Test Methods for Determining the Impact of Motor Condition on Motor Efficiency and Reliability (Re-Publish from 2000)

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Abstract

This article discusses the financial impact of motor condition on electric motor efficiency and reliability by reviewing a combination of Motor Circuit Analysis (MCA) and vibration techniques. Cost impacts on energy, production and maintenance will be outlined. The topic will surround a utility study and US Department of Energy market transformation success during 2000 and 2001. The primary areas of concern are phase balance, rotor bars, cleanliness and bearing issues. It is an update to an article originally published in 2000 based upon Dr. Penrose's work at the University of Illinois at Chicago's Energy Resources Center from 1997-1999.

Introduction

Electric motors are the prime mover of industry and our general comfort in commercial buildings. The motor systems consume 20% of all energy used in the United States and 59% of all electricity generated. Within each sector:

- ☐ 78% of electrical energy in industrial systems (>90% in process industries)
- ☐ 43% of the electrical energy in commercial buildings
- ☐ 37% of the electrical energy in the home

There are well over 1.2 billion electric motors, of all types, used throughout the United States. However, electric motors are often 'out-of-sight, out-of-mind,' until production is down due to a burn-out or catastrophic bearing failure.

It is important to understand that equipment usually fails over time, reliability decreases and losses increase (efficiency decreases) over time prior to most catastrophic failures. Although some equipment faults are instantaneous, the larger majority of catastrophic faults that impact production are the result of a failure in the implementation of a maintenance program. This failure is primarily due to management not fully understanding that maintenance is an investment in the business and not an 'expense of doing business.' If you do not invest in materials, equipment and people, you do not have product to sell: If you do not invest in predictive maintenance practices (PM, TPM, RCM, or any other program), you do not have product to sell or less of it at a higher overall production cost.

Proper implementation of a maintenance program has been shown to reduce energy consumption in plants by as much as 10-14%,[1,2] while also reducing unplanned production downtime. Average downtime costs are shown as follow:

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[1] Industrial Productivity Training Manual, 1996 Annual IAC Directors' Meeting, Rutger's University, US Department of Energy Office of Industrial Technologies, 1996.

[2] Electric Motors Performance Analysis Testing Tool Demonstration Project, Pacific Gas & Electric, 2001.

Table 1: Estimations for Downtime Costs[3]

Industry	Average Downtime Costs, per hour
Forest Products	$7,000
Food Processing	$30,000
Petroleum and Chemical	$87,000
Metal Casting	$100,000
Automotive	$200,000

In a recent utility energy and reliability project, a group of electric motors from 5 to 200 horsepower were reviewed in several industries, including: Petroleum and Chemical; Forest Products; Food Processing; Mining (Quarry); and Pulp & Paper. The plants varied from having no existing planned maintenance program to full implementation, including an existing energy program. Of these motors, randomly evaluated, 80% were found to have at least one deficiency with 60% of those (48% of the original) found to be cost effective to replace. The plants without programs had the greatest number of defective motors, the plants with existing maintenance and energy programs had the least number of defective motors. Eight percent of the motors were evaluated to determine the types of faults and the potential cost avoidance with corrective action (repair or replace) by using vibration analysis and motor circuit analysis (MCA). Several had a combination of electrical and mechanical problems:

Table 2: Utility Energy Project Findings

Type of Test	Percentage of Faults
Vibration Analysis	45% of motors tested
Motor Circuit Analysis	70% of motors tested
Insulation Resistance (Meg-Ohms)	5% of motors tested

Several motors had combined vibration and electrical faults. A few had winding faults combined with insulation resistance faults. Several had shorted windings that were continuing to cause production problems, but were written off as 'nuisance' trips (detected in the study by using MCA). "Findings of the advanced portion of the Motor PAT Tool demonstration project indicate that measuring for … phase unbalance of resistance, inductance, impedance, phase angle and I/F (current/frequency response) provided more useful results."[4] The combined incremental production cost avoidance of 20 of the defective motors, from 5 to 250 horsepower, was $297,100, rendering implementation costs insignificant.

The purpose of this paper is to first provide information for determining cost avoidance through the application of a maintenance program on electric motors. This will be followed with a discussion of the implementation of motor circuit analysis (MCA) and vibration analysis.

Cost Avoidance Through Maintenance

There are a number of ways to determine cost avoidance through the implementation of maintenance programs. In this discussion, the focus will be on the methods introduced through the US Department of Energy's Industrial Assessment Centers (IAC's), which provide a very basic and conservative method. The PAT Tool Demonstration Project used a much more

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[3] Industrial Productivity Training Manual, 1996 Annual IAC Directors' Meeting, Rutger's University, US Department of Energy Office of Industrial Technologies, 1996.

[4] Electric Motors Performance Analysis Testing Tool Demonstration Project, Pacific Gas & Electric, 2001.

complex method[5], which is outside the scope of this article. However, some of the tools, such as MotorMaster Plus[6], will be used to provide cost information for motor repair costs.

"Utility representatives have indicated that in a survey of facilities with no preventive maintenance programs, motor rewinds represented 85% of the total number of motor repairs (on average). After preventive maintenance programs were established, the number of rewinds were reduced to about 20% of the total."[7] This statement has been found to hold true through research projects including: Dreisilker's Total Motor System Maintenance and Management Program (DTM^2 ™), the PAT Tool Project, and others.

For the purpose of this discussion, we will consider a paperboard plant with 485 motors. There are two operating production lines that have a potential downtime cost of $6,575 each. An average of 3 motors were repaired per month, of which a majority (70%) required rewind replacement (normally caused by immersion, contamination or the motors became coated in material). The facility operated 8,000 hours per year with the catastrophic failures normally causing one line to fail at a time. Additional costs, not covered by this discussion, included cleaning of the system prior to re-starting the operation. No maintenance program in place.

Table 3: Breakdown of Motor Horsepower and Repair Costs

Motor Size	**Number of Motors**	**Rewind Cost**	**Recondition Cost**
< 20 horsepower	347 (Replacement, not repaired)	-	-
20	15	$660	$220
25	10	$760	$255
30	2	$880	$295
40	3	$1,020	$340
50	27	$1,295	$430
75	18	$1,500	$500
100	21	$1,610	$540
125	32	$1,820	$610
400	6	$3,400	$1,200
750	4	$7,735	$2,600

The first step is to calculate the unplanned production downtime costs:

Equation 1: Unplanned Production Downtime Cost

$$PC_{\text{Downtime}} = (\text{MF/Yr}) \times (P_{\text{Lost}}/\text{failure}) \times (P_{\text{Cost}})$$
$$= (36 \text{ motors/yr}) \times (4 \text{ hrs/failure}) \times (\$6{,}575/\text{hr})$$
$$= \$946{,}800/\text{year}$$

Where PC is the annual cost of unplanned downtime, MF is the number of motor failures, P represents production

Step 2 is to calculate the average cost of rewinding equipment. In this case, we will concentrate on just 20 horsepower and larger.

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[5] "Electric Motor Energy and Reliability Analysis Using the US Department of Energy's MotorMaster Plus," Maintenance Technology, Penrose, et.al., October, 2000.

[6] MotorMaster Plus is a free motor energy and management software available through the US Department of Energy – www.oit.doe.gov/bestpractices/

[7] Industrial Productivity Training Manual, 1996 Annual IAC Directors' Meeting, Rutger's University, US Department of Energy Office of Industrial Technologies, 1996.

Equation 2: Average Cost of Rewinding Motors

$$\begin{gathered}R_{avg} = ((N_{n1} \text{ x } RWC_{n1}) + \ldots + (N_{nn} \text{ x } RWC_{nn}))/N_T \\ = ((15_{20} \text{ x } \$660_{20}) + (10_{25} \text{ x } \$760_{25}) + \ldots + (4_{750} \text{ x } \$7735_{750})) \text{ / 138 motors} \\ = \$1{,}650\end{gathered}$$

Where R_{avg} is the average rewind cost, N_n is the number of motors for each horsepower, RWC_n is the rewind cost for each horsepower

The average cost for reconditioning the motors is calculated the same way, except the reconditioning cost is used instead of rewind costs. For this example, the average reconditioning cost would be $555.

Step 3 is to calculate the average repair cost per motor before and after maintenance implementation.

Equation 3: Average Repair Cost per Motor

$$\begin{gathered}R_{avg} = (\text{\% Recondition x \$/Recondition}) + (\text{\% Rewind x \$/Rewind}) \\ = (30\% \text{ x } \$555) + (70\% \text{ x } \$1{,}650) \\ = \$1{,}322 \text{ / motor}\end{gathered}$$

Assuming that the number of motors rewound versus reconditioned would be inverse with the application of the program, the number of rewound motors would be 30%, and the average cost of repair would be $884 per motor. Once the program is implemented, the number of motors to be repaired, overall, will be reduced.

Step 4 uses the number of motors repaired per year and the difference between the reconditioned motors vs rewound in order to come up with a conservative estimate of savings.

Equation 4: Repair Cost Reduction Estimate (RRC_{est})

$$\begin{gathered}RRC_{est} = (\text{motors repaired/year x initial repair costs}) - (\text{motors repaired/year x new repair costs}) \\ = (\text{36 motors/yr x \$1,322/motor}) - (\text{36 motors/yr x \$884/motor}) \\ = \$15{,}768 \text{ per year}\end{gathered}$$

Step 5 is to determine potential energy savings. For the purposes of conservative estimation, a 2% improvement in efficiency will be assumed. Maintenance components include (and the type of test system, vibration and MCA only, for this paper, used to evaluate):

- ☐ Improved lubrication (vibration)
- ☐ Proper alignment and balancing (vibration)
- ☐ Correction of circuit unbalances (MCA)
- ☐ Reduced motor temperatures (MCA, vibration)
- ☐ Reduced efficiency losses caused by rewinds (US Department of Energy estimates one percentage point efficiency reduction per rewind)
- ☐ Improved drive system performance

Equation 5: Energy Cost Savings

Energy Savings = (total hp of motors considered) x (load factor) x (operating hours) x (% savings) x (.746 kW/hp) x (Electrical usage costs)
= 14,930 horsepower x 75% load x 8,000 hrs x 2% savings x 0.746 kW/hp x $0.06/kWh
= $80,192 per year

Step 6 is to determine the in-house labor costs to implement the program. Assume 1 man-hour per motor per year. Estimated costs for this example will be based upon $25 per hour.

Equation 6: In-House Labor Costs

Labor = (1 hr/month/motor) x (# of motors) x (12 months/yr) x ($/man-hour)
= 1hr/month/motor x 138 motors x 12 months/yr x ($25/man-hour)
= $41,400 per year

Step 7 is the purchase price for the MCA and vibration analysis equipment. For the purposes of this article, the same equipment selected for the utility PAT Project will be used. The estimated combined costs for the ALL-TEST IV *PRO*™ 2000 MCA instrument and the Pruftechnik vibration analysis equipment is $22,000.

Step 8 are the training costs for implementing the system. Assuming equipment training costs of $4,500 per person and maintenance training costs of $6,000 per person, the cost should be approximately $10,500 per person.

The final step is to determine the simple payback for the implementation of the program. In the case of this example, assume a 50% reduction in unplanned downtime for the first year:

Table 4: Costs and Savings for Maintenance Implementation

Maintenance Savings	**Maintenance Costs**
$473,400 Reduced Downtime	$41,400 Labor Costs
$15,768 Reduced Motor Repair Costs	$22,000 Equipment Costs
$80,192 Energy Cost Reduction	$10,500 Training Costs
$569,360 Total Savings per Year	**$73,900 Total Costs per Year**

Equation 7: Simple Maintenance Payback

Payback = (Total Costs per Year)/(Total Savings per Year)
= $73,900 / $569,360
= 0.13 years or 1.6 months

The smaller size of this particular plant would allow for complete implementation of a maintenance program. Larger manufacturing plants will often have thousands of electric motors and may require a breakdown of departments or areas for successful implementation.

Application of Vibration Analysis

Vibration analysis is used by maintenance professionals as a means to detect mechanical and some limited electrical faults in rotating equipment. By performing regularly scheduled testing, the operating reliability of an electric motor can be determined through trending.

Based upon bearing failure, greasing, belt tension, misalignment, or other unbalances, increases in energy losses can occur. These losses show as vibration, noise and heat. Improper belt tension and greasing will increase the friction and windage losses of the motor. This can be calculated as:

Equation 8: Bearing Losses

Watts Loss = (load,lbs x JournalDiameter,inches x rpm x f) / 169
.f is dependant upon oil used and temperature, 0.005 is typical

Vibration analysis for troubleshooting will detect bearing (41% of failures) faults, balance and alignment (12% of failures) faults, primarily. It will also detect rotor faults (10% of failures) and some electrical faults (37% of failures), to some extent. However, electrical and rotor faults tend to fall in frequency ranges that can be related to other equipment, and are directly load related. Vibration analysis requires the electric motor to be operating at a load that is constant during each test that would be trended.

Application of Motor Circuit Analysis

"There are many tools available to perform quality preventive maintenance of individual motors. Of these, motor circuit analysis (MCA) systems hold great promise for identifying motor problems before expensive failure and for improving the general efficiency of motor systems in general."[8]

Motor circuit analysis allows the analyst to detect winding faults and rotor faults in the electric motor. One power of this type of test method is that it requires the equipment to be de-energized, which allows for initial incoming testing of the electric motors and troubleshooting when equipment fails. Primary energy losses that can be detected include phase unbalance and I^2R losses, while faults include shorted windings, loose connections, ground faults and rotor faults.

A resistive fault gives of heat, as a loss. For instance, a 0.5 Ohm loose connection on a 100 horsepower electric motor operating at 95 amps:

Equation 9: Resistive Losses

Kilo-Watts Loss = $(I^2R)/1000$
= $(95^2 \times 0.5)/1000$
= 4.5 kW (demand loss)

Equation 10: Energy Usage Loss

$/yr = kW x hrs/yr x $/kWh
= 4.5 kW x 8000 hrs/yr x $0.06/kWh
= $2,160 / year

Electric motor phase unbalances (inductance and impedance) effect the current unbalances, cause motors to run hotter and reduce the motor's ability to produce torque. The percentage unbalance of impedance can be evaluated to determine efficiency reduction and additional heating of the

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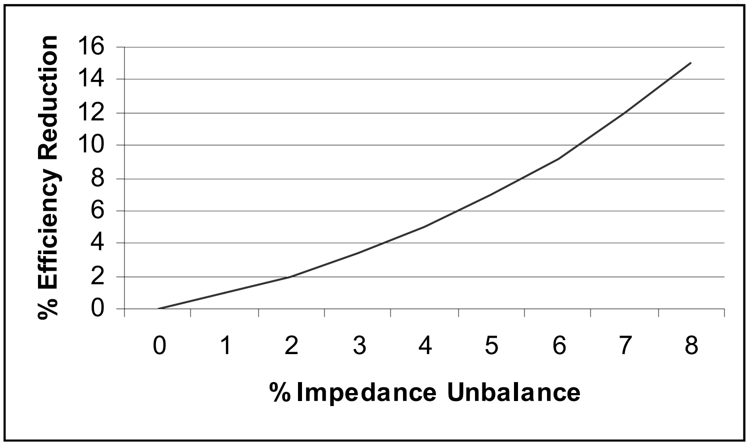
[8] DrivePower, Chapter 12, 1993

electric motor. A general rule is that, for every 10°C increase in operating temperature, the life of the equipment is reduced by half.

Figure 1: Efficiency Reduction Due to Impedance Unbalance

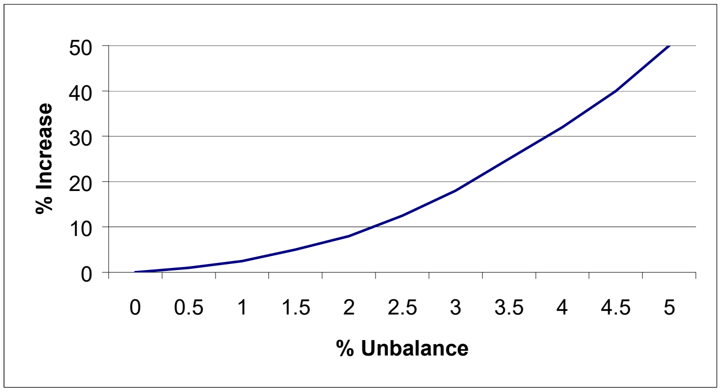


For instance, the paperboard company has a 100 horsepower electric motor, that would normally be 95% efficient, that has a 3.5% impedance unbalance. The efficiency would be reduced by 4 points of efficiency, or to 91%.

Equation 10: Energy Cost Due to Phase Unbalance Losses

$/yr savings = hp x 0.746 x %load x $/kWh x hrs of operation ((100/Le) – (100/He))
= 100 hp x 0.756 x .75 load x $0.06/kWh x 8000 hrs ((100/91) – (100/95))
= $1,240 / year

Figure 2: Increase in Temperature Rise Due to Phase Unbalance



The impedance unbalance will also cause an increase in operating temperature based upon an increase in I^2R losses. In the case of the 100 horsepower electric motor, this means a temperature rise of about 30°C, or a reduction in motor insulation life to 13% of its original.

Motor Circuit Analysis is also used to evaluate the windings for contamination. “Frequent cleaning of a motor’s intake (if any) and cooling fins is especially important in dirty environments… Tests confirm that even severe duty, generously rated, and oversized motors can quickly fail in such conditions if they become thickly coated or if lightly coated and with their airflow reduced by half. Their insulation life can then fall to 13 – 25% of normal."[9] The same phenomenon occurs if the windings become coated in contaminants.

The MCA rotor test requires inductance and impedance readings through 360 degrees of rotation of the rotor. The readings are graphed and viewed for symmetry. Rotor test results provide a definitive condition of the rotor and is often performed following identification of a possible rotor fault by vibration, as part of an acceptance program, during repair or when the motor is identified as having torque problems.

Conclusion

The implementation of an electric motor maintenance program will have a significant impact on a company's bottom line. Whether the company has a few hundred motors or many thousands, the simple payback from the investment into vibration and MCA is usually termed in months. Payback is impacted from savings from production availability, reduced equipment repair costs and improved energy costs, all with a minimum investment in manpower, training and equipment.

The application of these two technologies compliment each other while also evaluating the progress of the maintenance program and improving upon equipment availability. Vibration analysis evaluates the mechanical condition of equipment while MCA evaluates the electrical condition of equipment. Combined, the analyst has the ability to view the complete condition of the electric motor.

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[9] DrivePower, Chapter 12, 1993