GE Industrial Systems

Evaluation and Application of Energy Efficient Motors

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Motor Selection Based Only On Purchase Price Can Be A Costly Mistake

The 1992 Federal Energy Bill (EPAct) is now the law of the land and therefore there are no more opportunities to achieve additional savings.

This couldn't be further from the truth. Technology has continued to advance, and manufacturers have moved to new levels of premium efficiency products. However premium efficiency motors may not be for everyone. Their use should be carefully examined to ensure that the extra cost can be justified, and that the proper manufacturer is selected. Not all premium efficiency motors have the same overall performance. Premium efficiency motors can represent an investment of up to 20% over the cost of ordinary energy efficient motors. While this premium may be recovered in a reasonable period of time, the first objective should be to maximize the return on this extra investment. To reach this goal, the user needs to understand motor efficiency, how the design could adversely affect the total system, and how to carry out an economic evaluation.

Understanding Motor Losses

Motor efficiency is simply of the watts output divided by the watts input (Figure 1). This is better expressed as the watts output minus the losses, divided by the watts input.

$$\text{Efficiency} = \frac{746 \text{ x Hp Output}}{\text{Watts Input}}$$

$$= \frac{\text{Input - Losses}}{\text{Input}}$$

Figure 1. Efficiency Equation

The only way to improve efficiency is to reduce motor losses. The components of motor losses can be broadly defined as no-load and load losses. Figure 2 shows typical loss distribution for a 4-pole motor.

	% Total
No-Load Losses	
• Windage, Friction	14
• Core Losses	16
Load Losses	
• Stator I^2R Losses	33
• Rotor I^2R Losses	15
• Stray Load Losses	22
Total	100

Figure 2. Distribution of Losses

No-load losses typically account for 30% of the total, and include windage and friction losses plus core losses. The windage and friction losses are mechanical losses from bearing friction, plus fan and rotor windage. Core losses are a combination of hysteresis and eddy current losses in the magnetic steel core.

Load losses comprise the remaining 70% of the total, and include stator and rotor I^2R losses as well as stray load losses. Stator losses are computed as the product of stator input current (at load) squared and the stator resistance at operating temperature. Rotor losses result from rotor currents, and are equal to the product of the induced rotor current squared and the rotor resistance at operating temperature.

Stray load losses arise from additional harmonic and circulating current losses in the magnetic steel and windings. These losses are a result of design and manufacturing processes. Some of the factors which contribute to stray load losses are shown in Figure 3.

- Number of Slots
- Stator and Rotor Slot Geometry
- Rotor Slot Insulation
- Air Gap Length
- Manufacturing Process Control

Figure 3. Stray Load Loss Factors

Improving Efficiency Takes Know-how

The design engineer of energy efficient motors strives for optimization using techniques shown in Figure 4.

Selection of lamination and rotor steel is a key element of design. Low grade steel typically has losses in the 3.0 watts/lb. range and costs approximately the same as cold rolled steel. To reduce hysteresis and eddy current losses, manufacturers may choose to construct energy efficient motors with high grade silicon steel. This steel has an electrical loss of 1.5 watts/lb. and costs approximately 50% more than standard motor lamination steel.

- Improved Steel Properties
- Thinner Laminations
- Increased Wire Volume
- Improved Slot Designs
- More Steel
- Improved Rotor Insulation System
- More Efficient Fan Design

Figure 4. Efficiency Improvement

To further reduce eddy current losses, high grade silicon steel can be purchased in a thinner gauge. Typical lamination thickness is .018 inches for silicon steel as opposed to .022 inches for others. Silicon steel also has a surface coating of insulation to provide high inter-lamination resistance to eddy currents.

By increasing the volume of copper wire, stator I^2R losses can be reduced. To accommodate this increase, slot areas must also be increased by as much as 50%. To compensate for the increase in slot size and corresponding decrease in remaining active steel, the motor's rotor and stator core are increased in size.

The challenge is to have the expertise to design a motor that achieves the desired efficiency without increasing locked rotor current beyond the requirements of NEMA Design B. If a manufacturer is unwilling to add the offsetting steel, efficiency gains are simply traded for higher locked rotor amps. This approach is acceptable for the motor, but the higher locked rotor amps may be excessive for the existing circuit breakers, incoming power lines or even the local distribution transformer. The user should evaluate the total system impact, since lower initial motor cost may be more than offset by needed additional investments to upgrade other components.

Rotor I^2R losses are improved through redesign of the rotor slots to increase the conductor cross section. In doing so, the rotor full-load speed is increased slightly. Again, the slot redesign must be made in such a way as to continue to provide NEMA Design B torques and locked rotor currents. This requires careful selection of the slot shape as well as its size.

Some losses in the motor come from unplanned conduction paths resulting from normal manufacturing processes. One such path is along the rotor surface where the rotor OD is turned down to provide a uniform air gap. This is where manufacturing expertise is key. Careful choice and control of the process are required to keep losses at a minimum.

Because of the lower electromagnetic losses in an energy efficient motor, this type does not require the same amount of cooling as a standard motor design. The designer can now optimize fan design to reduce windage losses and achieve quieter operation.

In summary, by optimizing the motor design and controlling the manufacturing process, losses are decreased and efficiency improvements are gained, while allowing cooler running machine. As market conditions dictate and materials and technology improve, further efficiency gains may be achieved.

Making The Standards Work For You

Efficiency terminology can be very confusing. NEMA Standard MG1-1998, Part 12 establishes the definition, testing and labeling requirements for motor efficiency. This standard states that efficiency shall be determined at rated output, voltage and frequency and shall be tested by IEEE Std 112 Method B using a dynamometer.

Due to variations of materials, manufacturing processes and tests, there will be variations in tested motor efficiency from one motor to another. As a result, the full load efficiency for a large population of motors is not a unique value, but is distributed over a range of efficiency. The range of efficiency appears as a normal distribution commonly called a Bell Curve. NEMA MG1, Part 12 establishes a series of nominal efficiencies and an associated minimum efficiency for each nominal efficiency value.

NEMA MG1, Part 12 and the efficiency tables published by NEMA for energy efficient and premium efficiency motors identify the levels that must be equaled or exceeded for the motor to be classified as "energy efficient." These energy efficiency tables parallel those found in the 1992 Federal Energy Act (EPAct) and the Canadian standard CSA 390-93. A significant point to understand is that the minimum efficiency standard allows 20% greater losses than its associated nominal efficiency value (see Figure 5).

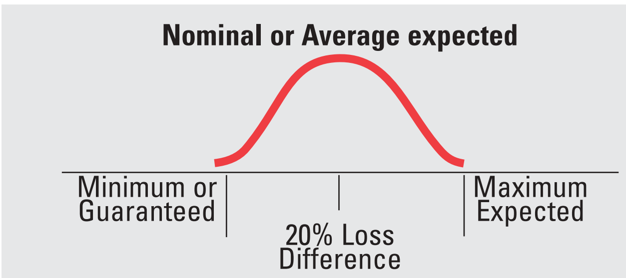

Figure 5. Efficiency Terminology

In June of 2001, NEMA formalized a specification defining premium efficiency. NEMA Premium Efficiencies were developed in cooperation with the members of the National Electric Manufacturers Association (NEMA), major US conservation groups and the Department of Energy. The specification follows the definition for qualification of EPAct, but covers a larger range of product than the 1–200 horsepower covered by EPAct. The NEMA Premium standard defines the nominal efficiency of motors rated 1–500 Hp and includes ratings at 4000 volts. (See http://nema.org/publication/ei/oct00/premiummotor.htm)

With a majority of the NEMA Premium ratings requiring a 20% decrease in nominal motor loss compared with the EPAct values, NEMA Premium is important to the user for three reasons. First, the nominal efficiency values are higher, offering the user greater energy savings. Second, some manufacturers offer real premium motors with a guaranteed minimum efficiency with no more than 10% additional losses. This results in superior repeatability of efficiency values and relates to higher efficiencies and greater savings. Third, manufacturers offering motors with no more than 10% additional losses are more likely to adhere to tighter manufacturing processes. This provides higher product reliability and reduced potential for user downtime cost exposure.

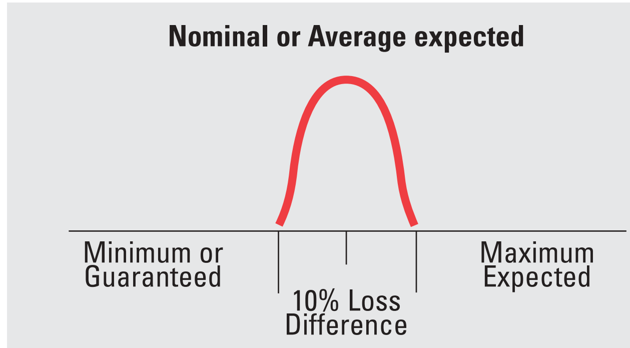

Figure 6. Efficiency Terminology

To maximize return on investment, users should always specify motors which have guaranteed minimum efficiencies. In most cases these motors will have the minimum efficiency value listed on the nameplate. For easy comparison of EPAct vs. NEMA Premium, refer to GE publication e-GEK-M1003.

In making a financial evaluation of motor alternatives, the user should consider only guaranteed minimum efficiencies. This will maximize true return on investment. While this approach is conservative, it ensures that the calculated savings are actually realized. Other critical reasons for evaluating energy efficient motors using guaranteed minimum efficiencies are as follows:

- Nominal efficiency represents a band of efficiencies. The replacement motor could have an actual efficiency that differs from the nominal value. As a result, the calculated savings may not be realized.
- Demanding guaranteed minimum efficiency provides the user with a basis for rejection if the motor received fails to meet the guaranteed level. This forces the manufacturer to demonstrate how efficiency is verified, and ensures that the user receives the product performance paid for.
- Finally, this allows the user to evaluate and purchase in confidence that the savings calculated will actually be realized.

With this basic understanding of motor efficiency, let's look toward how it should be evaluated.

The Premium Efficiency Motor Decision

Specification and installation of Premium efficiency motors can yield attractive economic results compared to the use of standard energy efficient motors for the same installation.

To fully understand these benefits, the buyer should make either a simple payback calculation or a comprehensive economic evaluation including a life cycle cost analysis. Typically, as the quantity of motors increases and the value of the installation grows, a more detailed analysis is performed.

How To Calculate Annual Savings

In comparing the efficiencies of two motors, the buyer must consider the type of motor involved, the annual hours of operation, motor load, electrical costs, and the motor efficiencies. The same basic factors apply whether the comparison is between a pre-EPAct motor repair and an EPAct motor, or between an EPAct and a NEMA Premium Efficiency motor. Regardless of the comparison, it is essential that the efficiency values be on the same basis. You must compare nominal vs. nominal or guaranteed minimum vs. guaranteed minimum. As previously discussed, the guaranteed value will provide the most realistic analysis.

With that in mind, the equation in Figure 7 can be used to determine annual savings for two 50 horsepower, 1800 rpm, totally enclosed fan-cooled motors operating at rated load. The nominal efficiency value for the standard EPAct motor is 93 while the comparable value for the NEMA Premium efficiency motor is 94.5. If operated continuously (8,760 hours per year) with an electrical cost of $.07/kWh, the annual savings would be $390.

$$s = .746 \times Hp \times L \times C \times N \left[\frac{(100)}{(E_B)} - \frac{(100)}{(E_A)}\right]$$

$$s = .746 \times 50 \times \frac{100}{100} \times .07 \times 8760 \left[\frac{(100)}{(93.0)} - \frac{(100)}{(94.5)}\right]$$

$$s = \$390 \text{ per year}$$

- s — Annual savings
- L — Percent load divided by 100
- C — Cost of electricity ($/kWh)
- N — Annual hours of operation
- E_A — Premium efficient motor efficiency
- E_B — Standard motor efficiency

Figure 7. Annual Savings

Evaluating your electrical savings based on a contract charge per kilowatt can be misleading. In all likelihood, the contract number will not include demand charges, fuel adjustment charges, possible connect charges or taxes. Your real power cost is the actual payment to the power company divided by the total kilowatts used.

Calculating Simple Payback

Using the equation and example in Figure 8, the buyer can divide the price premium of the NEMA Premium motor by the annual savings to obtain simple payback. Assuming typical motor prices of $1,524 for the 50 Hp EPAct motor described above and $1,833 for the comparable NEMA Premium motor, the simple payback is .79 years.

$$\text{Simple Payback Period} = \frac{\text{Price Premium}}{\text{Annual Savings}}$$

$$= \$282/\$390$$

$$= .79 \text{ years}$$

Figure 8. Payback Period

By substituting different power costs and annual hours of operation, the equations in Figures 7 and 8 can be used to calculate payback under various assumptions. As shown in Figure 9, the relationship between power cost and annual hours of operation is significant. Buyers should understand this relationship to determine if premium efficiency motors are an attractive economic investment for a given application.

Simple Payback Period (Years)
50 Hp, 1800 RPM, TEFC Premium Efficiency

Annual Hours of Operation	Power Cost ($/kWh) .04	.06	.08
2,080 (1 shift)	5.3	3.6	2.7
4,160 (2 shifts)	2.7	1.8	1.3
8,760 (continuous)	1.3	0.8	0.6

Figure 9. Effect of Power Cost on Payback

Where power costs are low, premium efficiency motors may still be attractive if the motor runs continuously. Conversely, where power costs are high, premium efficiency motors may be justified even where they operate for only one shift. Each buyer should evaluate his applications and let the economics decide. We cannot overstate the importance of using your real power cost in any evaluation.

Making A Life Cycle Analysis

Annual savings and simple payback calculations will establish whether or not the buyer should consider premium efficiency motors. If the facts are favorable, a life cycle analysis should be completed to determine the true economic benefits of specifying premium efficiency motors.

By introducing the number of years of operation or the period of evaluation into the annual savings calculation, the user can define the savings over the life of the motors. This is easily done by developing an evaluation factor (EF) as shown in Figure 10. This method takes into consideration the cost of electricity, annual hours of operation and the number of years over which the user evaluates the project or installation.

$$EF = C \times N \times n$$

EF	Evaluation Factor
C	Average power cost ($/kWh)
N	Annual hours of operation
n	Number of years of operation or period of evaluation

Figure 10. Evaluation Factor

The evaluation factor is then substituted in the annual savings calculation as shown in Figure 11 to determine life cycle savings achieved by applying premium efficiency motors.

$$LCS = .746 \times Hp \times L \times EF \quad \frac{(100)}{(E_B)} - \frac{(100)}{(E_A)}$$

LCS	Life Cycle Savings
EF	Evaluation Factor
E_A	Premium efficient motor efficiency
E_B	Standard motor efficiency

Figure 11. Life Cycle Savings

Using the previous motor example and assuming a seven year period of evaluation, the evaluation factor will be $4,292/kW as shown in Figure 12.

$$EF = .07 \times 8760 \times 7$$
$$= \$4,292/kW$$

Figure 12. Evaluation Factor

By substituting the evaluation factor in the earlier annual savings calculation, the life cycle savings of the example will be $3,904 as shown in Figure 13.

$$LCS = .746 \times 50 \times \frac{100}{100} \times 6132 \quad \frac{(100)}{(93)} - \frac{(100)}{(94.5)}$$
$$= \$3,904$$

Figure 13. Life Cycle Savings

Depending on the individual user and the application under consideration, evaluation factors can range from $800/kW to $10,000/kW. In approaching the evaluation of premium efficiency motors, each user should determine individual evaluation factors to fully understand the economic benefits of premium efficiency motors in their operation.

It should be noted that the life cycle savings are not annual savings, but a pretax estimate of savings based on the years of anticipated operation. This evaluation can be expanded to include the time value of money and the expected escalation of power costs.

Choosing The Most Efficient Motors

Once the buyer has decided that premium efficiency motors are a sound investment, the right supplier must be chosen to maximize the return on investment. There are many motor suppliers who manufacture “premium efficiency” motors, but their efficiency claims may differ. It is important to make your own supplier selection and savings calculation. This is also an excellent time to factor in guaranteed minimum efficiencies in order to be certain of realizing all the calculated savings.

Using the previously calculated evaluation factor of $4,292/kW and comparing a motor to existing standard efficiency levels shows the importance of evaluating even a tenth of a point of efficiency difference. This calculation is done using known standard or pre-EPAct, EPAct and NEMA Premium efficiencies.

Figure 14 shows the difference in life cycle operating savings resulting from different nominal efficiencies.

Pre-EPAct	EPAct	NEMA Premium
91%	93%	94.5%
	$5,615 LCS	$2,732 LCS

Figure 14. Life Cycle Comparison of Known Standards at 50 Hp

Not all premium efficiency motors are the same, and detailed comparisons should be made to assure the greatest possible life cycle savings for premium efficiency motors. This comparison should go beyond the efficiencies to include other design factors that may affect the user’s system.

This summary is even more significant when looking at pre-EPAct motors. Although no longer legally available from manufacturers, there are literally millions of pre-EPAct motors running in industry today. They will ultimately fail and be evaluated for replacement or repair. If the life cycle factor is high enough, the user may elect to retrofit prior to a forced downtime.

However the simplest evaluation remains Premium vs EPAct motors.

Based on the difference in the efficiencies of the premium and the EPAct motors, the EPAct motor would cost an additional $2,732 to operate over the motor's lifetime. For equal total cost of ownership, you would have to reduce the initial price of the EPAct motor by $2,732. In fact, in this case the EPAct motor would cost more to own even if the motor were free!

This clearly demonstrates the importance of an efficiency evaluation, and that not all premium motors are the same. When deciding if premium efficiency motors are the right economic decision, it is important to keep the following points in mind:

- Evaluate the financial benefits of premium efficiency motors based on guaranteed minimum efficiencies.
- Prepare a life cycle savings comparison to clearly understand the total cost of ownership.
- The total cost of ownership equals the purchase price plus the life cycle efficiency evaluation.
- Analyze the other trade-off in manufacturer's design that could effect system needs for incoming power.

Don't Let First Cost Drive The Decision

In addition to lower operating costs, premium efficiency motors offer additional value in terms of longer life, application versatility and improved performance. Along with lower losses, premium efficiency motors have much lower temperature rise than standard motors. Consequently winding life can be up to four times longer, and lubricant life twice as long compared with a standard motor. As shown in Figure 16, premium efficiency motors can provide the user with application versatility in many of the following severe operating conditions.

- High altitude and high ambient conditions
- Impaired ventilation
- Frequent starting
- Non-standard waveforms associated with variable frequency drives
- High load inertia
- Greater stall capacity
- Premium efficiency motors also operate more quietly and have lower no-load losses.

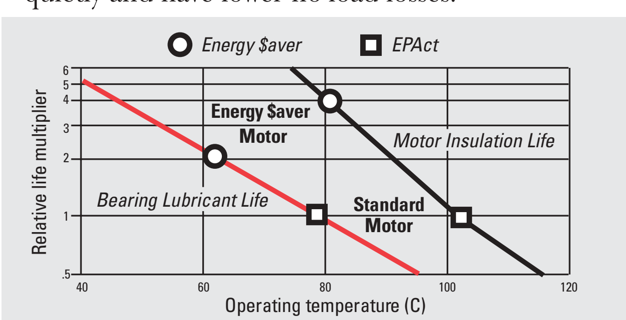

Figure 16. Temperature Effect on Lubricant and Insulation Life

All premium efficiency motors are not created equal. In designing for the optimum efficiency there are trade-offs that can have dramatic effects on other motor characteristics. For a given stator diameter, the engineer can adjust stator slot geometry, wire size, rotor slot configuration and rotor material. If optimum efficiency were the only goal, then relaxing other performance limits – such as allowing higher than NEMA B locked rotor amps, or possibly modified torque characteristics – may make possible a high efficiency design at low cost. However these design trade-offs can have a dramatic impact on the application when this motor is used to upgrade an existing system. The existing starter may be too small, circuit breakers may need to be replaced, and if there is a significant change-out to improve total efficiency, power leads and even the distribution transformer may need consideration.

Not all motor manufacturers are members of NEMA and so may approach their designs differently. Look carefully at the motors being offered. Check, for example, the calculated locked rotor amps to make sure they meet the NEMA design letter on the nameplate. Evaluate the power factor. A lower power factor may be worth sacrificing to gain higher efficiency. Motor efficiency can only be optimized by initial design, while power factor can be improved with a one time investment in the system. Efficiency savings are then realized for the life of the motor.

We at GE are unique, with over 100 years of motor design and application-related experience. We have the expertise to make sure all of the additional benefits of Premium Efficiency motors add up to greater motor reliability and the best overall return on your investment. This experience extends beyond motors alone, offering opportunities for further total system productivity by combining Energy $aver motors with the option of a complete line of GE Drives.

All of these additional benefits clearly add up to greater motor reliability for the user and a better return on your investment.

For additional information on evaluating the replacement of failed motors with energy efficient motors, or retrofitting existing motors with energy efficient motors, contact your local GE Industrial Systems distributor and ask for the following brochure: Impact of Rewinding on Motor Efficiency, GET-8014.
For more information, log on to www.geindustrial.com

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