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Utilising high and premium efficiency three phase motors with VFDs in a public water supply system

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Abstract **– The increased reliability and ultimately reduced life cycle cost of high and premium efficiency three phase motors in a process control application is discussed. The reduced energy consumption of these motors is evaluated in a public water system case study under variable frequency conditions. The importance of the consideration of a combined system, which includes variable speed control, motor and load - as opposed to only replacing with high efficiency motors for energy saving purposes - is practically observed and reported on. The paper reports on the marginal improvement in energy consumption at reduced supply frequency for motor replacement only (not surprising) but a very impressive 46% saving in energy consumption by controlling pumped water at a reduced but constant delivery rate.**

Key Words - High and premium efficiency motors, VFDs, Centrifugal pump systems, Energy efficiency.

I. Introduction

As electric motors in industrial applications account for approximately 40% of total energy consumed worldwide, [8] it is not surprising that engineers and process controllers are constantly focusing on the energy efficiency improvement of motor driven systems, be it water pumping systems, fan systems, compressed air and many other processes [2]. The ultimate aim is not only to save energy and reduce life cycle costs of industrial processes, but also to reduce the emission of greenhouse gasses into the environment.

Although high and premium efficiency three phase motors with variable frequency drive (VFD) applications have been introduced and are manufactured in North America, China and the European Union over the past three to four years, its widespread application has not yet been observed on the African continent and more specifically in South Africa [1]. Sporadic instances of a 1:1 replacement of standard efficiency EFF2 squirrel cage induction motors with high efficiency IE2 (International Efficiency) are found without considering the importance of the optimization of an overall system which includes motor, VSD, mechanical transmission and energy converter e.g. centrifugal pump, fan, compressor etc. and then running the risk of increased energy consumption (and service levels).

This paper focusses on an energy conservation measure where a public water pumping system in South Africa has been optimised from 2 off 45 kW standard efficiency EFF2 squirrel cage induction motors running at constant speed to a variable frequency drive pumping system using a 45kW high efficiency IE2 induction motor as well as a 45 kW premium efficiency (IE3) synchronous reluctance (SynRM) motor. Each of these new motors feeds similar sized centrifugal water pumps in parallel. The system flow is assisted by gravity.

A brief background is provided on the differences in energy consumption of the EFF2 and IE2 squirrel cage induction motors as well as the IE3 SynRM motors in variable frequency drive applications. The paper reports on the actual energy efficiency impacts in a centrifugal pump reticulation system application.

The public water system in the Limpopo Province of South Africa feeds 14 Ml per day over a distance of 50 km. It is mainly gravity fed with the motors under consideration being used as booster pumps. Improved control of the new high efficiency three phase motors have resulted in an overall energy saving of 46% whilst maintaining unchanged service levels. Operating frequency was dropped from 50 Hz to 40 Hz on both the IE2 and IE3 motors whilst maintaining the same ultimate delivery rate of water to the end user.

The application of IE2 and IE3 motors in parallel, each driving similar centrifugal pumps, has created an ideal opportunity to study the efficiency differences between the two motors in more detail and this has been reported on in this paper.

It is hoped that this paper will evoke consensus that the overall energy impact of a properly controlled complete pumping system is far better than that obtained by changing motors only and that the introduction of premium efficiency motors into drive systems will further reduce the life cycle cost as compared to lower efficiency motors.

II. Energy Efficiency Classes For Three Phase Motors

In recent years manufacturers of electric motors have achieved greater motor efficiencies by using improved design, production techniques and materials.

The International Electrotechnical Commission (IEC) has published an international standard that lately defines 5 distinct energy efficiency classes for three phase motors: IE1, IE2, IE3, IE4 and IE5. The IE classes replace the previous CEMEP EFF classes. This is outlined in Fig. 1.

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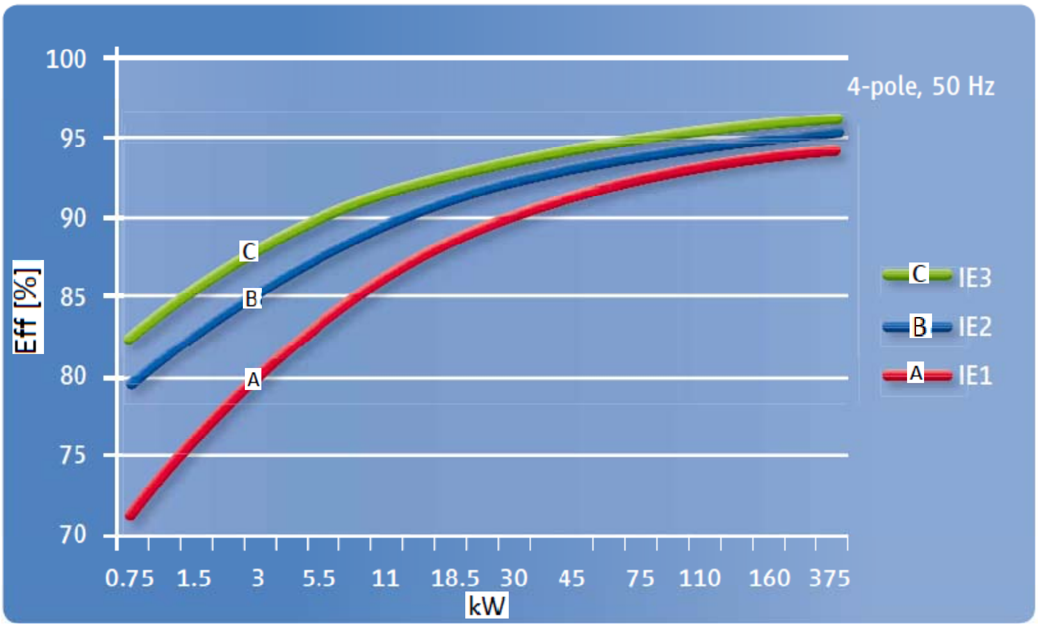

Fig. 1. Comparison of efficiency levels of different 4-pole motors [7]

A. High Efficiency IE2 Motors

This was previously referred to as EFF1-motors by motor manufacturers and the European Commission. This classification expired during November 2010 and was replaced by the new international efficiency class system: the IE2 high efficiency induction motor [6].

The IE2 motor is an affordable upgrade to the conventional EFF2 or IE1 squirrel cage induction machine with reduced copper losses in the rotor and stator and improved magnetic materials. Efficiencies are usually expressed at specific frequencies of supply (rotational speeds) and at specific load conditions. The efficiency of a 45 kW 4- pole IE2 motor at 50 Hz will be approximately 92% as compared to the 88% of its IE1 or EFF2 predecessor.

Although efficiency improvements of motors only seem small, this technology lends itself to efficiency improvements of up to 50% when a total drive system is considered, which includes a variable frequency drive, motor and energy transducer e.g. pump system, compressor or fan.

B. Synchronous Reluctance IE3 Motors (SynRM)

This motor is referred to as a premium efficiency motor and is an improvement to the IE2 high efficiency motor which followed the IE1 motor described above.

SynRM combine the performance of a permanent magnet motor with the cost-efficiency and simplicity of an induction motor. A typical 4-pole 45 kW fixed speed SynRM motor will have an efficiency of 95% [8].

The stator has a distributed winding similar to squirrel cage induction motors. However, the rotor is quite different. The rotor is cylindrical but with an anisotropic magnetic structure and is neither magnetic nor has windings. *Therefore the rotor suffers virtually no power losses* and runs exceptionally cool with the associated lower bearing temperature and increased reliability. Bearing failure usually causes about 70% of unplanned motor outages [5].

The SynRM is ideally suited for industrial application where variable speed is required as well as optimum efficiency, whilst simultaneously reducing life cycle cost and reliability.

III. THE INSTALLATION

The historic installation comprised of two off 45 kW 4-pole low efficiency three phase induction motors each driving a KSB 290 (262) mm centrifugal pump at a constant speed and frequency of 1475 rpm and 50 Hz respectively.

Two new ABB motors and drives were installed. The 45 kW 4-pole IE2 motor was installed with an ABB ACS 550 VFD whilst the 45 kW IE3 SynRM motor was installed with an ABB ACS 880 VFD with excellent partial load efficiency performance of SynRM technology. The old EFF2 motors could be replaced on a 1:1 basis having the same frame size as the new IE2 and IE3 motors. The total pumping system is outlined below in simple block diagram format in Fig. 2.

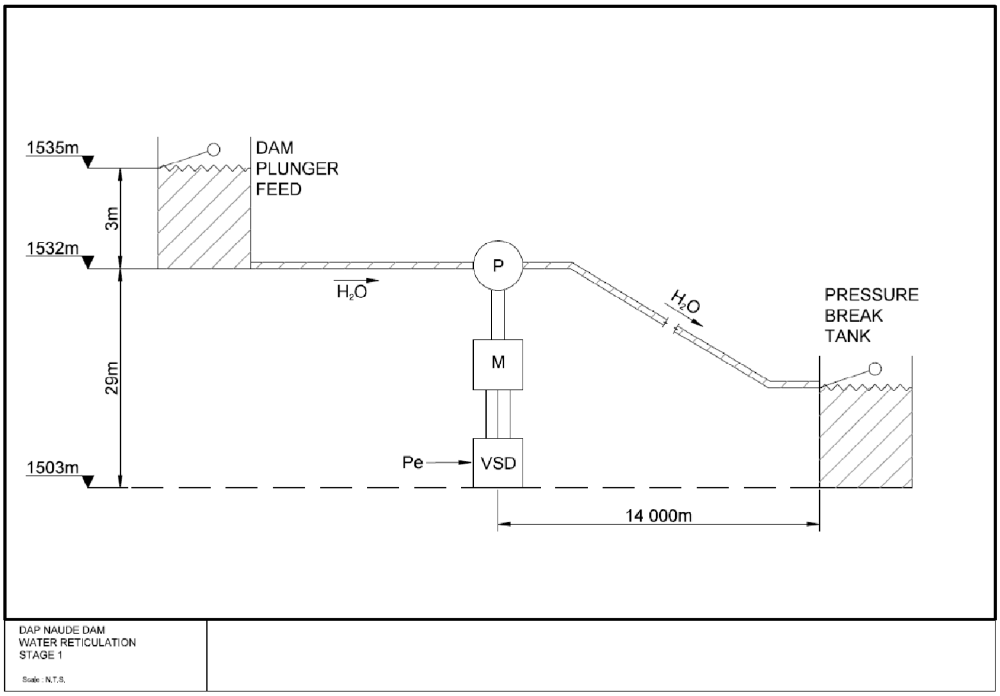

Fig. 2. Block/flow diagram of system - Stage 1

Water is reticulated from a large storage dam to a purification plant some 50 km away utilizing a gravity scheme with pressure break tanks to control water flow and reduce overall system pressure. The first pressure break tank is found 14 km away from the dam. Booster pumps at the dam wall are utilised to increase the water flow rate during the day when water demand increases. Only one motor and pump (other pump on standby) is started during the day and then controlled in an on/off mode utilising the level sensing probes in the first pressure break tank to prevent overflow. This motor has traditionally been operated at full speed with a supply frequency of 50 Hz.

This arrangement created an ideal opportunity to evaluate the three individual three-phase motors by systematically exchanging motors with the same centrifugal pump – to ensure constant load – and then measuring actual power consumption with a Fluke 45 Power logger. Power measurements were firstly done at 50 Hz and then repeated at a reduced supply frequency which would in each case provide the same differential pressure on the centrifugal pumps, ensuring constant load. Pressure was measured in kN/m^2 (kPa) to two decimal accuracy.

The water delivery requirements for the overall reticulation system was also studied over a period of 12 months to establish the booster pump requirements during the day. This allowed the pump system to be set at a minimum frequency with a constant lower delivery rate which could provide the same service level over 24 hours as that of the daily on/off control and gravity feed at night of the old system. This was implemented and the water supply was monitored on the user side to confirm acceptable daily service levels.

IV. Results

A. General

Water delivery rates were calculated using the Hazen Williams formula below for both the gravity fed system and the additional effect of the booster pump. These service levels formed the basis of all further results as energy impact/saving with a reduction in service level would be futile.

$$Q = 3{,}763 \times 10^{-6} \times C \times D^{2.63} \times (P/L)^{0.54} \qquad (1)$$

Q: Flow rate m^3/hr

C: Hazen Williams Constant (100 for steel pipe)

D: Pipe internal diameter (mm) (500 mm)

P: Pressure head (kPa)

L: Length of pipe (m) (14,000 m)

A summary of flow rate calculations is presented in Table 1 below:

TABLE I. FLOW CALCULATION RESULTS AT 50 HZ AND 40 HZ SUPPLY FREQUENCIES

Measurements done with IE2 motor-pump combination				
Parameter	Static Head	Pressure	Flow rate	Duty Cycle
Pump off	32m	320 kPa	170 l/s	
Pump motor at 50 Hz		100 kPa		50%
Total system pressure		420 kPa	197 l/s	
Pump motor at 40 Hz		50 kPa		
Total system pressure		370 kPa	184 l/s	100%
System requirements				
Minimum flow rate			130 l/s	
Maximum flow rate			197 l/s	

Notes:

a) The flow rate to the end-user following the pressure break tanks, can only change if the level of fluid varies in the tanks. It has been established that the system has historically been fine tuned to be in a state of equilibrium with gravity feed only and pumps turned off.

b) Any increase in flow is then initiated by starting up a booster pump which can either over deliver at 197 l/s (previous 50 Hz) for approximately 50% of the day or slowed down to deliver 184 l/s on a continuous basis, as established from the actual operating profile at 50 Hz.

B. *Practical Power Consumption Evaluation of Motors*

The integrated system consisting of electrical motor, VFD, centrifugal pump and water supply presented an ideal opportunity to determine the electrical power consumption of each type of motor referred to in this paper by adjusting supply frequency to ensure a constant differential pressure on the pump at all times. Motors were also mounted onto the same physical pump for purposes of this comparison. Table 2 shows the results for the comparative study and Fig. 3 and 4 show actual power measurement displays.

TABLE II. COMPARISON OF POWER CONSUMPTION OF MOTORS

Power consumption of three types of motors in practical application				
	Type	Supply Frequency	Differential Pressure	Power Consumption
		Hz	kPa	kW
EFF 2	Squirrel Cage Ind	50 Hz	100 kPa	41.3 kW
		40 Hz	50 kPa	24 kW
IE2	Squirrel Cage Ind	50 Hz	100 kPa	40.3 kW
		40 Hz	50 kPa	24 kW
IE3	Syn. Reluctance	50 Hz	107 kPa	41.1 kW
		40 Hz	50 kPa	23.5 kW

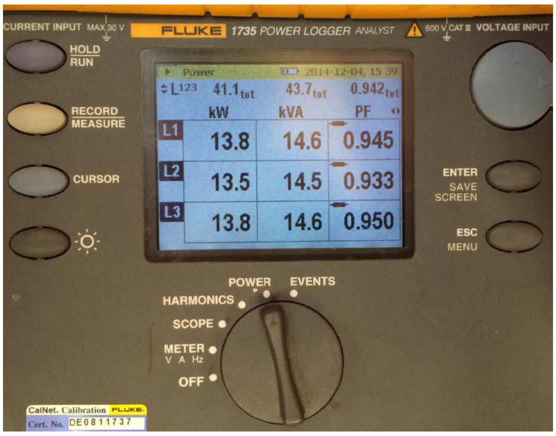

Fig. 3. IE3 Motor Power measurement at 40 Hz

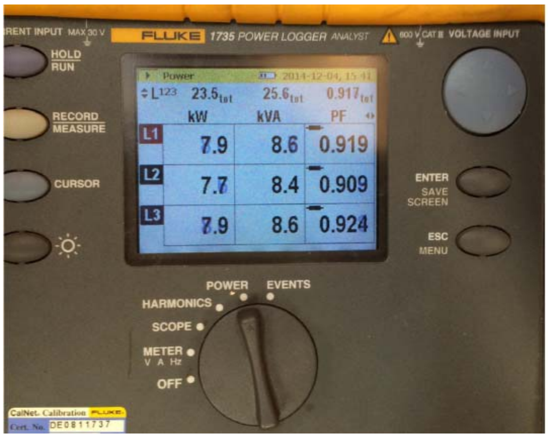

Fig 4. IE 3 Motor Power measurement at 50 Hz

Notes:

a) Motor sizes all 45 kW, 400V IE2/3: ABB, EFF2: Alstom.

b) Centrifugal pumps: KSB 290 (262)

c) Water delivery rate and pipe sizes as above.

d) The power consumptions measured imply that the efficiency levels of the three motors tested in this paper are for all practical purposes similar, with a very small difference between IE2 and IE3 at the 50% loading conditions.

C. *Energy Impact of Overall System at Reduced Supply Frequency*

A baseline was established over a period of 3 months - prior to the intervention - with the EFF 2 motor operating at 50 Hz supply frequency and delivering 197 l/s in an on/off control mode. By studying the average daily load profile of the 45 kW motor (baseline) a duty cycle of approximately 50% is found over the 3 month period. During the remaining 50% of each day, only a gravity feed is used with the pumps turned off. This implies an average daily flow rate requirement of:

Q (Daily) = (170 l/s x 12 hours + 197 l/s x 12 hours) / 24 hours
= 184 l/s average

During the optimisation of the minimum operating frequency of the new motors, the differential pressure of the pump system
was reduced so as to ensure the above delivery rate and found to be 40 Hz.

The baseline (before) and actual (after) profiles are shown in Fig. 5 and 6 with power measured (P_e) at the input of the VFDs. Table 3 summarises the impact of the overall pumping system intervention.

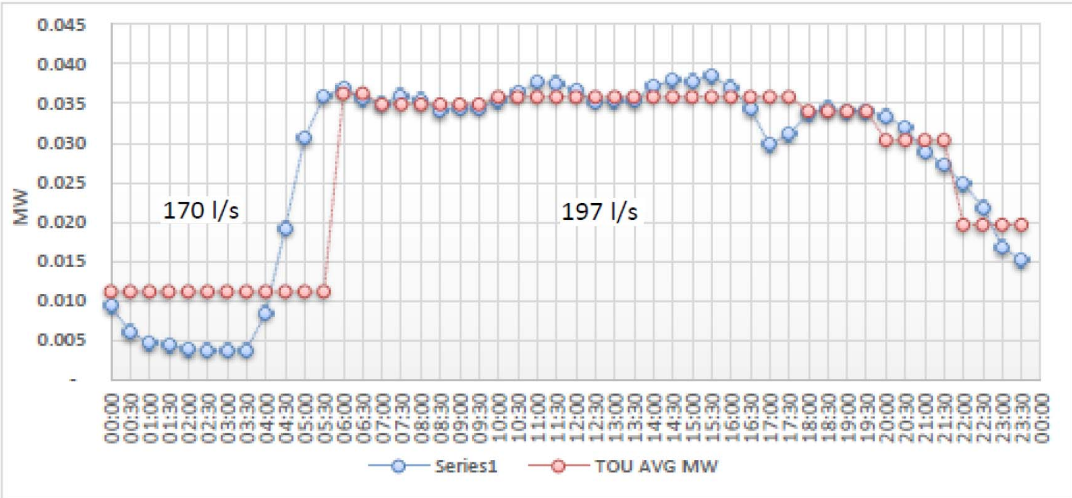

Fig. 5. Baseline 45 kW EFF2 Motor, 50 Hz, Jul-Sept 2014

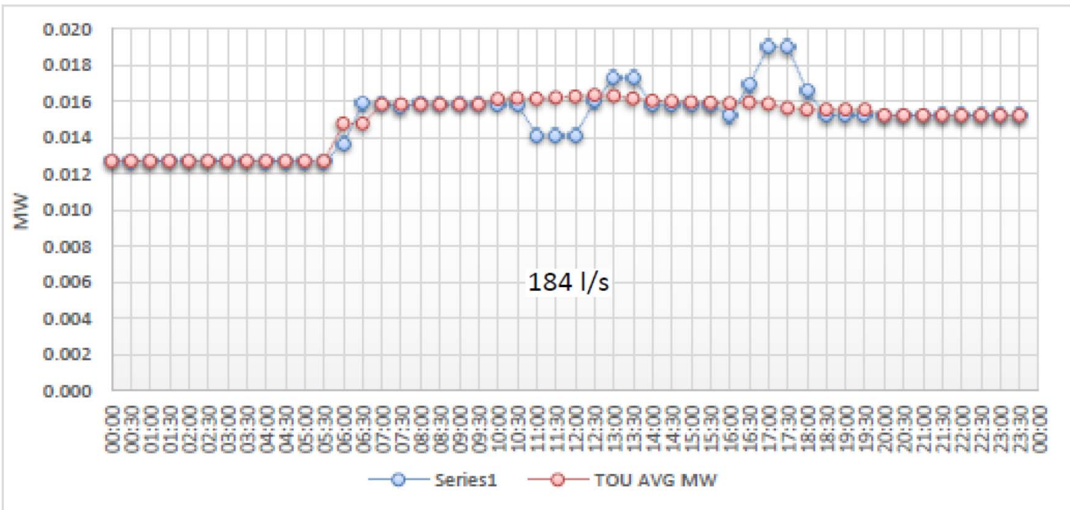

Fig. 6. Actual 45 kW IE2 motor, 40 Hz , Oct/Nov 2014

TABLE III. ENERGY IMPACT OF IMPROVED CONTROL SYSTEM

DAP NAUDE DAM IMPACT CALCULATIONS OVER 1 MONTH

Table 3: Actual weekday impact

	Weekday/Sat/Sun (MW)							
	Morning Off-peak	*Morning Standard*	*Morning Peak*	*Midday Standard*	*Evening Peak*	*Evening Standard*	*24 hours ave*	*Sat + Sun*
Adj Baseline	0.011	0.036	0.035	0.036	0.034	0.030	0.028	0.028
Actual	0.011	0.015	0.016	0.016	0.016	0.015	0.015	0.015
Impact	0.000	0.021	0.019	0.020	0.018	0.015	0.013	0.013
Intended Impact								
Over / Underperformance	0.000	0.021	0.019	0.020	0.018	0.015	0.013	0.013

Table 4: Total energy consumption: 1-31 October 14 (23 Wk, 4 Sat, 4 Sun)

		Weekdays	***Saturdays***	***Sundays***	***Total MWh***
			24 Hrs	***24 Hrs***	
Baseline		15.2352	2.650	2.650	20.534
Actual		8.28	1.440	1.440	11.160
Impact		**6.955**	**1.210**	**1.210**	**9.374**

Table 5: Total emission impact- 1 Oct 2014 - 31 Oct 2014

Total Monthly					
	CO_2 (tons)	*NO_x (kg)*	*SO_x (kg)*	*Particles*	*Water (kl)*
Baseline	20	86	159	7	29
Actual	11	47	86	4	16
Impact	9	39	73	3	13

V. CONCLUSION

This paper concludes that an overall energy impact of 9.374 MWh was obtained by replacing the on/off controlled EFF 2 motors with slower running higher efficiency motors whilst not affecting service levels on the end-user side. An energy saving of 46% has been achieved with a reduction of 53% in demand during the supply utility's critical evening peak in South Africa.

The individual comparison of the EFF2, IE2 and IE3 motors as far as power consumption with constant load is concerned, was less impressive with the IE3 motor performing marginally better than the other two motors by approximately 2% at 50% loading.

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