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Energy conservation by using energy efficient electric motors

Mehmet Akbaba*

Electrical Engineering Department, College of Engineering, University of Bahrain, PO Box 33547, Isa Town, Bahrain

Abstract

This paper deals with energy conservation by installing energy-efficient (EE) motors instead of standard efficiency motors. This transition become a necessity as a direct result of limitation in energy sources and escalating energy prices. As electric motors use about three quarters of the total electric energy in Bahrain, attempts to conserve the energy consumed by electric motors recently received intensive research efforts. Therefore, the energy efficiencies of energy efficient motors are compared with those of standard efficiency motors ranging from 5 to 300 HP. To provide more clarification in this regard, full design details of 200 HP standard-efficiency and energy-efficient motors are compared. Pay back periods when replacing standard-efficiency motors with energy-efficient motors, with reference to Bahrain's market, have been discussed. Finally the energy-conservation capability of EE motors in the petrochemical industry has been discussed.

Keywords: Energy conservation; Energy-efficient motors; Pay-back periods

1. Introduction

Over the last decade, the cost of electric energy has more than doubled in most of the countries all over the world. As a direct result of this, the annual energy cost to operate the motors also doubled. In many industrialized countries, more than 70% of the total produced energy is consumed by electric motors. Therefore the cost of energy to operate motors has become a real concern for industry. On the other hand, the concern for the environment particularly through the emission of green-house gases and other pollutants has prompted the regulators of utilities to enforce alternative measures to meet load growth, instead of building additional power stations.

* Corresponding author. Tel.: +973-688-327; fax: +973-684-844.
E-mail address: akbaba@eng.uob.bh (M. Akbaba).

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The most popular is demand-side management, one aspect of which is to improve the efficiency to offset load growth [1–6]. These facts led electric-motor manufacturers to seek methods for improving the motor efficiencies, which resulted in a new generation of electric motors that are known as energy-efficient (EE) electric motors. Several leading electric motor manufacturers, mainly in USA, have developed product lines of energy-efficient electric motors.

In this paper, the characteristics of EE electric motors will be compared with those of standard efficiency (SE) motors. Efficiency and energy saving issues will be discussed. Full design details of a 200 HP EE motor will be compared with the design details of an SE motor of the same rating, and it will be shown how the losses of EE motors can be minimized. Consequently a considerable amount of energy can be saved through the life cycle of the motor, by improving the magnetic circuit design and using lower-loss electric grade laminations. Finally possible energy savings in petrochemical industries, by replacing SE motors with EE motors, will be presented with a numerical example.

2. Economics of installing energy-efficient motors

EE motors can be installed in the following cases: (a) when a new motor is purchased, (b) in lieu of rewinding an existing motor that has burned out, (c) as a retrofit replacing an operating SE motor with an EE motor.

The relevant cost for financial analysis depends on the type of installation. When a new motor is purchased, the incremental cost of EE motors over SE motors is the value to be used in calculations of pay-back period. The analysis to be presented in the following section will make it clear that, under any circumstances, when purchasing a new motor, it is definite that purchasing an EE motor is more economical instead of purchasing an SE motor. In fact, in some developed countries, such as the USA, by regulation it is a must to install EE motors for all new installations.

When installing an EE motor instead of rewinding a burned out SE motor, users need to consider two key economic criteria. The first is the cost difference between rewinding a burned out SE motor and buying a new EE motor. The second is that the rewound motor might not be as efficient as the user expects when it returns from the repair shop, either because some pre-existing damage that is not detected and corrected during the repair or because the repair itself damages the motor. The possibility of such performance degradation is often overlooked in the effort to minimize the initial cost. Although in theory, rewinding can produce a motor with the same efficiency-rating as it had when it was new, in practice motor efficiency is often degraded through normal rewinding practices, making the initial low cost a potentially poor investment [7]. In early 1980s, the General Electric Company in the USA conducted a survey on measured rewind losses, based on tests made over a 1 year period in the company's repair facilities [7]. The study found an increase in core losses, compared with manufacturer ratings for these motors when they were new, ranging from zero to 400%, with an average of 32%. This survey further concluded that 8–10% of the motors had at least double the core losses, that 50–60% of the rewound motors had core loss increases ranging from 10 to 100%, and that the losses were most pronounced in large motors, which most likely had to be rewound repeatedly. It is further concluded that rewinds cause an overall average efficiency reduction of 1.5%. Larger core losses cause higher energy bills and reduced motor lifetimes, as large losses increase the motor's temperature, which decreases the insulation lifetime. Therefore, the author of this paper recommends replacing the burnt out motors with new EE motors instead of rewinding them, especially in the case of motors larger than 20 HP.

When an EE motor is installed as a retrofit, the cost of the efficiency gains includes the cost of the new motor plus the labour cost to remove the old motor and install a new one. The salvage value of the old retiring motor is ignored, because it should be scrapped not re-used, and scrap value of the metal is small. For some developing countries like Bahrain, motor prices are high and energy prices are relatively cheap. Therefore, retrofitting may or may not be economic. For example, when compared with market prices in USA, motor prices in Bahrain are at least 100% more. Therefore, a detailed study is necessary before making a decision concerning retrofitting, until the motor costs and energy costs in Bahrain become comparable with the prices in the motor-producing countries. It will be clear, from the detailed study to be presented in the following section, even with existing energy and motor costs, retrofitting EE motors instead of SE motors in Bahrain may be economic in some cases. Installing EE motors in Bahrain will be economic and recommended when:

- replacing a burned out motor,
- installing new additional motors,
- new installations in a new company,
- in some cases, as retrofit instead of an operating SE motor.

3. Comparison of an EE motor and a SE motor of the same output size

Using the induction motor-design program developed by the author of this paper [8], an EE motor of 200 HP is designed and full design details are compared with those of an existing SE motor of the same rating. The difference in the performances of the motors resulted mainly from using high-quality steel sheets (high flux density and low specific iron losses) in the EE motor and the skill of the designer in optimizing the design for high efficiency. The magnetizing characteristics of the steel sheets used in both machines are given in Fig. 1. Also the specific iron losses (W/kg) of the both steel sheets are compared in Fig. 2.

Comparison of the full design details of the both machines is given in the Table 1.

The results given in Table 1 show that an EE motor uses relatively more copper but less steel material. But there are significant drops in copper and iron losses. A 4.6% increase was achieved in efficiency, which resulted from using better grade steel laminations and in optimizing the design. Choosing the right values for current density, ampere-conductors, flux density, slot dimensions, length-to-pole pitch ratio and number of turns has very significant effects on the energy efficiency of the motors.

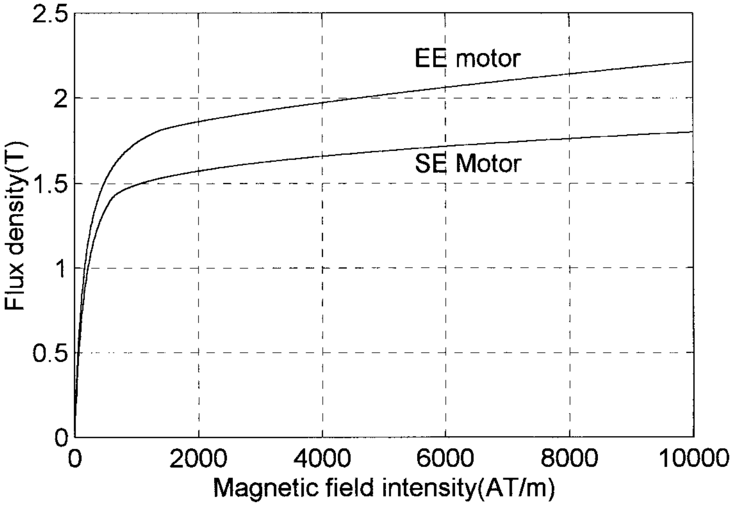

Fig. 1. Magnetizing characteristics of EE and SE motors.

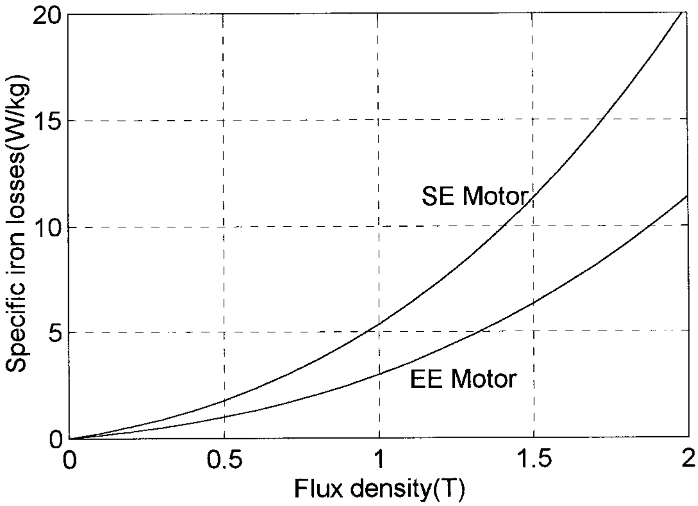

Fig. 2. Specific iron losses of EE and SE motors.

4. Discussion of the pay-back period in Bahrain for retrofitting EE motors

The input power of the 200 HP EE motor under study, which has an efficiency of 0.9588 as given above, is: $P_{inEE} = 200 \times 746/0.9585 = 155612$ W

But the input power of the SE motor under study, which has an efficiency of 0.9126 is: $P_{inSE} = 200 \times 746/0.9126 = 163183$ W

Table 1
Comparison of the full design details of a 200 HP SE motor and a 200 HP EE motor

Design parameter	Standard-efficiency motor	Energy-efficient motor
HP rating (HP)	200	200
Rated voltage (V)	440	440
No of poles	4	4
Rated speed (rpm)	1468	1486
Efficiency	0.9126	0.9585
Power factor	0.90	0.94
Gap flux density (T)	0.45	0.62
Ampere conductor (per metre)	35000	50000
Current density (stator) (A/mm^2)	6.20	4.40
Length-to-pole pitch ratio	1.20	0.94
Core length (cm)	31,9	24.6
Air gap diameter (cm)	33.9	29.3
Turns per phase	70	70
Phase current (A)	136.51	125.91
Stator-slot width (mm)	38.0	36.59
Stator-slot height (m)	7.98	8.29
Rotor-slot width (mm)	9.25	11.10
Rotor-slot height (mm)	21.21	20.58
End-ring height (mm)	21.21	20.58
End-ring width (mm)	23.69	28.08
Air-gap length (mm)	0.86	0.70
Stator-core height (mm)	56.49	81.89
Rotor-core height (mm)	87.85	66.13
Outer diameter (mm)	517.56	530.11
Magnetizing reactance (Ω)	31.86	26.46
Stator leakage reactance (Ω)	0.6184	0.3336
Rotor leakage reactance (Ω)	0.5479	0.2593
Stator winding resistance (Ω)	0.1116	0.0422
Rotor winding resistance (Ω)	0.0701	0.0313
Total steel volume (cm^3)	45084.8	35670.1
Total iron losses (W)	4702.47	2902.8
Total copper losses (W)	10082.17	3409.51

The net saving in power is: $\Delta P = P_{inSE} - Pin_{EE} = 163183 - 155612 = 75731$ W or 7.57 kW.

For 8000 working hours per year, the total saved energy will be: $W_{saved} = 8000\Delta P = 8000 \times 7.57 = 60560$ kW/year

With the unit energy cost of 16 fils/kW, the amount of money saved annually will be: $M = 0.016 \times 60560 = 969$ BD/year.

The cost of the 200 HP EE motor in the US market is about 3450 \$(= 1304 BD). Although energy-efficient motors are not readily available in the Bahrain market, EE motors usually cost about 20% more than SE motors. Therefore such a motor will cost about $2 \times 1304 = 2608$ BD. Adding 10% for removing the old motor and installing the new motor (as labour costs are relatively cheap in Bahrain), the total cost for replacing a 200 HP SE motor with a 200 HP EE motor will be approximately: $COST_{EE} = 1.1 \times 2608 = 2869$ BD.

Therefore the pay-back period will be:

PBP = 2869/969≅2.96 years≅3 years

A survey in the USA [9] showed that pay-back periods of up to 3 years are acceptable to some motor users but many companies need to see a pay back period of less than 3 years. Therefore, the cost of retrofitting EE motors in Bahrain is on the border of being acceptable. This is encouraging and promising, as it is expected that energy prices will rise faster than motor prices and replacing SE motors with EE motors will become fully economic in the near future.

5. Energy efficiency and trend of saved energy for EE motors

Using the program developed by the author of this article, [8], full design details of EE motors ranging from 5 to 300 HP are calculated and, based on this, their efficiencies are compared with those of SE motors of the same rating. This comparison is given in Fig. 3. From this figure, it is clearly seen that a significant gain is achieved in the efficiency leading to a saving of a huge amount of energy through the life cycle of the motor. It should be noted here that, as can be seen from Fig. 3, the efficiency difference between EE motors and SE motors does not continue rising as the size of motor increases. This is because the efficiency of all motors naturally increases with the size of motor and the efficiency limit is almost reached when the motor size is about 1000 HP.

Fig. 4 shows the variation of the saved energy per year with the size of the EE motor. From this figure, it is clearly seen that for a 300 HP motor size, using an EE motor will save about 79 MWh per year, based on 8000 h of operation per year. Variation of the cost of the saved energy per year with motor size is given in Fig. 5,

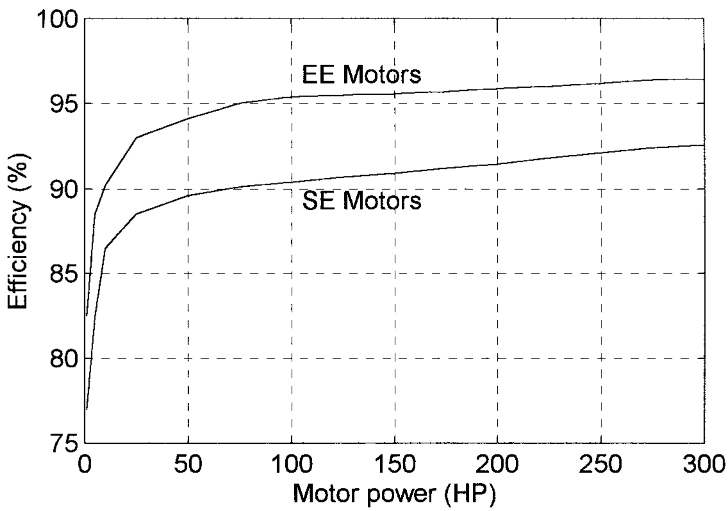

Fig. 3. Comparison of the efficiency of EE and SE motors.

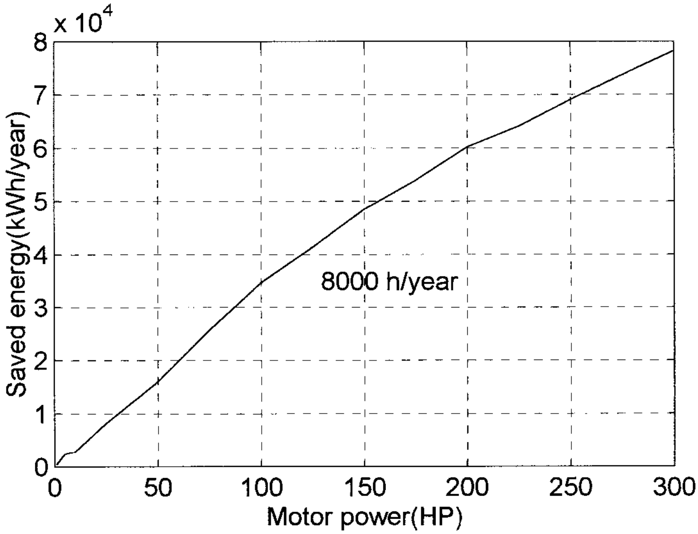

Fig. 4. Variation of the saved energy per-year with the motor size.

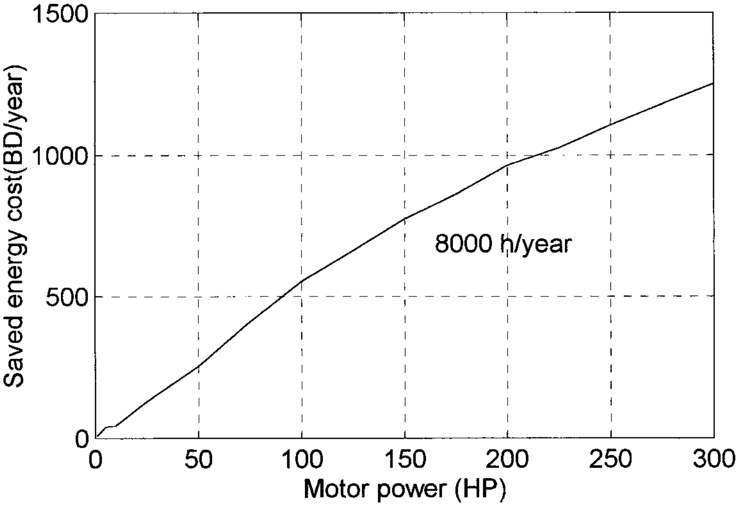

Fig. 5. Variation of the saved energy cost with motor size.

assuming 8000 h of operation per year. From this figure, it is evident that using a 300 HP EE motor instead of 300 HP SE motor will save energy costs of about 1240 BD/year based on 16 fils/kWh.

The above discussion indicates that large companies that are using large numbers of motors will save a very significant amount of energy if EE (rather than SE) motors are used. For example, if a company uses 100 HP EE motors of 300 HP instead of 100 SE motors of 300 HP, the cost of the saved energy in 20 years (which can be considered as the minimum life-cycle of each motor) will be:

TSM = 20×100×1240 = = 2.48 million BD

The above figure clearly indicates that, in, the near future, EE motors will invade the industry by replacing the SE motors rapidly.

Another important characteristic of EE motors is that they maintain their high efficiency for a wide range of load levels, below and above the rated load, which is not the case with SE motors. This characteristic is demonstrated in Fig. 6. Close observation of this figure indicates that EE motors will save even more energy than what is demonstrated in the above text, when they operate on low load levels or at tolerable overloads.

6. Motors in the petrochemical industry

The petrochemical industry is one of the heavy users and relatively large motors. On the other hand, this industry has a special value for Bahrain, as it is one of the biggest industries in the country. Therefore, special attention will be devoted to motors in this industry. The torque of the motors used in the petrochemical industry is proportional to the square of the speed. Therefore the torque–speed characteristic may be expressed as:

$$T = K\omega^2 \qquad (1)$$

where K (Nm/A) is the torque constant of the motor and ω is the angular speed of the motor in rad/s. Applying this relation for the EE motor:

$$T_{\mathrm{EE}} = K\omega_{\mathrm{EE}}^2 \qquad (2)$$

for the SE motor:

$$T_{\mathrm{SE}} = K\omega_{\mathrm{SE}}^2 \qquad (3)$$

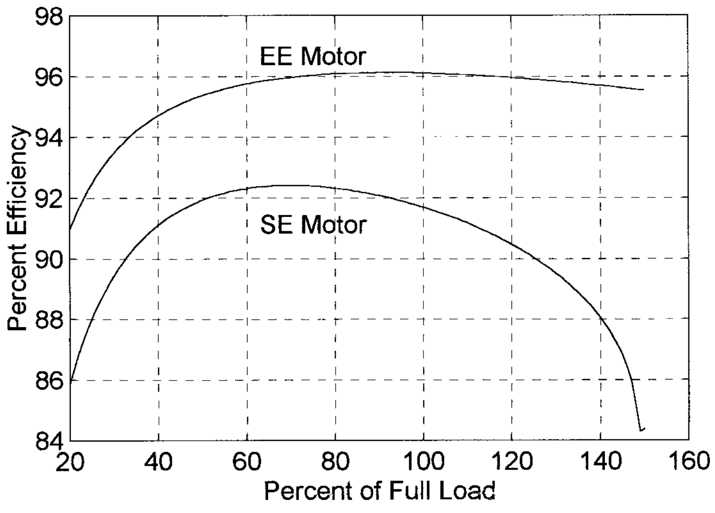

Fig. 6. Comparison of efficiency versus load level characteristics of EE and SE motors.

Since input power of a motor is equal to the ratio of output power to the efficiency, then the input power of the EE motor will be:

$$P_{iEE} = P_{oEE}/\eta_{EE} = K\omega_{EE}^{3}/\eta_{EE} \tag{4}$$

where P is the power of the motor and η is the efficiency of the motor. Similarly the input power of the standard efficiency motor will be:

$$P_{iSE} = P_{oSE}/\eta_{SE} = \frac{k\omega_{SE}^{3}}{\eta_{SE}} \tag{5}$$

To have the same input power for both motors, we should have;

$$\frac{T_{EE}\omega_{EE}}{\eta_{EE}} = \frac{T_{EE}\omega_{SE}}{\eta_{SE}} \tag{6}$$

From Eq. (6):

$$P_{oSE} = P_{oSE}(\frac{\eta_{SE}}{\eta_{SE}}) \tag{7}$$

Combining Eqs. (4), (5) and (7) yields:

$$P_{oEE} = P_{oSE}(\frac{\omega_{EE}}{\omega_{SE}})^{3} = P_{oSE}(\frac{n_{EE}}{n_{SE}})^{3} \tag{8}$$

where n is the speed of the motor in rpm. On the other hand, from the design calculations given in Table 1, it is seen that the rated speed of the EE motor is always higher than the rated speed of the SE motor, i.e. the EE motor has a rated speed of 1486 rpm, whereas the SE motor has a rated speed of 1468 rpm. If the example motor under consideration (200 HP) is used in the petrochemical industry, the output of the EE motor as compared with the output of the SE motor will be

$$P_{oEE} = P_{oSE}(1486/1468)^{3} = 1.077\mathrm{P}_{oSE} \tag{9}$$

Therefore the 200 HP EE motor will have 3.7% more output as compared with the SE motor. Similar calculations were extended to motors ranging from 20 to 300 HP and it was observed that EE motors in petrochemical industries can have from 3 to 4.5% more output, for the same input energy, as compared with SE motors.

7. Conclusions

The analysis presented shows that EE motors are up to nearly 5% more efficient as compared with those of SE motors. This characteristic leads to saving a very significant amount of energy. The high efficiency of EE motors is achieved by using high-grade steel sheets in the magnetic circuit and skillful design concerning the reductions of copper and iron losses from the motor. Installing EE motors instead of SE motors will be economic in the following cases:

- replacing a burnt out motor,
- installing new additional motors,
- new installations in a new company
- in some cases, as a retrofit instead of an operating SE motor.

Although the unit energy price is low and motor costs are at least 100% more in Bahrain than in the USA retrofitting EE motors instead of SE motors may be economic in many cases as pay back periods of about 3 years can be achieved. As petrochemical industries are important to many developing countries, such as Bahrain, the behaviour of EE motors in petrochemical industries has been analyzed. It is shown that, with the same amount of energy consumption, it is possible to increase their output by 3–4.5% by installing EE motors, which will lead to a very significant saving over the life cycle of the motors.

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