Motors Efficiency Estimation and Its Evaluation in Energy Analysis

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Abstract

Efficiency in motors has always played an important role in energy analysis in industry. Their importance is dramatic as motors account for about 50% to 60% of the energy used by industries. Particularly considering that energy costs generate a high impact over profitability in the industry sector. However, several studies have demonstrated how different can be the approach and subsequently the results from energy analysis, depending on how the efficiency motor is estimated. Actually, some changes have been identified in European standards (IEC 34-2) in order to improve the accuracy level obtained, requested and finally offered to the industry within efficiencies motor standards. Meanwhile, other studies have demonstrated the convenience of American standards (IEEE 112 and National Electric Manufacturers Association - NEMA) related to actual values of efficiencies, and compared with other standards available and generally accepted world-wide.

Due to the high relevance of motor efficiency estimation over energy analysis, this work includes a new pragmatic approach, based on previous analysis related to the most accurate standard, generally accepted in the industry. It develops a way of estimating the efficiency of the motor according to its size (in hp) and its rpm. The procedure shows very accurate efficiency value for that motor (under certain standard conditions), required for motors energy management analysis.

One of the main advantages offered by this approach is that it gives a reliable and quick estimation of motors efficiencies, available for the analysts with little data gathering. Most importantly, the results are in excellent agreement with American standards references.

In addition, we present with our findings, and using extrapolation techniques, 3-dimensional efficiencies surfaces to show and justify, the best working conditions.

Finally, a brief background and an example of energy analysis for a motor replacement is presented, based on the cost savings obtained due to a difference in the motors efficiency level in its design.

KEYWORDS: Motor Efficiency, International Efficiency Standards, Motor Size, RPM, Curves Adjustment, Least-Squares Technique, NEMA, IEEE 112, IEC 34-2, MotorMaster.

Resumen

La eficiencia en motores ha jugado un rol importante en los análisis de usos de la energía en la industria. Su importancia es dramática tomando en cuenta que del 50% al 60% de la energía en la industria, es suministrada por motores. Esto es fundamental porque el costo de la energía genera un alto impacto en los beneficios de la industria. Sin embargo, varios estudios han demostrado que tan diferentes pueden ser los resultados de diversos enfoque de análisis de energía, dependiedo de como es estimada la eficiencia de los

motores. Efectivamente algunos cambios han sido identificados en el estandar europeo (IEC 34-2) para mejorar el nivel de precisión obtenido y requerido por la industria, siguiendo los estandares de eficiencia. Otros estudios han demostrado ciertas ventajas para los estandares americanos (IEE 112 y NEMA: National Electric Manufacturers Association) con respecto a los valores de

eficiencia de otros estandares conocidos a nivel mundial.Debido la preponderancia de la eficiencia de los motores sobre los análisis de energía, este trabajo introduce un nuevo paradigma basado en análisis previos, relacionados con una mayor precisión. Este desarrolla un procedimiento para estimar eficiencia de acuerdo con su tamaño (en HP) y su rpm (revoluciones por minutos). Este enfoque muestra mucha precisión en los valores de eficiencia (bajo ciertas condiciones), requeridos para el análisis del manejo de la energía en motores.Una de las principales ventajas ofrecidas por este enfoque es una rápida y confiable estimación de la eficiencia de motores, disponible para los analistas con poca información recolectada. Y mas importante aún, los resultados están en concordancia con los estandares americanos. Adicionalmente, presentamos en nuestros resultados el uso de una técnica de

extrapolación para la eficiencia en superficie tridimensionales para mostrar y justificar las mejores condiciones de trabajo. Finalmente, presentamos brevemente, para el reemplazo de motores, los

fundamentos y un ejemplo de análisis de energía, basado en los costos que se reducen debido a la diferencia en los niveles de eficiencia del motor dado su diseño.

1. Introduction

It is well known that motors use about 50% of the total electric energy used in industry, which in turn consumes about 35% of the energy used in U.S. The relevance on efficiency motors estimation is based on the impact that this metric has over energy management analysis, which includes the evaluation of data and systems performance in current or future energy utilization. Certainly, it is known that the motor efficiency can be understood by everyone in the industry as the ratio of its useful power output to its total power input.

However, the approach taken to estimate these terms may vary significantly based on the standard used. According to previous research [1], the difference among European Standard and American standard could be up to 2.5% for motors in 1-100 hp range. This situation has been recognized and now the International Electro technical Commission (IEC 34-2) is looking to improve its deficiencies according to real values.

Today, it is recognized that efficiency estimation coming from IEEE-12-B and NEMA provides the most accurate information among the generally world-wide accepted standards; therefore the need to have a pragmatic and reliable approach to apply this standard in our energy analysis arises.

In this work we show how from basic motor efficiency concepts supported on reliable experiments results [2], the electric-efficiency behaviors can be predicted. We develop a simple but useful procedure to facilitate the motor efficiency estimation based on very little data collection.

In the next section we review some useful motor efficiency concepts. Then a current widely used standards background is presented. To start our derivations we show some previous results found in the literature. At this point we present our analysis through some curves and equations development. We then discuss our results and present 3-dimensional efficiency surfaces for motors under known working conditions.

In October 1997, federal standards for new motors required manufacturers to produce motors that met new minimum efficiency ratings. Since then high efficiency motors have been built, and we refer to them as standard efficiency motors. We refer to motors that exceed these as premium efficiency motors.

Finally, in the last section we present our conclusions.

2. Motor efficiency concepts

In order to be able to develop our electrical motors energy analysis, below we discuss the variables that affect the estimation of motor efficiency.

Power Factor (PF): It is the mathematical ratio of Active Power (Watts = W) to Apparent Power (Volts Ampere = VA). Where Active Power or Real Power corresponds to the power supplied by the power system to actually turn the motor on [3]. Low power factor increases losses in electrical distribution and utilization equipment. Power factor is usually

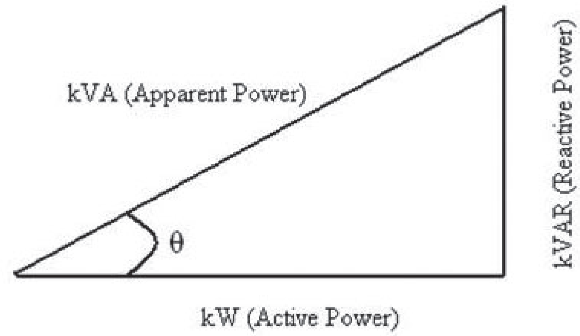

FIGURE 1: The power triangle

$$PF = \cos(\theta) = \frac{kW}{kVA} ...[eq.1]$$

$$kVA^2 = kW^2 + kVAR^2 ...[eq.2]$$

Full Load Amps (FLA): It refers to the amount of current the motor can be expected to draw under full load (torque) conditions [3]. Most electric motors are designed to operate at 50 to 100 percent of their rated load, in order to look for higher efficiency in motors. However, if motors are improperly loaded, then motors reflect a low power factor and low efficiency:

$$LF = \frac{kW \times Efficiency}{0.746 \times hp} ...[eq.3]$$

Where for 3 phases:

$$kW = \sqrt{3} \times V \times I \times PF ...[eq.4]$$

Load Factor (LF): In addition, the LF is a measured, operational value that is computed as the ratio between measured and rated amps by a motor, as showed in eq. 5

$$LF = \frac{Amp.Measured}{Amp.Rated} ...[eq.5]$$

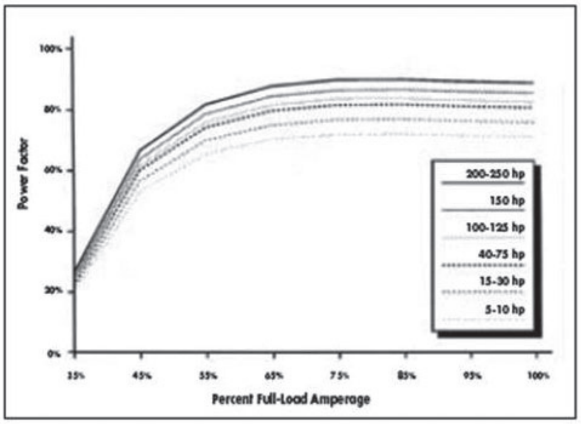

FIGURE 2: Motor power factor (as a function of the % full-load amp) [4]

The graph in Figure 2 presents the relationship between Power Factor and the percent Full-Load Amperage for different motor sizes [4]. As it can see, the higher the FLA percent, the higher the achievable power factor in every category, before reaching a common level of stabilization

Efficiency of a Motor (η): is the ratio of the mechanical power output to the electrical power input. This may be expressed as η:

$$\eta = \frac{Output}{Input}$$

$$= \frac{(Input - Losses)}{Input} = \frac{hp \times 0.746 \times LF}{kVA \times PF} ...[eq.6]$$

Other terms that are considered in the analysis, include:

Utilization Factor (UF): it is the ratio of time the equipment is in use to the total operating time.

Diversity Factor (DF): it is a variable that is appropriate to use when a group of motors are not turned on at the same time, and they are connected in parallel.

3. Standards background

Currently, and among several standards generally accepted world-wide, the three most known ones due to their relevance include the European standard (IEC 34-2), the Japanese standard (JEC-37), and the American standard (IEEE 112-B).

Our goal is to identify one single source to prepare the foundation for a solid, reliable and accurate estimation. For this it is necessary to understand these three major standards. This will help us later on to develop the approach in our estimation model. Several studies have demonstrated the quantitative differences among the three standards [2], recognizing that the standard that reflects the most accurate output expected from efficiency estimation is the American one [2]. The following table summarizes the advantages and disadvantages for each standard:

IEE 112-B requires that three tests must be performed: Thermal test at the rated load, No-load test, and Variable load test. It determines the motor losses and subsequently calculates the motor efficiency.

The major disadvantage from IEC 34-2 includes an imposition for the stray losses, which are considered as a function of the squared stator current, and are assumed at a rated load condition equal to 0.5% of the absorbed power at rated load.

Table 1: Main Advantages & Disadvantages for International Standards

Standard	Main Advantages	Main Disadvantages
USA IEE 112-B	- More comprehensive approach (Thermal test, No-load test, Variable lad test). - Affordable information for consumers.	- It requires that some loss terms be corrected.
European IEC 34-2	- It provides several methods and procedures for the efficiency measurements in accordance with the type and sizes of machine, with the wanted accuracy. - Its methods are easy to use and to reproduce [5]	- Stray Losses assumed to be 0.5% of the power for the motor efficiency estimation in the indirect method.
Japanese JEC-37	- Its techniques might be used to determine either input or output, or both, when a direct measurement is not available.	- Null Stray Losses assumed. - No thermal correction of the Joules losses is specified. - Little available information about measurement procedures.

Meanwhile, the JEC-37 has mainly the disadvantage of being less restrictive than the other two standards, where the efficiency evaluation is imposed by neglecting the stray losses. Consequently, you will usually expect to get higher efficiency values from this approach.

4. Previous test results

According to the research done by Almeida, Ferreira, Busch, and Angers [1] the main differences between the standards can be allocated to the Stray Load Losses that occur in the motor. Several experiment measurements were performed, evaluating its behavior in different conditions. The summary of the main differences found are summarized in table 2:

Table 2: Summary OF MAIN Differences between IEC 34-2 and IEEE 112-B

	IEC 34-2 (Indirect Method)	IEEE 112-B
Type of measurement	Summation of losses	Direct
Core loss with voltage drop compensation	Yes	Yes
SLL using regression analysis	No	no
Temperature corrected winding losses	No	Yes
Thermal equilibrium at rated load	No	Yes
Stabilization of no-load losses	No	Yes
Dynamometer torque correction	No	Yes
Instrumentation Accuracy (+/- % of full scale):		
Electrical	1.0	0.2
Instrument transformer	1.0	0.2
Frequency	1.0	0.1
Speed	1.0	1 rpm
Torque	1.0	0.2
Resistance	0.5	0.2

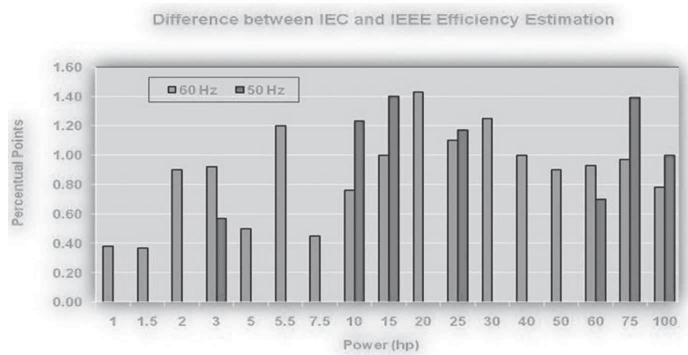

FIGURE 3: AVERAGE DIFFERENCE BETWEEN EFFICIENCY AVERAGE VALUES. [1]

In terms of efficiency differences between IEC 34-2 and IEEE 112-B test standards for 50 and 60 Hz motors, the results are shown in Figure 3:

The analysis derived from those experiments suggests that in the 89 motors evaluated, IEC 34-2 efficiency overestimation is about 0.9% for 60Hz motors and for the 36 motors of 50Hz 1.2% with respect to IEE 112-B.

On the other hand, Boglietti, Cavagnimo, Lazzari, and Pastorelli [2] found that this difference presents a similar behavior at different rated loads: 4, 7.5, 11 and 15 kW, as presented in table 3.

Table 3: Motor efficiency at the rated load for different standards as compared with the Direct Method [1]

Standard	4 kW	7.5 kW	11 kW	15 kW
IEEE 112-B	82.9	85.9	86.1	84.9
IEC 34-2	84.6	86.5	86.4	85.5
JEC 37	85.4	87.1	87.1	85.5
Direct Method	83.0	85.7	86.6	85.5

For the first two loads the IEEE method provides motor efficiencies estimation very close to the efficiency measured by the direct method. Meanwhile the efficiencies given by the European (IEC 34-2) and the Japanese (JEC 37) methods give overestimated values. For the last two loads the American method underestimates the motor efficiency in 0.58% and 0.70% respectively.

Therefore, in the light of the results provided by the two different analyses shown the IEEE 112-B can be considered the most suitable standard for the stray losses measurements and, as consequence, for the motor efficiency estimation.

5. Analysis: curves & equation development

According to our experience in the UF-Industrial Assessment Center, it is commonly found in industry that motors are in a high proportion within the type of totally-enclosed fan cooled motors (TEFC), so we will focus our analysis on this type.

Based on standard tables contained within the Energy Policy Act of 1992 (appendix 1), which includes NEMA designs, and according to the rpm of the motor and its load, the corresponding nominal efficiency values for motors are set.

In terms of load, the behavior of motor efficiency, in average, can be visualized as a function of the size of the motor, as shown in Figure 4.

Table 4: Average Motor Efficiency given Load Percentage.

	Load		
Hp	75%	50%	25%
10	87.7	86.7	78.9
15	88.5	87.4	80.0
20	90.0	89.2	82.1
25	90.3	89.3	81.2
30	90.9	89.2	83.8
40	90.1	87.7	83.6
50	91.0	90.0	85.0
75	91.6	90.5	86.0
100	91.9	91.2	84.9
125	92.3	91.3	85.8
150	93.0	92.1	87.8
200	93.7	92.7	86.4
250	94.0	93.3	89.9
300	94.1	93.0	89.9

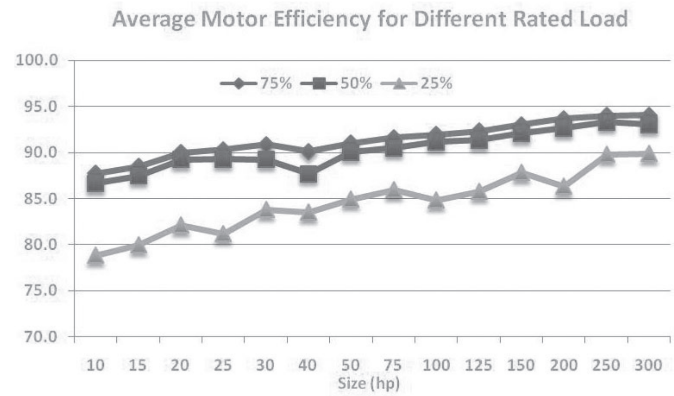

FIGURE 4: average motor efficiency for different rated loads.

We will use these values, as reference to develop the analysis of motor efficiency estimation. In our study we will consider that the size of the motor (hp) and the corresponding speed (rpm) at which the motor is under consideration, that normally works are known. This will help us to get a better estimation of the motor efficiency as we also consider its rated load.

The graphs shown in Figures 5, 6 and 7, show the relation between these variables.

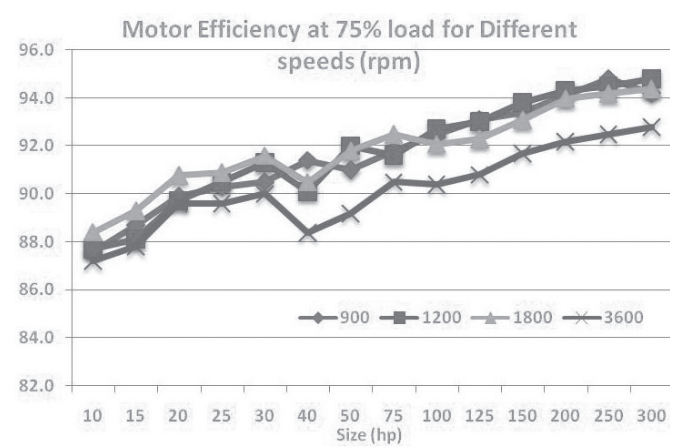

FIGURE 5: Motor efficiency at 75% load.

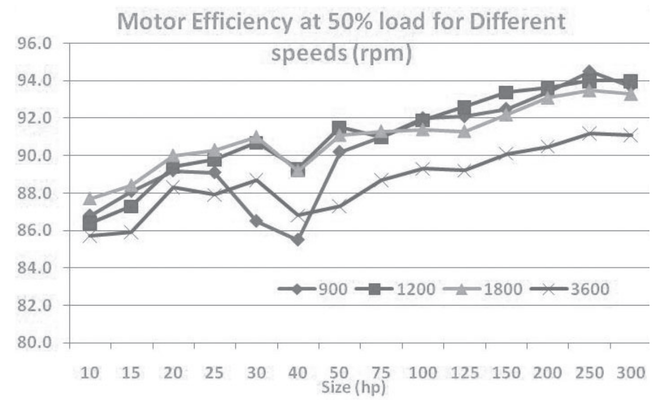

FIGURE 6: Motor efficiency at 50% load.

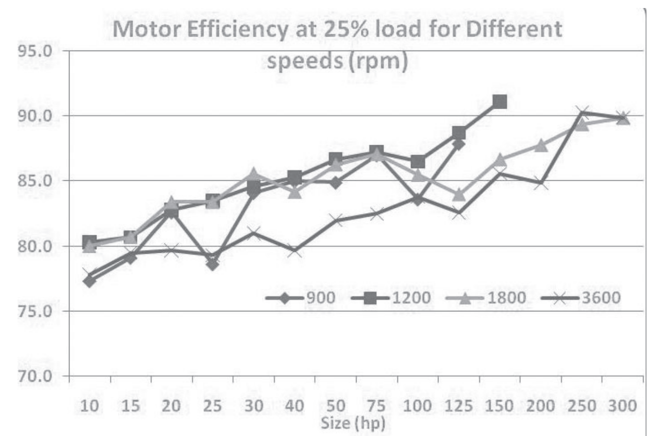

FIGURE 7: Motor efficiency at 25% load.

It becomes clear that the linearity of the efficiency as a function of the motor size seen at 75% load starts to disappear when moving to lower loads. At 50% load we see a dramatic change between 25 hp and 50 hp, but somehow kept otherwise (Fig.6). At 25% load we see a complete loss of linearity (Fig. 7). This is particularly true at extreme rpm's, i.e. lower and higher.

To understand these effects we performed a curve adjustment to determine the motor efficiency (y-variable), once the data about the motor is known (rpm and rated load). This generated the following equations for the efficiencies as a function of the motor size – hp (x-variable):

These equations come from curve adjustments through the application of least squares technique. This method for fitting a curve is based on the idea that one would like to minimize the difference between the data and the fitted or predicted curve. This minimum difference is found by comparing each of the data points Y_i to their predicted values.

It is not sufficient to simply add up these differences, since the positive and negative errors would cancel. The accepted practice is to add up the squares of these differences and minimize that sum (hence the name least squares). Details about the Error obtained for each case are shown in Tables 6 – 9, below.

Table 5: Equations for Motor Efficiency Estimation

Load	Rpm	Error
	900	
75%	y = 83.6975 + 1.9393*ln(x)	0.3%
50%	y = 80.8865 + 2.2984*ln(x)	1.0%
25%	y = 69.6891 + 3.7024*ln(x)	1.8%
	1200	
75%	y = 83.3304 + 2.0425*ln(x)	0.5%
50%	y = 82.3320 + 2.1256*ln(x)	0.6%
25%	y = 72.8809*x^0.04178722	0.7%
	1800	
75%	y = 85.4484 + 1.5583*ln(x)	0.5%
50%	y = 84.8205 + 1.5007*ln(x)	0.6%
25%	y = 75.5671 + 2.3657*ln(x)	1.2%
	3600	
75%	y = 84.1687 + 1.4664*ln(x)	0.6%
50%	y = 82.5462 + 1.4788*ln(x)	0.6%
25%	y = 78.8668 + 0.0392*x	1.1%

Table 6: Curve Adjustments Results
For 900 rpm

	900 rpm @75%			900 rpm @50%			900 rpm @25%		
hp	Std Ref	ηe	Error	Std Ref	ηe	Error	Std Ref	ηe	Error
10	87.6	88.2	0.6%	86.8	86.2	-0.7%	77.3	78.2	1.2%
15	88.7	88.9	0.3%	88.1	87.1	-1.1%	79.1	79.7	0.8%
20	89.9	89.5	-0.4%	89.2	87.8	-1.6%	82.6	80.8	-2.3%
25	90.3	89.9	-0.4%	89.1	88.3	-0.9%	78.6	81.6	3.7%
30	90.5	90.3	-0.2%	86.5	88.7	2.5%	84.1	82.3	-2.2%
40	91.4	90.9	-0.6%	85.5	89.4	4.3%	85.0	83.3	-2.0%
50	91.0	91.3	0.3%	90.2	89.9	-0.4%	84.9	84.2	-0.9%
75	91.8	92.1	0.3%	91.0	90.8	-0.2%	87.0	85.7	-1.5%
100	92.5	92.6	0.1%	92.0	91.5	-0.6%	83.6	86.7	3.6%
125	93.1	93.1	0.0%	92.1	92.0	-0.1%	87.9	87.6	-0.4%
150	93.4	93.4	0.0%	92.5	92.4	-0.1%			
200	94.1	94.0	-0.1%	93.4	93.1	-0.4%			
250	94.8	94.4	-0.4%	94.5	93.6	-1.0%			
300	94.2	94.8	0.6%	93.7	94.0	0.3%			

It is not enough to simply add up these differences, as positive and negative errors would cancel. Instead, the squares of these differences are added and its sum minimized (hence the name least squares). Errors for each case are shown in Tables 6 – 9.

TABLE 7: Curve adjustments results
for 1200 rpm

1200 rpm @75%				1200 rpm @50%			1200 rpm @25%		
hp	Std Ref	ηe	Error	Std Ref	ηe	Error	Std Ref	ηe	Error
10	87.7	88.0	0.4%	86.4	87.2	0.9%	80.3	80.2	-0.1%
15	88.1	88.9	0.9%	87.3	88.1	0.9%	80.7	81.6	1.1%
20	89.7	89.4	-0.3%	89.4	88.7	-0.8%	82.8	82.6	-0.2%
25	90.5	89.9	-0.7%	89.8	89.2	-0.7%	83.5	83.4	-0.2%
30	91.3	90.3	-1.1%	90.7	89.6	-1.3%	84.6	84.0	-0.7%
40	90.1	90.9	0.8%	89.3	90.2	1.0%	85.3	85.0	-0.3%
50	92.0	91.3	-0.7%	91.5	90.6	-0.9%	86.7	85.8	-1.0%
75	91.6	92.1	0.6%	91.0	91.5	0.6%	87.2	87.3	0.1%
100	92.7	92.7	0.0%	91.9	92.1	0.2%	86.5	88.3	2.1%
125	93.0	93.2	0.2%	92.6	92.6	0.0%	88.7	89.2	0.5%
150	93.8	93.6	-0.3%	93.4	93.0	-0.4%	91.1	89.9	-1.4%
200	94.3	94.2	-0.2%	93.6	93.6	0.0%			
250	94.5	94.6	0.1%	94.0	94.1	0.1%			
300	94.8	95.0	0.2%	94.0	94.5	0.5%			

TABLE 8: Curve adjustments results
for 1800 rpm

1800 rpm @75%				1800 rpm @50%			1800 rpm @25%		
hp	Std Ref	ηe	Error	Std Ref	ηe	Error	Std Ref	ηe	Error
10	88.4	89.0	0.7%	87.7	88.3	0.7%	80.0	81.0	1.3%
15	89.3	89.7	0.4%	88.4	88.9	0.5%	80.7	82.0	1.6%
20	90.8	90.1	-0.8%	90.0	89.3	-0.8%	83.4	82.7	-0.9%
25	90.9	90.5	-0.5%	90.3	89.7	-0.7%	83.4	83.2	-0.3%
30	91.6	90.7	-0.9%	91.0	89.9	-1.2%	85.6	83.6	-2.4%
40	90.5	91.2	0.8%	89.2	90.4	1.3%	84.2	84.3	0.1%
50	91.8	91.5	-0.3%	91.1	90.7	-0.5%	86.3	84.8	-1.7%
75	92.5	92.2	-0.4%	91.3	91.3	0.0%	87.1	85.8	-1.5%
100	92.1	92.6	0.6%	91.4	91.7	0.4%	85.5	86.5	1.1%
125	92.3	93.0	0.7%	91.3	92.1	0.8%	84.0	87.0	3.4%
150	93.1	93.3	0.2%	92.2	92.3	0.2%	86.7	87.4	0.8%
200	94.0	93.7	-0.3%	93.1	92.8	-0.4%	87.8	88.1	0.3%
250	94.2	94.1	-0.2%	93.5	93.1	-0.4%	89.4	88.6	-0.9%
300	94.4	94.3	-0.1%	93.3	93.4	0.1%	89.9	89.1	-0.9%

Here, ηe is our estimated value, Std Ref is the NEMA Standard. The ERROR= (ηe – Std Ref) / ηe…[eq. 7]

Our curve adjustment reveals that at higher load (75%) the error is smaller. At lower loads (50% and 25%) the error increases but at acceptable values. This is also due to the lower rpm considered (900).

Table 7 shows lower errors in our adjustments for all the loads considered. This indicates the importance of the speed of the motor.

Table 9: Curve Adjustments Results for 3600 rpm

	3600 rpm @75%			3600 rpm @50%			3600 rpm @25%		
hp	Std Ref	ηe	Error	Std Ref	ηe	Error	Std Ref	ηe	Error
10	87.2	87.5	0.4%	85.7	86.0	0.3%	77.8	79.3	1.8%
15	87.8	88.1	0.4%	85.9	86.6	0.8%	79.5	79.5	-0.1%
20	89.6	88.6	-1.2%	88.3	87.0	-1.5%	79.7	79.7	-0.1%
25	89.6	88.9	-0.8%	87.9	87.3	-0.7%	79.3	79.8	0.7%
30	90.0	89.2	-0.9%	88.7	87.6	-1.3%	81.0	80.0	-1.2%
40	88.4	89.6	1.3%	86.8	88.0	1.4%	79.7	80.4	0.9%
50	89.2	89.9	0.8%	87.3	88.3	1.2%	82.0	80.8	-1.5%
75	90.5	90.5	0.0%	88.7	88.9	0.3%	82.5	81.8	-0.8%
100	90.4	90.9	0.6%	89.3	89.4	0.1%	83.8	82.8	-1.2%
125	90.8	91.2	0.5%	89.2	89.7	0.5%	82.6	83.8	1.4%
150	91.7	91.5	-0.2%	90.1	90.0	-0.2%	85.6	84.7	-1.0%
200	92.2	91.9	-0.3%	90.5	90.4	-0.1%	84.9	86.7	2.1%
250	92.5	92.3	-0.3%	91.2	90.7	-0.5%	90.3	88.7	-1.8%
300	92.8	92.5	-0.3%	91.1	91.0	-0.1%	89.9	90.6	0.8%

On the other hand the results in Table 8 show that the error is lower at 75% and 50% loads, but with increased error at 25% load.

Finally, the results on Table 9 shows the same pattern of the previous cases.

Our deviations (errors) show to be very small for practically all speeds and loads considered. This fact allows us to consider that our efficiency estimation for motors equations, shown in table 5 are in very good agreement with known values (the American standard.)

6. Discussion: 3-dimensional efficiency surfaces

Once we have developed the previous equations, which help to estimate the motor efficiency based on load percentage and motor size, we are now able to perform a tri-dimensional analysis in order to globally assess the behavior of motor efficiency in a complex but realistic environment.

This analysis considers the implications over a motor size selection with its efficiency requirements and its possibilities through load variations.

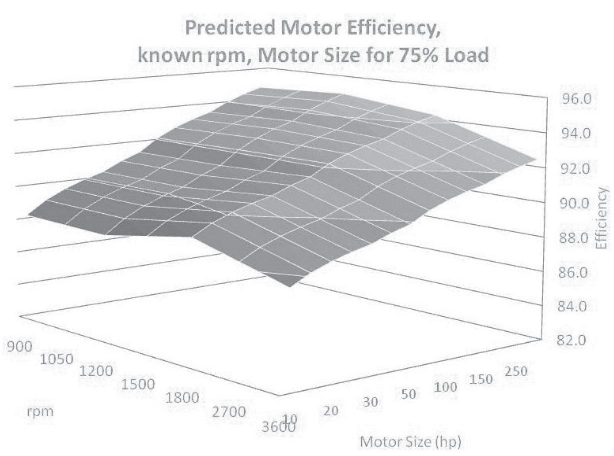

Fig 8: Predicted motor efficiency, at a given rpm and motor size, at 75% load

Considerations on Figure 8, where the load is fixed at 75%:

- In general, for a constant rpm, the bigger the motor in size (hp) the higher the predicted efficiency of the motor even if they run at moderate speeds (1200 rpm).
- For the same motor size, the motor efficiency can be maximized not at maximum speed (3600 rpm), but at lower levels around the 1800 rpm.
- In average, there are two major increases in motor efficiency, no matter the speed (rpm) at which the motor runs. Such increases occur between 10 and 15 hp (0.81% increase in efficiency) and 50 and 75 hp (0.78%).
- At 1200 rpm a minimum of efficiency is reached, and hence should be avoided. This is of particular interest when VFDs (Variable Frequency Drives) are to be considered. The same happens at higher than 1800 rpm values.
- Over 75 hp motor size, a dramatic increase on efficiency happens. In this region of the surface it becomes clear that the efficiency increases with the motor size. For the same size though, the efficiency is higher at 1800 rpm but increasing at higher speeds.

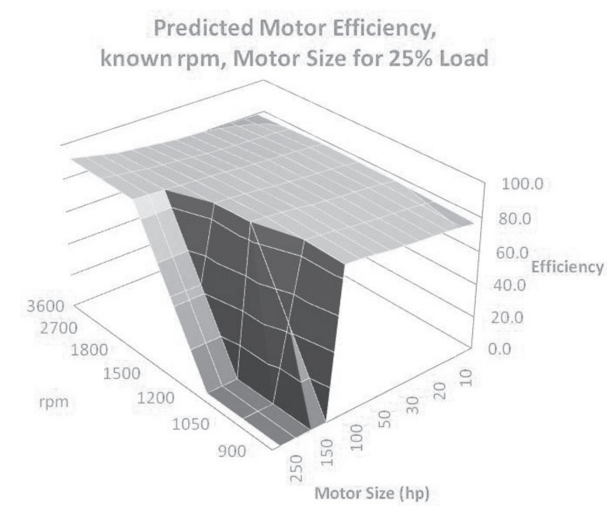

FIG 9: PREDICTED MOTOR EFFICIENCY, AT A GIVEN RPM AND MOTOR SIZE, AT 25% LOAD

Considerations on Figure 9:

- The efficiency behavior can be noticed very stable, with around 90% of the values between 80-90% efficiency values, no matter the size of the motor (hp) or its working speed (rpm).

- Best performance with highest efficiency (90.6%) can be obtained through the biggest motors (300 hp) at only its maximum speed (3600 rpm).
- Lowest efficiency values are given in two minor areas with the smaller motor sizes (10 hp.) For extreme low speeds (900 rpm) and extreme high speeds (3600 rpm.)
- This rather flat surface, with little variation on the efficiency present an extreme disruption in the graph, which is featuring a kind of “black-hole” behavior in the area for largest motor sizes at lower speeds represent the inoperability of electrical motors in such conditions. The NEMA standard does not provide any efficiency value for these cases, and does neither our estimation model.

On the other hand, the versatility of our model allow to evaluate the behavior of the motor efficiency, at a constant speed (rpm) but now altering the load at which the motors are set to work. The following 3D graphs give insight about this set-up.

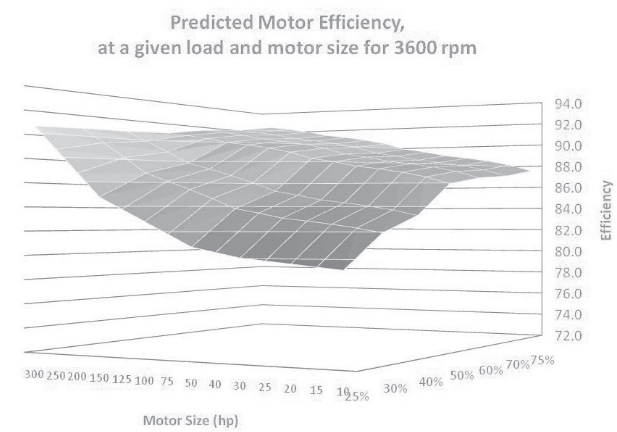

Fig10: Predicted motor efficiency, at a given load and motor size, at 3600 rpm

Considerations on Figure 10:

- The efficiency motor is negatively affected by load reduction, especially in motors with smaller sizes.
- In general, the bigger the motor in size (hp) and higher loads, the higher the predicted efficiency.

- For a same motor size, it can be identified several stable areas with similar efficiency values with load variations i.e. a 50 hp motor present efficiency values with mean of 89.45% with a variation of 1% among of 60% and 75% loads.
- For any motor, but particularly for medium and small sizes (hp) the best efficiencies are obtained when the motor runs at loads 50% or higher.

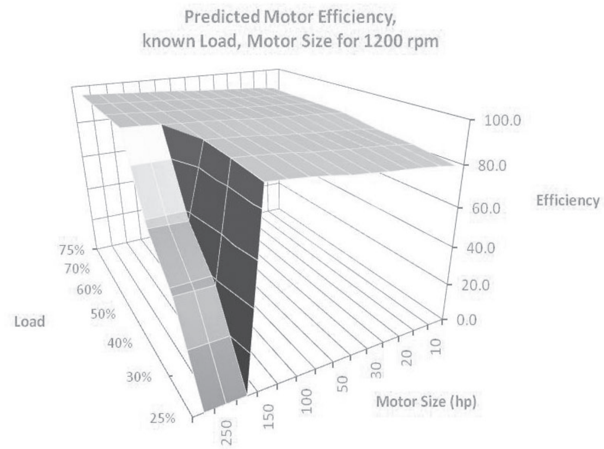

Fig 11: Predicted motor efficiency, at a given load and motor size, at 1200 rpm

Considerations on Figure 11:

- Three major areas of stable efficiency values can be identified in this figure: a) between 80-85% efficiency for low load values and small motor sizes b) a broad spectrum of loads and motors sizes for 85-90% efficiency values c) higher efficiency values between 90-95% for upper-limit in motor size and loads.
- In general, the macro-trend reflects a similar pattern, just like when the load is known (Fig.10), which also is reflected in the efficiency at 900 rpm, when the load and motor size are known (Fig.12). A lower impact over motor efficiency due load variations. In other words, the motor efficiency seems to be more sensitive to changes in speed (rpm) rather than changes in loads.
- Once again, an extreme disruption in the graph, which is featuring a kind of “black-hole” behavior in the area for largest motor sizes at lower speeds represent the inoperability of electrical motors in such conditions. The NEMA standard does not provide any

efficiency value for these cases, and neither our model.

Considerations on Figure 12:

- As mentioned before, the common pattern is reaffirmed in this graph, which at 900 rpm, present only two major segments for motor efficiency. Smaller motors (10-30 hp) present efficiency values between 80-90%, for all load spectrum, while bigger motors (40-300 hp) present 90-95% efficiency values.
- In the same fashion, it can be seen a "black-hole" in the area for bigger motors in lower loads.

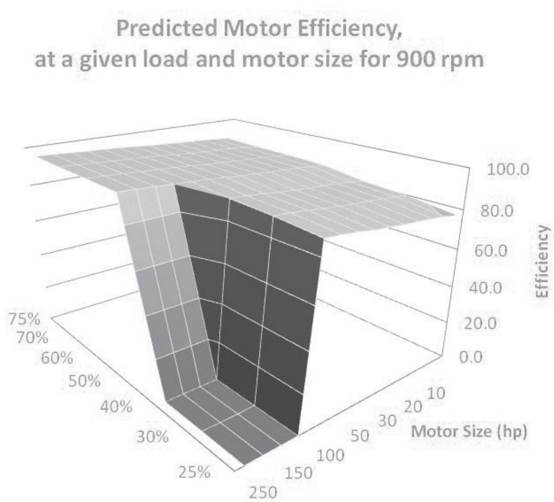

FIG 12: PREDICTED MOTOR EFFICIENCY, KNOWN LOAD AND MOTOR SIZE AT 900 RPM

7. Energy analysis for motor replacement

The minimum efficiency standards for new motors mean that when an older motor fails, you now have three options.

You can:

- Replace it with a new Premium-efficiency motor. Operating Efficiency. 3 to 4 % higher than Std. Efficiency motors. *
- Replace it with a new Standard-efficiency motor. Operating Efficiency better than rewound motor.
- Rewinding the failed motor.

** Depending on the Horse Power of the motor*

Normally, a cost premium (or cost differential) must be paid for higher-efficiency motors.

We have performed an analysis to identify the best motor replacement policy for individual motors to give maximum cost savings. We have considered the following parameters for our analysis:

1. The operating hours of the motors.
2. The electric charges.
3. The cost of replacement.
4. The efficiency of replacement motors.

We have used the MotorMaster software in order to obtain efficiencies for performing our analysis.

MotorMaster

The United States Department of Energy (US DOE) has developed a computer program that analyzes motor replacements for specific motors. With MotorMaster you can compare the cost effectiveness of replacing a specific motor that has failed with a number of different replacement motors. It provides you with a list of potential replacement motors from different manufacturers. You can also compare the cost effectiveness of rewinding the motor with the alternative of purchasing new motors of different efficiencies. You may download the software at no cost from the US DOE Motor Challenge website at http://www.oit.doe.gov/bestpractices/software_tools.shtml.

High-Efficiency vs. Rewound Motor

Facilities often rewind their failed motors because the cost of rewinding a motor is less than purchasing a new one. However, rewinding a motor reduces its efficiency from 1 to 5 percent each time it is rewound, and this often makes a rewound motor more costly in the long-run because its operating costs are higher. MotorMaster conservatively assumes a reduction of 2% in motor efficiency due to rewinding. You can change this percentage in MotorMaster when conducting your analysis.

Our analysis is performed using mathematical programming to determine the best motor replacement to give you maximum cost savings with simple payback period below 5 years. Below is the description of the mathematical program used. This was programmed into a spreadsheet to obtain the results.

Objective

Maximize Cost Savings

Constraints

1) Simple Payback Period for the motors project <= 5 years*

2) Choose only one efficiency level per motor

**Depending on the policy of the company, sometimes it could be less than 5 years.*

Notation

Si => Standard Efficiency motors

Pi => Premium Efficiency motors.

CSSi => Cost Savings, Standard Efficiency

CSPi => Cost Savings, Premium Efficiency

ICSi => Implementation Cost, Standard Efficiency

ICPi +> Implementation Cost, Premium Efficiency.

Mathematical model to obtain maximum cost savings

Maximize

$$\sum (Si \times CSSi) + (Pi \times CSPi)$$

Maximize the cost savings.

Subject to

$$\frac{\sum (Si \times CSSi) + (Pi \times CSPi)}{\sum (Si \times ICSi) + (Pi \times ICPi)} \leq 5$$

The simple payback period of the project has been set to be less than 5 years (arbitrarily by choice).

$Si + Pi = 1$ - Either the Standard EFFc or the Premium EFFc motor must be selected.

$Si, Pi\{0,1\}$ - Variables *Si* & *Pi* are Binary

Demand, Energy, and Cost Savings Calculations for Motors

The equations to compare the demand, energy, and cost savings for two motors of the same size and specifications but different efficiencies are shown below. The monthly demand reduction (DR) can be estimated as follows:

$$DR = HP \times LF \times C \times (1/EFF_c - 1/EFF_p) \times \# \text{ units}$$

Where,

HP = Horsepower of motor considered, hp

LF = Fraction of rated load at which motor normally operates

C = Conversion constant, 0.746 kW/hp

EFF_c = Estimated efficiency of comparison motor (rewind), no units

EFF_p = Estimated efficiency of proposed motor, no units

The annual energy savings (ES) can be estimated as follows:

$$ES = DR \times H \times UF$$

Where,

H = Annual operating hours of equipment driven by motor, hr/yr

UF = Use factor (% of annual operating hours motor is in use) – varies

The annual cost savings (CS) for an energy only structure can be estimated as:

CS = DR × Cost of Demand × 12 months/yr + ES × Cost of Electricity without Demand

Where

Cost of Demand = \$10.457/kW/month

Cost of Electricity Without Demand = \$0.048/kWh

Using a 20-hp motor as an example, we will compare the cost savings of replacing a failed motor with a premium-efficiency motor instead of rewinding.

Analysis of Rewound vs. Premium-Efficiency motor (savings from purchasing a premium-efficiency motor instead of rewinding):

DR = HP × LF × C × (1/EFFc - 1/EFFp) × # units
= 20hp×1×0.746 kW/hp×(1/0.875–1/0.923)×1
= 0.89 kW

ES = (0.89kW) × (6,240 hrs/yr) × 1.0
= 5,533 kWh/yr

CS = 0.89 kW/mo × $10.457/kW-mo × (12 mo/yr) + (5,533 kWh/yr) × ($0.048/kWh)
= $377 /yr

Implementation Cost

The cost premium or implementation cost (IC) is calculated as the difference between purchasing a premium-efficiency motor (CP) and the cost of rewinding the failed motor (CR). Depending on the manufacturer selected, then the specific cost can be estimated through:

IC = CP-CR

Once the previous analysis is completed for all the motor units you are considering, then it is possible to calculate the entire figures for Cost Savings, and corresponding Implementation Costs. Thus several financial rations may be calculated in order to assess the level of attractiveness of such project.

8. Conclusions

We have presented a new approach to estimate motors efficiency under several operational scenarios. We started our discussion analyzing currently accepted standards for motors efficiency as are the American (IEEE 112-B), the European (IEC 34-2), and the Japanese (JEC 37). For these we have discussed their main advantages and disadvantages, and reviewed their differences.

Then we chose the American standard as model (including the 1992 Energy Policy Act) with NEMA designs. We then studied their efficiencies and provided afterward new equations for the motor efficiency estimation (Table 5). The errors found were very small, making the equations an excellent tool.

Using extrapolation techniques we validated our results, developing 3-dimensional efficiencies surfaces to show the best operational conditions for the motors. In the near future, we are planning to include our results in an Industrial Energy Management program (software) [6, 7].

We have finished our study presenting a short example where through a mathematical model it is evaluated the impact of motor efficiency in the energy analysis for a motor replacement.

Our future work considers the implementation of this algorithm as a subroutine in our energy management program.

9. Appendix 1

NEMA TABLE

MOTOR EFFICIENCY AT 75% RATED LOAD				
Load	75%			
hp / rpm	900	1200	1800	3600
10	87.6	87.7	88.4	87.2
15	88.7	88.1	89.3	87.8
20	89.9	89.7	90.8	89.6
25	90.3	90.5	90.9	89.6
30	90.5	91.3	91.6	90.0
40	91.4	90.1	90.5	88.4
50	91.0	92.0	91.8	89.2
75	91.8	91.6	92.5	90.5
100	92.5	92.7	92.1	90.4
125	93.1	93.0	92.3	90.8
150	93.4	93.8	93.1	91.7
200	94.1	94.3	94.0	92.2
250	94.8	94.5	94.2	92.5
300	94.2	94.8	94.4	92.8

NEMA TABLE

MOTOR EFFICIENCY AT 50% RATED LOAD				
Load	50%			
hp / rpm	900	1200	1800	3600
10	86.8	86.4	87.7	85.7
15	88.1	87.3	88.4	85.9
20	89.2	89.4	90.0	88.3
25	89.1	89.8	90.3	87.9
30	86.5	90.7	91.0	88.7
40	85.5	89.3	89.2	86.8
50	90.2	91.5	91.1	87.3
75	91.0	91.0	91.3	88.7
100	92.0	91.9	91.4	89.3
125	92.1	92.6	91.3	89.2
150	92.5	93.4	92.2	90.1
200	93.4	93.6	93.1	90.5
250	94.5	94.0	93.5	91.2
300	93.7	94.0	93.3	91.1

NEMA TABLE

MOTOR EFFICIENCY AT 25% RATED LOAD				
Load	25%			
hp / rpm	900	1200	1800	3600
10	77.3	80.3	80.0	77.8
15	79.1	80.7	80.7	79.5
20	82.6	82.8	83.4	79.7
25	78.6	83.5	83.4	79.3
30	84.1	84.6	85.6	81.0
40	85.0	85.3	84.2	79.7
50	84.9	86.7	86.3	82.0
75	87.0	87.2	87.1	82.5
100	83.6	86.5	85.5	83.8
125	87.9	88.7	84.0	82.6
150	-	91.1	86.7	85.6
200	-	-	87.8	84.9
250	-	-	89.4	90.3
300	-	-	89.9	89.9

10. References

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