.5	10	90.1	90.4	89.1
11	15	91.2	91.4	90.3
15	20	91.9	92.1	91.2
18.5	25	92.4	92.6	91.7
22	30	92.7	93.0	92.2
30	40	93.3	93.6	92.9
37	50	93.7	93.9	93.3
45	60	94.0	94.2	93.7
55	75	94.3	94.6	94.1
75	75	94.7	95.0	94.6
90	125	95.0	95.2	94.9
110	150	95.2	95.4	95.1
132	175	95.4	95.6	95.4
160	215	95.6	95.8	95.6
200	270	95.8	96.0	95.8
260	350	95.8	96.0	95.8
300	400	95.8	96.0	95.8
335	450	95.8	96.0	95.8
375	500	95.8	96.0	95.8

Table 7. Premium Efficiency IE3 50Hz

Rating (kW)	Rating (hp)	Poles		
		2	4	6
0,75	1	77,0	85,5	82,5
1,1	1,5	84,0	86,5	87,5
1,5	2	85,5	86,5	88,5
2,2	3	86,5	89,5	89,5
3,7	5	88,5	89,5	89,5
5,5	7,5	89,5	91,7	91,0
7,5	10	90,2	91,7	91,0
11	15	91,0	92,4	91,7
15	20	91,0	93,0	91,7
18,5	25	91,7	93,6	93,0
22	30	91,7	93,6	93,0
30	40	92,4	94,1	94,1
37	50	93,0	94,5	94,1
45	60	93,6	95,0	94,5
55	75	93,6	95,4	94,5
75	75	94,1	95,4	95,0
90	125	95,0	95,4	95,0
110	150	95,0	95,8	95,8
150	200	95,4	96,2	95,8
185	250	95,8	96,2	95,8
200	270	95,8	96,2	95,8
260	350	95,8	96,2	95,8
300	400	95,8	96,2	95,8
335	450	95,8	96,2	95,8
375	500	95,8	96,2	95,8

Table 8. Premium Efficiency IE3 60Hz (NEMA Premium)

## Annex 3. CEI efficiencies

## Annex 4: Acronyms

- ASD Adjustable speed drives
- ACEEE American Council for and Energy Efficient Economy
- CEE Consortium for Energy Efficiency
- DOE Department of Energy
- EISA Energy Independence & Security Act
- EPAct Energy Policy act
- EU European Union
- GHG Greenhouse gas emissions
- IPCC International Panel on climate change
- OEM Original equipment manufacturer
- MG 1 Motor Generator
- MEPS Minimum energy performance standard MEPS
- MDM Motor Decisions Matter (MDM)
- NEMA National Electrical Manufacturers Association

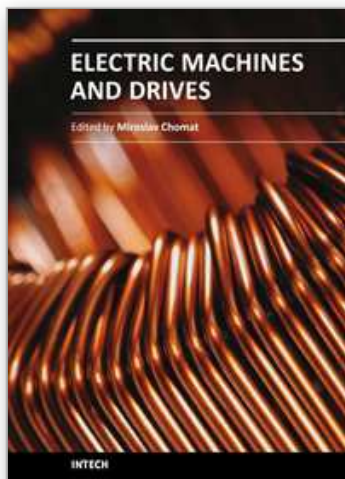
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## **Electric Machines and Drives**

Edited by Dr. Miroslav Chomat

ISBN 978-953-307-548-8

Hard cover, 262 pages

**Publisher** InTech

**Published online** 28, February, 2011

**Published in print edition** February, 2011

The subject of this book is an important and diverse field of electric machines and drives. The twelve chapters of the book written by renowned authors, both academics and practitioners, cover a large part of the field of electric machines and drives. Various types of electric machines, including three-phase and single-phase induction machines or doubly fed machines, are addressed. Most of the chapters focus on modern control methods of induction-machine drives, such as vector and direct torque control. Among others, the book addresses sensorless control techniques, modulation strategies, parameter identification, artificial intelligence, operation under harsh or failure conditions, and modelling of electric or magnetic quantities in electric machines. Several chapters give an insight into the problem of minimizing losses in electric machines and increasing the overall energy efficiency of electric drives.

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M. Benhaddadi, G. Olivier, R. Ibtouen, J. Yelle, and J-F Tremblay (2011). Premium Efficiency Motors, Electric Machines and Drives, Dr. Miroslav Chomat (Ed.), ISBN: 978-953-307-548-8, InTech, Available from: <http://www.intechopen.com/books/electric-machines-and-drives/premium-efficiency-motors>

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51000 Rijeka, Croatia  
Phone: +385 (51) 770 447  
Fax: +385 (51) 686 166  
[www.intechopen.com](http://www.intechopen.com)

### **InTech China**

Unit 405, Office Block, Hotel Equatorial Shanghai  
No.65, Yan An Road (West), Shanghai, 200040, China  
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元  
Phone: +86-21-62489820  
Fax: +86-21-62489821

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