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Efficiency estimation and payback periods

The impact for industrial electric motor users

Summary

This white paper discusses why efficiency estimation is important; the parameters that can affect efficiency readings and how these measurements once obtained can be used to the advantage of a motor management specialist.

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1. About the authors

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Baker Instrument Company is an SKF Group company.

2. Abstract

The ability to understand and calculate the efficiency of an electrical motor is vital in respect to energy conservation, cost savings, and reduced emissions. Industrial customers require this information for applications such as power conversion, conveyer belt motors and water pumps to name a few. Having a method in which to obtain this efficiency calculation, as well as to identify key concerns for improving efficiency in the field is essential to running a successful, safe and efficient operation. On December 19th, 2007, President George W. Bush signed into law the Energy Independence & Securities Act of 2007. This law, which goes into affect on December 19th, 2010, states the mandatory minimum efficiency level for motors is designated by the NEMA Premium Efficiency® Program. Included in this program are all motors previously covered under the Energy Policy Act of 1992 plus the following list: motor ratings 1-200Hp (including u-frame), Design C, close looped pump , footless, vertical shaft-normal thrust, 8-pole and polyphase motors. Also required by this law are those motors ranging from 200-500Hp in the Design B Class. These motors must meet the requirements as stated in NEMA MG-1 Table 12-11.

This white paper discusses why efficiency estimation is important; the parameters that can affect efficiency readings and how these measurements once obtained can be used to the advantage of a motor management specialist.

3. Introduction

So what is Efficiency? Merriam and Webster Dictionary define Efficiency as a noun created in 1633. 1: the quality or degree of being efficient or 2: a: efficient operation b (1): effective operation as measured by a comparison of production with cost (as in energy, time, and money) (2): the ratio of the useful energy delivered by a dynamic system to the energy supplied to it. WIKIPEDIA.com describes it as follows. The efficiency of an entity (a device, component, or system) in electronics and electrical engineering is defined as useful power output divided by the total electrical power consumed (a fractional expression).

$$\text{Efficiency} = \frac{\text{Useful power output}}{\text{Total power input}}$$

The real question is why is this important? In today's market, prices are going up while the value of the dollar has declined. Global warming is causing a concern for the health of our environment, bringing high taxes and fines for companies that don't maintain clean and efficient work places. Also with high numbers of corporate mergers, losses of highly trained personnel and sufficient time for effective monitoring and diagnoses of plant parameters have diminished. These issues are further impeded with the fact that nearly 60% of all electrical power used in the industrial sector, is consumed by electric motors. Throw in higher maintenance costs, production costs, and personnel costs and year end profits suffer. As a motor maintenance professional your job is to ensure that the plant stays running safely and smoothly. However, industry wide, responsibilities have been added, causing increased stress and require greater skill sets. Saving company money by the use of the most efficient motors and taking advantage of rebates provided by the federal government and local power companies has been included in the job description of most maintenance professionals.

4. The "ins and outs" of efficiency

As described, efficiency is the ratio of a motor's mechanical output to its electrical input. However, what affects this ratio, and why are each of these factors important to motor maintenance professionals?

4.1. Electrical input

The power condition of a motor, i.e. the quality of power delivered to a motor is comprised of the voltage level, unbalance, and distortion. The voltage at 100% rated load is typically found labeled on the nameplate of the motor. In an ideal condition voltage would be 100% with 0% unbalance and distortion. However, motors operate in the real world and often can be found running with anywhere from 5-10% over or under voltage. Under voltage is described as the condition when the average terminal voltage is below full load nameplate voltage. Over voltage is the exact opposite, described as the average terminal voltage above the nameplate voltage. Note here that it was stated "terminal voltage" not voltage displayed at the panel meters of the motor control cabinet (MCC). If the leads from the MCC are long, then there typically is an appreciable voltage drop across them; causing the operating voltage of the motor to be lower than the voltage measured at the MCC's. This is the key to understanding why voltage plays into efficiency.
Power as they say is as easy as Pie, where P(power)=I(current)*E(voltage). If the voltage is lower than expected, current will increase to balance the equation, resulting in additional heat stresses felt on a motor. This additional heat causes the winding insulation deteriorate more rapidly, thereby reducing the life of a motor. NEMA and EASA suggest a general rule of thumb, that for every 10°C of additional heat to the windings, the motor's insulation life is reduced by half.

Operating with *over voltages* is a common cause for excessive harmonic current generation. This is the reason for a drop of the operating power factor, which may be a cause for power factor penalties. If the voltage level is sufficiently high, the motor will drop the operating efficiency, causing the heat in the motor to increase. An increased level of stator current can produce severe overheating in a motor, resulting in increased copper loss (I2R). Bad over voltage conditions are far less hazardous to the motor than under voltage conditions. According to NEMA MG1, Part 12, Page 20: “AC induction motors shall operate successfully up to plus / minus 10% of rated voltage, with rated current.”

Other factors that affect the level of voltage are speed and torque, during transients. The lower the voltage level the higher the expected slip will be for a given load. With torque, the lower the voltage, the lower the torque will be. In some instances, i.e. rotor bar issues, reversible motors, and VFD driven motors, the torque may not be sufficient enough to allow for the motor to stay in motion. The majority of panel meters have the average buss voltage across all 3 phases. Each individual phase voltage is generally not displayed.

4.2. Voltage balance

According to NEMA MG-1, Voltage Balance is defined as the maximal deviation from the average line voltage, divided by the average line voltage. The higher this voltage unbalance percentage the higher your current unbalance will be in response, once again leading to additional induced heat. NEMA MG-1 also states: “The currents at normal operating speed with unbalanced voltages will be greatly unbalanced in the order of approximately 6 to 10 times the voltage unbalance.” According to the EPRI study “Voltage Power Quality Issues, Related Standards & Mitigation Techniques: Effect of Unbalanced Voltage on End Use Equipment Performance”, 34% of US distribution systems operate with a voltage unbalance exceeding 1%. This point is in reference to distribution systems only, which means at the point of common coupling entering the industrial facility. Hence, the chances are that clearly more than 34% of motor voltage busses are exceeding the 1% allowed by NEMA’s MG-1.
Other effects caused by Voltage Unbalance include increased torque ripple, decreased locked-rotor and startup torques, increased level of vibrations, slightly reduced speeds and increased temperatures.

In vibration, the negative sequence voltage introduced by voltage unbalance elevates the vibration level at multiples of two times the electrical fundamental frequency. A good goal in industrial environments is to attempt to keep voltage unbalance below the 1% level for all motors. Experience at Baker Instrument Company, an SKF Group Company shows that voltage unbalance and poor motorload matches are among the most common electrical problems found in the field.

Also, take into consideration the stresses induced from VFD’s and other components that generate internal harmonics on a motor. If only voltage, current and load levels are monitored, the maintenance professional may be led to believe that the motor is running in good standing (green) with no abnormal heat stress. However, when voltage unbalance and distortion percentages are taken into account, there may be unnecessary heat induced into that motor.

4.3. Voltage distortion

Voltage distortion is the amount of voltage at fundamental frequency, compared to the total voltage at all other frequencies. Any distortion in the voltage signal creates currents in the motor that do not significantly contribute to the generation of torque. On the contrary a large portion of these additional currents within the motor slow the rotor down and act as an electrical break to the system. These currents are responsible for additional heating. The amount of voltage distortion sent to the motor by the power source is smaller than the amount of current distortion that it causes. This means that a relatively small amount of voltage distortion creates a larger amount of current distortion and heat. Other parameters affected by voltage distortion are speed, torque, and vibration. The speed tends to decrease with a higher voltage distortion. The torque band increases slightly for higher levels of distortion. With vibration, voltage distortion increases the noise levels, in particular multiples of the 60 Hz fundamental and can often be heard audibly. Power factor is also affected due to the fact that pf is composed of both displacement and distortion power factors. The distortion pf decreases with higher %THDv, which decreases the overall power factor. Total Harmonic Distortion (THDv%) is defined by the following equation:

$$\%THDv = 100 \cdot \frac{V_{dist}}{V_{fund}}$$

Where:

V*dist*. is the voltage distortion (all components other than the fundamental)
V*fund*. is the fundamental voltage (50Hz or 60Hz for line operated motors)

The %THDv is a very common value in field instrumentation. NEMA MG-1 specifies the use of HVF (Harmonic Voltage Factor) and percent voltage unbalance for calculating the derating factor. This is calculated with a different equation beyond the scope of this paper; however, Figure 1 the curves that are used in this calculation are shown.

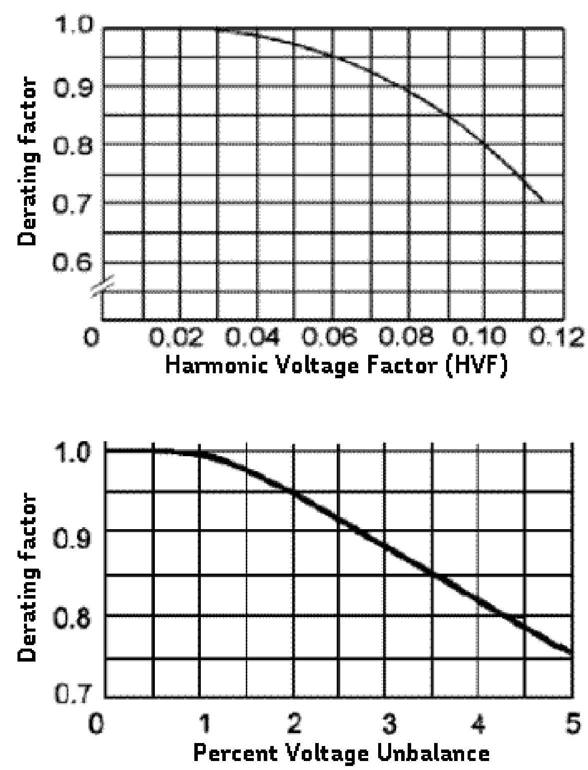

Figure 1. Harmonic voltage factor curves

Percentage NEMA derating is the total derating caused by poor power condition. A few quick tips for troubleshooting and spotting power condition problems are that they typically are generated from the upstream power distribution system (i.e. voltage source). A problem felt on one motor will be seen on all motors related to that particular buss. These stresses are particularly detrimental to motors operating at higher loads or with more frequent cycle times.

Looking at the overall motor performance the user must consider all the issues directly related to the probable overheating of a motor. A motors performance in this instance can be defined by the current level and effective service factor. Common reasons for over heating of a motor can be found at the motor control cabinet (MCC) by looking at the current level, the quality of the voltage and the operating load level. Poor motor performance conveys reasons for excessive stress in the motor. Excessive heat generated by this performance will destroy the insulation system, causing premature electric motor failure. Motor performance issues can either be avoided by properly diagnosing and correcting the root cause of the stress, or they can be mitigated so that future motor operation does not need to change to avoid shortening the motor's life. Motor performance problems frequently are a combination of up-stream and down-stream issues. Motor performance problems rarely affect the whole voltage buss. When solving performance problems, it is important to understand where the root cause of the problem is located. Figure 2 displays a representation of how various factors affect a motor. This diagram is handy for troubleshooting mechanical and electrical issues.

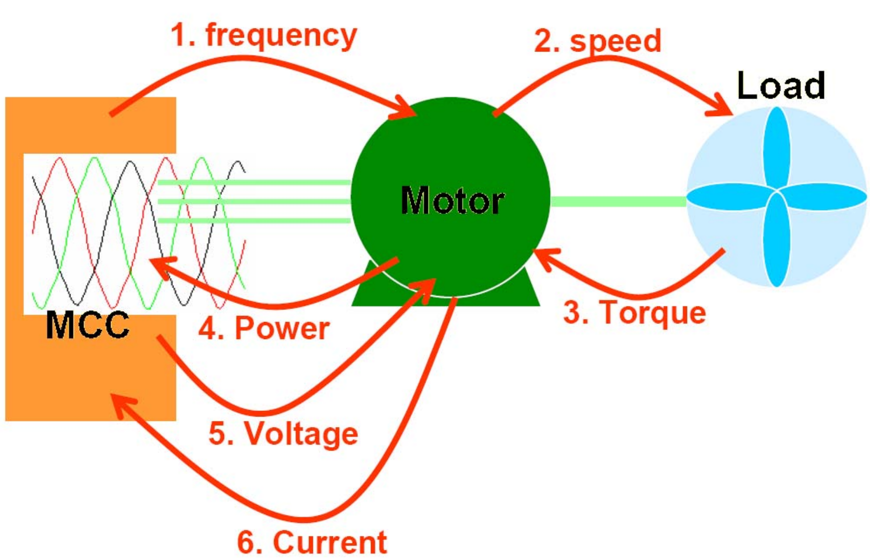

Figure 2. How various factors affect a motor

If the condition is created mainly due to over load, then the operation of the motor has to be changed. If the condition is caused by a poor power condition, then the power quality of the supply has to be enhanced. Mitigation of motor performance problems is possible, by managing the thermal issues. Additional chilling, or force cooling of a motor are measures that can bring the operating temperature back into the design limits, without requiring a change to the load or power conditions. These types of measures will raise the life expectancy of the motor back into acceptable levels.

4.4. Current level

Current Level is defined as the highest line current delivered to the motor, and is a common focal point when discussing added heat concerns. Motors are designed to operate long term at maximum nameplate current. Current level is one of the characteristic responses of the motor to a given combination of the overall power condition and load. Sometimes it is found that current level is defined as the average current level for all phases. For predictive maintenance reasons; however, the highest line current developed is of a much larger importance, since heat is one of the main degradation mechanisms for insulation. The heat in each winding depends to the amount of the current through that particular winding. Hence, the weakest point to the motor's insulation with respect to current level has to be identified as the phase with the largest current. Current level is influenced by the level of load, voltage level, voltage unbalance, and the voltage distortion. During line startup, the motor is exposed to typically 6 to 10 times the rated current. This process is cause for severe heating, and should be avoided unless necessary. Soft starts, Delta-Wye starters or wound motors are common additions to an electrical system that aide in diminishing the deteriorating influence of frequent startups. With respect to severe over currents, NEMA MG1 states:
"Induction motors while running and at rated temperature shall be capable of withstanding a current equal to 150% of the rated current for 30 seconds".

With respect to some special type of DC generators, NEMA MG1 also specifies:

"These generators shall be capable of carrying, (...)
a) 115% of rated current continuously (...)
b) 125% of rated current for 2 hours (...)
c) 200% or rated amperes for 1 minute (...)"

Similar specifications can be frequently obtained regarding allowable overload and over current conditions for induction motors. This type of information can be obtained from motor manufacturers.

5. Effective service factor

When all of the aforementioned issues discussed previously are combined, they affect the calculation called effective service factor. Effective service factor, a Baker Instrument Company derived equation, is defined as %Load divided by %NEMA derating. Motors are designed to operate with a maximal thermal stress. Operating at temperatures higher than that quickly reduces the life of the motor. Insulation failure is imminent if the motor is operated under temperatures that are too high. Factors that can increase the temperature in a motor are high ambient temperatures, operating at higher elevations, restricted airflow, high load requests, poor supplied power quality, broken rotor bars, poor terminal contacts, etc. The most frequently encountered scenario for thermal overloading are due to either load, or a combination of load with a poor power condition.

6. Load

Load is defined as the domain that uses the motor as a sensor to look at the driven load. The question to be asked is whether the motor load is sufficiently low so that the poor power condition does not affect the motors healthy. Load level problems are always caused by the load. The motor reacts, and tries to deliver the torque that the load requires.

From a predictive maintenance standpoint, the really important issue is up time, which is not limited to just motor health. Load condition monitoring is a new aspect that online monitoring offers. Load level and load signature are the tools of choice to further understand the motor load system. This tool is offered by Baker Instrument Company, an SKF Group Company's torque monitoring software (T3000). In these cases, refer to the NEMA derating curves. The graphs in Figure 3 both display how much a motor has to be derated if the voltage condition is of a certain quality.

Just like with motor conditions effective service factor problems are frequently a combination of up-stream and down-stream issues. These problems rarely affect the whole voltage bus. When solving effective service factor problems it is important to understand where the root cause of problem is located. Mitigation of effective service factor problems is also possible, by managing the thermal issues identified. Once again, if the condition is created mainly due to over load, then the operation of the motor has to be changed. If the condition is caused by a poor power condition, then the power quality of the supply has to be enhanced.

7. Energy assessment

Energy assessment is a review of all issues relevant to energy and efficiency. With rising energy costs, increasing operating efficiency is becoming of more importance. In order to perform good energy assessment, one must be able to answer the following questions. Are my motors running efficiently? Is it worth it for me to exchange this motor for a higher efficiency one? Should I wait until the next necessary repair of this efficient motor before I exchange it? Where has this motor been before? Has it been repaired? How efficient would a motor of X design run at Y% Load?

Efficiency identifies whether a NEMA class motor operates at similar efficiencies as a comparable, healthy motor could under normal conditions. With Baker Instrument Company's Explorer Series tester, EfficiencyD:\Program Files\Baker

Instrument\MotAna\help\Energy Assessment\Efficiency.htm compares the motor under test to a database containing NEMA designed motors that look for matches in rating, number of poles and voltage level. It interpolates available motor data to the load level measured in the field, and compares the operating efficiency to the one that the database identifies. Operating Efficiency of a motor can not be easily measured in a field application. Relevant standards of IEEE, IEC, JEL and similar organizations have a number of requirements which commonly can only be fulfilled in a laboratory environment. These standards also usually concentrate on ensuring a proper description of a motor's capabilities under good operating voltage conditions. In the field, however, there is little room for requirements like uncoupling a motor or regulating the voltage level for a saturation run. Questions regarding a particular motor's capabilities are found to be secondary in importance when compared to the operating efficiency under given conditions in the field. The result of such an environment is that true efficiencies, as defined by IEEE, IEC, or JEL are unrealistic to obtain.

Operating efficiencies, however, are of crucial importance to energy conscious management. Requirements for true measurements of operating efficiencies in field environments are ample and unrealistic. They can include installing torque transducers on the shaft of the motor, and measuring the input power to the motor at the motor terminals frequently at high voltage levels. Instead of a true efficiency measurement, efficiency estimation becomes the only field friendly approach for energy management. The difference between operating efficiency measurement and operating efficiency estimation is that the former attempts to find the true operating efficiency via direct measurement, while the latter accepts a small measure of inaccuracy for severely increased user friendliness. It is important to note that different motor designs operate with different efficiencies.

8. Efficiency details

Advances in motor design, motor manufacture and legislation requirements are the most important reasons for higher efficiencies in newer motors. Load levels below 50% will typically show lower efficiencies. Current level increases with lower voltage levels, which tends to decrease the efficiency. Commonly a motor running at rated voltage, or only slight over voltages, will show the highest efficiency. Voltage unbalance increases the average current only mildly, but the losses in one or more of the phases are substantial. This causes the efficiency to drop drastically. Current level increases strongly with mild increases in voltage distortion, equating higher currents to lower efficiencies. Broken rotor bars or endrings cause the motor to need more slip for delivery of the required torque. This has the effect of additional current in the stator, which also decreases the operating efficiency. Motors operating at low efficiencies are burning up larger amounts of heat in losses. This does not automatically mean that these motors will run hotter. Older motor designs, for example, include larger fans for additional heat reduction. Unfortunately this causes additional losses from friction and windage created by these larger fans. Newer motor designs frequently allow the motor to operate under higher temperatures, since the quality of the insulation material has improved with respect to older motors. This allowed the motor designers to additionally increase the efficiency of the motors by decreasing the amount of cooling and windage loss with a smaller fan. For any motor; however, any reason causing it to operate at lower efficiencies is reason for expecting higher operating temperatures, and lower life due to insulation deterioration.

9. What does this mean to motor health, life, and cost to companies?

As stated previously there are many factors that can affect the health and longevity of a motor. The list of problems that has been discussed in the white paper is just a portion of what can occur. A overwhelming number of issues can cause the efficiency of motors to drop and the cost of power consumption to increase. So how is the cost of replacing inefficient motor or repairing process to increase efficiency calculated in terms of payback.

9.1. Payback Period Calculation

Payback Period is a simple payback calculation identifying motors that could be exchanged for more efficient motors at a monetary gain. Payback Period takes the values obtained as a target efficiency and subtracts the values of the operating efficiency. The difference can be considered as wasted energy points. With the knowledge of how many hours per day and days per week the motor is run, the $ per kWh, and shelf price for the replacement motor, it is then possible to identify a straight payback period. Plant managers require a good working knowledge of operating efficiencies. The root causes of low efficiencies (i.e. poor motors, power condition, or load mismatches) must be known and scrutinized. It is not worth the time or effort to solve a case with very low efficiency, if the motor is operating safely but only for few hours per day. The payback period of such an application would be exceedingly high. Payback period identifies whether the motor load application under test is worth investigation. It compares the list price of the motor with the potentially energy cost savings for motors under normal under normal operation and target efficiencies.

Low loads are sources of poor power factor, and low efficiencies. Unless there are clear reasons for doing otherwise, loading of 75% to 100% is viewed as optimal for efficiency. Below is a chart that was made possible by research and help from SIMMCO, Larry Zaring and John Holmes of Integrated Power Services, Mike Renfro of US Motors, Robert B. Boetler and Adan Reinosa at the Los Angeles Department of Water and Power Energy & Efficiency group.

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10. Efficiency Estimation and Payback Period

10.1. Equations

- Motor Run Cost per year($/yr) = hp * L * 0.746 * hr * C * (100/Estd)
- Annual Savings = hp * L * 0.746 * hr * C (100/Estd - 100/Eee)
- Annual kWh used = hp * L * 0.746 * hr * (100/Estd)
- Simple Payback (yrs) = (Price Premium + Installation Cost - Utility Rebate) / Annual Savings
- hp = Horsepower rating of Motor
- L = percentage of Full load / 100
- 0.746 = conversion from hp to kW
- hr = hours of run time, for this case study we will use 3000 hrs to simulate a motor that is run for ~ 5 days a week for 10 hours a day and 8000 hrs to simulate a motor run 24/7
- C = $/kWh, for this study we used $0.10/kWh
- Estd = the efficiency of the motor currently installed
- Eee = the efficiency of a higher quality premium efficiency motor

10.2. Assumptions

Installation cost = $88.00/hour/person or $1350/day for 12 hours. John Holmes of SIMMCO said typically he sees ~$1800/install			$ 1,800.00
US Motors 200hp General Purpose ODP Premium Efficient D200P2C (96.2%)			$ 1 0,044.00
US Mtrs 500hp Titan General Purpose TEFC Premium Efficiency C500P2W (95.4%)			$ 59,106.00
DOE Rebate	$ 3,000.00	DOE Rebate	$ 7,500.00
Utility Rebate for 200hp	$ 5,922.00	Utility Rebate 500hp	$30,453.00

Since the utility rebate (LADWP's current proposal) is 50% of the project cost then the top portion of the simple payback equation will always be the same as the rebate.

Based on the average US fuel Mix the amount of CO_2 emitted (in Lbs) per 1 kWh gnerated =	1.5
Based on the average US fuel Mix the amount of NO_x emitted (in Lbs) per 1 kWh gnerated =	0.004
Based on the average US fuel Mix the amount of SO_2 emitted (in Lbs) per 1 kWh gnerated =	0.008

200 / 500 HP Mtr	75% of full load	$0.10 / kWh	80%, 85%, 90% and 95% efficiencies are actual running mtr efficiency	3000 / 8000 runtime hours

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10.3. Calculations

Legend	
Type of motor	
Typical motor efficiency used	
High efficiency motor	

Table 1. Motor cost to run per year

	200hp @ 3khrs	200hp @ 8khrs	500hp @ 3khrs	500hp @ 8khrs
80.0%	$ 41,962.50	$ 111,900.00	$ 104,906.25	$ 279,750.00
85.0%	$ 39,494.12	$ 105,317.65	$ 98,735.29	$ 263,294.12
90.0%	$ 37,300.00	$ 99,466.67	$ 93,250.00	$ 248,666.67
94.5%	$ 35,523.81	$ 94,730.16	$ 88,809.52	$ 236,825.40
95.0%	$ 35,336.84	$ 94,231.58	$ 88,342.11	$ 235,578.95
95.4%	$ 35,188.68	$ 93,836.48	$ 87,971.70	$ 234,591.19
96.2%	$ 34,896.05	$ 93,056.13	$ 87,240.12	$ 232,640.33

Table 2. Annual savings

	200hp @ 3 khrs	200hp @ 8khrs	500hp @ 3khrs	500hp @ 8khrs
80-94.5%	$ 6,438.69	$ 17,169.84	$ 16,096.73	$ 42,924.60
80-95.4%	$ 6,773.82	$ 18,063.52	$ 16,934.55	$ 45,158.81
80-96.2%	$ 7,066.45	$ 18,843.87	$ 17,666.13	$ 47,109.67
85-94.5%	$ 3,970.31	$ 10,587.49	$ 9,925.77	$ 26,468.72
85-95.4%	$ 4,305.44	$ 11,481.17	$ 10,763.60	$ 28,702.92
85-96.2%	$ 4,598.07	$ 12,261.51	$ 11,495.17	$ 30,653.79
90-94.5%	$ 1,776.19	$ 4,736.51	$ 4,440.48	$ 11,841.27
90-95.4%	$ 2,111.32	$ 5,630.19	$ 5,278.30	$ 14,075.47
90 - 96.2%	$ 2,403.95	$ 6,410.53	$ 6,009.88	$ 16,026.33
95-95.4%	$ 148.16	$ 395.10	$ 370.41	$ 987.75
95 - 96.2%	$ 440.79	$ 1,175.45	$ 1,101.98	$ 2,938.61

Table 3. Annual kWh used

80.0%	419,625.00	1,119,000.00	1,049,062.50	2,797,500.00
85.0%	394,941.18	1,053,176.47	987,352.94	2,632,941.18
90.0%	373,000.00	994,666.67	932,500.00	2,486,666.67
94.5%	355,238.10	947,301.59	888,095.24	2,368,253.97
95.0%	353,368.42	942,315.79	883,421.05	2,355,789.47
95.4%	351,886.79	938,364.78	879,716.98	2,345,911.95
96.2%	348,960.50	930,561.33	872,401.25	2,326,403.33

Table 4. CO2 emmission generated (in lbs)*

	200hp @ 3 khrs	200hp @ 8khrs	500hp @ 3khrs	500hp @ 8khrs
80.0%	629,437.50	1,678,500.00	1,573,593.75	4,196,250.00
85.0%	592,411.76	1,579,764.71	1,481,029.41	3,949,411.76
90.0%	559,500.00	1,492,000.00	1,398,750.00	3,730,000.00
94.5%	532,857.14	1,420,952.38	1,332,142.86	3,552,380.95
95.0%	530,052.63	1,413,473.68	1,325,131.58	3,533,684.21
95.4%	527,830.19	1,407,547.17	1,319,575.47	3,518,867.92
96.2%	523,440.75	1,395,842.00	1,308,601.87	3,489,604.99

* Based on the US average fuel mix, ~1.5lbs of CO2 is emitted per kWh generated.
(Side note- 1 acre of forest will consume 30 tones of CO2 per year)

Table 5. Nox Emission Generated (in lbs)**

80.00%	1,678.50	4,476.00	4,196.25	11,190.00
85.00%	1,579.76	4,212.71	3,949.41	10,531.76
90.00%	1,492.00	3,978.67	3,730.00	9,946.67
94.50%	1,420.95	3,789.21	3,552.38	9,473.02
95.00%	1,413.47	3,769.26	3,533.68	9,423.16
95.40%	1,407.55	3,753.46	3,518.87	9,383.65
96.20%	1,395.84	3,722.25	3,489.60	9,305.61

** Based on the US average fuel mix, ~0.004Lbs of Nox is emitted per kWh generated.

Table 6. SO2 Emission Generated (in lbs)***

80.0%	3,357.00	8,952.00	8,392.50	22,380.00
85.0%	3,159.53	8,425.41	7,898.82	21,063.53
90.0%	2,984.00	7,957.33	7,460.00	19,893.33
94.5%	2,841.90	7,578.41	7,104.76	18,946.03
95.0%	2,826.95	7,538.53	7,067.37	18,846.32
95.4%	2,815.09	7,506.92	7,037.74	18,767.30
96.2%	2,791.68	7,444.49	6,979.21	18,611.23

***Based on the US average fuel mix, ~0.004Lbs of SO2 is emitted per kWh generated.

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Table 7. Annual kWh saved

	200hp @ 3 khrs	200hp @ 8khrs	500hp @ 3khrs	500hp @ 8khrs
80-94.5%	64,386.90	171,698.41	160,967.26	429,246.03
80-95.4%	67,738.21	180,635.22	169,345.52	451,588.05
80-96.2%	70,664.50	188,438.67	176,661.25	471,096.67
85-94.5%	39,703.08	105,874.88	99,257.70	264,687.21
85-95.4%	43,054.38	114,811.69	107,635.96	287,029.23
85-96.2%	45,980.68	122,615.14	114,951.69	306,537.85
90-94.5%	17,761.90	47,365.08	44,404.76	118,412.70
90-95.4%	21,113.21	56,301.89	52,783.02	140,754.72
90 - 96.2%	24,039.50	64,105.34	60,098.75	160,263.34
95-95.4%	1,481.63	3,951.01	3,704.07	9,877.52
95 - 96.2%	4,407.92	11,754.46	11,019.81	29,386.15

Table 8. Time to payback with government proposed $15 hp rebate (in years)

80-94.5%	1.37	0.52	3.32	1.24
80-95.4%	1.31	0.49	3.15	1.18
80-96.2%	1.25	0.47	3.02	1.13
85-94.5%	2.23	0.84	5.38	2.02
85-95.4%	2.05	0.77	4.96	1.86
85-96.2%	1.92	0.72	4.65	1.74
90-94.5%	4.98	1.87	12.03	4.51
90-95.4%	4.19	1.57	10.12	3.79
90 - 96.2%	3.68	1.38	8.89	3.33
95-95.4%	59.69	22.38	144.18	54.07
95 - 96.2%	20.06	7.52	48.46	18.17

Table 9. Time to payback with Utility Rebate Only (in years)

	200hp @ 3 khrs	200hp @ 8khrs	500hp @ 3khrs	500hp @ 8khrs
80-94.5%	0.92	0.34	1.89	0.71
80-95.4%	0.87	0.33	1.80	0.67
80-96.2%	0.84	0.31	1.72	0.65
85-94.5%	1.49	0.56	3.07	1.15
85-95.4%	1.38	0.52	2.83	1.06
85-96.2%	1.29	0.48	2.65	0.99
90-94.5%	3.33	1.25	6.86	2.57
90-95.4%	2.80	1.05	5.77	2.16
90 - 96.2%	2.46	0.92	5.07	1.90
95-95.4%	39.97	14.99	82.21	30.83
95 - 96.2%	13.43	5.04	27.63	10.36

Table 10. Total time to payback both rebates combined (in years)

80-94.5%	0.45	0.17	1.43	0.53
80-95.4%	0.43	0.16	1.36	0.51
80-96.2%	0.41	0.16	1.30	0.49
85-94.5%	0.74	0.28	2.31	0.87
85-95.4%	0.68	0.25	2.13	0.80
85-96.2%	0.64	0.24	2.00	0.75
90-94.5%	1.65	0.62	5.17	1.94
90-95.4%	1.38	0.52	4.35	1.63
90 - 96.2%	1.22	0.46	3.82	1.43
95-95.4%	19.72	7.40	61.97	23.24
95 - 96.2%	6.63	2.49	20.83	7.81

Table 11. CO2 emissions reduction (in lbs) - due to replacement of inefficient motor

	200hp @ 3 khrs	200hp @ 8khrs	500hp @ 3khrs	500hp @ 8khrs
80-94.5%	96,580.36	257,547.62	241,450.89	643,869.05
80-95.4%	101,607.31	270,952.83	254,018.28	677,382.08
80-96.2%	105,996.75	282,658.00	264,991.88	706,645.01
85-94.5%	59,554.62	158,812.32	148,886.55	397,030.81
85-95.4%	64,581.58	172,217.54	161,453.94	430,543.84
85-96.2%	68,971.02	183,922.71	172,427.54	459,806.78
90-94.5%	26,642.86	71,047.62	66,607.14	177,619.05
90-95.4%	31,669.81	84,452.83	79,174.53	211,132.08
90 - 96.2%	36,059.25	96,158.00	90,148.13	240,395.01
95-95.4%	2,222.44	5,926.51	5,556.11	14,816.29
95 - 96.2%	6,611.88	17,631.69	16,529.71	44,079.22

Table 12. NOx emissions reduction (in lbs) - due to replacement of inefficient motor

80-94.5%	257.55	686.79	643.87	1,716.98
80-95.4%	270.95	722.54	677.38	1,806.35
80-96.2%	282.66	753.75	706.65	1,884.39
85-94.5%	158.81	423.50	397.03	1,058.75
85-95.4%	172.22	459.25	430.54	1,148.12
85-96.2%	183.92	490.46	459.81	1,226.15
90-94.5%	71.05	189.46	177.62	473.65
90-95.4%	84.45	225.21	211.13	563.02
90 - 96.2%	96.16	256.42	240.40	641.05
95-95.4%	5.93	15.80	14.82	39.51
95 - 96.2%	17.63	47.02	44.08	117.54

Table 13. SO2 emissions reduction (in lbs) - due to replacement of inefficient motor

	200hp @ 3 khrs	200hp @ 8khrs	500hp @ 3khrs	500hp @ 8krs
80-94.5%	515.10	1,373.59	1,287.74	3,433.97
80-95.4%	541.91	1,445.08	1,354.76	3,612.70
80-96.2%	565.32	1,507.51	1,413.29	3,768.77
85-94.5%	317.62	847.00	794.06	2,117.50
85-95.4%	344.44	918.49	861.09	2,296.23
85-96.2%	367.85	980.92	919.61	2,452.30
90-94.5%	142.10	378.92	355.24	947.30
90-95.4%	168.91	450.42	422.26	1,126.04
90-96.2%	192.32	512.84	480.79	1,282.11
95-95.4%	11.85	31.61	29.63	79.02
95-96.2%	35.26	94.04	88.16	235.09

Table 14. Possible Scenario based on say the City of Los Angles: this is a complete assumption just to show enormity of this issue.

200hp X 10000 units	Energy Savings kWh	Energy Cost Savings	less CO2 emitted (in Tons)	less NOx emited (in Tons)	less SO2 emitted (in Tons)
80-94.5%	1,716,984,126.98	$171,698,412.70	1,287,738.10	3,433.97	6,867.94
80-95.4%	1,806,352,201.26	$180,635,220.13	1,354,764.15	3,612.70	7,225.41
80-96.2%	1,884,386,694.39	$188,438,669.44	1,413,290.02	3,768.77	7,537.55
85-94.5%	1,058,748,832.87	$105,874,883.29	794,061.62	2,117.50	4,235.00
85-95.4%	1,148,116,907.14	$114,811,690.71	861,087.68	2,296.23	4,592.47
85-96.2%	1,226,151,400.27	$122,615,140.03	919,613.55	2,452.30	4,904.61
90-94.5%	473,650,793.65	$47,365,079.37	355,238.10	947.30	1,894.60
90-95.4%	563,018,867.92	$56,301,886.79	422,264.15	1,126.04	2,252.08
90 - 96.2%	641,053,361.05	$64,105,336.11	480,790.02	1,282.11	2,564.21
95-95.4%	39,510,095.99	$3,951,009.60	29,632.57	79.02	158.04
95 - 96.2%	117,544,589.12	$11,754,458.91	88,158.44	235.09	470.18

As shown, even with the use of generalities, i.e. 75% full load, 3000 or 8000 per year run time hours, $0.10/kWh, and a rough average of install cost, even a small motor consumes a lot of power and costs a great deal. Now replace a inefficient motor, upgrade it to a premium efficiency motor. The energy savings are tremendous but also the gains can be substantial. Less maintenance downtime spent repairing or replacing broken or breaking motors, less money spent on emergency repairs, more production time and products being built, overall increases to the quality of life and greater efficiency and profits for the company.

11. Measuring Efficiency

There are many ways in which to calculate the efficiency of a motor; however, some are cumbersome, and others are completely intrusive and out of the question when it comes to real world scenarios. A paper written by Oregon (OSU) and Washington (WSU) State Universities titled "A Laboratory Assessment of In-Service and Non-Intrusive Motor Efficiency Testing Methods" covers these methods in detail. For further clarification on laboratory testing please refer to "3 Phase Induction Motor Field and Laboratory Efficiency Testing" written by Ernesto Wiedenbrug, Ph.D., SM IEEE.

When it comes to efficiency field estimation there are currently 4 test methods utilized today that are considered non-intrusive. Note the word estimation. Some degree of inaccuracy is expected as a price to pay for an in-service field test over a no load un-coupled laboratory test on a dynamometer. These tests are the Nameplate method, Upper-Bound with Resistance method, ORMEL 96 and the Instantaneous Current Method. The Baker Instrument Companies, an SKF Group Company's EXP3000 tester uses the Instantaneous Current Method.

This method requires a measurement of the motors input power and a calculated estimate of the motors output power. Current transformers and potential transformers are utilized to gather incoming rotating voltage and currents for all 3- phases. Then calculations are made based on these values for speed and torque. Air gap torque is calculated using the Park's Vector (or 2-Axis) Theory. Friction, stray load and windage losses are estimated and then subtracted from the air gap torque calculation to get an estimate of the output torque. As was mentioned efficiency is the ratio of the mechanical output to electrical input. Since speed does not require a physical measurement taken near or on the motor, it is estimated through the gathered currents and voltages. All data can be gathered safely from the motor's control cabinet (MCC), making this a highly non-intrusive method to test for efficiency. Also in the study done by WSU and OSU, the findings for all test methods showed the fact that instantaneous current method does not try to estimate losses; but rather the output power. It is less sensitive to the efficiency of the predicted motor. This means it has a smaller margin of error on estimating lower end efficiencies, making it not only a good non-intrusive test method but also a highly accurate test method.

12. Applying more Efficient Motor Findings

Once it has the operating efficiency, the EXP3000 extracts a comparable efficiency from a motor database which contains over 22000 different NEMA design motors of numerous motor manufacturers. The percentage difference in the losses between the tested motor and a comparable motor (target efficiency) is then evaluated with respect to the thresholds. There are a few organizations available today that have a listing of these NEMA prescribed motors as well as methods in how to go about selecting the right motor. MotorMaster+ is a third-party software tool for energy-efficient motor selection and management. The MotorMaster+ software was developed by Best Practices, a program under the U.S. Department of Energy's Office of Industrial Technologies. MotorMaster+ 3.0 software includes a catalog of over 20,000 AC motors. Version 3.0 features motor inventory management tools, maintenance log tracking, efficiency analysis, savings evaluation, energy accounting, and environmental reporting capabilities. It can be obtained at no cost from the following website: http://www.energy.wsu.edu/cfdocs/mmdownload/register.cfm.

Motor Master+ is a standard application utilized by the EXP3000. Another very handy and well designed website can be found at http://www.motorsmatter.org/. This site offers a very useful 1-2-3 step program that aides in the decision process of buying, replacing, and managing motors. In fact the title of one of their main books is "The 1-2-3 Approach to Motor Management - Users Manual". Also available for download is a spreadsheet that can be used to check off steps in the 1-2-3 process.

13. Summary

In today's society with the environmental and economic needs, a more reliable, safe and beneficial way to help the economy, reduce energy demand, and stop global warming is needed. The number one way for the maintenance and motor management group to aide in this goal is to ensure that the motors, drive systems and loads under their control are running as efficiently and smoothly as possible. One way to carry out this necessity is to determine the efficiency of the motor and correct issues with the surrounding system that directly relate to, or affect, the motors efficiency. Correcting issues, such as a cavitating pumps, overcurrent situations, and improperly tuned drives, can increase the efficiency and life of the motor while reducing the maintenance costs, down-times, and production losses. To illustrate again lets use a 200Hp motor running at 8000hrs per year at 85% efficiency. This motor would:

1. Cost the facility $105,317.65 per year to run (not including penalties for poor power factor and any carbon tax paid),
2. The facility will use 1,053,176.47 kWh per year on this motor, and
3. Cause approximately 790 Tons of CO2 to be produced and emitted into the atmosphere.

Swapping this 85% efficient motor for a NEMA Premium 96.2% efficient motor will result in the following:

1. An annual energy savings of $12,261.51, which by the end of the first year more than pays for the motor

2. an annual kWh reduction of 122,615.14, thus reducing energy demands
3. decreasing the CO2 buildup by roughly 91 Tons.

Due to utility rebates currently in existence and the possibility of a government introduced rebate program, the payback period for this motor is approximately 8.6 months. Each associated year of use will produce approximately $12,000 additional cost savings that can be put to good use in any number of ways. The necessity for efficiency estimation and knowledge of payback periods is an essential tool that every motor management professional should have at the ready in their tool bag. For more information on this subject, please contact Baker Instrument Company, an SKF Group Company or the co-authors of this white paper.

14. References / Standards and Related Information

IEEE519. More information on power condition standards can be found in IEEE working groups under http://grouper.ieee.org/groups/

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