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

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Abstract

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

Introduction

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

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

Minimum Efficiency Performance Standards

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

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

Market Survey of Existing High Efficiency Motors

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

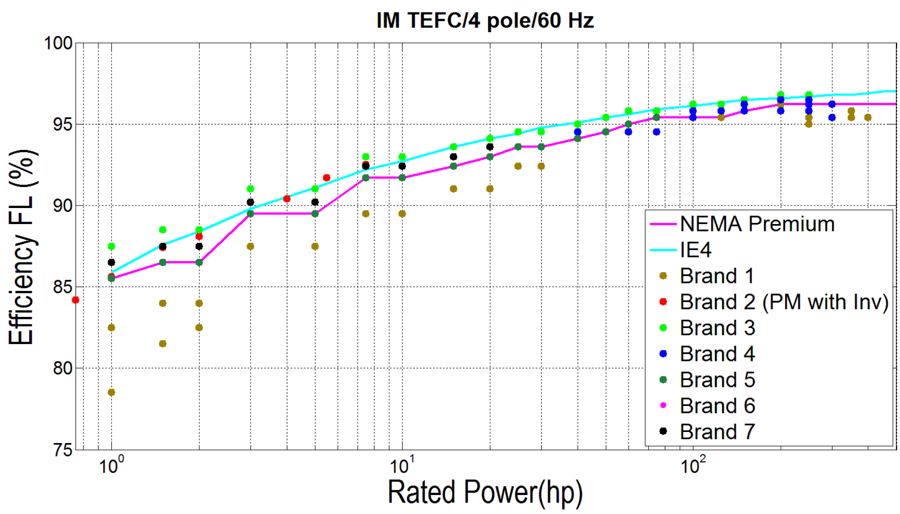

Figure 1 – Full Load Efficiency for Three-Phase Induction and PM Motors/4 pole/60Hz (US Market)

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

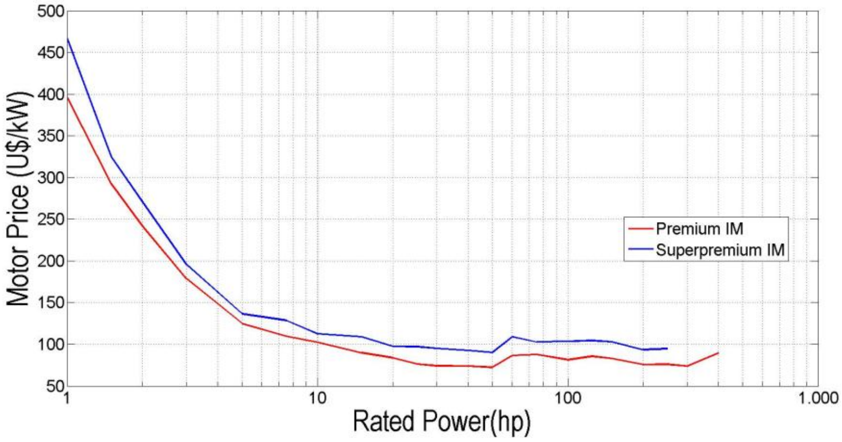

Figure 2 - US Market (Discount 40% Superpremium, 45% Premium)

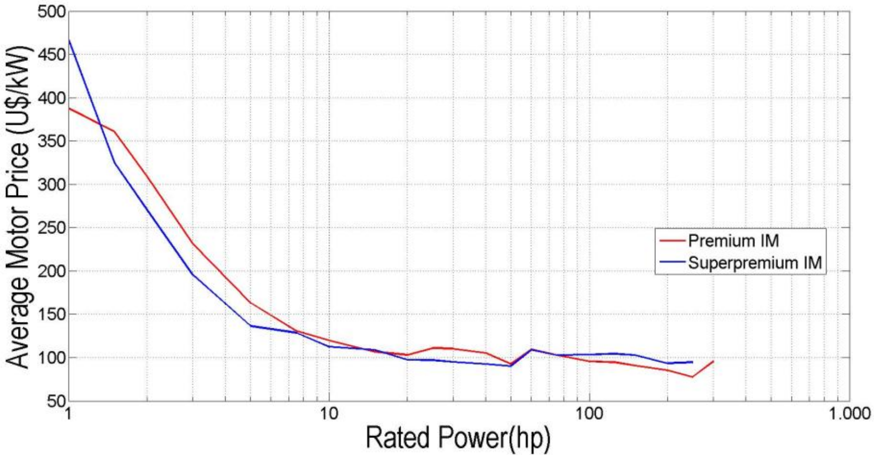

Figure 3 - US Market Average (Discount 40% Superpremium, 45% in Average Premium Motors)

Economic Considerations

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

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

Figure 4 – Key steps of US Rule making

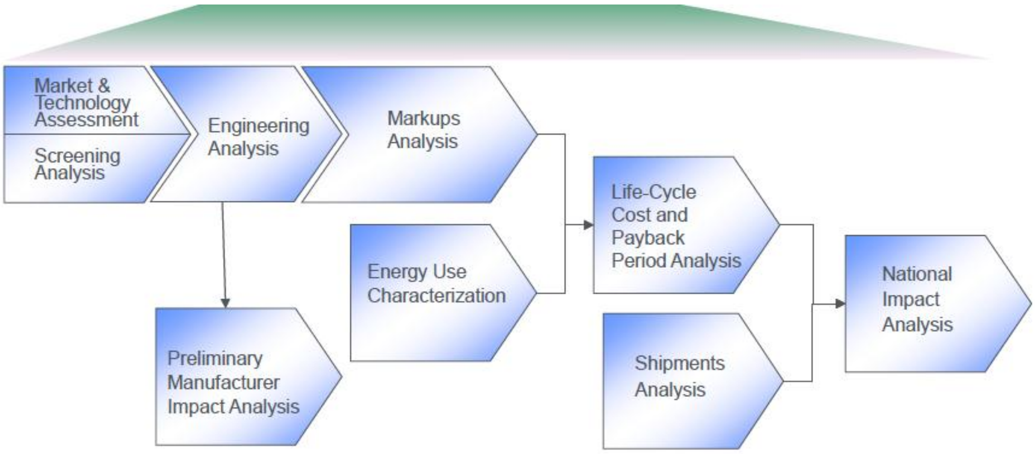

Figure 5 – Steps of Preliminary Analyses [7]

A. Life Cycle Costs

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

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

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

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

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

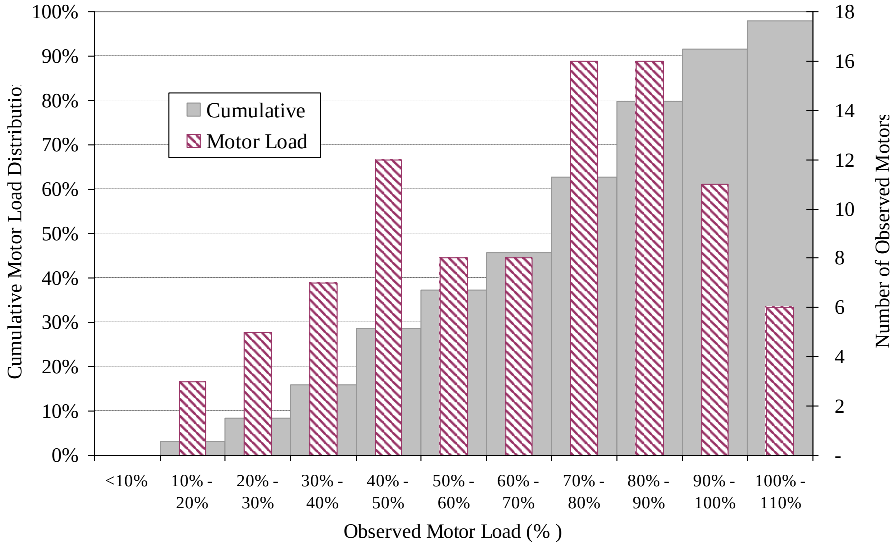

Fig 6: Operating load of 100 surveyed motors rated 50hp-150hp in US industry [8]

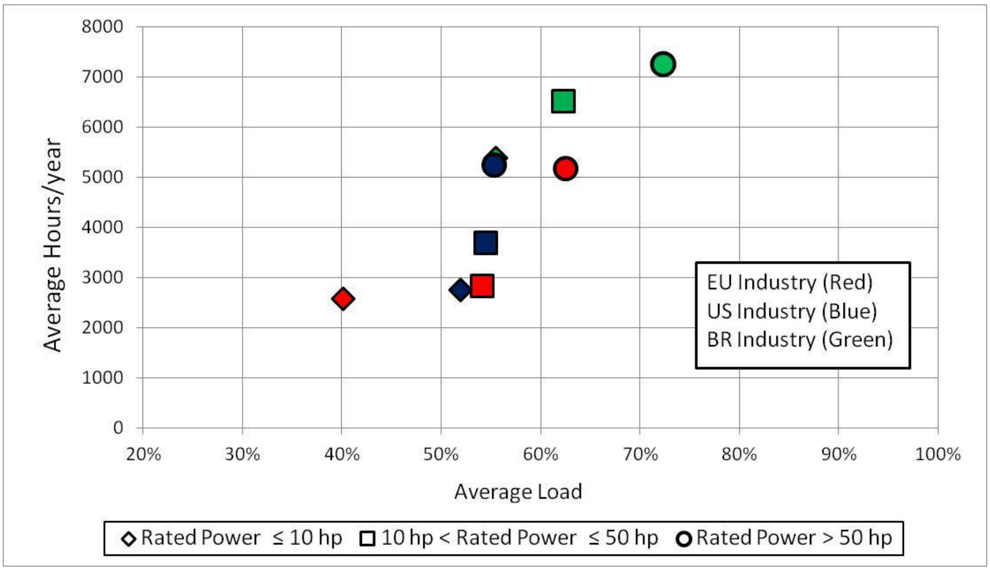

Figure 7: Average operation points for electric motors in the Industry of the US, EU and Brazil

B. Viability Analysis

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

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

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

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

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

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

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

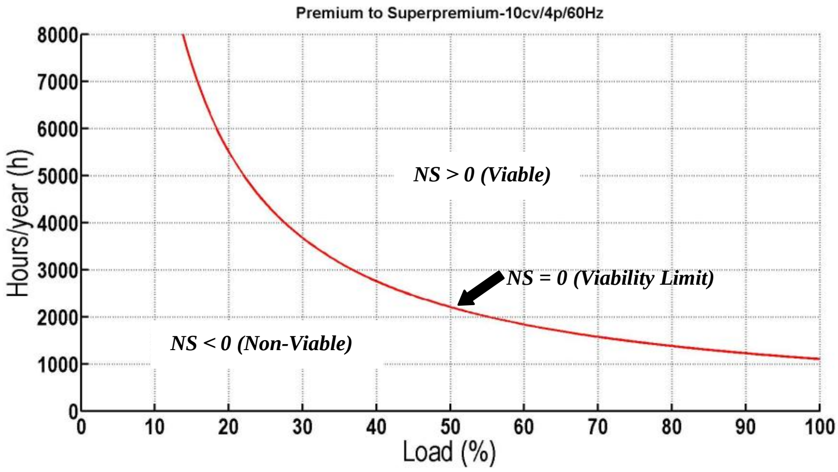

Figure 8: Viability curve for a motor efficiency improvement
(n=12 years, C = 0.0718U$/kWh, d=3%, e=2%)

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

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

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

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

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

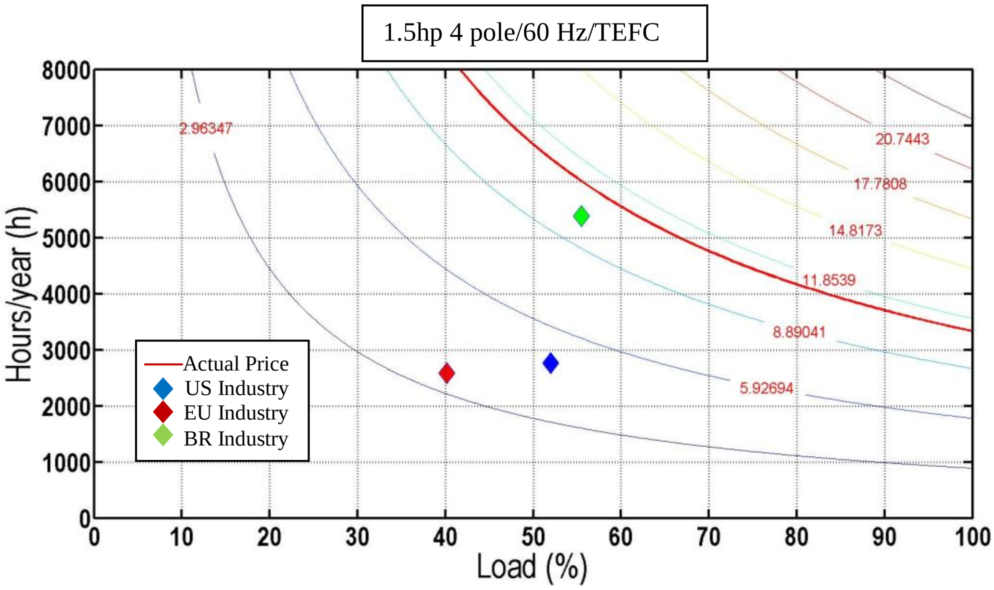

Figure 9: Viability curve of premium to super-premium for a 1.5hp/4 pole/60 Hz motor

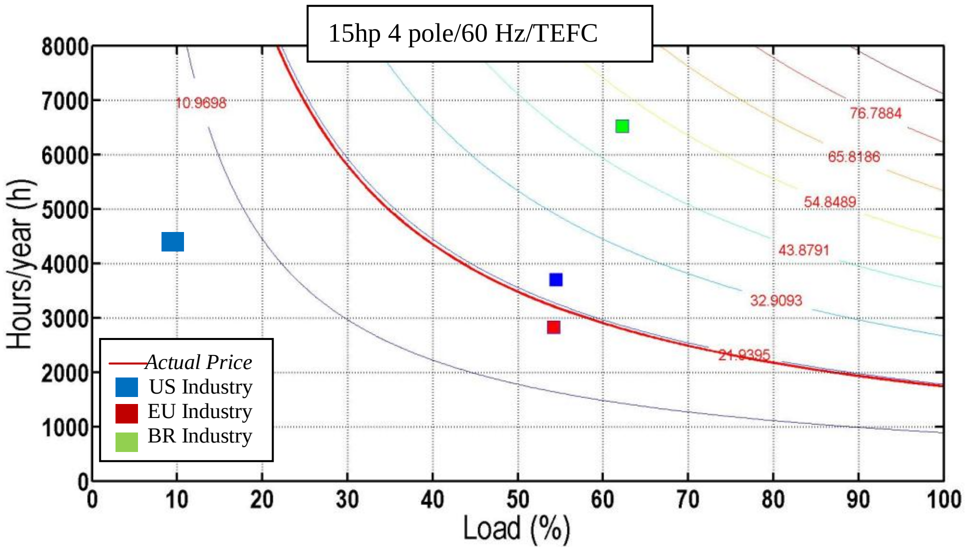

Figure 10: Viability curve of premium to super-premium for a 15hp/4 pole/60 Hz motor

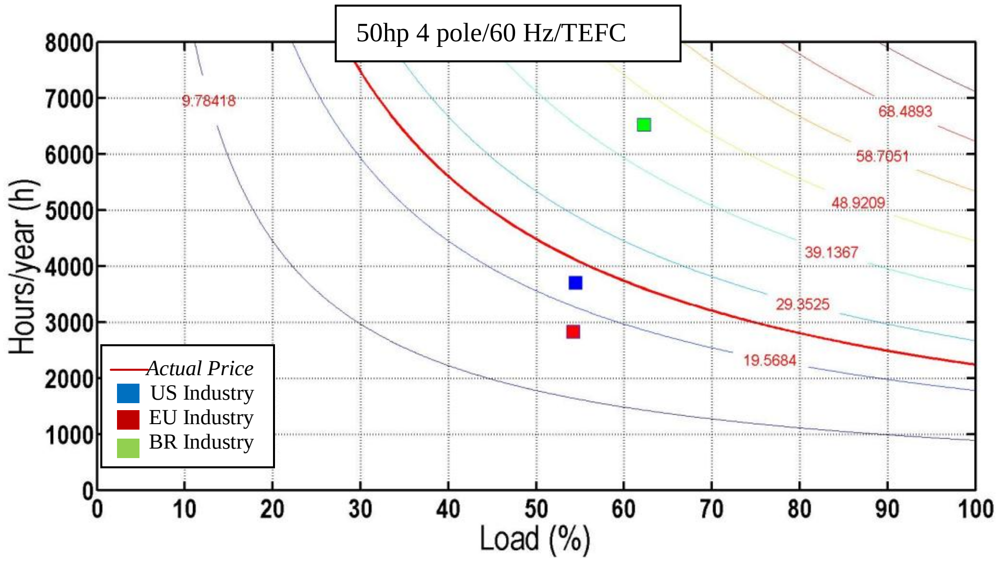

Figure 11: Viability curve increase from premium to super-premium of a 50hp/4 pole/60 Hz motor

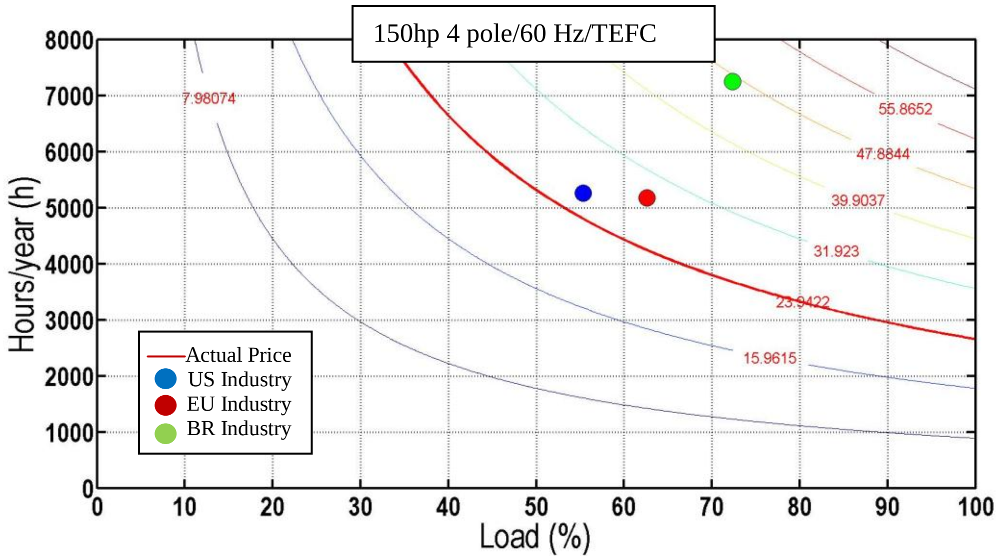

Figure 12: Viability curve of Premium to Super-premium level for a 150hp/4 pole/60 Hz motor

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

C. Efficiency Cost Relationship

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

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

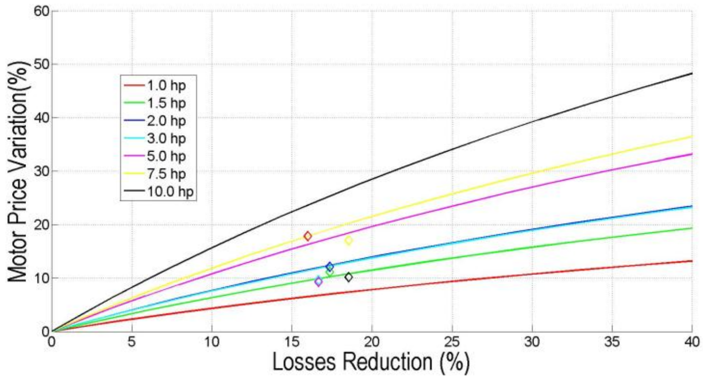

Figure 13: Price variation above Premium (Load = 52%, Hours = 2759)

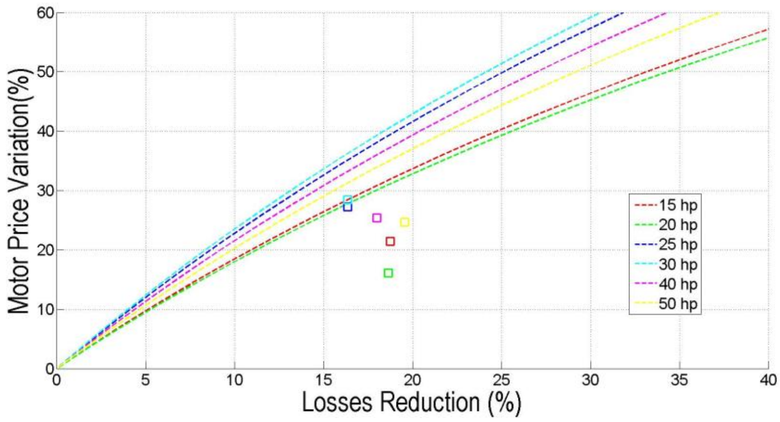

Figure 14: Price variation above Premium (Load = 54.5%, Hours = 3700)

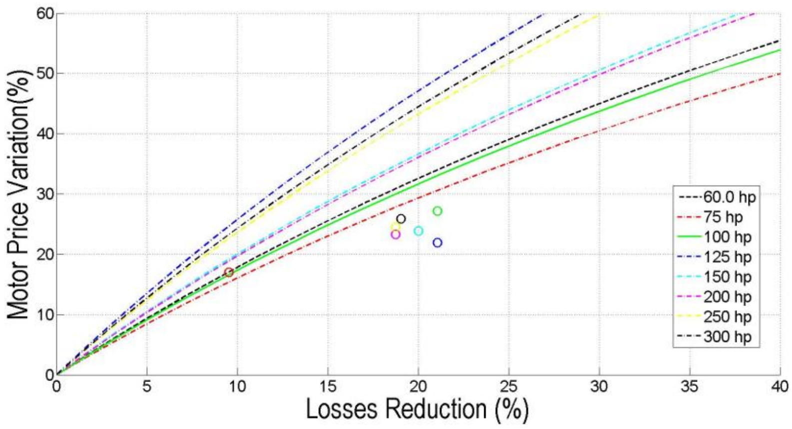

Figure 15: Price variation above Premium (Load = 55.3%, Hours = 5256)

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

Technology Considerations

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

A. Motor Losses

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

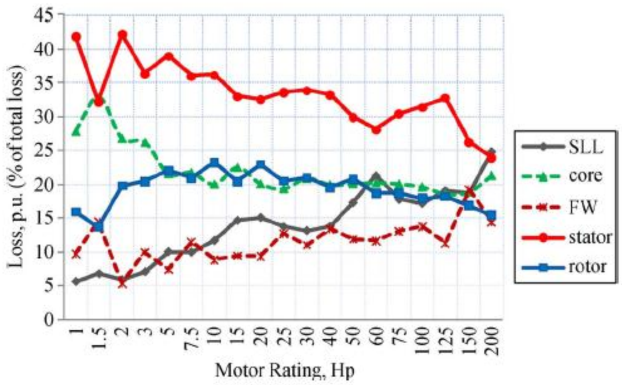

Fig. 16: Average per unit induction motor losses versus rating [10]

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

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

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

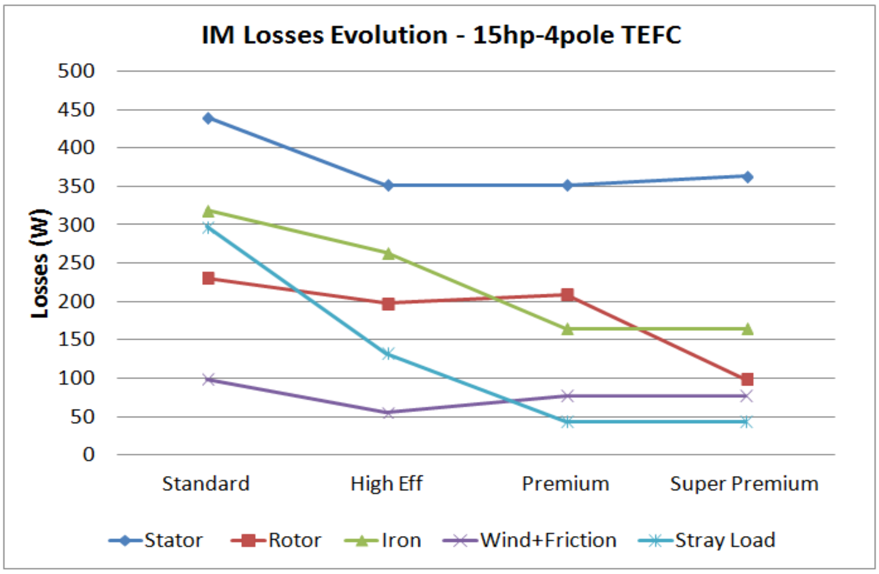

Figure 17: Evolution of the Losses in a 15hp/4 pole/TEFC Induction Motor

B. Copper Rotor Technology

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


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

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

C. Stack Lengthening

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

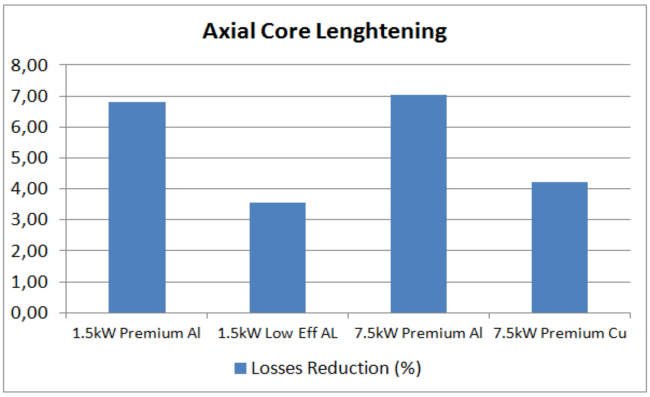

Figure 19: Losses reduction for axial core lengthening

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

D. Locked Rotor Performance

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

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

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

Efficiency Testing Considerations

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

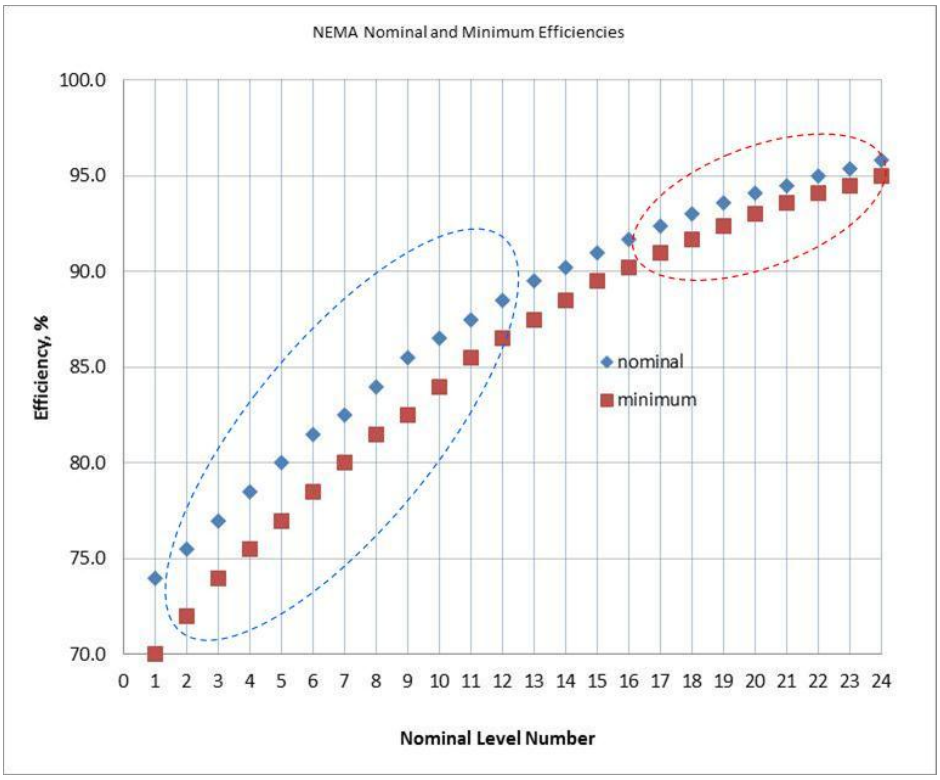

Figure 20: Nominal and minimum efficiency levels

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

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

Conclusion

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

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

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

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