Y-12

OAK RIDGE Y-12 PLANT

LOCKHEED MARTIN

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ANALYSIS OF PRODUCTION LINE MOTOR FAILURE

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ABSTRACT

The Oak Ridge National Laboratory (ORNL) was approached by a Food Products Manufacturer (FPM) to investigate the rapid failure of motors in a manufacturing facility. It was reported that some motors or their bearings were being replaced after as little as four months of service. The deciding symptom for replacement was always high motor vibration.

To protect against unscheduled downtime in the middle of a process run, the FPM's maintenance team removes a motor from service when its vibration level reaches a conservative threshold of approximately 0.4 inches per second. In their experience, motors left in service after reaching this vibration threshold can fail at any time within the time span of the next process run causing significant losses of raw material and production capacity.

A peculiar finding of vibration level trend analysis was that at least one motor (number 5) exhibited cyclic variations with 24-hour periodicity. As shown in Figure 1, the vibration level reached a maximum at about 4:00 a.m., ramped down during the day, and then rose again during the night. Another peculiarity was that most of the vibration energy in the affected motors was at the 120 Hz frequency. Since this is twice the 60 Hz line frequency the FPM suspected the vibration was electrically induced.

The electric loads at the FPMs plant remain constant during the five days of a continuous production run. Thus, the periodicity of the vibration observed, with its daily peaking at about four am, suggested the possibility of being driven by changes in the electrical power grid external to the plant.

Objective

The objective of this CRADA was to determine the root cause of production line motor failure.

Discussion of Objective

The objectives of the CRADA were met. The root causes were identified.

Benefits to (DOE) Defense Programs

The work done under the CRADA revealed the fact some NEMA motor Types cannot be operated at their rated specifications when there is a combination of environmental factors, each within NEMA limits, which combine synergistically to degrade the motor.

Technical Discussion

INTRODUCTION

The Oak Ridge National Laboratory (ORNL) was approached by a Food Products Manufacturer (FPM) to investigate the rapid failure of motors in a manufacturing facility. It was reported that some motors or their bearings were being replaced after as little as four months of service. The deciding symptom for replacement was always high motor vibration.

To protect against unscheduled downtime in the middle of a process run, the FPM's maintenance team removes a motor from service when its vibration level reaches a conservative threshold of approximately 0.4 inches per second. In their experience, motors left in service after reaching this vibration threshold can fail at any time within the time span of the next process run causing significant losses of raw material and production capacity.

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POWER QUALITY

A power quality survey was planned to monitor the power supply to the FPMs plant and to the motor's terminals. Voltage, current, and harmonics were monitored and recorded in each of the three electrical phases at selected points in the plants grid. The survey was conducted over a two-week period, 24 hours a day, with data collection every 15 minutes. The motor that demonstrated the greatest swing in vibration level over each 24 hour period was motor number five. Motor number five was a 7.5 horsepower, 2 pole, 1.0 service factor Energy Efficient Motor (EEM) being operated very near its rated horsepower.

At the terminals of motor five, the level of the voltage 5th harmonic was found to be swinging daily mostly between two levels. It varied daily but on the average it went low (about 2% of fundamental voltage) at about 4:00 a.m. and went low (about .75% of fundamental voltage) at about 10:30 p.m.. Curiously, this was just the inverse of the vibration trend. (Figure 1a) The current unbalance, however, correlated reasonably well with vibration (Figure 1b). It appears that the vibration was more related to current unbalance than it was to the level of the 5th harmonic. Analysis of the overall vibration data showed no direct time correlation between higher levels of harmonic distortion and a higher level of vibration in any of the motors. The voltage unbalance at the motor terminals was found to be less than one percent in magnitude during the survey. The harmonic distortion and voltage unbalance were individually within normally accepted limits (Reference 1).

Only motor number five manifested any periodic features in the vibration time trends. Analysis of the spectral content of its vibration signal revealed that the dominant frequency was 120 Hz and that the increase in vibration observed daily at about 4 a.m. was mostly due to an increased 120 Hz component, which is characteristic of a power unbalance.

Figure 1

As it can be seen in Figure 1b, the daily cycling of the level of 120 Hz vibration frequency for motor number 5 correlated well with variations in the current unbalance between the motors three phases: Higher current unbalance produced stronger 120 Hz vibration. The current unbalance and its associated power unbalance can be caused by unbalance in one or more of the following: magnitude of the three phase voltages, displacement angle between the three phase voltages, and internal impedances of the motor. The daily cycling of the vibration was caused by a daily swing in the voltage unbalance at the plant.

Impedance measurements at the motor terminals revealed small impedance unbalances that varied with the position of the rotor and temperature. Impedance unbalance is determined by measuring the impedance between each of the three winding terminals. These three values are averaged and the maximum deviation from the average is expressed in percent. We do not believe that the impedance unbalance in the motor cycled daily, but there is evidence that the impedance unbalance grew with time as the motor degraded.

The measured magnitude of impedance unbalance in motor number 5 increased as the motor aged. Data taken by the FPM on February 24, 1994 indicated a maximum impedance unbalance of 5.6%. Data taken on June 10, 1994 indicated a maximum unbalance of 8.0%. Both of these measurements were taken immediately after the motor was de-energized from continuous operation at room temperature. After the motor was removed from service and allowed to cool to room temperature, the unbalance was found to be a maximum of 3.4%. This indicates that the unbalance may be a function of unbalanced heat deposition in the motor, possibly due to a resistance change with temperature.

Several weeks after the power survey, motor number 5 was removed from service and dismantled at ORNL's Electric Machinery Systems Test Center (EMSTC). It was found that the bearings had negligible damage, exhibiting slight indications of axial thrust and

eccentricity, and a slight indication of misalignment. The motor's rotor was checked for out-of-roundness (run-out). The maximum run-out measured over the entire core was 1 thousandths of an inch. This eliminated rotor bow and ellipticity from consideration in the search for sources of unbalance. It was noted however, that the rotor had turned a dark blue color indicating excessive heating.

EFFECT OF HIGHER RPM ON MOTOR LOAD

When a standard efficiency motor powering a pump or fan is replaced with an EEM, the higher speed of the EEM can result in operation at a higher point in the load curve of the pump or fan. The increase in load is proportional to approximately the cube of the increase in speed. This means that the motor must produce more horsepower. Because the temperature rise in a motor increases slightly less than the square of the horse power output, the net effect is that the temperature rise of the motor is roughly proportional to the fifth power of the increase in rotor speed. This means that if a EEM is used to replace a standard efficiency motor on a pump or fan, where the standard efficiency motor was operating exactly at its rated horse power, the EEM may be operating above its rated horse power. See Reference 2 for a complete discussion of this effect.

POSSIBLE EFFECTS OF COST OPTIMIZED EEM DESIGN CHARACTERISTICS

Motor number five was a cost optimized EEM, that is, the manufacturer had designed the motor to enhance its value from the cost perspective. EEMs typically have some unique design characteristics which distinguish them from standard efficiency motors. In general, manufacturer's literature and EEM guidebooks indicate that EEMs have one or more of the following features: longer rotors, more magnetic material, larger gauge wire in the windings, lower flux density, a smaller air gap, (Ref. 3,4 and 5) operate at a higher speed, that is, at smaller slip, (Ref. 6 and 7) and a lower temperature rise than standard efficiency motors.

It was suspected that the cost optimized EEM may have had some unique design characteristics which made it susceptible to degradation from the service environment. The cost optimized EEM was therefore compared with a premium EEM to see what the differences could be observed. The most obvious difference was that the cost optimized EEM was of rolled steel construction while the premium EEM was cast iron. The nameplate data from the two motors is provided in Table 1.

Table 1. Nameplate motor data

<u>Nameplate parameter</u>	<u>Cost Optimized Motor</u>	<u>Premium Motor</u>
Frame size	184 JM	213 T
Power, hp	7.5	7.5
Voltage, volts	230/460	230/460
Current, amps	17.2/8.6	18.6/9.3
Speed, rpm	3450	3525
Service factor	1.0	1.15
Code	L	J
Class	F	F
Design	B	A
Efficiency	87.5% (Full Load)	90.2 % (Guaranteed Minimum) 91.7 % (Nominal)

It is interesting to note that a search in Motor Master Data Base (Ref. 13), produced 119 motors with the search criteria of 7.5 hp, 3600 rpm, Totally Enclosed, 460 Volts. Of these 119 motors, only 12 have a frame size of 184, and in general, these are the less expensive, lower efficiency motors. It is also interesting to note that NEMA MG1 provides a table 12-10 of EEMs and their minimum and nominal efficiencies. This table shows that a 7.5 hp, 2 pole enclosed motor should have a nominal efficiency of 89.5% and a guaranteed minimum efficiency of 87.5%. (The nominal efficiency is the efficiency of a large population of motors of the same design.)

Both motors were operated in ORNL's Electric Machinery Systems Test Center. The observed efficiencies and speed at 100% power at rated voltage and negligible voltage unbalance are shown in Table 2.

Table 2. Measured efficiencies and speeds (rated conditions, no unbalance)

<u>Parameter</u>	<u>Cost Optimized Motor</u>	<u>Premium Motor</u>
Measured Efficiency	88.7%	91.2
Measured RPM	3489	3530

The premium motor's speed is slightly higher than the cost optimized motor's, which, as was mentioned earlier, is another characteristic of an EEM.

A comparison of the temperature rise of the cost optimized motor and premium motor was made. To do this, a calculation of the temperature rise of the windings was done based on the winding resistance change from room temperature (cold motor) to that measured immediately after the motor was run at full load for one half hour at rated voltage. The results are shown in Table 3.

Table 3. Measured resistances and calculated temperature rise (rated conditions, no unbalance)

<u>Parameter</u>	<u>Cost Optimized Motor</u>	<u>Premium Motor</u>
Average cold phase to phase resistance ($\frac{1}{2}$)	1.526	1.051
Average hot phase to phase resistance ($\frac{1}{2}$)	1.881	1.187
ΔT based on change in resistance ($^{\circ}C$)	60	33

Thus the temperature rise of the cost optimized motor is almost double the rise of the premium motor. Both motors have Class F insulation. The allowable temperature rise for a 1.0 Service Factor motor with Class F insulation is 110 degrees C in a maximum ambient of 40 degrees C. Figure 8 would indicate that during unbalanced conditions there is much more of a temperature rise for the Cost Optimized motor than for the Premium motor.

The rotors from the two motors were removed and compared. Comparative dimensional data is provided in Table 4.

Table 4. Motor dimensional data

<u>Dimension</u>	<u>Cost Optimized Motor</u>	<u>Premium Motor</u>
Rotor Core Overall Diameter (in.)	3.695	4.702
Rotor Core Length (in.)	5.0	4.7
Air Gap (in.)	0.027	0.024
Rotor Weight (lb.)	23.3	26.5

It is interesting to note that while the premium efficiency rotor has roughly the same surface area as the cost optimized rotor, it is approximately 14% heavier and has a radius that is about 27% greater. A simplifying assumption can be made that the rotor can be represented as a solid cylinder*, with a moment of inertia of:

$$I = \frac{mR^2}{2}, \text{ where } m = \text{mass and } R = \text{cylinder radius}$$

Using this somewhat crude estimate, the moment of inertia of the premium efficiency rotor is more than 80% greater than that of the cost optimized rotor.

If there is a voltage unbalance, this will result in negative sequence current flow in the stator. The resulting current flowing in the rotor will have a frequency of twice stator frequency minus slip, or very nearly 120 Hz at full load. (Ref. 10) This current, if it is large, will result in significant heating in the rotor.

The rotor currents produce a rotating magnetic field in the direction opposite to the direction of the rotor rotation. There are now two torques acting on the rotor, and in opposite directions. The interaction of these two torques produces a sinusoidal torque ripple at 120 Hz. Reference 10 provides an excellent discussion of this effect. Testing of the cost optimized EEM in the laboratory showed clearly the development of this 120 Hz torque vibration, as discussed below.

LABORATORY TESTS OF EEMS

In order to develop a better understanding of the relationship between vibration and motor unbalance conditions, the cost optimized and premium motors were tested at voltage unbalance levels ranging from 0 to 4%. The cost optimized motor used for the test was identical to motor five at the FPM.

Testing was conducted at ORNL's EMSTC using a generator to load the motors to rated load. The following parameters were monitored:

- Current (3 phases)
- Voltage (3 phases)
- Radial, motor inboard horizontal vibration
- Torque (in-line torque cell)
- Speed (magnetic pickup, and independently, from the vibration, motor power, and torque spectra)

From the monitored parameters, motor input power and output power and spectral content of the torque, power, and vibration data were determined. Of particular interest was the 120 Hz component of the spectra.

In Figure 2, Motor A, on the left, is the Cost Optimized Motor. Motor B on the right, is the Premium motor. The first row shows the current unbalance that results from given levels of voltage unbalance for both motors. The voltage was unbalanced by making one phase high and two phases low. It can readily be seen that the slope of the current

* The actual moment of inertia for a rotor obviously departs somewhat from this, since the rotor is not of homogeneous construction, this equation does not account for the portion of the shaft extending beyond the rotor or for attached cooling fan blades, etc. The simplified solid cylinder model provides a crude, but reasonable approximation in many cases.

unbalance plot was much higher for the cost optimized motor. A higher level of current unbalance would correspond to a higher level of negative sequence current flow.

Figure 2

Figure 3 shows the magnitude of the 120 Hz component of torque plotted against the magnitude of the current unbalance. The normalized torque is the RMS amplitude of the 120 Hz component of the torque divided by the average torque. This plot shows that the cost optimized motor has a maximum 120 Hz component of torque of about 15%, while the premium motor has a maximum 120 Hz component of torque of about 5%. As discussed above, the negative sequence current in the stator is responsible for the development of the 120 Hz torque oscillation. As the negative sequence current is much lower for a given voltage unbalance in the premium efficiency motor, the resulting torque oscillation is also much lower.

Figure 3

Figure 4 is a plot of the 120 Hz component of motor vibration measured horizontally at the inboard bearing against the magnitude of the current unbalance. The cost optimized motor shows a good correlation with a relatively steep slope. The premium motor shows little effect. The disparity in vibrational response is believed to be primarily attributable to the heavier, more rigid cast iron structure of the premium efficiency motor, as contrasted with that of the cost optimized motor (rolled steel frame with stamped steel feet welded to the frame).

Figure 4

Figure 5 shows a comparison of the 120 Hz motor input power ripple vs. current unbalance for the two motors. Like the torque ripple, the motor input power ripple is presented in a normalized fashion (RMS amplitude $\div$ average power). Note that the slopes of the cost optimized motor and the premium motor are about the same because the 120 Hz component of power is primarily just a function of the current unbalance in the three phases.

Figure 5

Figure 6 shows the 120 Hz component of torque plotted against the 120 Hz component of input power. Here, the cost optimized motor is seen to have a much higher slope, primarily because of the significantly lower rotational inertia of its rotor. The ratio of the slopes was found to be in close (but not perfect) agreement with the ratio of the rotational inertias.

Figure 6

Figure 7 shows the highest phase current against voltage unbalance. This plot is relatively similar to the plot of current unbalance against voltage unbalance (Fig. 2), but indicates the actual absolute value of the maximum current. This strongly suggests that in addition to the effect of the lower rotational inertia in the cost optimized motor, there may be another effect that allows a greater current unbalance and thus negative sequence current flow for a given voltage unbalance. This effect may also be due to the geometry

of the cost optimized motor. Also note that the circumferential I^2R heating profile for the two motors would be quite different because of the differences in current distribution and resistances for the two motors.

Figure 7

Finally, Figure 8 shows the efficiencies of the two motors as a function of voltage unbalance. The cost optimized motor less efficient for no unbalance, and is significantly more affected by changes in unbalance.

Figure 8

References:

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Inventions

No inventions were made or reported.

Assessment of Commercialization Possibilities

There are no commercialization possibilities.

Plans for Future Collaborations

There are no plans for future collaboration.

Conclusions

First, it must be stressed that these findings represent just a cursory review of two EEMs and they must not be extrapolated to form any general conclusions. The results are intended only to be of interest as they show the relationship of harmonic current flow in the rotor, rotor overheating and 120 Hz vibration. NEMA MG1 (Ref. 1), Section IV, Part 30, provides a discussion of application considerations for constant speed motors powered from a bus with harmonic content. A de-rating curve is provided for de-rating the horsepower of the motor to reduce the possibility of damage to the motor from overheating. Derating for voltage unbalance is considered separately, as discussed below. The reference also provides a definition for Harmonic Voltage Factor (HVF). The de-rating curve does not require de-rating until the HVF reaches 0.03. In the case of the FPM, the calculated HVF was about 0.01, and derating was not required for this condition alone.

NEMA MG1 (Ref. 1) also provides a discussion of the effects of unbalanced voltage, and gives a de-rating curve for voltage unbalance. The curve shows that horsepower derating must be considered at unbalances as low as one percent. The maximum unbalance noted at the motor five terminals during the survey period was about 1%, indicating that the motor was on the edge of requiring derating. Motor number five was also operating with approximately a five percent overvoltage. This is well within the NEMA limit of 10%. There is no derating curve for under or over voltage. The combination of harmonic distortion, overvoltage and voltage unbalance together probably merit some amount of derating, although the authors are not aware of any published guidelines for derating due to the combined effect of these factors.

The current unbalances produced by relatively small voltage unbalances appear to be a serious concern in susceptible motors if they are operated with a small or no service margin, as in the case of motor number five. Unbalance can be due to either unbalance in the motor itself or unbalance in the power supply due to unbalance in voltage magnitudes or phase angles or level of harmonic distortion between phases. In this particular case, impedance unbalance in motor number five was measured, and it appeared to be growing with time. This may have been caused by unbalanced heating of the stator. Unbalance in the motor can be due to a problem in manufacturing such as unequal number of turns in the windings, misaligned rotor or asymmetric stator. Regardless of the source of the unbalance, unbalanced voltages result in negative sequence currents which cause additional motor heating, unbalanced forces, and reduction in speed.

A related trend is that EEMs are often being applied with very little margin in their rated power. This may be due to the trend in engineering to use software to size pumps and their motors based on pump's horsepower requirement without consideration of service margin. This of some concern from the view point of motor reliability; but also note that

motor efficiency is slightly reduced because the typical EEM will operate at a slightly higher efficiency (perhaps 2%) at 85% load than at 100% of rated load.

It is prudent to select EEMs with a service factor of 1.15 and design for their operation at 85% of rated load to provide for maximum efficiency, variations in load during the process, and uncertainties in calculating the load. This study has shown that, at least for these two sample motors, a premium EEM will run cooler and with less vibration than a cost optimized EEM. In addition, the cost optimized motor's efficiency dropped by about 2.5% percent at a 4 % voltage unbalance, while there was only a 1 % drop with the premium EEM (Fig. 8).

Energy Efficient Motors are saving truly significant amounts of energy. It is important that they be applied correctly and their full efficiency benefit be obtained. Cost optimized motors have their place, however installing one in a service condition with small levels of voltage unbalance, over voltage and harmonic distortion while operating it at its rated full load will likely reduce its lifetime.

Figure 1a. Power 5th harmonic and vibration vs date. Data was digitally smoothed to minimize noise.

Figure 1b. Current unbalance and vibration vs date. Data was digitally smoothed to minimize noise.

Figure 2. Current unbalance vs voltage unbalance for a cost optimized motor (Motor A) and premium motor (Motor B)

Figure 3. Normalized torque ripple vs current unbalance for a cost optimized motor (Motor A) and premium motor (Motor B)

Figure 4. 120 hz vibration (MIH) vs current unbalance for a cost optimized motor (Motor A) and premium motor (Motor B)

Figure 5. Normalized power ripple vs current unbalance for a cost optimized motor (Motor A) and premium motor (Motor B)

Figure 6. Normalized torque ripple vs power ripple for a cost optimized motor (Motor A) and premium motor (Motor B)

Figure 7. Highest phase current vs voltage unbalance for a cost optimized motor (Motor A) and premium motor (Motor B)

Figure 8. Motor efficiency vs voltage unbalance for a cost optimized motor (Motor A) and premium motor (Motor B)

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