Replacing Motors, Counting Savings

Results from a 100-Motor Study: Part I of III

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Introduction

The total U.S. electric motor base exceeds 100 million motors and consumes more than 50% of all electricity generated in the country. Small motors—fractional horsepower to 20-hp—comprise 99% of the motor population but consume only 25% of all generated electricity (Refs. 1,3,10,14). Large motors—only 1% of the general motor population—consume 25% of all electricity generated in the United States and are primarily located in industrial applications.

This article considers the economics and reliability of replacing older industrial motors. The data collected from 100 motors and case studies indicate that the economics of replacing motors operating at less than 60% of rated load—more than 40% of the motors studied—are not adequately represented by the *MotorMaster+* software tool.

Part II: *Industrial Motor Decision Support Tools*, coming next issue, will look at the impact the 100-motor study has made on various tools that facilitate industrial motor management, particularly the repair vs. replace decision.

Part III: *Decision Support Tools for Small Motors*, coming in two issues, will discuss considerations in determining the economics of motor purchases from the viewpoint of an original equipment manufacturer (OEM). In particular, Part III will discuss how to evaluate warranty risk compared to motor reliability.

Background

Industrial electric motors convert electrical energy into mechanical work at such a magnitude that their energy costs eclipse their initial purchase cost. You wouldn't normally compare a mundane, 75-hp industrial motor to a Lamborghini or Ferrari. However, when you include operating costs over 10 years, the motor can cost more than either of these luxury cars (Table 1). Moreover, the initial purchase price of the electric motor accounts for less than 1% of life-cycle costs, while energy costs make up 99% of the life-cycle costs. Therefore, any increase in operational efficiency can have significant impact on the life-cycle costs of the motor, particularly in terms of payback on the incremental cost of a higher-efficiency motor. Because they are prime consumers of electricity, the efficiency of these motors has significant impact on their replacement economics.

Calculating the replacement economics includes several factors specific to the company, facility, and application—payback period/return-on-investment (ROI) criterion, average electric rate ($/kWh), operating hours and load. The simplest payback calculation is

$$T = \frac{X_{replace} - X_{repair}}{0.746 \times hp \times SF \times C \times U\left(\frac{100}{\eta_{old}} - \frac{100}{\eta_{new}}\right)} \quad (1)$$

where

- T is the simple payback period in years,
- $X_{replace}$ is the purchase price of the new motor, including any discounts,
- X_{repair} is the cost to repair the old motor,
- hp is the horsepower rating of the motor,
- SF is the motor operating load, ex-

Which would you rather purchase, own and operate for 10 years, a Lamborghini Gallardo or a 75 hp industrial motor? See Table 1, below, for a direct lifecycle cost comparison.

pressed as a percent of rated load,

- C is the average facility electric cost ($/kWh),
- U is the annual operating hours of the motor, and
- η is the rated load efficiency of the old and new motor, respectively.

If the payback period calculated is acceptable, the motor should be replaced with a new motor; if the payback period is unacceptable, then the motor should be sent for repair.

Some argue that this model is too simple for application in the complex economy of industry (Refs. 3, 6). When a new motor purchase is planned and specifically budgeted, particularly for expansion or upgrade, it makes sense to account for the present value of the energy savings, as these authors argue. Interestingly, their models do not account for the depreciation of the capital cost of the motor, which should also be included in a more complex analysis. However, maintenance budgets rarely include factors for energy savings by upgrade and capital depreciation, so at the level where these decisions are most commonly made, the simple model provides enough justification for the decision at hand.

This simple model of the economics is used in several motor decision tools. *The Horsepower Bulletin*, published by Advanced Energy, rearranges this equation, solving for horsepower, to determine a "horsepower breakpoint"—the horsepower rating at and below which all motors should be replaced at failure, and above which all motors should be repaired. Previous publications of this tool required the user to make several assumptions regarding the factors that influence the payback period, including motor operating load, efficiency and acceptable payback period; however, this tool was recently reinvented as an online calculator where the user inputs his or her particular factors.

Similarly, *MotorMaster+*, created and maintained by the Washington State University Energy Program, uses this simple payback equation, and later versions of this software allow the user to select more advanced economic models, including net present value and depreciation, and to enter their rates (Ref. 9).

A sensitivity analysis of Equation 1 shows that the most influential factors are electric cost and payback period. It is

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Table 1: Comparison of Electric Motor and Luxury Car Lifecycle Costs

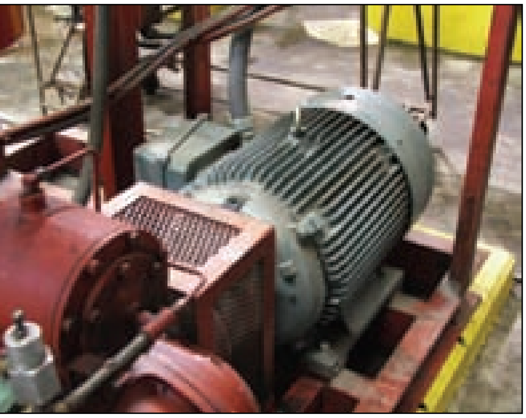
	75-Hp Motor [1]	Ferrari 612 Scaglietti [2]	Lamborghini Gallardo [2]
Initial cost	$ 2,500	$262,600	$195,000
Annual operation	8,000 hours	12,000 miles	12,000 miles
Efficiency	94.1%	17 mpg	17 mpg
Energy consumed	475,664 kWh	706 gal	706 gal
Energy rate	$ 0.060 / kWh	$ 2.659 / gal	$ 2.659 / gal
Annual energy cost	$ 28,540	$1,877	$1,877
Lifecycle cost	**$ 287,999**	**$ 281,369**	**$ 213,769**
Initial as % of life	**1%**	**93%**	**91%**

[1] Electric motor data from MotorMaster+ with no discount applied

[2] Vehicle data from Edmunds.com

interesting to note that these factors are both particular to the facility and not a function of the motor or its application. In fact, factors that are a function of the motor itself, especially the change in efficiency, only have a slight effect on the breakpoint. Motor loading also has a slight effect on the breakpoint, on par with the effects of the change in efficiency. However, efficiency improvement and motor loading are the factors with the highest uncertainty.

The increase in operational efficiency is highly dependent on several factors, including efficiency and operating speed of the old motor; efficiency and operating speed of the new motor; loading condition; and loading type. New induction motor efficiency improvements have been well studied (Refs. 2, 3, 7, 8, 11) and are controlled through standards set forth in the Energy Policy and Conservation Act of 1992 (EPCA). Motors currently operating in industry, herein referred to as "old" motors, also have been surveyed to determine population distributions within particular industries or geographical locations (Ref. 12). Additionally, several authors have considered the economics of motor repair/replace decisions from a theoretical stance (Refs. 4, 5, 6, 13, 15). While these studies concede the importance of motor loading on the effective operational efficiency of the motor, they do not utilize standard testing methods to determine this efficiency but rather assume nameplate values for their comparisons.



MotorMaster+ (MM+), published by the U.S. Department of Energy to aid motor users in selecting the best motor management options, assumes that a motor operates near its nominal efficiency unless loading condition is known. If the motor load is between 25% and 125% of rated load, then the software interpolates an average efficiency based on all motors in its database (*MM+*). Additionally, some studies (Refs. 5, 6) have shown that motor repair can change—either for the better or the worse—the operational motor efficiency. Therefore, old motor efficiency is a large unknown in the payback equation.

Since the efficiency of the motor to be replaced is such a critical component of the economic analysis, it is important to understand if this assumption is valid. Therefore, the purpose of this study is to determine— through laboratory testing of old motors—the appropriateness of assuming that the actual efficiency of an old motor is near its nominal efficiency. For the study, nominal efficiency is defined as the full-load efficiency printed on the nameplate of the motor, or—when no efficiency is printed on the nameplate—the *MM+* default value for the motor at full load. The appropriateness of the nominal efficiency assumption is then scrutinized by (1) comparing nominal efficiency to tested efficiency as if the loading condition is not known and (2) considering the efficiency of the motor at its current loading condition.

The 100-Motor Study

To complete this study, it was important to find old motors in operation at facilities, not just in stock or inventory, and have them tested for efficiency using a commonly accepted standard—in this case, IEEE Standard 112, Method B, the method set forth in EPCA for the certification of motor efficiency. This testing method requires a dynamometer and power monitoring equipment; therefore, motors included in this study were pulled out of service and sent to Advanced Energy to be tested at their NVLAP-accredited motor testing facility. (*Editor's Note: NVLAP stands for National Voluntary Laboratory Accreditation Program. NVLAP is offered by the U.S. National Institute of Standards for certification of a laboratory's documentation, equipment calibration, and other practices. NVLAP motor lab accreditation requires a biannual audit process and annual round-robin testing with other accredited labs.*)

Participating facilities received a new NEMA Premium motor with full manufacturer warranty as a replacement for the displaced old motor.

Several criteria were chosen to control the population of motors being studied to those manufactured before EPCA took effect and to create a sample size large enough for statistical significance within the available project funding. Hence, candidate motors were limited to select horsepower ratings (50-, 75-, 100- and 150-hp) that were manufactured before 1994, foot-mounted and running at least 4,000 hours each year. Motors could not be operated on a variable frequency or other drive device due to efficiency effects, and were accepted whether or not they had been rewound to adequately represent motors found in service today. To verify study criteria, a site visit was conducted before the candidate motor was accepted into the program. During this site visit, the motor was inspected, and voltage, current, input power (kW) and speed (rpm) were measured to determine the operating load of the motor.

Results

Of the 100 motors accepted into this study, four failed on the test stand by internal shorts and two were lost or damaged in shipment. Full statistical analysis of this data has been presented in several published papers, but the most relevant discussion focuses on the economics of the repair vs. replace decision and the impact different efficiency and loading assumptions make on this calculation.

Load Condition

It was quickly noted that many motors were observed with a lower than expected load. In general, systems are designed and motors selected to run near 75% of rated load. Therefore, this value is often assumed for motor load when no readings are available. However, as shown in Figure 1, the average loading condition for motors accepted into this program is calculated at 68.2%, with a considerable number of motors with even lower loads.

Efficiency Assumptions

The difference in efficiencies between the nominal, tested operational, and *MotorMaster+* default efficiencies at operating load results in significant differences in calculated annual energy cost savings. Unfortunately, the data suggests using neither *MotorMaster+* nor nominal efficiency at rated load provide consistent and adequate approximations of the actual annual energy savings experienced by installing a more efficient motor. The savings predicted by *MotorMaster+* and the nominal efficiency are compared to the annual energy cost savings calculated from the tested efficiency of both the old and the NEMA Premium replacement motor at the observed operating load—the verified annual energy cost savings of replacing the motor.

The energy savings estimated by *MotorMaster+* are optimistic because the default efficiency of the motor at operating load averages 0.72 efficiency points below the tested efficiency of the motor at that load point. This results in an optimistic payback period and will favor the installation of a high-efficiency motor. On the other hand, using the nameplate or *MotorMaster+* default efficiency for the motor at rated load—defined in this study as the nominal efficiency—to determine energy savings provides, in general, a conservative estimate of the actual energy savings and may obscure opportunities where a motor meets return criteria for replacement. The annual energy cost savings based on the nameplate value average substantially lower than the actual savings, because the nominal efficiency averages nearly 0.28 efficiency points higher than the tested efficiency at the operating point.

This emphasizes the importance of knowing the actual tested operating efficiency of the motor—not just the nominal value—and adds importance to government regulations, such as the EPCA, which requires the testing of motors to verify nameplate. As EPCA and other high-efficiency motors permeate the market, the deviations seen in this analysis will have less of an implication because higher-efficiency motors, such as NEMA Premium motors, have relatively flat efficiency curves over load. However, when considering replacement of a pre-EPCA motor, this study indicates the importance in verifying the motor efficiency, preferably through testing when available, or at least understanding the inaccuracies in the different assumptions made to determine annual energy cost savings for economic justification calculations.

Conclusions

It is important to accurately identify the efficiency of a motor to make the best economic decisions, particularly with regards to motor repair and replacement decisions. While tools such as *MotorMaster+* are available for determining the actual operational efficiency of the motor, particularly when no nameplate information is available, no previous studies had been conducted to determine if the assumed values based on manufacturer data of available motors accurately reflected the motors found in industry.

Based on this study of 100 motors operating in industry for at least the past 10 years, it is determined that tested values at rated load do not deviate significantly from their nominal efficiency. However, when considering operating conditions and load factors, the operating efficiency averages 0.28 efficiency points below the nominal efficiency, where nominal efficiency is assumed to be the nameplate efficiency when one is listed and the default efficiency value from the *MotorMaster+* database for a standard motor with the same horsepower, speed, frame and enclosure ratings. Moreover, the operating efficiency based on motor test results

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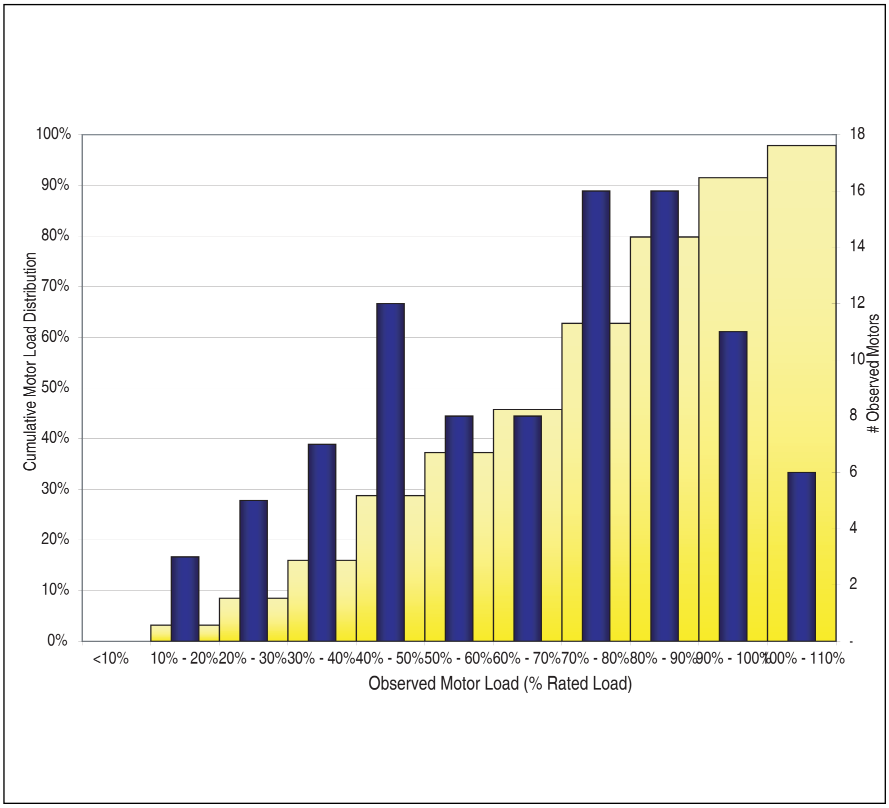

Figure 1—Distribution of Observed Motor Load.

did not compare well to the operating efficiency estimated by *MotorMaster+*, even though the standard deviation was too large to call the difference statistically significant.

By comparison, new NEMA Premium motors showed no significant deviation between their tested value and their nominal nameplate value, nor between their operational efficiency and nominal efficiency. This further emphasizes the significance in the results from the old motor because they cannot be attributed to randomness.

This data leads to several preliminary conclusions as well as several questions. Since the nominal efficiency values are higher than the tested motor efficiency values, the simple payback period calculated by nominal, or nameplate efficiency, is significantly higher than would actually be seen at replacement. The calculated payback is too much higher than that of the tested efficiency to be considered "conservative" and may result in many motors being passed over for replacement that actually meet facility economic return criteria. On the other hand, *MotorMaster+* operational efficiencies of the motors provide an optimistic payback period that may actually indicate more motors qualify for replacement than in actuality, according to a comparison with actual energy cost savings.

Moreover, since the database values used in *MotorMaster+* were derived from manufacturer data, this begs the question of where the deviation originates. The motors included in this study have operated in industry for at least 10 years, experiencing a variety of conditions, including failure. Unfortunately, most facilities did not have records indicating which of the motors in this study were rewound, and so that remains a possible confounding factor that this study cannot eliminate.

The next part of this series will explore the changes being made by Advanced Energy and the Washington State Energy Program on two of the most frequently used motor decision tools—*The Horsepower Bulletin* and *MotorMaster+*—based on the results of this 100-motor study.

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