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MOTOR CIRCUIT ANALYSIS (MCA) TESTING – AN UNDERSTANDING OF IT'S VALUE TO YOUR BUSINESS

The basics of motor circuit analysis

(Acknowledgement: Article by Andy Page)

(Andy Page is the director of Allied Reliability's training group, which provides education in reliability engineering topics such as root cause analysis, Reliability-Centered Maintenance and integrated condition monitoring. He has spent 15 years in the maintenance and reliability field, holding key positions at Noranda Aluminum (maintenance engineer) and Martin Marietta Aggregates (asset reliability manager). Andy has an engineering degree from Tennessee Tech and is a Certified Maintenance and Reliability Professional (CMRP) through the Society for Maintenance and Reliability Professionals (SMRP). Contact him at pagea@alliedreliability.com.)

Quite a bit of confusion exists on the subject of motor circuit analysis. The confusion is centered on two issues:

1. The very name of the technology.
2. What this technology is capable of.

This article will focus on alleviating that confusion with a discussion of the technology's capabilities and its proper name.

One of the biggest reasons why confusion exists about the very name of this testing methodology is the prevalent use of three-letter acronyms (TLAs) in the condition monitoring industry. We have TLAs for everything: CBM (condition-based monitoring), PdM (predictive maintenance), RCA (root cause analysis), FFT (Fast Fourier Transform), etc., etc.

It is the pervasiveness of TLAs that has created this confusion around motor circuit analysis. MCA can mean two different things. Motor circuit analysis (MCA) is often and easily confused with motor current analysis (MCA), which is an abbreviated version of motor current signature analysis (MCSA). This is a common mistake and one that has contributed to the confusion surrounding the second common mistake. For the balance of this article, the term motor circuit analysis will be referred to as MCA.

The second common mistake lies in the confusion around the capabilities of this technology for condition monitoring and testing. For those who have mistakenly associated MCA with motor current signature analysis, the belief is that the only type of testing performed is on the motor current. While a portion of this is correct, current analysis is just a part of the total testing barrage that is collectively known as MCA. There is a second group of people that believe MCA only pertains to measuring the motor circuit's resistance-to-ground characteristics. This belief also reflects an incomplete understanding of the spectrum of tests covered under MCA. While MCA does incorporate these aforementioned testing techniques, it also includes much more.

Before we go any further, let us clarify the ultimate goal of MCA. The goal of MCA is to ascertain the health of the motor. This assessment is accomplished through the detection of electrical imbalances in the motor and

the detection of insulation degradation. The unbalances create stray, circulating currents through the motor. These circulating currents create excessive heat and lead to accelerated insulation degradation, inefficient operation and ineffective control techniques (in some motor types). Insulation degradation leads to shortened motor life and can lead to unsafe operating conditions.

To begin, let us break up MCA into two major categories. The first category is online testing, named because the tests are conducted while the motor is operating under normal conditions. The second category is offline testing; tests are conducted while the motor is de-energized.

MCA online can be further split into two categories - current analysis and voltage analysis. Current analysis is primarily focused on the rotating components. Loose or broken rotor bars, cracked end rings, rotor eccentricity, misalignment and coupling/belt problems are some of the "big-hitter" failure modes detected in the current signature. Power quality issues like harmful harmonics, voltage imbalances and under/over-voltages are among the issues identified with voltage analysis.

MCA offline is most famous for the resistance-to-ground measurement. But other measurements make motor circuit defects easy to find. Measuring electrical characteristics like impedance, inductance and capacitance tell the analyst plenty about the condition of the windings. Inductance is a great indicator of turn-to-turn shorts. Capacitance to ground measures the amount of winding contamination (water, dirt, dust, etc.). Changes in each of these affect impedance (total resistance of an AC circuit). These characteristics are measured phase to phase and phase to ground and compared to each other and to percent change from baseline to identify motor circuit defects.

Some of the tests can serve as one-time go/no-go types of inspection. Some must be trended over time to understand the defect progression. The best strategy is the testing of motors on a set schedule. This allows you to properly trend these characteristics and gives the reliability program the best conditional probability of finding motor circuit defects.

All of the failure modes listed are very real and create unplanned downtime. A comprehensive, failure modes-driven maintenance strategy for electric motors incorporates all of these test methods.

How many are you using to effectively and efficiently ensure your operation's production capacity?

(So far Andy Page. Thank you.)

The cost component of off-line motor circuit analysis (motor installed)

Motor circuit analysis (MCA) – to the less-informed – appears a costly exercise. A substantial contributor to this “feeling” of being expensive is limited understanding of the process and the extent to which MCA tests interrogate and report on a motor's condition. It is a superior test programme to simple megger testing which only provides a momentary glimpse at the condition of a motor's insulation, but provides no information about other developing conditions within the motor. MCA test results, if understood correctly, not only give DC resistance, impedance, inductance, phase angle, I/F and insulation resistance results, but can also provide information of developing mechanical issues within the motor, such as rotor and shaft faults.

Electric Motor Solutions Pty Ltd Specialist Testing Services has been conducting on-site MCA testing for approximately five years now. In that time we have successfully advised clients on the condition of their motors up to and beyond 400kW.

One of the most beneficial and satisfying aspects of on-site MCA testing is the ability to determine if the problem in an installation is motor related, or may be control or cable or site supply related. Cost savings achieved by not removing a motor unnecessarily for maintenance, only to find the problem is still present after motor refurbish and re-installation, can be substantial. Another beneficial aspect of on-site MCA testing is being able to clear a motor of winding damage in the event of supply or control equipment failure, and thus avoid unnecessary removal. On-site MCA testing is also of benefit in understanding motor condition prior to moving transportable equipment to sites remote from base.

Any on-site MCA test conducted by **Electric Motor Solutions Pty Ltd Specialist Testing Services** includes for the on-site test and provision of a written report showing computer analysis of the test results achieved.

This is included in the cost per motor charge for this service. The minimum cost per motor for this service may vary depending on motor size and the extent to which site services need to be disconnected to achieve a sound result. Installations controlled by VSD or soft-starter will more than likely require disconnection (we recommend it) to overcome the tendency for gated solid state devices to close and give obscure results.

Computer analysis and averaging of data accumulated in the last five years has been plotted and provides the following information:-

1. Motors sized 22kW and smaller cost 10% or more of the purchase price of a new motor (at the EMS selling price) to provide a test and report. And
2. Motors sized 30kW and above cost less than 10% of the purchase price of a new motor (at the EMS selling price) to provide a test and report. As the motor size increases the cost can drop below 2% of the purchase price.

This means that:-

1. Only critical specials sized 22kW or lower need be tested. Furthermore, dependent on a client's access to supply of new motors and the critical nature of a particular motor within a plant, critical (new) spares should be held in client's inventory.
2. It can be beneficial to adopt an MCA test regime within a plant for motors 30kW and above, especially for those units where downtime costs can far outweigh the cost of the MCA test programme.

In conclusion, MCA test and report costs are 'motor size' dependant due to the additional time considerations necessary for larger motors (VSD's, soft-starters, disconnects, larger distances between controls and plant). The percentage impact of these costs, however, diminishes as the motor size (and by default it's importance to the process) increases.

It is important to understand for ANY type of motor testing that:-

- Results show a snapshot of the motor condition at the time of test. No guarantees can be given or implied that events or circumstances beyond our control prior to or subsequent to the tests will not later impact on the motor condition after the tests are completed.
- The performance and reliability of the motor is also dependent on the condition of associated load and control equipment. Tests and reports do not draw conclusions on the effect this equipment might have on the reliability of the motor.

(Refer also to “**nps46 A Presentation by HW Penrose**” which dwells at some length on the technology and how it can benefit your business.)

(“**Cost relationship curve – on-site MCA tests**” also forms part of this article.)



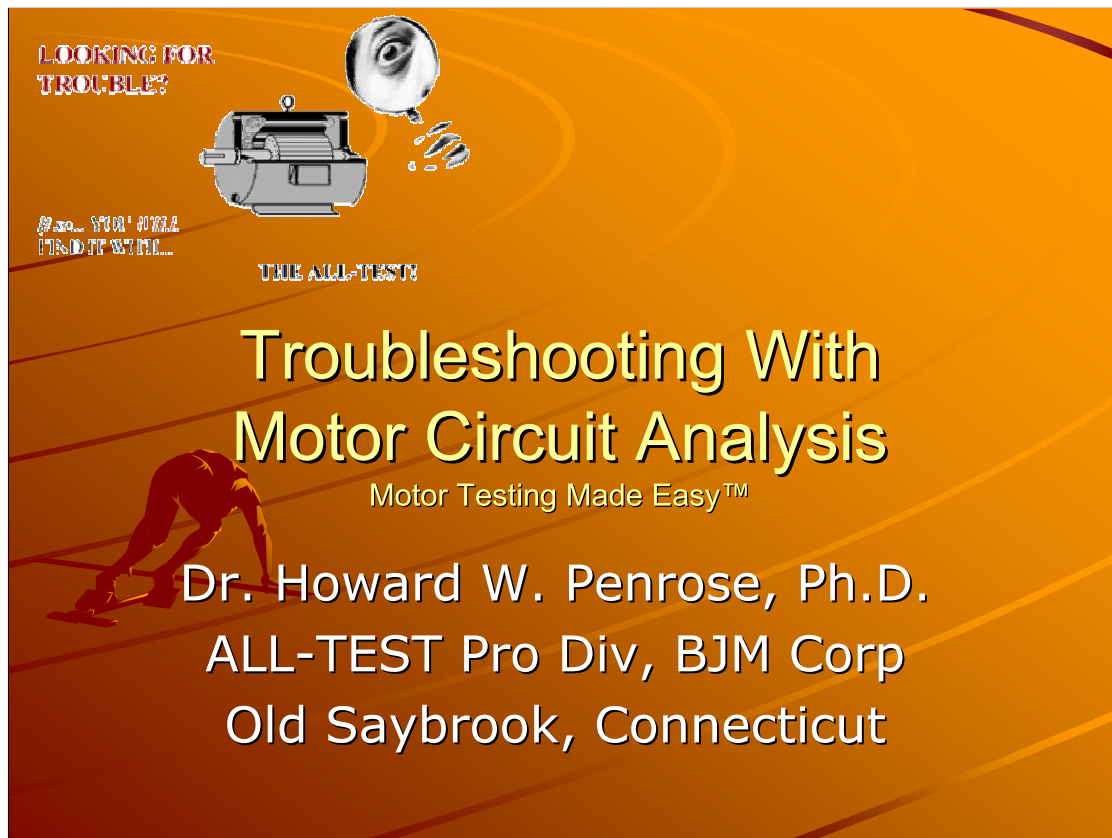
Kindest regards

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Discuss your motor and control needs from a professional perspective. We support, sell, service and recommend many products, including:-





Motor Testing Made Easy™ is a presentation brought to you by ALL-TEST Pro, A division of BJM Corp. Your presenter is Dr. Howard Penrose, the leading expert in motor circuit analysis.

BJM Corp is a cutting edge manufacturer of electrical submersible pumps and motor circuit analysis equipment. Established 1983 in Old Saybrook, Connecticut by Steve Bjorkman, BJM Corp added motor circuit testing to its equipment line to, initially, test its own equipment as part of QA, and to test submersible pumps in place and in repair. The ALL-TEST Pro division introduced its equipment to general industry in 1985 with the analog ALL-TEST CWT II, which was heavily used by the elevator and nuclear industry. In 1993, it introduced the ALL-TEST III, which quickly won the Plant Engineering Product of the Year award. In 1996, ALL-TEST introduced the ALL-TEST IV PRO, which won the 1996 Plant Engineering Product of the Year award. ALL-TEST has continued by developing data interpretation standards that are so precise simple software packages can be used to interpret and trend data for any type of AC/DC electric motor, transformer or coil. These packages are available for Windows PC's, laptops and pocket PC's.

Dr. Penrose joined ALL-TEST Pro in 1999 following fifteen 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, and many others. Dr. Penrose taught engineering at the University of Illinois at Chicago as well as serving as a Senior Research Engineer in the 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, including the coordination of the industry-funded modifications to the US Department of Energy's MotorMaster Plus software in 2000. 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 trained vibration analyst, infrared analyst and motor circuit analyst.

Above all, Dr. Penrose's focus is to take complex engineering and scientific matters and present them in an easy to understand manner.

Presentation Outline

- ◆ Overview of Testing
- ◆ Financial Impact of MCA
- ◆ Cause of Failure
- ◆ Evaluating Three Phase Motors
- ◆ Evaluating Induction Motor Rotors
- ◆ Evaluating Servo and Brushless DC Motors

In the first of four presentations being presented this year, we introduced the basics of motor circuit analysis which included: Where it is used; What it can detect; How data is interpreted; MCA related industry standards; and, Case studies.

In the next two presentations we will cover: MCA for predictive maintenance and reliability and software applications. We will also discuss estimated time to failure after a fault is detected using MCA for predictive maintenance.

In this presentation, we will cover:

- A quick overview of the test limits, pass/fail values, and detection capability of motor circuit analysis.
- The financial impact of using motor circuit analysis for troubleshooting.
- Causes of failures and presentation of the three stages of motor winding failure
- Evaluating three phase motors
- Evaluating induction motor rotors.
- Evaluating servo motors and brushless DC motors

Testing Overview

- ◆ Resistance – Loose/High Resistance
- ◆ Impedance/Inductance
 - Phase Unbalance
 - Winding Contamination
 - Rotor Testing
- ◆ Phase Angle and I/F – Shorted Windings
- ◆ Insulation Resistance – Faults to Ground

As presented in the first presentation, data interpretation is very simple:

- Resistance is used to detect loose and high resistance connections. Unbalance should be less than 3-5%.
- Impedance and inductance are used to detect phase unbalances, winding contamination and used for rotor testing. Phase unbalances are normal when an electric motor rotor is in one position, especially in smaller low voltage motors. When comparing the phases from a single reading at the motor, or from an MCC or disconnect, the cause of phase unbalance can be determined. If they follow a similar pattern, for example inductance readings are low, medium and high, and impedance readings are low, medium and high, then the unbalance is due to the position of the rotor and the winding is in good condition. If they do not, such as inductance showing low, medium and high and impedance showing high, low and medium, then the unbalance is due to winding contamination or overheated windings (such as in single phasing or overheated conditions). Also, by taking inductance or impedance readings over equal positions of the rotor, data can be used to detect casting voids, broken or fractured rotor bars, eccentric rotors and more rotor fault conditions.
- Phase Angle and Current/Frequency response tests are used to detect turn-to-turn, coil-to-coil and phase-to-phase winding faults. The phase angle should be within one digit of the median reading, current/frequency should be within 2 digits of the median reading. If both measurements are bad, the fault is a turn to turn fault; If the phase angle is bad and the current/frequency is good, then the fault is most likely a coil to coil fault; and, If the phase angle is good and the current/frequency is bad, then the fault is most likely a phase to phase fault.
- Insulation to ground testing is used to detect continuity between conductors and ground. As per the IEEE Std 43-2000, for random wound motors manufactured after 1974, the insulation resistance should be over 5 MegOhms; For form wound motors and DC armatures, the insulation resistance should be over 100 MegOhms; and, for motors manufactured before 1974, the insulation resistance should be 1 Megohm plus 1 MegOhm per kV rating of the motor. For example, a 480 Volt motor manufactured before 1974, should have an insulation resistance of over 1.5 MegOhms.

These test limits and pass/fail values are applicable for any three phase motor compared between phases, when comparing like motors to each other, including like DC motors and single phase/three phase coils.

Industry Average Downtime Costs*, per hour

Industry	Avg Cost per Hour
Forest Products	\$7,000
Food Processing	\$30,000
Petro-Chemical	\$87,000
Metal Casting	\$100,000
Automotive	\$200,000

***US DOE Best Practices Program in US Dollars**

When considering the cost impact of troubleshooting with motor circuit analysis, you must know a number of key items. These include: The impact of lost production time, repair parts and associated time. In particular, if you know the particular production impact of the loss of the equipment associated with the electric motor or fault.

This chart represents the average per hour downtime costs in US Dollars associated with specific industries. In many cases, unfortunately, the common method for troubleshooting is to replace parts until a problem is found. In worse conditions, if the fault is not identified immediately, the equipment is nursed along until it fails catastrophically, possibly damaging other parts of the equipment. In the meantime, production is not operating at optimum, having a significant impact on throughput.

Very accurate maintenance income due to early fault detection can be determined when historical data is available on similar faults.

Financial Impact of Troubleshooting with MCA

◆ Time from MCA vs Traditional Methods

- Hours x cost/hour = Troubleshooting Cost A
- 0.25 hours x cost/hour = Troubleshooting Cost B
- Cost A - Cost B = Earnings

◆ Test Equipment on Receipt

- ~5 minutes per motor
- Install/Remove time x cost/hour = Earnings

◆ Application of MCA is Purchasing Time on Production



Evaluating equipment before Installation at Vermont Yankee Nuclear station

Maintenance and maintenance applications should not be considered an expense. They are actually an investment in the available time that production equipment is available. Motor circuit analysis is one of the tools that are used in order to quickly and accurately identify faults. The key to de-energized testing with equipment, such as ALL-TEST, is that motors can be troubleshot when they stop operating.

In the first case, the Return on Investment for the application of motor circuit analysis can be determined when troubleshooting. Determine the time to troubleshoot a similar failure, including the time and trouble to confirm the finding. Multiply the time, in hours, with the cost/hour of the application. For instance, in a tripping problem on a VFD, time is spent trying to determine the fault, including removing and installing a new drive, only to find that the problem still persisted. Assuming a conservative estimate of 6 hours troubleshooting and a cost per hour of \$4,995, the Troubleshooting Cost A would be: \$29,970. After which, the problem turned out to be a turn to turn short in the end turns of the electric motor that was not detected using an ohm meter and insulation resistance tester and only found after the motor was replaced as part of the troubleshooting process. If the motor had been evaluated using MCA, the initial troubleshooting would have taken 0.25 hours, with an estimate of \$1,250 for an overall maintenance earning of \$28,720.

Another method for using MCA to improve the availability of production equipment is to evaluate the condition of the equipment before it is installed. For instance: A 50 horsepower motor is installed before a problem with the winding is determined. It takes four hours to install, align and connect the motor, the fault is determined and the motor is removed in two hours. Through early detection of the problem, the warranty can be addressed with fewer questions (ie: the application caused the problem) and in a timely manner with six hours of production earned.

Numbers tend to be even more significant when applied to medium and high voltage motors. Such as a calculated earnings through the detection of faulted rotor field coils in an 8,000 hp, 200 RPM, 13.2 kV synchronous motor being in excess of \$2,000,000 by reducing troubleshooting time from 48 hours to approximately one hour, in this case (reference the case study in the first Motor Testing Made Easy presentation).

Time Saving Example (Automotive Plant)

Proactive Cost

labor & down \$ 4405

repair cost \$ 1500

TOTAL \$ 5905

Reactive Cost

labor & down \$ 7380

repair cost \$ 2537

TOTAL \$ 9917



Total Cost Avoidance

Reactive cost \$ 9917

(minus) Proactive cost \$ 5905

Net Cost Avoidance \$ 4012

In this example, a machine tool motor at an automotive manufacturer has an issue. The problem is found quickly through detection of the fault early enough to provide a more minor repair than if it was left in operation longer and allowed to fail catastrophically.

When the history of a similar fault was found it was determined the costs had been a total of \$9,917 in combined downtime and repair costs. In the proactive fault detection, the problem was found quickly with an ALL-TEST IV PRO, with a combined downtime and repair cost of \$5,905. This resulted in a cost avoidance of \$4,012. In 3 months, at this particular plant, maintenance income using just one instrument on all motor problems in just one department, the following was calculated:

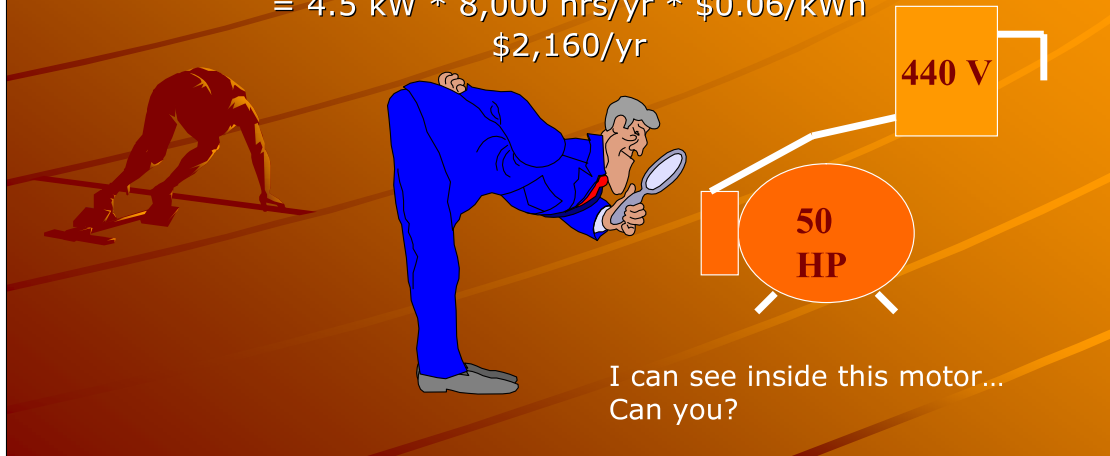
- Calculated historical troubleshooting costs: \$229,734 (Oct – Dec, 2001)
- Actual costs when using MCA: \$13,354 (Oct – Dec, 2001)
- Maintenance income: \$216,380 (Oct – Dec, 2001)

Application of MCA

Resistive faults give off heat as energy
(100 hp, 0.5 Ohms, 95 Amps)

$$\begin{aligned} \text{kW loss} &= (I^2R) / 1000 \\ &= (95^2 * 0.5) / 1000 = 4.5 \text{ kW (demand loss)} \end{aligned}$$

$$\begin{aligned} \$/\text{yr} &= \text{kW} * \text{hrs/yr} * \$/\text{kWh} \\ &= 4.5 \text{ kW} * 8,000 \text{ hrs/yr} * \$0.06/\text{kWh} \\ &= \$2,160/\text{yr} \end{aligned}$$



With motor circuit analysis using ALL-TEST, I can see inside this motor, can you?

Testing can also be performed during the commissioning of an electric motor prior to applying power to confirm that the motor is ready, electrically.

In this case, a 0.5 ohm resistance is left in one of the motor connections. The result is a significant I^2R loss increase. Assuming that this motor will operate at 95 Amps, the resulting loss is 4.5 kW (~6 hp) at the loose connection. This ends with a much reduced reliability, a significant current unbalance that will cause reliability problems with the motor winding life and, an increase in operating energy costs. Assuming a combined demand and kWh cost of 0.06 cents per kWh and the motor operating 8,000 hours per year, there would be an increase of \$2,160 in energy costs due to just this electric motor. There may be many motors of this type in a plant.

Motor System Test Methods

◆ Motor Circuit Analysis

- Transformer
- Capacitors
- Connections
- Cabling
- Winding Faults
- Rotor Faults – broken rotor bars, eccentric rotor, casting voids, etc.
- Some mechanical faults

It is important to understand that problems detected from the motor control center or disconnect will detect:

- Connection problems
- Cable problems, including shorted cabling and insulation breakdown in the cable
- Motor winding faults

Motor circuit analysis can be used to also troubleshoot:

- Transformer problems
- Capacitor problems
- Rotor faults
- And some mechanical problems.

A Fault is Identified, Now What?

- ◆ Fault Found at MCC/Disconnect
- ◆ Go to motor connection box
- ◆ Retest
- ◆ If the fault is still present, the fault is in the motor
- ◆ If the fault is not present, the fault is before the motor



If a fault is detected from the motor control center or disconnect, check at the motor connection box. Note: that without performing the insulation to ground test, you can use MCA without having to disconnect from a variable frequency drive or amplifier.

If the fault is still found at the motor connection box, then the problem is in the motor. If not, it is in the cabling and connections between the MCC/disconnect and the motor.

Individual components in the system that may be at fault can be detected using the manual resistance, impedance, inductance, capacitance and phase angle tests of the ALL-TEST.

You've Gotta Be Kidding!

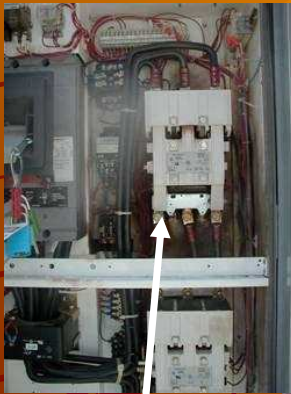


While troubleshooting, faults can be visually identified.

In this case, several problems are immediately apparent. The fuses to this 150 horsepower motor are incorrect, with a lighting fuse used on the B phase of this motor. When the fuse failed, the power to hold the starter contacts in was maintained by A and C phase. The motor operated single phased for a significant amount of time and failed due to a single phased winding.

The other problem is the amount of dust and dirt found within this MCC panel. Dust and contaminants will present a potential fire hazard, in particular when the motor finally failed. The amount of current carried by the starter during the failure could have potentially started a fire in the MCC.

Example of Starter Problem



-Fault not visible
-Checked and found motor and Cable OK

- Operation Stops
- Checked motor from Starter
- Discover Starter Problem



Fault: Poor Contact; Motor OK



An electric motor trips off line. During the setup to check the electric motor from a starter, a starter fault is detected.

The contacts are checked in the starter and the B phase contacts appear to have exploded. As it turns out, the motor was tested and found to be, electrically, in good condition. The fault was determined to be the result of arcing in the contacts, most likely due to a loose contact.

The starter was replaced and the equipment put back in operation.

Causes of Failure

- ◆ Primary: Winding Shorts

- ◆ Caused by one or more:

- Thermal Problems

- ◆ Aging
 - ◆ Overloading
 - ◆ Cycling

- Mechanical

- ◆ Coil movement
 - ◆ Rotor strikes
 - ◆ Parts

- Electrical

- ◆ Dielectric Stress
 - ◆ Corona
 - ◆ Transients

- Environmental

- ◆ Moisture
 - ◆ Contamination
 - ◆ Foreign objects



The primary cause of electric motor winding problems and nuisance tripping problems in variable frequency drive applications is turn to turn shorts.

The winding faults are generally caused by one or more of the following conditions:

- Thermal problems: Aging due to the Arrhenius Chemical Equation. Electrical insulation ages based upon temperature and time with a general rule of thumb that the insulation resistance reduces by half for every 10 degrees Centigrade increase in operating temperature. The insulation system also has a thermal limit, or a point where the insulation breaks down quickly. If the motor is overloaded, the winding temperature increases dramatically resulting in thermal breakdown and carbonization of the electrical insulation system. Over-cycling also causes problems, in particular with the motor rotor. Every time the motor starts, the rotor sees a high current and resulting heat which takes time to cool. If the motor is started too many times, the rotor and windings do not have time to cool and the motor will overload or the rotor bars of the rotor fail.

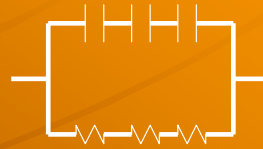
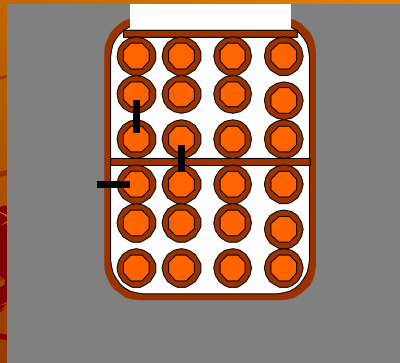
- Mechanical problems include coil movement when the motor starts across the line. Each time high starting current passes through the windings, they physically flex. Over time, the insulation will wear and mechanically fail where the coils exit the stator core. If the motor moves during operation and the rotor strikes the stator core, laminations may be moved that will cause shorts or grounds between the windings and frame. Other parts may come into contact with the windings, resulting in winding failure.

- Electrical stresses, including additional stresses due to variable frequency drive operation, will cause breakdown of the insulation system as will corona and transient voltages. These stresses can cause immediate shorts between conductors of the winding.

- Environmental problems including moisture, contamination and foreign objects in the windings. Moisture may cause continuity to ground and will also get into cracks and fissures in the insulation and will expand when exposed to the magnetic fields within the motor, wearing away at the system. Contamination will cause a thermal blanket over the insulation system that will cause overheating of the insulation system. Foreign objects may also include rodents, insects and other objects.

Each will cause faults to occur over time.

Electrical Insulation System



$$\text{Capacitance} = 0.0884 \times 10^{-12} A/t$$

A = Area; t = spacing

Electrical insulation systems are made up of dielectric materials. These may be modeled as parallel capacitors and resistors. As faults begin to occur, changes begin to occur in the resistances and capacitances between wires, coils and phases. The changes can be measured as changes in phase angle, current/frequency, inductance and impedance.

If a fault occurs between conductors, changes occur in the capacitances within the conductors of the coils. By comparing the coils to each other, these changes can be identified allowing for fault detection.

In the following slides, we will discuss the three stages of winding failure.

Stages of Winding Failure

◆ Time to Failure

- Severity of the Fault
- Potential Between Conductors
- Type and Amount of Insulation
- Cause of the Fault
- Cycling and Load

◆ Contamination, Thermal, Moisture Incursion, Corona, Transients, Overloads, etc. may initiate fault.

The time before the failure becomes catastrophic depends on:

- The severity of the fault – how many conductors and the cause of the fault
- The potential energy between the conductors involved.
- The type and amount of insulation in the electric motor.
- The cause of the fault.
- Cycling and loading will decrease the time to failure.

Stage 1

- ◆ Insulation between conductors stressed
- ◆ Changes to R and C between conductors
- ◆ High temps and reactive faults
- ◆ Carbonization begins to occur
- ◆ MCA values of F_i and I/F begin to change

In a Stage 1 winding failure:

- Insulation between wires in the motor are stressed, electrically or mechanically.
- The result is changes to the resistances and capacitances between conductors.
- Energy begins to cross the weakness in the system and elevated temperatures occur at the fault point.
- Carbonization of the windings at the point of the fault begin to occur.
- MCA values of phase angle and current/frequency response begin to change.

Stage 2

- ◆ Fault becomes more Resistive
- ◆ Mutual Inductance between good and bad
- ◆ I^2R losses increase at point of fault
- ◆ Motor may start tripping although may run after short cooling period (ins res increases as insulation cools)

In Stage 2 winding failure:

- The point of the fault becomes more resistive, causing a greater change in the phase angle and current/frequency test.
- Mutual inductance begins to occur between the good and bad portions of the winding. This may cause slight changes to inductance that will show when the winding is hot and that may be masked by rotor position inductive unbalances.
- I^2R losses begin to occur at the point of fault causing accelerated heating at the point of failure.

In Stage 2 winding failure, the motor may begin to 'nuisance trip' but will appear to run after a short cooling period. This is because, unlike a resistor, the insulation resistance in an insulation system is inversely proportional to temperature. When the point of failure is very hot, the insulation resistance may appear very low. However, when the motor cools, the resistance may be high enough not to show the fault.

Stage 2 failure is also the point where a motor will trip on a variable frequency drive, but will operate in bypass for a significant period of time. When this occurs in a VFD application, it may be mistakenly interpreted that a fault exists in the VFD.

Stage 3

- ◆ Insulation breaks down
- ◆ Possible explosive rupture
- ◆ Vaporization of windings
- ◆ Inductance and sometimes resistance may change

In Stage 3 winding failure:

- The insulation breaks down and there is a catastrophic failure
- The winding may end in an explosive rupture with a vaporization of the winding. This can be physically identified as small beads of copper found in the motor housing or embedded in the frame near the fault.
- Inductance may detect the problem at this point and phase resistances may change. The degree of the changes will be determined by the amount of the winding involved. The motor may not show a fault to ground, depending on the location of the fault.
- Smoke, odor and more may also be used to help detect this stage.

Stage 3 Fault

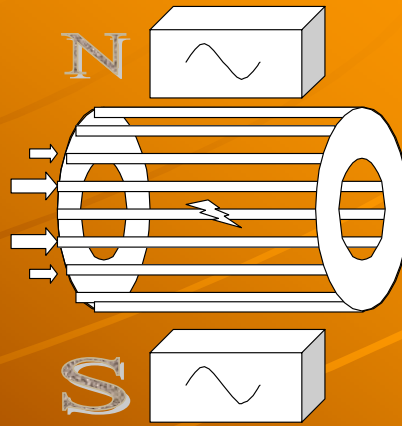


This ten horsepower motor shows the result of a Stage 3 failure. Note the following: The ties have broken due to heat, there is separation in at least one conductor and a copper ball is located on the winding next to the fault.

This motor was still operating. It was nuisance tripping and only removed from operation due to noise that turned out to be the ties hitting the cooling fins on the rotor.

Rotor Testing

- ◆ Flux linkage across airgap
- ◆ Inductive balance depends on rotor bar and winding location
- ◆ Detects: Broken rotor bars; poor airgap; voids in rotor casting

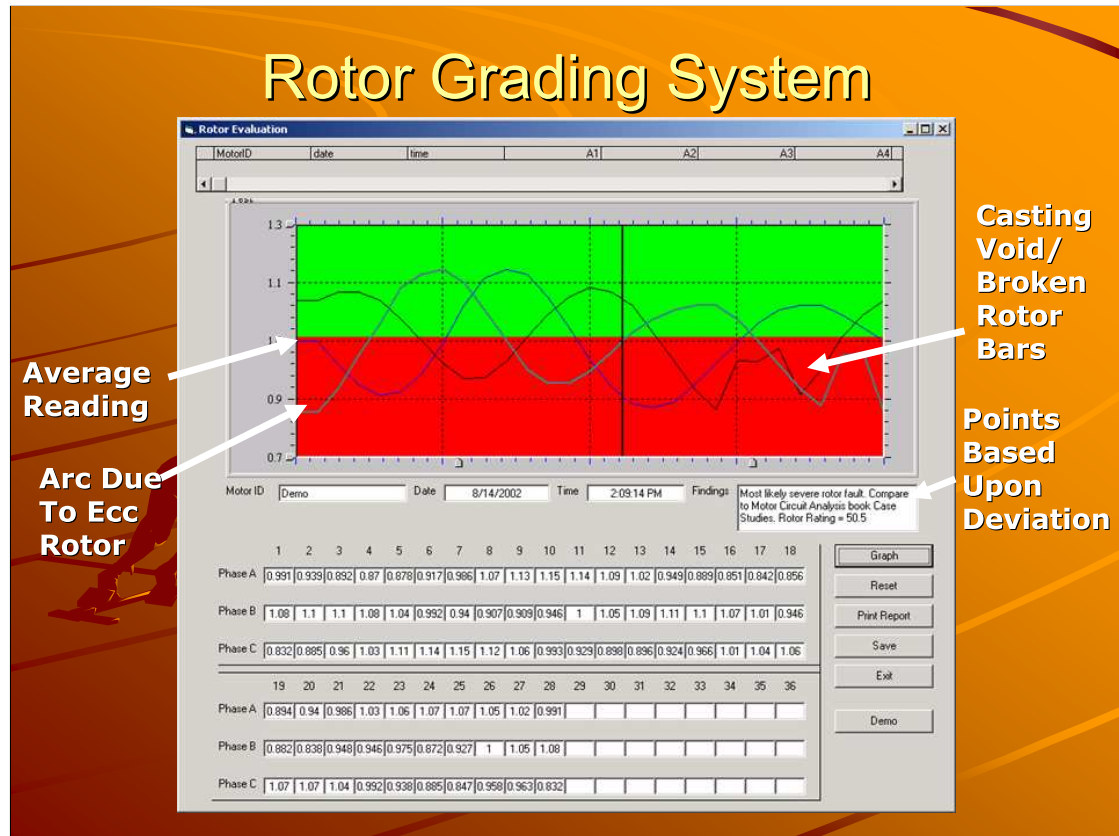


In the case of rotor testing using inductance:

When an inductive field is introduced into one winding in an electric motor, and the rotor is turned, the influence of the rotor winding is detected. This will result in an increase and decrease in the induction readings, as the rotor is rotated, that should show an even pattern.

If a rotor bar is broken, more current flows through the windings on either side of the break, dramatically altering the inductance readings. As more rotor bars break, due to the increased current flow and heat developed, the motor is less able to provide torque and will overheat, causing the windings to fail. In addition, it causes more work for the motor to turn the rotor, increasing the operating cost of the motor, due to decreased efficiency.

Rotor Grading System

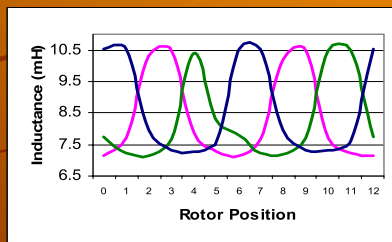


The degree of fault can be determined by applying a grading system.

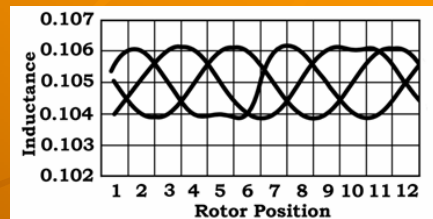
In the case of the Rotor Grading System used in the Electric Motor Circuit Analysis Tool (EMCAT) software, a value of less than 5 is considered good, a value between 5 and 15 is considered poor and values greater than 15 are considered severe.

The arc from left to right in this example shows that the rotor is eccentric (off center). The impact in the peaks of two of the sine waves indicate a severe casting void that has impacted the ability of the motor to develop torque.

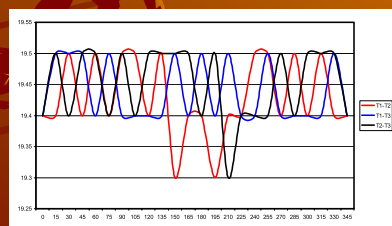
Rotor Evaluation Comparison



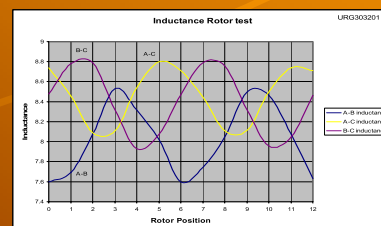
Casting Void



Broken Bar/Casting Void



Fractured/Broken Bars

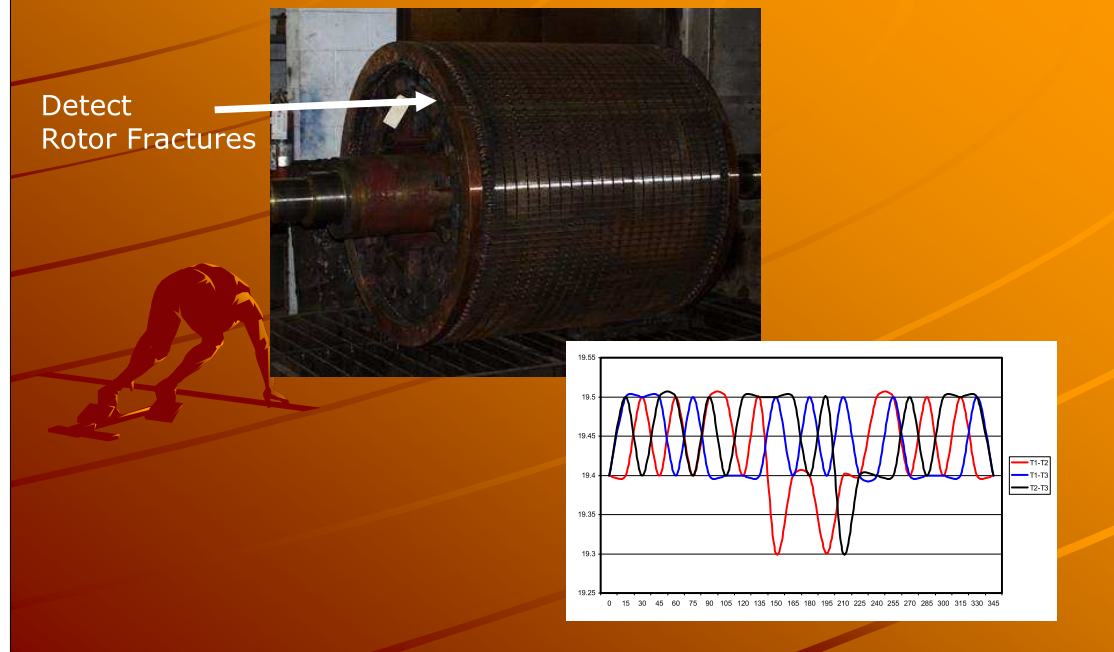


Phase Unbalance

These rotor tests identify the four most common faults detected with RGS, as well as eccentric rotors.

- Casting voids that will not impact the ability of the motor to operate tend to show on the sides of the sine-waves. Casting voids occur in virtually all cast aluminum rotors. Motors should not normally be rejected for this type of result.
- In the case of the Broken Bar/Casting Void example, when the test shows indentations or deviations in the peaks or valleys of the sine-waves, the result will impact the ability of the motor to produce torque and should be repaired.
- In the Fractured/Broken Bar example, sometimes small cracks or fractures will not show through standard methods of testing when the rotor is cold. These fractures will still show with inductance testing.
- Phase unbalances show as a shifted phase in rotor testing.

Rotor Faults



The common methods for testing rotors include:

- Growler testing: The rotor is placed on half a transformer and voltage is applied. By moving a sheet with metal filings across the bars, you can detect fractured or broken bars. This is normally performed in a repair shop after the motor is disassembled. It is recommended that the rotor is heated before performing this test in order to allow the rotor bars that are fractured to separate.
- Single phase testing: The motor is single phased with 10% of the nameplate voltage. An amp meter is attached to the leads and the shaft is rotated carefully. Deviations of current over 3% indicate a problem. This is a very dangerous test method.
- Dye testing: A dye is applied to the rotor and a visual inspection looks for the broken bars and small fractures.
- Inductance testing while the motor is assembled is the safest method of testing.

Machine Tool Motors

	T1-T2	T1-T3	T2-T3
Resistance	2.239	1.554	1.367
Impedance	101	40	25
Inductance	20	8	5
Phase Angle	81	76	70
I/F	-47	-47	-46
Insulation	>99M		

Brushless DC motor with Coil to Coil short ($> \pm 1$)

Machine tool motors, including brushless DC, are tested in the same way as standard three phase motors.

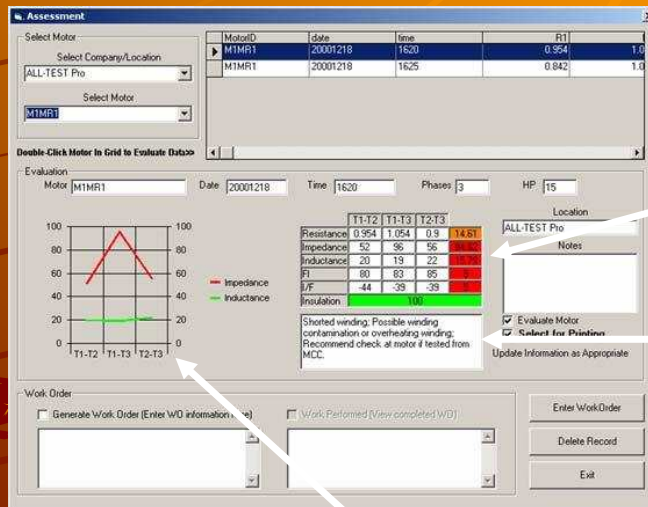
This example shows a shorted coil to coil fault in a brushless DC motor. Note that the impedance shows high, medium and low and the inductance shows high, medium and low.

The resistance shows a fault, the current/frequency test shows balanced and the phase angle shows greater than ± 1 from the median reading. This indicates a coil to coil short.

Insulation resistance is high.

The fault was a Stage 3 winding failure in the end turns of the stator.

Troubleshooting in Software



Data Analysis

Auto Analysis

Phase Balance Evaluation

When properly applied and with instruments that produce a complete set of information in resistance, impedance, inductance, phase angle, current frequency response and insulation to ground, testing motor circuit analysis can identify faults regardless of motor, transformer or coil size. The results are the same regardless of motor size allowing for easy data interpretation in software. This allows EMCAT software to perform data interpretation automatically during data upload.



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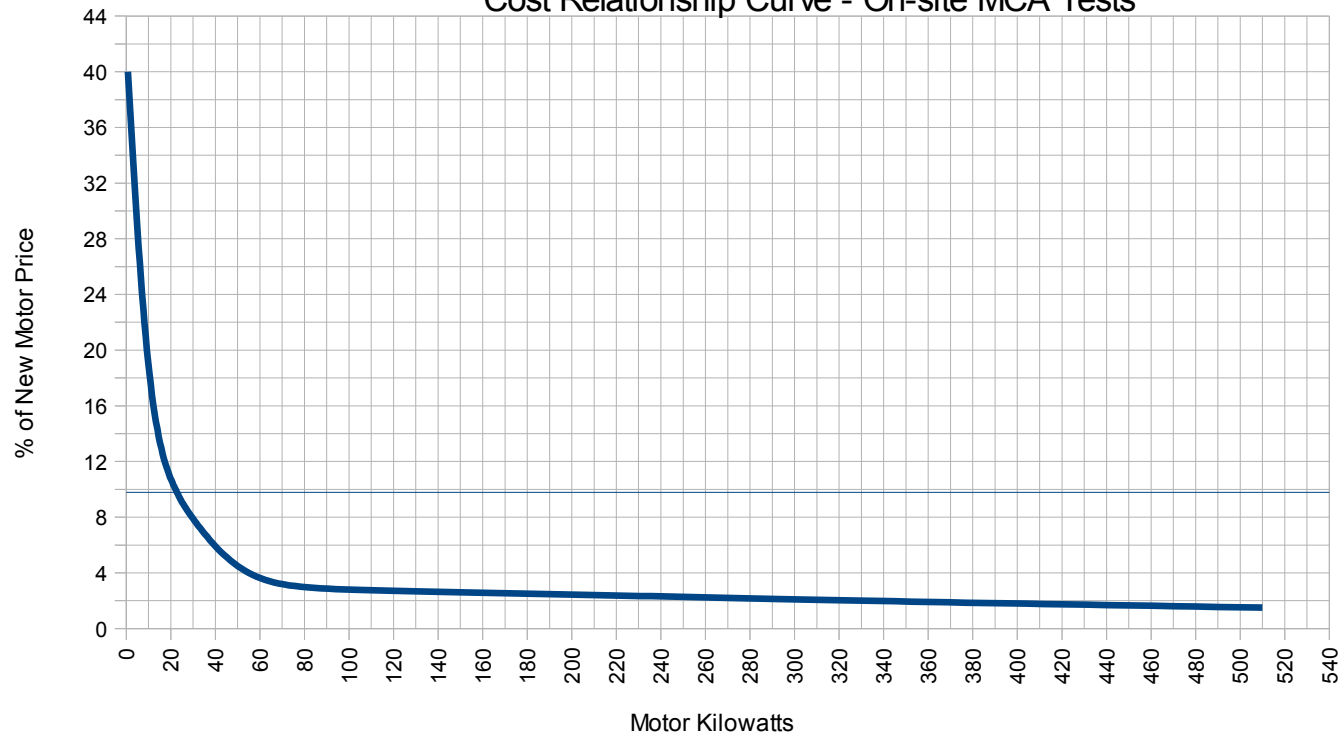
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Cost Relationship Curve - On-site MCA Tests



For further information

Contact the technical support personnel
at



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