Basic Overview of Reliability-Centered Maintenance Based Approach for Motor Management Programs

Howard W. Penrose, Ph.D.
Vice President, Electrical Reliability Programs
T-Solutions, Inc.
howard@motordiagnostics.com
www.motordiagnostics.com

Abstract: Electric motor systems are the primary drivers of all industrialized nations. The application of a motor management program is necessary for bottom-line profits in all industrial facilities and commercial buildings. A key consideration for the development of these motor management programs is ensuring that it is the most cost effective program possible. The use of combined Reliability-Centered Maintenance (RCM) based and a follow-up Backfit RCM based program, for continuous improvement, is an outstanding process for achieving this goal. The purpose of this paper is to discuss the application and implementation of an electrical RCM/backfit RCM based program designed to guide the user in the development and continuous improvement of a motor management and motor diagnostics program and not to discuss the details of the processes.

An example of a 50 horsepower pump and motor system, as one of many critical systems, will be used. Basic findings, decisions, selection of equipment, root cause failure analysis and review using Backfit RCM will be followed with the assumption that the pump system met the appropriate criteria. Finally, a discussion of simple payback for the application of the program will be presented.

Introduction

The United States generated over 3,848 Billion kWh of electricity in 2003 of which approximately 2,270 Billion kWh (59%) were consumed by electric motor systems. Over 70% of the electric energy bill of an average manufacturing facility, and over 90% of an average process facility, is consumed by electric motor systems. It is not unknown for an electric motor system fault to shut down a facility, or portion of a facility, for hours, days or longer. However, the reliability of the motor system, as well as general motor maintenance and repair, is one of the least understood parts of any maintenance and reliability program.

In order to start and operate an electric motor program, you must have an overview of the motor systems in your facility, the failure modes of those systems, the equipment that can monitor this condition and how to verify the effectiveness of the program. The best method of performing these tasks effectively is to use an RCM based approach followed with a Backfit RCM based approach for reviewing the effectiveness of the program.

The RCM based process involves the identification of the expected functions of the equipment to be used, the identification of the components of the system, the potential faults for each component and the identification of methods to allow the faults to occur, identify the faults or design the faults out of the system. The Backfit RCM process involves the review of failures in the system and history, then the effectiveness of the maintenance processes that had been implemented.

An electric motor system is complex in that it consists of the distribution system, the controls, the motor, the coupling, the driven equipment and the load. For the purposes of this paper, we shall consider a 50 horsepower pump supplying cooling water to a critical process, as we run through an example of how the process may be applied.

The RCM Process

In the first part of the RCM process, critical equipment is selected that will have an effect on process or safety. This is completed by including production, maintenance, operators and an RCM specialist in the associated meetings. In the case of our example, it is determined by the committee that the 50 horsepower cooling pump is critical to the process and should be included in the process. The next step is then to identify potential faults in the pump system by performing an FMEA (Failure Mode and Effects Analysis).

The FMEA involves breaking the system down into components then reviewing the potential faults for each of the components. The chance of each fault is estimated then the impact of each fault is evaluated against the purpose (mission) of the equipment. Following these steps, methods for testing, design or allowing the faults to occur are determined.

Following is an example of a simple FMEA breakdown of components and failure modes:

1. Power Distribution System
   - 1.1. Power Quality
     - 1.1.1. Voltage and Current Harmonics: System heating, degradation of electronic components and controls. Limits are 3% Current and 5% Voltage THD. In our example, this is a strong possibility due to computers, electronic controls and variable frequency drives. It is decided that this could have some impact on overall operations, but little effect on the pump system. It is determined that this condition should be monitored.
     - 1.1.2. Over/Under Voltage Conditions: Can cause winding failure in the motor. It is decided that this is a rare occurrence, but serious. It is determined that this condition should be monitored as the equipment used to evaluate voltage and current harmonics will also accomplish this task.

1.1.3. Voltage Unbalance: Can cause winding failure in the motor. It is determined that this is a possibility and that the impact is severe. It is determined that an electronic overload can be installed in the motor control that can alarm this condition.

1.1.4. Power Factor: Can cause winding overload, cable faults and can exaggerate other electrical faults including voltage sag on motor starting. It is determined that power factor correction has been applied and that no monitoring is required.

1.1.5. Sags/Swells and Transients: It is determined that these are rare and have limited effect on the pump system.

1.1.6. Overload: It is determined that the system is sized correctly and no action is required.

1.2. Transformer Faults (The transformer is a critical part of the system)

1.2.1. Insulation to Ground: Will cause the electrical system to fail. This is considered extremely serious but rare. Monitoring is recommended.

1.2.2. Winding Shorts: Same as insulation to ground. Monitoring is recommended.

1.2.3. Loose Connections: Will cause both a potential electrical problem and can be a fire hazard. It is determined that monitoring is required.

1.2.4. Electrical Vibration: May be the root cause for the other faults. In addition, is a potential noise hazard. It is determined that monitoring is recommended.

1.3. Cables (Critical part of the system)

1.3.1. Thermal Breakdown: Will cause other cable faults due to insulation failure. It is considered both extremely serious and a potential safety hazard, but rare. Monitoring is considered.

1.3.2. Contamination: May cause thermal breakdown, shorts or grounds. Considered common but this type of failure is determined to be rare. Monitoring is considered.

1.3.3. Shorts and Grounds: Will cause failure of the system and is determined to be rare. Monitoring is considered.

1.3.4. Open Connection/Broken Conductors: Will cause failure of the system and is determined to be rare. Monitoring is considered.

2. Controls and Motor Control Center

2.1. Loose Connections: Will cause failure of the system if left uncorrected. Monitoring is required.

2.2. Bad Contacts: Same as loose connections and considered common. Monitoring is required.

2.3. Bad Contactor Coil: Will cause system failure but extremely rare. Monitoring not considered.

2.4. Control Circuit Fuse: Will cause system failure but extremely rare. Monitoring not considered.

2.5. Failure of Power Factor Correction Capacitors: Little to no impact on the electrical system. Monitoring not considered.

3. Electric Motor

3.1. Mechanical Faults

- 3.1.1. Bearings: Normally a long term fault that can be monitored. Considered occasional, but related to normal maintenance practices. A review of greasing practices recommended and monitoring recommended.
- 3.1.2. Bad Mechanical Fits: Same as bearings, usually related. Monitoring considered.
- 3.1.3. Vibration/Unbalance: Will reduce long term reliability. Monitoring considered.

3.2. Electrical Faults

- 3.2.1. Winding Shorts: Normally a long term fault that can be monitored in this size motor. Considered rare. Monitoring recommended.
- 3.2.2. Insulation to Ground Faults: Same as winding shorts, but less frequent. Monitoring recommended.
- 3.2.3. Contamination: Common and will lead to winding shorts, insulation to ground faults and mechanical faults. Considered serious in this application so monitoring is required.
- 3.2.4. Rotor Faults: Nearly non-existent in this size and type of application. Monitoring not considered, but may occur as part of other monitoring practices.
- 3.2.5. Air Gap Faults: Normally the result of mechanical issues such as soft foot, a poor base or faulty assembly. Monitoring is considered.

4. Coupling
   - 4.1. Misalignment: May cause premature failure of system components. Considered extremely rare in cases where the alignment is checked on installation. Monitoring is not considered.
   - 4.2. Insert Wear: Can cause failure of equipment to perform. Considered rare. Monitoring is considered.
5. Pump
   - 5.1. Seals: Will not cause the system to fail, but can cause safety issues due to water leakage. Monitoring is considered.
   - 5.2. Impellor Wear: Will cause the system to eventually not meet operational requirements. Considered rare. Monitoring is recommended.
   - 5.3. Bearings: Normally a long term fault that can be monitored. Considered occasional, but related to normal maintenance practices. A review of greasing practices recommended and monitoring recommended.

The following conclusions can be determined from the review:

1. Future designs of this type of critical process should be considered for a redundancy.
2. Power quality monitoring should be included as part of the Condition Based Monitoring (CBM) program. As this will have some bearing on the operation of the critical equipment, it should be performed semi-annually.
3. Transformer monitoring should also be included as part of the CBM program. It should be performed annually.

4. Cabling should be visually inspected and inspected as an incidental part of the transformer and motor CBM program.
5. In the MCC, contacts should be visually inspected and CBM performed quarterly. An electronic overload should be installed.
6. The motor should have quarterly electrical and mechanical CBM performed. A greasing program should be reviewed and implemented.
7. Monitoring of the coupling should be incidental to the motor and pump CBM. A visual inspection should be performed on the insert quarterly as part of the CBM.
8. Visual monitoring of the pump seal should be performed when inspecting the coupling insert. The impellor and bearings should be inspected as part of the CBM program quarterly.

Once this stage is complete, a review of CBM equipment to accomplish the task should be performed. Of course, this is normally performed following a review of all equipment.

Selection of CBM Equipment

The selection of appropriate condition based monitoring equipment is critical to the success of the program. This requires a review of the technologies and the capabilities of each. Following are a number of the technologies and their applications:

De-Energized Testing:

- ✓ DC High Potential Testing – By applying a voltage of twice the motor rated voltage plus 1,000 volts for AC and an additional 1.7 times that value for DC high potential (usually with a multiplier to reduce the stress on the insulation system), the insulation system between the motor windings and ground (ground-wall insulation) is evaluated. The test is widely considered potentially destructive.[1]
- ✓ Surge comparison testing: Using pulses of voltage at values calculated the same as high potential testing, the impedance of each phase of a motor are compared graphically. The purpose of the test is to detect shorted turns within the first few turns of each phase. The test is normally performed in manufacturing and rewinding applications as it is best performed without a rotor in the stator. This test is widely considered potentially destructive, and is primarily used as a go/no-go test with no true ability to trend.
- ✓ Insulation tester: This test places a DC voltage between the windings and ground. Low current leakage is measured and converted to a measurement of meg, gig or tera-Ohms.

[1] Potentially Destructive: Any instrument that can potentially change the operating condition of the equipment through mis-application or finish off weakened insulation conditions shall be considered potentially destructive.

- ✓ Polarization Index testing: Using an insulation tester, the 10 minute to 1 minute values are viewed and a ratio produced. According to the IEEE 43-2000, insulation values over 5,000 MegOhms need not be evaluated using PI. The test is used to detect severe winding contamination or overheated insulation systems.
- ✓ Ohm, Milli-Ohm testing: Using an Ohm or Milli-Ohm meter, values are measured and compared between windings of an electric motor. These measurements are normally taken to detect loose connections, broken connections and very late stage winding faults.
- ✓ Motor Circuit Analysis (MCA) testing: Instruments using values of resistance, impedance, inductance, phase angle, current/frequency response, and insulation testing can be used to troubleshoot, commission and evaluate control, connection, cable, stator, rotor, air gap and insulation to ground health. Using a low voltage output, readings are read through a series of bridges and evaluated. Non-destructive and trendable readings often months in advance of electrical failure.

Energized Testing:

- ✓ Vibration Analysis: Mechanical vibration is measured through a transducer providing overall vibration values and FFT analysis. These values provide indicators of mechanical faults and degree of faults, can be trended and will provide information on some electrical and rotor problems that vary based upon the loading of the motor. Minimum load requirements for electric motors to detect faults in the rotor. Requires a working knowledge of the system being tested. Can detect bearing wear well in advance of a fault.
- ✓ Infrared analysis provides information on the temperature difference between objects. Faults are detected and trended based upon degree of fault. Excellent for detecting loose connections and other electrical faults with some ability to detect mechanical faults. Readings will vary with load. Requires a working knowledge of the system being tested.
- ✓ Ultrasonic instruments measure low and high frequency noise. Will detect a variety of electrical and mechanical issues towards the late stages of fault. Readings will vary with load. Requires a working knowledge of the system being tested.
- ✓ Voltage and current measurements will provide limited information on the condition of the motor system. Readings will vary with load.
- ✓ Motor Current Signature Analysis (MCSA) uses the electric motor as a transducer to detect electrical and mechanical faults through a significant portion of the motor system. Usually used as a go/no go test, MCSA does have some trending capabilities, but will normally only detect winding faults and mechanical problems in their late stages. Sensitive to load variations and readings will vary based upon the load. Requires nameplate information and many systems require the number of rotor bars, stator slots and manual input of operating speed.

- ✓ Electrical Signature Analysis (ESA) also uses the electric motor as a transducer to detect electrical and mechanical faults. However, with the ability to perform FFT analysis on both current and voltage, ESA allows the operator to look both upstream and downstream of the point of test. Considered very trendable, ESA can detect winding and mechanical faults, through a larger part of the system, much earlier than MCSA.

The full capability of each technology looks at only a portion of the electric motor system. Therefore, the best approach is a combination of technologies. In addition, each technology, when properly applied, supports at least one other technology. The ability to compare test results provides a far more accurate program. Other considerations include: Training requirements; Frequency of testing; Portability; and, Application and purchase costs.

In the case of our example, the motor runs a claimed 24 hours per day, seven days per week. However, during the RCM analysis, it is determined that it can be out of service for up to 60 minutes at a time without a serious impact on operations. As such, it is determined that a look at the full potential of a combined energized and de-energized testing approach could be considered. A series of tables is developed (See Attachment 1) in order to perform comparisons of equipment.

One key issue is determined: Vendor costs varied widely on most 'high tech' test technologies and the costs were not related to the ability or accuracies of the equipment. Therefore, several of the RCM group are tasked with evaluating the vendors of each technology selected.

In this case, the selected technologies are:

- ✓ Vibration Analysis: To detect mechanical conditions as early as possible. Requires training and experience but is an established technology. It is determined that a quarterly check will be performed on the pump.
- ✓ Infrared Analysis: To detect loose connections, some power issues, electrical issues and mechanical faults. As with vibration analysis, it requires training and experience, but is an established technology. It is determined that a semi-annual check will be performed.
- ✓ Electrical Signature Analysis: To check the condition of all electrical components, including power quality analysis, and to support the detection of potential mechanical failures. Requires some training and experience and is an established technology. It is determined that a quarterly check will be performed.
- ✓ Motor Circuit Analysis: To check the condition of all insulation systems including capacitors, cabling, transformer and the early detection of winding shorts and rotor conditions. Requires little training and experience and is an established technology. It is determined that a quarterly check will be performed.

The technologies and technicians are implemented with the plan to perform a Backfit RCM analysis 18 months later to determine its effect.

Root Cause Failure Analysis

During the 18 month period, the system has two critical issues. The first is a large current unbalance which is detected with ESA and Infrared. The second is a detection of early failure of the bearings an average of every six months. In both cases, it is determined that a Root Cause Failure Analysis (RCFA) is required.

During a routine infrared test, which is staggered with the other tests, an unusual overheating is detected on one phase. ESA and MCA are both ordered for additional fault analysis due to the potential safety hazard of a loose connection. ESA detects a sizeable current unbalance while the MCA determines that there are no loose connections and the winding is in good condition. An unusual power factor test result from ESA and high 5^{th} and 7^{th} harmonics are detected. MCA is used to test the power factor correction capacitors and one is found open with a blown fuse. The fuse is replaced and the current unbalance is corrected.

The fault is investigated by the electrical group and it is determined that the fault was caused by electrical resonance from the high harmonics in the electrical system. The power analysis capabilities of the ESA device are used to determine the location of the high harmonic content and filtering applied. ESA is performed on the pump circuit again, and the harmonic content is found to have decreased significantly.

On the baseline vibration analysis of the bearings on both the pump and motor, an early indication of bearing wear is detected. On the following analysis both vibration and ESA detect later stage faults in the motor and progressing bearing failure in the pump. The motor bearings are replaced. Within 6 months, the pump bearings are replaced and the motor bearings show signs of wear. A mechanical group is put together to perform RCFA.

The investigation almost immediately identifies that the problem has to do with improper mixing of grease base types and bearing failures are found to be on the rise plant-wide. Interviews identify that the greasing program had been investigated and implemented. However, the purchasing department was not included in the evaluation and the dangers of mixing different grease types was not communicated. A short course on greasing is set up through a local bearing vendor for both maintenance and purchasing.

Details of both RCFA’s are recorded for later review in the Backfit RCM process.

Backfit RCM Analysis

After 18 months, the decision is to review the tasks using Backfit RCM. Through this process, age degradation of the equipment, applicability of the task and effectiveness of the task are reviewed.

Over the last 18 months, the RCFA and history of the pump is reviewed as part of the Backfit process. In the case of the pump, several components failed, but were caught prior to system unplanned downtime and further damage, using the processes selected. The original assumptions made in the RCM analysis are reviewed.

Through the process, it is determined that at least several of the failure modes occurred. All four selected technologies were used in detecting, analyzing and confirming the corrections implemented. The applied condition based monitoring techniques are found to be effective and the decision is made to continue the existing monitoring practices. In another 12 months, the program will be reviewed again.

Worksheets and records are completed and placed on file.

Program Simple Payback

For the simple payback analysis, we will assume that there are 100 critical systems in the plant of which each has a related downtime cost of $10,000 per hour. The next assumption, based upon historical records, is an average of 8 hours downtime per failure, or $80,000 per failure. The next assumption is that the combined cost per hour of the personnel involved in the RCM committee is $1,000 per hour.

Table 1: Simple Payback Analysis, Expenses

Program/Equipment	Notes	Costs per System
RCM Analysis	Average 8 hours per system	$8,000
CBM Data Analysis	4 hrs per system per year, $50 per hour	$200
Equipment	Infrared, ESA, MCA, Vibration and training	$1,000
Backfit Process	Average 4 hours per system	$4,000
	Total	**$13,200**

The three potential failures in the pump system account for $240,000 in cost avoidance. The result is found in Equation 1:

Equation 1: Simple Payback

$$Payback = \left(\frac{\$13{,}200}{\$240{,}000}\right) * 350 days = 19.25 days$$

Conclusion

In this example of one of 100 critical systems, an overall pump system is evaluated using a classic RCM process. Condition Based Monitoring equipment and personnel are selected and the process implemented. Root cause failure analysis is implemented to review several CBM detected failures. The next step is a Backfit RCM process review to determine the effectiveness of the existing program. Utilizing conservative numbers, a simple payback of 19.25 days is realized.

About the Author

Dr. Penrose joined T-Solutions, Inc. in January of 2005, following over twenty years in the electrical equipment repair, field service and research and development fields. Starting as an electric motor repair journeyman in the US Navy, Dr. Penrose lead and developed motor system maintenance and management programs within industry for service companies, the US Department of Energy, utilities, states, military, and many others. Most recently he led the development of Motor Diagnostic technologies within industry as the General Manager of the leading manufacturer of Motor Circuit Analysis and Electrical Signature Analysis instruments and training. Dr. Penrose taught engineering at the University of Illinois at Chicago as an Adjunct Professor of Mechanical and Industrial Engineering as well as serving as a Senior Research Engineer at the UIC Energy Resources Center performing energy, reliability, waste stream and production industrial surveys. Dr Penrose has repaired, troubleshot, designed, installed or researched a great many technologies that have been, or will be, introduced into industry. He has coordinated US DOE and Utility projects including the industry-funded modifications to the US Department of Energy's MotorMaster Plus software in 2000 and the development of the Pacific Gas and Electric Motor System Performance Analysis Tool (PAT) project.
Dr. Penrose is the Vice-Chair of the Connecticut Section IEEE (Institute of Electrical and Electronics Engineers), a Past-Chair of the Chicago Section IEEE, Past Chair of the Chicago Section Chapters of the Dielectric and Electrical Insulation Society and Power Electronics Society of IEEE, is a member of the Vibration Institute, Electrical Manufacturing and Coil Winding Association, the International Maintenance Institute, NETA and MENSA. He has numerous articles, books and professional papers published in a number of industrial topics and is a US Department of Energy MotorMaster Certified Professional, as well as a trained vibration analyst, infrared analyst and motor circuit analyst.

Table 2: Motor System Diagnostic Technology Comparison

	PQ	Cntrl	Conn	Cable	Stator	Rotor	Air Gap	Brgs	Ins	Vibe	Align	Load	VFD
Off-Line Testing													
High Potential Testing	-	-	-	-	-	-	-	-	X	-	-	-	-
Surge Test	-	-	-	-	X	-	-	-	-	-	-	-	-
Insulation Tester	-	-	-	-	-	-	-	-	X	-	-	-	-
Ohm Meter	-	-	L	-	L	-	-	-	-	-	-	-	-
PI Testing	-	-	-	-	-	-	-	-	X	-	-	-	-
MCA Test	-	X	X	X	X	X	X	-	X	-	-	-	-
On-Line Testing													
Vibration Analysis	-	-	-	-	L	L	L	X	-	X	X	X	-
Infrared	X	X	X	L	L	-	-	L	-	-	L	L	-
Ultrasonics	-	L	-	-	L	-	-	X	-	-	-	L	-
Volt/Amp	L	L	L	-	L	L	-	-	-	-	-	-	-
MCSA	L	L	L	-	L	X	X	L	-	L	L	L	L
ESA	X	X	X	-	X	X	X	L		X	X	X	X

Table 3: Management Considerations

Test Method	Estimated Pricing	Non-Destructive	Requires Experience	Dedicated Personnel	Included Software	Other Applications
Off-Line Test						
High Potential	$10,000 +	Potentially Destructive	High	Recommend	No	No
Surge Test	$25,000 +	Potentially Destructive	High	Recommend	Some	No
Insulation Tester	$1,000 +	(NDT) Non-Destructive	Some	No	No	Yes
Ohm Meter	$500 +	(NDT)	Some	No	No	Yes
PI Tester	$2,500 +	(NDT)	Medium	No	Some	No
MCA	$1,000/ $9,000 +	(NDT)	Some	No	Yes	Yes
On-Line Test						
Vibration	$10,000 +	(NDT)	High	Recommend	Yes	Yes
Infrared	$10,000 +	(NDT)	High	Recommend	Yes	Yes
Ultrasonics	$10,000 +	(NDT)	High	Recommend	Some	Yes
Volt/Amp	$500 +	(NDT)	Some	No	No	Yes
MCSA/ESA	$16,000 +	(NDT)	High	Recommend	Yes	Yes

Table 4: Common Approaches

	PQ	Cntrl	Conn	Cable	Stator	Rotor	Air Gap	Brgs	Ins	Vibe	Align	Load	VFD
Insulation Resistance and PI	-	-	-	L	-	-	-	-	X	-	-	-	-
Infrared and Vibration	L	X	X	L	L	L	L	X	-	X	X	X	-
Surge and Hi-Pot	-	-	-	-	X	-	-	-	X	-	-	-	-
MCA and ESA	X	X	X	X	X	X	X	X	X	X	X	X	X
MCA and Infrared / Vibe	L	X	X	X	X	X	X	X	X	X	X	X	L

PQ – Power Quality; Cntrl – Control issues/contacts; Conn – Loose/damaged connections; Cable – Shorts and grounds; Stator – Shorted windings; Rotor – Broken/damaged bars; Air Gap – Rotor eccentricity; Brgs- bearing faults; Ins – Insulation to ground faults; Vibe – Unbalance and other vibration faults; Align – Misaligned direct shaft and insert or belts; Load – Load related faults such as impellor or bearing wear in a pump; VFD – Variable Frequency Drive faults.

Table 5: Additional Considerations

Test Method	Where Can You Test
High Potential Testing	At Motor – Requires disconnect
Surge Test	At Motor – Requires disconnect
Insulation Tester	From MCC
Ohm Meter	At Motor – Requires disconnect
PI Testing	At Motor – Disconnect Recommended
MCA Test	From MCC
Vibration Analysis	At each location tested
Infrared	At each location tested
Ultrasonics	At each location tested
Volt/Amp	From MCC
MCSA/ESA	From MCC

More motor testing resources are located at Reliabilityweb.com