The Multi-Technology Approach to Motor Diagnostics

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Introduction

There has been a persistent misconception that there is a 'magic bullet,' in the form of a Condition Based Monitoring (CBM) instrument, that will provide all of the information that you need to evaluate the health of your electric motor system. This misconception is often brought about by the commercial presentations of the manufacturers or sales forces of these CBM instruments. It is the very job of the salesperson to focus on the area of strength for their particular instrument(s) and present it as 'the only solution you will ever need to solve your every problem.'

In reality, there is no one instrument that will provide you with every piece of information that you need. No 'Holy Grail' of CBM and reliability. However, through an understanding of the electric motor system, and the capabilities of CBM technologies, you can have a complete view of your system, its health and have confidence in estimating time to failure in order to make a good recommendation to management.

The purpose of this paper is simple: Outline the components of an electric motor system; Discuss the modes of failure of each major component; Discuss how each of the major technologies address each component; Discuss how the technologies can be integrated for a complete view of the system; and, Discuss the bottom-line impact of the Multi-Technology approach. The types of CBM equipment to be reviewed are standard off-the-shelf technologies that are used for periodic testing.

The Electric Motor System

The electric motor system involves far more than just the electric motor. In fact, it is made up of six distinct sections, all with their different failure modes. The sections are:

- ✓ The facility power distribution system which includes wiring and transformers.
- ✓ The motor control, which may include starters, soft starts, variable frequency drives and other starting systems.
- ✓ The electric motor – A three phase induction motor for the purpose of this paper.
- ✓ The mechanical coupling, which may be direct, gearbox, belts or some other coupling method. For the purpose of this paper, we will focus on direct coupling and belts.
- ✓ The load refers to the driven equipment such as a fan, pump, compressor or other driven equipment.
- ✓ The process, such as waste-water pumping, mixing, aeration, etc.

Most will view individual components of the system when troubleshooting, trending, commissioning or performing some other reliability-based function related to the system. What components are focused on depends upon several factors, which include:

- ✓ What is the experience and background of the personnel and managers involved. For instance, you will most often see a strong vibration program when the maintenance staff is primarily mechanical, or an infrared program when the staff is primarily electrical.
- ✓ Perceived areas of failure. This can be a serious issue depending upon how the motor system is perceived and will deserve more attention to follow.
- ✓ Understanding of the various CBM technologies.
- ✓ Training. But since when is training ever not an issue?

The perceived areas of failure provides an especially serious problem when viewing the history of your motor system. Often, when records are produced, the only summary might state something like, "fan failure, repaired," or "pump failure, repaired." The end result is that the perceived failure has to do with the pump or fan component of the motor system. This especially becomes more of an issue when relying upon memory to provide the answers to the most serious problems to be addressed in a plant, based upon history. For instance, when looking to determine what part of a plant has been causing the most problems, the answer might be, "Waste water pump 1." The immediate perception is that the pump has a consistent problem and, as a pump is a mechanical system, a mechanical monitoring solution might be selected for trending the pump's health. If a root-cause had been recorded on each failure, it might have been determined to be the motor winding, bearings, cable, controls, process or a combination of issues.

In a recent meeting, while discussing the selection of CBM equipment, the attendees were asked for modes of failure from their locations. The answers were fans, compressors and pumps. When discussed further, the fans were found to have bearing and motor winding faults being most common, pump seals and motor bearings for pumps, and, seals and motor windings for compressors. When viewed even closer, the winding faults had to do with control and cable problems, improper repairs and power quality. Bearing issues had to do with improper lubrication practices.

In effect, when determining the best way to implement CBM on your electric motor system, you need to take a system, not a component, view. The result is simple: Improved reliability; Fewer headaches; and, An improved bottom line.

Condition Based Monitoring Test Instruments

Following are some of the more common CBM technologies in use, more detail on the technologies can be found in "Motor Circuit Analysis"[1] Details as to the components of the system tested and capabilities can be found in Tables 1-4 at the end of this paper:

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.[2]
- ✓ 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.
- ✓ 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.
- ✓ 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 combinations of values for resistance, impedance, inductance, phase angle, current:frequency response, capacitance 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. Note: Different manufacturers of this technology use different combinations of test values.

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

[1] Motor Circuit Analysis: Theory, Application and Energy Analysis, Howard W. Penrose, Ph.D., SBD Publishing, ISBN: 0-9712450-0-2, 2002.

[2] 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.

motors to detect faults in the rotor. Requires a working knowledge of the system being tested.

- ✓ 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.
- ✓ Electrical Signature Analysis (ESA) 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, ESA does have some trending capabilities, but will normally only detect winding faults and mechanical problems in their late stages. Some manufacturers are 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.

Major Components and Failure Modes

Some of the major issues from the various components of the motor system shall be reviewed in order to provide an understanding of the types of faults found and the technologies used to detect them. As an overview, this may not encompass all of the modes of failure that you may experience.

Incoming Power

Starting from the incoming power to the load, the first area that would have to be addressed is the incoming power and distribution system. The first area of issue is power quality then transformers.

Power quality issues associated with electric motor systems include:

- ✓ Voltage and current harmonics: With voltage limited to 5% THD (Total Harmonic Distortion) and current limited to 3% THD. Current harmonics carry the greatest potential for harm to the electric motor system.
- ✓ Over and under voltage conditions: Electric motors are designed to operate no more than +/- 10% of the nameplate voltage.
- ✓ Voltage unbalance: Is the difference between phases. The relationship between voltage and current unbalance varies from a few time to many times current unbalance as related to voltage unbalance based upon motor design (Can be as high as 20 times).
- ✓ Power factor: The lower the power factor from unity, the more current the system must use to perform work. Signs of poor power factor also include dimming of lights when heavy equipment starts.
- ✓ Overloaded system: Based upon the capabilities of the transformer, cabling and motor. Detected with current measurements, normally, as well as heat.

The primary tools used to detect problems with incoming power are power quality meters, ESA and voltage and current meters. Knowing the condition of your power quality can help identify a great many ‘phantom’ problems.

Transformers are one of the first critical components of the motor system. In general, transformers have fewer issues than other components in the system. However, each tranformer usually takes care of multiple systems both in the electric motor as well as other systems.

Common transformer problems include (oil filled or dry-type transformers):

- ✓ Insulation to ground faults.
- ✓ Shorted windings.
- ✓ Loose connections, and,
- ✓ Electrical vibration/mechanical looseness

Test equipment used for monitoring the health of transformers (within the selection of instruments within this paper) include:

- ✓ MCA for grounds, loose/broken connections and shorts
- ✓ ESA for power quality and late stage faults
- ✓ Infrared analysis for loose connections
- ✓ Ultrasonics for looseness and severe faults
- ✓ Insulation testers for insulation to ground faults.

MCC's, Controls and Disconnects

The motor control or disconnect provides some of the primary issues with electric motor systems. The most common for both low and medium voltage systems are:

- ✓ Loose connections
- ✓ Bad contacts including pitted, damaged, burned or worn
- ✓ Bad starter coils on the contactor
- ✓ Bad power factor correction capacitors which normally results in a significant current unbalance.

The test methods for evaluating the controls include infrared, ultrasonics, volt/amp meters, ohm meters and visual inspections. MCA, ESA and infrared provide the most accurate systems for fault detection and trending.

Cables – Before and After the Controls

Cabling problems are rarely considered and, as a result, provide some of the biggest headaches. Common cable problems include:

- ✓ Thermal breakdown due to overloads or age
- ✓ Contamination which can be even more serious in cables that pass underground through conduit
- ✓ Phase shorts can occur as well as grounds. These can be caused by 'treeing' or physical damage.
- ✓ Opens due to physical damage or other causes.
- ✓ Physical damage is often a problem in combination with other cable problems.

Test and trending is performed with MCA, infrared, insulation testing and ESA.

Motor Supply Side Summary

On the supply side to the motor, the problems can be broken down as follows:

- ✓ Poor power factor – 39%
- ✓ Poor connections – 36%
- ✓ Undersized conductors – 10%
- ✓ Voltage unbalance – 7%
- ✓ Under or over voltage conditions – 8%

The most common equipment that covers these areas include MCA, infrared and ESA.

Electric Motors

Electric motors include mechanical and electrical components. In fact, an electric motor is a converter of electrical energy to mechanical torque.

Primary mechanical problems:

- ✓ Bearings – general wear, misapplication, loading or contamination.
- ✓ Bad or worn shaft or bearing housings
- ✓ General mechanical unbalance and resonance

Vibration analysis is the primary method for detection of mechanical problems in electric motors. ESA will detect late stage mechanical problems as will infrared and ultrasonics.

Primary electrical problems:

- ✓ Winding shorts between conductors or coils
- ✓ Winding contamination
- ✓ Insulation to ground faults
- ✓ Air gap faults, including eccentric rotors
- ✓ Rotor faults including casting voids and broken rotor bars.

MCA will detect all of the faults early in development. ESA will detect late stage stator faults and early rotor faults. Vibration will detect late stage faults, insulation to ground will only detect ground faults which make up less than 1% of motor system faults, surge testing will only detect shallow winding shorts and all other testiing will only detect late stage faults.

Coupling (Direct and Belted)

The coupling between the motor and load provides opportunities for problems due to wear and the application.

- ✓ Belt or direct drive misalignment
- ✓ Belt or insert wear
- ✓ Belt tension issues are more common than most think and usually result in bearing failure
- ✓ Sheave wear

The most accurate system for coupling fault detection is vibration analysis. ESA and infrared analysis will normally detect severe or late stage faults.

Load (Fans, pumps, compressors, gearboxes, etc.)

The load can have numerous types of faults depending on the type of load. The most common are worn parts, broken components and bearings.

Test instruments capable of detecting load problems include ESA, vibration, infrared analysis and ultrasonics.

Common Approaches to Multi-Technology

There are several common approaches within industry as well as several new ones (See Table 3). The best use a combination of energized and de-energized testing. It is important to note that energized testing is usually best under constant load conditions and trended in the same operating conditions each time.

One of the most common approaches has been the use of insulation resistance and/or polarization index. These will only identify insulation to ground faults in both the motor and cable, which represents under 1% of the overall motor system faults (~5% of motor faults).

Infrared and vibration are normally used in conjunction with each other with great success. However, they miss a few common problems or will only detect them in the late stages of failure.

Surge testing and high potential testing will only detect some winding faults and insulation to ground faults, with the potential to take the motor out of action should any insulation contamination or weakness exist.

MCA and ESA support each other and detect virtually all of the problems in the motor system. This accuracy requires MCA systems that use resistance, impedance, phase angle, I/F and insulation to ground and ESA systems that include voltage and current demodulation.

The newest, and most effective, approach has been vibration, infrared and MCA and/or ESA. The strength of this approach is that there is a combination of electrical and mechanical disciplines involved in evaluation and troubleshooting. As found in the Motor Diagnostic and Motor Health Study,[3] 38% of motor system testing involving only vibration and/or infrared see a significant return on investment. This number jumped to 100% in systems that used a combination of MCA/ESA along with vibration and/or infrared.

In one case, a combined application of infrared and vibration saw an ROI of $30k. When the company added MCA to their tool box, the ROI increased to $307,000, ten times the original by using a combination of instruments.

Application Opportunities

There are three common opportunities for electric motor system testing. These include:

- ✓ Commissioning components or the complete system as it is newly installed or repaired. This can provide a very immediate payback for the technologies involved and will help you avoid infant mortality disasters.
- ✓ Troubleshooting the system through the application of multiple technologies will assist you in identifying problems much more rapidly and with greater confidence.
- ✓ Trending of test results for system reliability, again using the proper application of multiple technologies. Using tests such as MCA, vibration and infrared, potential faults can be trended over the long term, detecting many faults months in advance.

Conclusion

This paper provided a brief overview of how multiple technologies work together to provide a good view of the electric motor system. Through an understanding and application of this approach, you will realize fantastic returns on your maintenance program.

About the Author

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[3] Motor Diagnostic and Motor Health Study, Penrose and O'Hanlon, SBD Publishing, 2003.

Table 1: 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	-	-	-	-	-	-	-
ESA	X	X	L	-	L	X	X	L	-	X	X	X	L

Table 2: 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
ESA	$16,000 +	(NDT)	High	Recommend	Yes	Yes

Table 3: 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

Table 4: 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**
ESA	**From MCC**

Definitions

- PQ: Power Quality Condition
- Cntrl: Control faults
- Conn: Loose or open connections
- Cable: Shorted or degraded cable
- Stator: Winding faults (shorts)
- Rotor: Open rotor bars
- Air Gap: Eccentricity, static and dynamic
- Brgs: Bearing degradation
- Ins: Insulation to ground (MegOhm) failure
- Vibe: Faults that result in mechanical vibration
- Align: Misalignment
- Load: Driven equipment faults and condition
- VFD: Variable frequency drive faults