A 100 Motor Study: Investigating Pre-EPAct Motors as a Subset of the Industrial Motor Population for its Effects on the Economics of Motor Replacement, Preliminary Results

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ABSTRACT

In the absence of hard data, the engineering world tends to be overly conservative in estimating benefits of change. The hypothesis herein discussed is that with hard data, the economics of motor repair/replace decisions could change significantly. If true, this could appreciably boost the efficiency of the industrial motor population by affecting the penetration of high-efficiency motors, such as NEMA Premiums.

The energy savings from motor replacement depend on the difference between the efficiency of the new motor and the old motor. There has been a great deal of work investigating new motor efficiency and very little work investigating the actual running efficiency of older motors in the field. Motors that have operated for years experiencing failures and repairs may operate below their original nameplate or assumed efficiency. This study is a preliminary investigation of the efficiency of motors in industrial settings with the purpose of updating currently available motor analysis software tools to more accurately reflect the economic benefits of utilizing high-efficiency industrial induction motors.

Introduction

Electric motors convert electrical energy into mechanical work at such a magnitude that their energy costs eclipse their initial purchase cost. In fact, 10 years of full-time operation of an energy-efficient 50-Hp motor at the current average motor list price and average energy cost of $0.05/kWh shows initial cost 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 impacts on the life cycle costs of the motor, particularly in terms of payback on the incremental cost of a higher efficiency motor.

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 (Bonnet 1994; Bonnet 2000; Kellum 1998; Malinoski, McCormick & Dunn 2003; Nailen 1993) and are controlled through standards set forth in the Energy Policy Act of 1992. 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 (Pillay & Fendley 1995). Additionally, several authors have considered the economics of motor repair/replace decisions from a theoretical stance (Brethauer, Doughty & Puckett 1993; El-Ibiary 2002; Guenther & Shearer 1992; Pillay 1995; Stroker 2002). 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. Motor decision tools, such as MotorMaster+, published by the US 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 between 25% and 125% of rated load, then the software interpolates an average efficiency based on all motors in its database (MotorMaster+). Additionally, some studies (Colby & Flora 1990; Darby 1996) 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 the appropriateness of assuming that the actual efficiency of an old motor is near its nominal efficiency through laboratory testing of old motors, where nominal efficiency is defined as the full load efficiency printed on the nameplate of the motor or the MotorMaster+ default value for the motor at full load when no efficiency is printed on the nameplate. 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, chosen to be IEEE Standard 112, Method B. 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. Participating facilities received a new, NEMA Premium motor with full manufacturer warranty as a replacement for the displaced old motor.

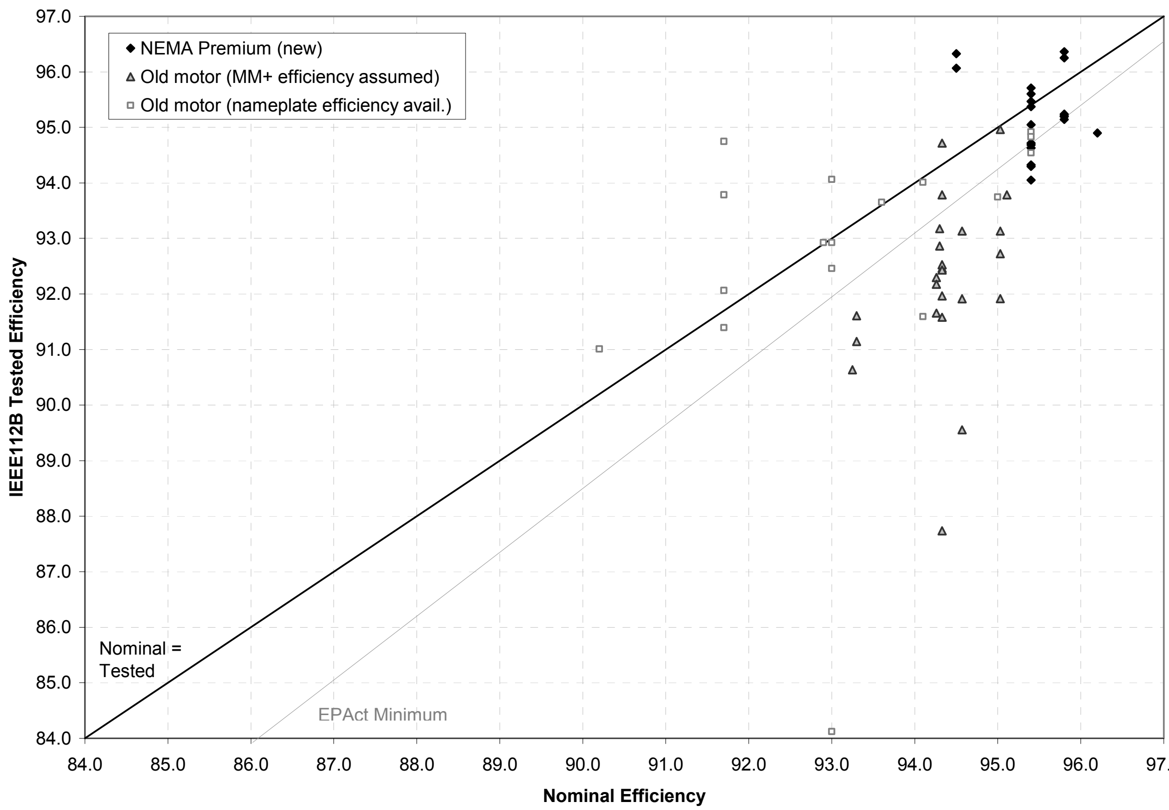
Several criteria were chosen to control the population of motors being studied to those manufactured before the Energy Policy Act took affect and to create a sample size large enough for statistical significance within the available project funding. Hence, candidate motors were limited to select horsepower 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 50 motors accepted into the replacement program to date, 42 have been replaced with a NEMA Premium motor and the old motor returned to the Advanced Energy lab in Raleigh, NC, for testing. One of the motors failed on the test stand by internal shorts; the preliminary testing results for the remaining 41 motors are herein presented.

Because of the nature of this project as an observational study with an unknown population, nonparametric statistical methods were employed to determine the nature of the population and what further analyses were viable. This method makes no underlying assumptions other than that the distribution of results is either continuous or binomial (Hines 2003). Therefore, this method adequately allows the comparison of efficiencies, segregated motor efficiency losses, and other continuous variables within each categorical horsepower rating.

Figure 1: Tested versus Nominal Efficiency at Rated (Full) Load



Non-parametric analysis shows that the deviation between the nominal and the tested efficiency value is not significant for the new motors, but is significant for the old motors. In other words, the deviation cannot be accounted for by random deviations. Further analysis of the old motors shows that deviation between nameplate and tested efficiency is not significant; but, when no nameplate efficiency is available and MotorMaster+ defaults are assumed, the variation is significant. This indicates an inaccuracy in the assumptions used for the MotorMaster+ tables.

Additionally, all of the distributions display a relatively normal distribution, determined by comparison of the mean and median. This allows further discussion and modeling that would not have been possible if the data were not approximately normally distributed.

First, the standard deviation is compared to the mean and a 99% confidence interval constructed for each of the populations and subsets. Because the old motor value was clearly influenced by whether the nominal efficiency came from the nameplate or from MotorMaster+4.0, the old motor subsets are considered individually, but the total old motor sample is not considered as a whole. Only old motors with nominal efficiency determined by MotorMaster+ show significant deviation between their tested and nominal efficiency, on the order of -2.12% efficiency points. A 99% confidence interval in this value shows that the values may range from as low as -2.87% to -1.37% from the nominal value as provided by MotorMaster+. Again, as determined by the non-parametric analysis and verified by the normal distribution significance tests, neither the new motors or the old motors with a nameplate efficiency showed a significant deviation between their tested and their nominal efficiency, although the observed mean deviation was -0.20% and -0.47%, respectively. It would be expected that the new motors, which are regulated by EPAct and NEMA efficiency standards, would not show any significant deviation; however, it is quite interesting that the old motors with nameplate efficiencies do not show any significant deviation as a whole.

To determine if there are any other effects due to other factors, the data is also analyzed in terms of horsepower rating and manufacturer. Non-parametric analysis by horsepower rating is inconclusive. There are significant effects when considering all 75-Hp motors tested, but not when considering the 50-Hp, 100-Hp and 150-Hp motors tested. Also, there is no clear trend in the magnitude of the deviation with horsepower for the new motors, all old motors, old motors with a nameplate nominal efficiency, or old motors using MotorMaster+ default efficiency as nominal.

Since the deviation is approximately normally distributed, looking at the confidence intervals sheds some light on the truly significant deviations and their magnitude. By this analysis, the old 75-Hp motors show a significant deviation in their tested efficiency from their nominal efficiency, on the magnitude of -1.21%. New 75-Hp motors also showed significant deviation on the order of -0.41% in efficiency points.

At this point in the testing, only one manufacturer, D, has shown any significant deviation from nominal over all of the testing. For this manufacturer, it is clearly a factor of if the motor is new or old, and also if the efficiency was printed on the nameplate or assumed by the MotorMaster+ defaults, as shown in the graph below.

Figure 2: Tested versus Nominal Efficiency, Manufacturer D

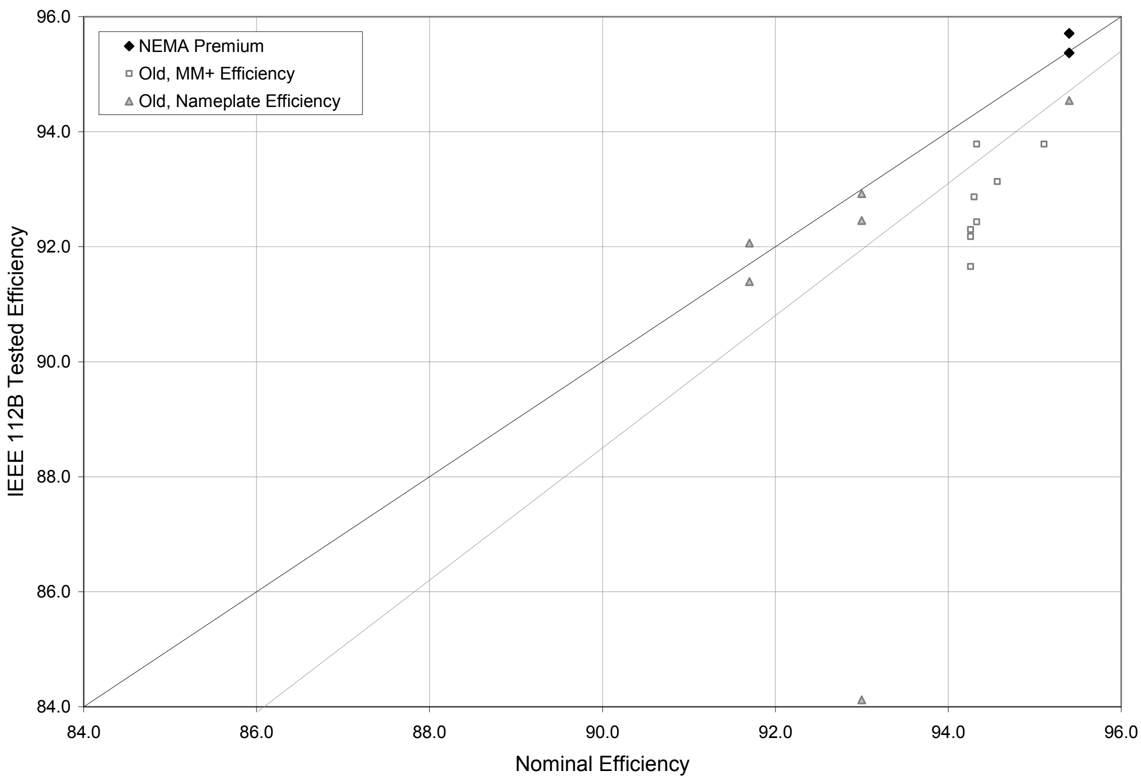


Table 1: Nominal, Tested, and Operational Efficiencies of Old and New Motors

Hp	Observed Operating Load (%FL)	Old Motor				NEMA Premium (New) Motor	
		Full Load Nominal Efficiency	Tested Full Load Efficiency	Tested Operational Efficiency	MotorMaster+ Operational Efficiency	Full Load Nominal Efficiency	Tested Operational Efficiency
50	47.79%	93.25%	90.64%	92.48%	90.30%	94.50%	94.73%
50	95.20%	91.70%	93.78%	93.88%	91.40%	94.50%	94.55%
50	82.36%	93.30%	91.14%	91.47%	91.50%	94.50%	94.82%
50	74.08%	93.30%	91.61%	92.00%	91.60%	94.50%	94.98%
50	77.81%	94.10%	91.59%	92.02%	91.60%	94.50%	94.92%
75	62.15%	94.26%	92.30%	92.84%	91.40%	95.40%	95.32%
75	60.97%	94.26%	91.65%	92.00%	91.40%	95.40%	95.32%
75	62.02%	94.26%	92.18%	92.60%	91.40%	95.40%	95.32%
75	81.89%	91.70%	92.06%	92.63%	91.90%	95.40%	95.28%
75	79.95%	91.70%	91.40%	92.21%	91.90%	95.40%	95.31%
75	56.96%	95.40%	94.54%	94.59%	91.20%	95.40%	95.30%
75	104.71%	94.33%	91.58%	91.31%	91.70%	95.40%	94.86%
75	31.33%	95.00%	93.75%	92.60%	86.60%	95.40%	95.16%
75	90.79%	94.33%	92.46%	92.56%	91.80%	95.40%	95.13%
75	76.35%	93.00%	94.06%	94.69%	92.00%	95.40%	95.37%
75	90.32%	94.33%	92.53%	92.44%	91.80%	95.40%	95.14%
75	95.57%	95.40%	94.92%	95.00%	91.70%	95.40%	95.05%
75	75.16%	95.40%	94.83%	95.30%	92.00%	95.40%	95.39%
75	105.86%	94.33%	93.78%	93.58%	91.70%	95.40%	94.83%
75	100.94%	94.33%	94.72%	94.70%	91.70%	95.40%	94.95%
75	99.93%	94.33%	91.96%	91.98%	91.70%	95.40%	94.98%
75	23.88%	94.33%	92.43%	87.30%	84.50%	95.40%	93.13%
75	41.60%	94.33%	87.74%	78.22%	89.00%	95.40%	94.58%
75	80.74%	91.70%	94.75%	94.56%	91.90%	95.40%	95.30%
100	64.75%	94.30%	92.87%	93.66%	91.80%	95.40%	94.95%
100	65.13%	94.30%	93.18%	93.06%	91.80%	95.40%	94.96%
100	53.37%	94.26%	91.65%	91.89%	91.40%	95.40%	94.81%
100	39.47%	90.20%	91.01%	86.90%	89.10%	95.40%	93.70%
100	82.33%	94.57%	91.91%	92.00%	92.20%	95.40%	94.98%
100	77.48%	94.10%	94.01%	92.02%	92.20%	95.40%	95.05%
100	36.60%	93.00%	92.46%	91.69%	88.60%	95.40%	93.42%
100	43.43%	94.57%	93.13%	92.71%	89.90%	95.40%	94.10%
150	83.57%	95.03%	93.13%	93.48%	92.90%	95.80%	96.18%
150	90.54%	92.90%	92.93%	93.03%	92.90%	95.80%	96.11%
150	95.10%	95.11%	93.78%	93.88%	93.00%	95.80%	96.06%
150	82.11%	95.03%	94.96%	95.09%	92.90%	95.80%	96.20%
150	87.64%	93.60%	93.65%	93.91%	92.90%	95.80%	96.14%
150	93.05%	95.03%	92.72%	92.69%	93.00%	95.80%	96.08%
150	92.85%	95.03%	91.92%	91.95%	93.00%	95.80%	96.08%
150	49.43%	93.00%	84.12%	79.75%	91.40%	95.80%	96.07%
150	72.53%	93.00%	92.93%	93.18%	92.70%	95.80%	96.26%

Overall, this seems to show that the MotorMaster+ defaults assume significantly higher full load efficiencies than are to be expected from the motors under actual testing conditions. However, it is also important to consider the operational efficiency, or efficiency of the motor under its current operating conditions, and how that compares to both the nominal efficiency value at rated load and the MotorMaster+ calculations for operational efficiency.

For this exercise, the data collected on site is used to determine the operational load condition of the motor, using corrected average current and input power compared to nameplate. Then, the tested efficiency curve for the motor is interpolated to produce the motors actual operational efficiency at that load point. For comparison, the new motor efficiency curves are averaged together by horsepower and then the average is interpolated at the load point to determine the operational efficiency of the new/replacement motor. Table 1, on the previous page, shows the results of these calculations.

Overall, the old motors show significant variation of -1.85% efficiency points between their operational efficiency and their nominal, while the new motors did not show any significant variation between their operational efficiency and their nameplate nominal efficiency. Because of the relatively flat efficiency versus load curves for the NEMA Premium, it was expected that any difference between the operational and nominal would be slight and not significant.

The operational efficiency calculated from actual test data is, on average, 1.3% higher than the operational efficiency as calculated by MotorMaster+ for the old motors; this is a statistically significant deviation ranging from 0.6% to 2.0% on a 99% confidence interval. However, looking at the data point by point, the points fit well within this interval but there are definitely outliers—two points show deviations of -10% or more from the tested efficiency.

To understand any confounding factors, the data was also processed in terms of the horsepower and whether the nominal efficiency came from the motor or from MotorMaster+. It was quite evident that 100-Hp motors had significantly lower operational efficiency than their nominal; however, on further investigation it was determined that the motors sampled for this rated load had a significantly lower loading condition at approximately 60% of rated load than the other horsepower ratings, whose loading averaged near 75% of rated load. Because of efficiency is roughly a parabolic function of loading condition, this lower value for the 100-Hp is easily explained by the sample.

Economics of Motor Replacement

The difference in efficiencies between the nominal, tested operational, and MotorMaster+ default efficiencies at operating load result in significant differences in calculated annual energy cost savings. As shown in Table 2, next page, neither using MotorMaster+ or 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.

Table 2: Annual Energy Cost Savings & Deviation of Models

Hp	Annual Run Hours	Annual Energy Cost Savings & Deviation from Actual Savings as a Percentage				
		Actual, Tested at Operating Load	Predicted, Nominal at Full Load		Predicted, MotorMaster+ at Operating Load	
50	6540	$152	$84	[-45%]	$307	[102%]
50	5000	$68	$291	[327%]	$329	[382%]
50	5500	$332	$117	[-65%]	$329	[-1%]
50	7810	$374	$149	[-60%]	$425	[14%]
50	8520	$417	$57	[-86%]	$480	[15%]
75	6540	$325	$146	[-55%]	$520	[60%]
75	6540	$429	$144	[-67%]	$510	[19%]
75	6540	$356	$146	[-59%]	$519	[46%]
75	3250	$227	$320	[41%]	$292	[29%]
75	3250	$260	$312	[20%]	$287	[10%]
75	4200	$54	$0	[-100%]	$321	[497%]
75	8400	$1,024	$297	[-71%]	$909	[-11%]
75	4200	$109	$17	[-85%]	$389	[257%]
75	8400	$634	$258	[-59%]	$827	[30%]
75	8520	$139	$500	[259%]	$710	[410%]
75	6500	$512	$198	[-61%]	$638	[25%]
75	8000	$13	$0	[-100%]	$835	[6,412%]
75	8000	$17	$0	[-100%]	$660	[3,805%]
75	6240	$265	$223	[-16%]	$676	[155%]
75	6240	$52	$213	[313%]	$669	[1,198%]
75	6240	$609	$211	[-65%]	$667	[10%]
75	7920	$386	$64	[-83%]	$589	[53%]
75	7920	$2,071	$111	[-95%]	$620	[-70%]
75	7920	$148	$769	[419%]	$705	[376%]
100	6540	$234	$196	[-16%]	$580	[148%]
100	6540	$347	$197	[-43%]	$585	[68%]
100	8760	$594	$225	[-62%]	$696	[17%]
100	8760	$1,095	$792	[-28%]	$723	[-34%]
100	8520	$906	$245	[-73%]	$843	[-7%]
100	8520	$866	$362	[-58%]	$813	[-6%]
100	6000	$167	$225	[35%]	$484	[189%]
100	6000	$158	$91	[-42%]	$491	[211%]
150	8520	$1,218	$342	[-72%]	$1,487	[22%]
150	8520	$1,511	$1,429	[-5%]	$1,575	[4%]
150	6500	$847	$266	[-69%]	$1,202	[42%]
150	5000	$283	$197	[-30%]	$861	[205%]
150	8400	$1,030	$1,027	[0%]	$1,517	[47%]
150	6240	$1,256	$279	[-78%]	$1,137	[-9%]
150	6240	$1,538	$279	[-82%]	$1,136	[-26%]
150	7920	$4,741	$699	[-85%]	$1,183	[-75%]
150	6000	$849	$777	[-8%]	$987	[16%]

The energy savings calculated by MotorMaster+ are optimistic because, as discussed earlier, the default efficiency of the motor at operating load averages 1.30% below the tested efficiency of the motor at that load point. This results in an optimistic payback period and will significantly 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 are substantially lower than the actual savings because the nominal efficiency averages nearly 1.9% 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 Energy Policy Act of 1992 (EPAct), which requires the testing of motors to verify nameplate. As EPAct and other high efficiency motors permeate the market, the deviations seen in this analysis will have less of an implication because, as discussed earlier, the higher efficiency motors, such as NEMA Premiums, have relatively flat efficiency curves over load. However, when considering replacement of a pre-EPAct 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 testing results of 41 motors operating in industry for at least the past ten years, it is determined that tested values at rated load deviate significantly from their nominal efficiency, on the order of -2%, particularly when nominal is derived from the MotorMaster+ database, and when considering operating conditions and load factors, the operating efficiency averages -1.85% from the nominal efficiency. 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. However, the operating efficiency based on motor test results compared well to the operating efficiency calculated by MotorMaster+. By comparison, new NEMA Premium motors showed no significant deviation between their tested value and their nominal nameplate value, as well as 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.

While these results are still preliminary, the data leads to several preliminary conclusions as well as several questions. Since the nominal values listed in the default table are significantly higher than the tested motor efficiency, the simple payback period calculated by nominal, or nameplate efficiencies, 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 use 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 8 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. Therefore, should the remaining 58 motors continue the trends found in these preliminary results, it will provide the impetus to conduct a double-blind study on motor repair practices and finally resolve the question of the effect rewinding a motor has on the efficiency of the motor.

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