

Estimating Electric Motor Life Using Motor Circuit Analysis

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Introduction

Electric motor life is a critical issue when discussing predictive maintenance and reliability programs. The primary question is: When will the motor fail? Unfortunately, this is not an easy question to answer, in particular as it relates to electric motor systems.

In this paper, we shall discuss the stages of a winding failure, causes and what effects the rate of failure in the winding. We shall then conclude with a discussion of the reliability of several winding faults over time and at what point action should be taken to correct or repair the fault. Based on application, electrical and physical environment, the materials presented will provide an average.

The motors covered by this paper will include low voltage (<600 Vac), standard, integral, three phase motors. This paper does not address similar higher voltage projects in progress.

Electric Motor Winding Failure

There are a number of primary causes for electric motor failure. Unfortunately, many of the causes are the direct result of the motor being used as a fuse and faulting due to some other issue within the electrical or mechanical system. Other causes include inefficient maintenance practices and/or no maintenance practices. In any of the cases, the basic laws of reliability ensure that an electric motor will fail over time. The mean time between failure (MTBF) should act as an indicator as to the health of the rest of the electric motor system (supply, load and maintenance).

The primary cause of electric motor winding failure is electrical shorts. These can occur between wires in a single coil (turn to turn), between coils in a single phase (coil to coil) or between coils in different phases (phase to phase). The fault can be caused by a single problem or combination of problems. These include:

1. Thermal Problems
 - a. Aging
 - b. Overloading
 - c. Cycling
2. Mechanical
 - a. Movement
 - b. Rotor
 - c. Parts
3. Electrical
 - a. Dielectric Stress
 - b. Corona
 - c. Transients
4. Environmental
 - a. Moisture
 - b. Contamination
 - c. Foreign Objects

Each of the major issues will be reviewed within this paper.

The Insulation System

“Electrical Insulation is a medium or a material which, when placed between conductors at different potentials, permits only a negligible current in phase with the applied voltage to flow through it. The term dielectric is almost synonymous with electrical insulation, which can be considered an applied dielectric. A perfect dielectric passes no conduction current and only capacitive charging current between conductors.”⁴

The simplest circuit representation of a dielectric is a parallel resistor and capacitor. The capacitance between conductors, in a vacuum, is $0.0884 \times 10^{-12} \text{ A/t}$ where A is the area of the conductor in square centimeters and t is the spacing of the conductors in centimeters. “When a dielectric material fills the volume between the electrodes, the capacitance is higher by virtue of the charges within the molecules and atoms of the material, which attract more charge to the capacitor planes for the same applied voltage.”⁹

Insulation Breakdown

Insulation breakdown, termed as ‘faults’ or ‘shorts’ within this paper, include contamination, arc tracking, thermal aging and mechanical faults. Each type of fault carries a common factor: The resistive and capacitive properties of the electrical insulation change.

Contamination, in particular water penetration, increases the insulation conductivity. The water tends to collect in insulation fractures and inclusions within the insulation system. The electrical fields cause changes to the contaminants, including expansion, which further break down the insulation system. Other contaminants, including gasses, vapors, dust, etc., can attack the chemical makeup of the insulation system. Once the insulation system is completely bridged the system is then considered shorted. This normally will occur first between conductors, where the insulation system is weakest. Key fault areas include the nonsecured portion of the coil, such as the end turns of a rotating machine (which also is the highest electrical stress point of the windings), and the highest mechanical stress point, such as the point the coils leave the slots of a rotating machine.

Arc tracking of insulation systems occur where high current passes between conductors across the surface of the insulation system. The insulation at those points carbonize, changing the capacitive and resistive components of the electrical insulation system. Arc tracking is often the result of: Strong electrical stresses; Contamination; or, both. This type of fault primarily occurs between conductors or coils and normally ends with a short.

Thermal aging of an insulation system occurs as electrical insulation systems degrade as a result of the Arrhenius Chemical Equation. The generally accepted “rule of thumb” is that the thermal life of the insulation system halves for every 10 C increase in operating temperature. The insulation will quickly degrade and carbonize once it obtains the temperature limit for the insulation system.

Other environmental factors also impact the thermal life of the insulation system including: Winding contamination, including oil, grease, dust, etc.; Moisture, in particular contaminated water such as salts, etc; Electrolysis; and, other electrical stresses.

A newly common electrical stress comes from the application of variable frequency drives. The high carrier frequency (2.5 to 18 kHz) of modern pulse-width-modulated inverters reduces the partial discharge inception voltage of the motor insulation system. Partial discharge involves small gas bubbles in the winding insulation system. A charge builds across the void, then discharges at a level that depends upon the severity and chemical makeup of the void. The result is ozone, which degrades the surrounding insulation material. Eventually, an ionized electrical path develops which allows electrical stresses (fast rise-time spikes) to cross the boundary and short. The tendency is for a few turns to short in the end-turns of the motor windings.

Mechanical faults in the electrical insulation system include stress cracking, vibration, mechanical incursion, and mechanical faults. The forces within a coil during various operations, will cause mechanical movement and may end in the fracturing of insulation materials. Electrical and mechanical vibration cause undue stress on the insulation system resulting in stress fractures and looseness of the insulation system. Mechanical incursion includes the movement of materials into the insulation system either between conductors and/or insulation system to ground. Mechanical faults include failures such as bearing faults that cause the bearing to come apart and pass through the moving components of the system. These faults may end as shorts between conductors, coils or coils to ground.

Stages of Winding Failure

There are three stages to winding failure that begin as a breakdown of insulation between conductors. These winding 'shorts' may, but not always, end up as an insulation resistance fault when the winding actually fails. The detection of changes between the conductors provides a greater chance of early repair or replacement action before the equipment stops operating. The actual rate of the failure depends on a number of factors including:

1. Severity of the fault
2. Potential between the conductors
3. Type and amount of insulation
4. Cause of the fault

The stages of a winding short are:

1. Stage 1: The insulation between conductors is stressed, causing a change to the resistive and capacitive values of the insulation at the fault point. High temperatures and similar reactive faults result in carbonization of the insulation at that point. Carbonization may also occur due to tracking across the insulation system. MCA values of phase angle and I/F will be effected at this point.
2. Stage 2: The point of fault becomes more resistive. A mutual inductance occurs between the 'good' portion of the winding (and other current carrying components of the system) and the shorting turns. I^2R losses increase at the point of fault due to the increase in current within the shorting turns, increasing the temperature at that point and causing the insulation system to carbonize quickly. The motor may start tripping at this point, although it may be able to run after a short cooling period.
3. Stage 3: Insulation breaks down and the energy within the point of the short can cause an explosive rupture in the insulation system and vaporization of the windings. Inductance and sometimes resistance, can detect the fault at this point.

Winding contamination, thermal breakdown, moisture incursion, corona, transients, overloads and mechanical flexion may initiate the winding fault.

Test Measurements for Evaluation

Basic electrical measurements for the evaluation of rotating machinery include the following tests:

1. Resistance (IEEE Std 118-1978, IEEE Std 389-1996) – Used for detecting variations in wire size, connections and open/high resistance circuits.
2. Inductance (IEEE Std 388-1992 Inductance and Impedance Unbalance, IEEE Std 1201989) – Inductance is a function of geometry and permeability. It is independent of voltage, current and frequency. The overall inductance measured is a combination of the mutual and internal inductances of the circuit, known as circuit inductance. Fault detection is possible in winding shorts only when the capacitance of dielectric insulation systems become resistive and a shorted circuit exists, resulting in mutual inductance between the 'good' part of the coil and the shorted turns. Mutual inductance is also used in the evaluation of rotor windings in rotating machines.
3. Impedance (IEEE Std 388-1992, IEEE Std 389-1996, IEEE Std 43-2000, and, IEEE Std 120-1989) – Impedance is frequency, resistance, inductance and capacitance dependent. Resistance has a relatively small impact on the overall impedance and the applied frequency impacts the inductive and capacitive reactance components. Increases in inductance have an additive effect to the impedance values while capacitance has an inverse impact on circuit impedance. For instance, an increase in the overall circuit inductance will generate a roughly parallel increase in impedance, a decrease in the overall circuit impedance will cause the impedance to decrease. When impedance does not follow inductance, the effect is normally a change in the capacitance of one phase to the next (winding contamination or carbonization). Inductive/Impedance comparison tests are covered by the AC test method in IEEE Std 43-2000 Annex B.
4. Phase Angle (IEEE Std 120-1989) – The circuit phase angle is a measurement of the lag time between voltage and current presented as degrees of separation. It is directly impacted by the circuit impedance, voltage and frequency applied. Small changes in the circuit capacitance result in significant changes to the circuit phase angle.
5. Frequency Response Tests (IEEE Std 3891996) – Frequency response tests can be evaluated using a number of

methods. For purposes of this paper, the evaluation will be presented as the percentage reduction in current of a coil when the frequency is doubled, also known as the current/frequency response test. Current/frequency responses are impacted by changes to the capacitances of the circuit as the frequency increases.

6. Insulation Resistance Tests – Covered under IEEE Std 43-2000.

Regardless of the measurements provided, the primary purpose is to identify unbalances between like coils, such as between phases in a three phase electric motor.

Introduction to Motor Circuit Analysis (MCA)

Winding Circuit Analysis using readings of resistance, impedance, inductance, phase angle, I/F and insulation resistance provides an outstanding and non-destructive troubleshooting tool. In addition, it has been shown that comparisons of these readings between like coils, transformers, AC and DC motors allow the user to set upper and lower control limits (see Previous QNPM papers by Author). By applying the same concept to existing electrical machines, periodic testing can be performed and trended.

At this point, we shall demonstrate the application of Winding (Motor) Circuit Analysis (MCA) techniques to Predictive Maintenance (PdM) for AC/DC motors, transformers and motor rotors. Several new concepts shall be presented including: MCA AC rotating machine trending; and, the EMCAT™ Rotor Grading System™ (RGS) for rotor analysis and trending. In each case, a definition of schedule-able findings and immediate action findings shall be described.

Trending Fault Descriptions

The limits to PdM testing using MCA are limited only to the range of the instrument, and are not dependant upon equipment size and voltage ratings. While it is true that a direct short in medium voltage equipment (above 600 Volts) develops and fails rapidly, the symptoms that lead up to the direct short are often seen well in advance of the failure. In reality, the detection of these faults depends upon frequency of testing and how the data is trended. It is the same as if the statement, “Once a bearing begins to come apart, it will do so rapidly, too rapidly to detect using vibration analysis,” were to be discussed. This would be a true statement if vibration analysis was unable to detect the degradation of the bearings over time. However, we all know that vibration analysis is highly accurate in longterm trending of bearing failure. It is the same with MCA, infrared, and most other PdM tools.

There is a simple secret to trending MCA test results: Comparison. The actual value of the data collected can be used for comparing equipment to each other and to set upper and lower control limits for manufacturing and acceptance testing. For trending and analysis purposes, MCA is a comparative tool using percent unbalance and difference between tests methods.

In the percent unbalance method, the difference between like coils (ie: between the phases in a three phase motor) is trended over time. This method is best for resistance, impedance and inductance. While resistance values are impacted by temperature, for instance, the relative difference between phases is not. By using the percent unbalance method, the user or software does not have to rely upon performing temperature correction calculations. Impedance and inductance are not significantly impacted by temperature. However, the unbalance method is the most convenient way of detecting faults over time. The limits are more visual than numerical: Graphical trending of the percent unbalance should not change visibly over time. An abrupt change in a graph indicates that a fault is occurring and must be addressed immediately. A slight change over time indicates that a fault is being trended and must be considered on a schedule (ie: next shutdown). Changes to the resistive unbalance normally indicate that connections are becoming loose. When inductance and impedance unbalance are due to rotor position (in a three phase motor this indicates a ‘good winding’) the relative unbalance will show similar values (ie: L = 11%, Z = 12% vs. L = 5%, Z = 50%). If the relative unbalance values between L and Z separate, this indicates a breakdown in electrical insulation over time and should be addressed.

The difference between tests method is used for phase angle, I/F and insulation resistance. In the case of phase angle (Fi) and I/F, changes over time in excess of two digits of difference between phases indicates a severe winding fault. This type of detection is an indicator of a breakdown of insulation between turns or coils in the windings. For instance, if the Fi trends between 0 and 1 difference between readings and the I/F trends between 1 and 2 difference between readings, a sudden change to Fi = 3 and I/F = 4 would indicate a significant fault has

occurred between conductors or coils. In the case of insulation resistance, any change within the range of the MCA device indicates a degradation of insulation between windings and ground.

AC Rotating Machine Testing

AC rotating machinery can be trended over time using simple graphical methods. An abrupt change to readings will indicate that a severe fault is occurring and must be addressed. Readings that require scheduled repairs will gradually change from green to yellow then to red. This would represent a change in readings as follow:

Table 1: Trending Limits

| Reading | Change from Baseline | Severity |
|------------------|----------------------|----------|
| R, Z, L | < 3% | Green |
| R, Z, L | >3%, < 5% | Yellow |
| R, Z, L | > 5% | Red |
| Phase Angle, I/F | < 1 pt | Green |
| Phase Angle, I/F | >1 pt < 3 pt | Yellow |
| Phase Angle, I/F | > 3 pt | Red |

Rotor Grading System (RGS)

The RGS represents a special, trend-able method for performing an initial evaluation of the condition of a rotor. The system is based upon the relative average difference of each rotor test sinusoidal waveform from each other. Points are scored for deviation from the average, with higher scores indicating higher deviation.

Because some motors do not produce a sinusoidal waveform, a rotor signature that shows a higher score than found in Table 2 should be compared to rotor test signature tables.

Table 2: Rotor Grading System

| Score | Evaluation |
|----------|---------------------------|
| < 5 | Good |
| >5, < 15 | Poor, Compare to Tables |
| > 15 | Severe, Compare to Tables |

These scores are trend-able and may be compared over time by setting a baseline and performing periodic comparisons to the baseline. Changes by more than 5 points RGS indicate rotor faults are occurring. The faults detected by RGS include: Eccentric rotor; Broken rotor bars; Large casting voids; and, Rotor fractures.

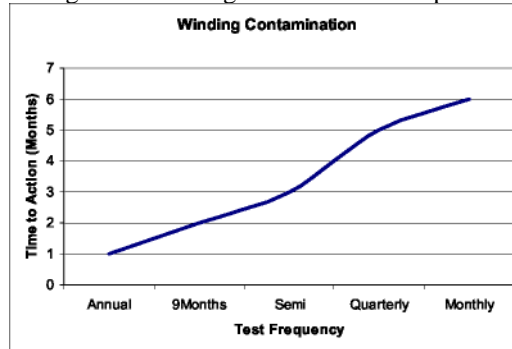
Estimating Time To Failure Using MCA

The purpose of reliability and predictive maintenance is to detect the presence of an unusual condition (or conditions) then to determine at what point the operation of the equipment is not reliable enough and corrective action is required. Several key benefits can result from this type of program: Corrective action can be less expensive than run to failure faults; and, Improved system efficiency through the correction of installation and minor system defects (ie: alignment, connections, etc.).

As readings begin to change over time, the time to failure will depend on the application, type of fault and severity of fault. Cycling loads, overloaded equipment, phase unbalances, and unusual supply power and loads make life estimation extremely difficult. For the purpose of this paper, a constantly loaded motor at 75 to 100% load, balanced voltage, operating 4000 hours per year and meeting nameplate and installation requirements will be assumed.

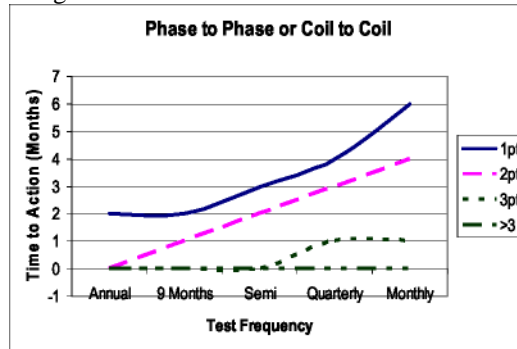
Based upon the three stages of winding failure, insulation fails over time. The greater the frequency of testing, the longer the time can be estimated to failure. If the fault is first detected from the motor control center or disconnect, it must be confirmed at the motor as cable faults may cause similar results.

Figure 1: Winding Contamination Impact

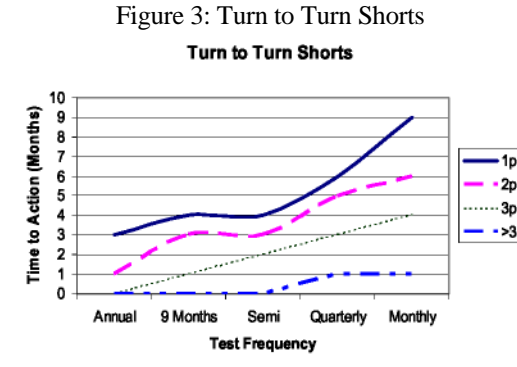


Winding contamination (Figure 1) will lead to winding shorts or breakdown of insulation to ground. In addition, severe contamination will cause blanketing of insulation and overheating of the insulation system. As winding contamination will not cause a change in impedance until the contamination has a chemical or thermal impact on the insulation system. If acted upon at the earliest convenience, the winding may be saved by cleaning, dipping and baking the stator. However, if the impedance has changed due to overheating (carbonization) of the insulation system, the winding will have to be replaced.

Figure 2: Coil to Coil or Phase to Phase Fault



Coil to coil and phase to phase shorts tend to be more severe than turn to turn shorts because of the potential energy between coils and phases. The result is that action must be taken sooner in order to avoid catastrophic failure. For instance, a 50 horsepower electric motor operating at 85% load, with 60 Hz power at a rated 480 volts phase to phase has a change of phase angle by 1 digit. This would indicate an early potential coil to coil fault (once confirmed at the motor connection) that should be corrected. If the motor is being evaluated quarterly, the correction should be made within the next four months. The frequency of testing should be increased to monthly, or more frequently, and action taken should any additional sudden changes occur.



Turn to turn shorts will last a significant amount of time in a 60 Hz application. As more severe changes occur, such as a change of over 3 digits between tests, action must be performed more urgently.

These recommendations are based upon statistical information and theoretical practices. A single point of data provides an inaccurate method for predicting system life other than pass/fail testing. Electric motors that have a significant impact on production and those that are tripping or operating improperly should be considered for more immediate attention.

Nuisance Tripping Situations

Nuisance tripping can occur in several instances. In the case of variable frequency drives, the motor may operate satisfactorily when set into bypass, but will have insulation breakdown between a few turns. Other faults may be the result of thermal breakdown of insulation. When an insulation system is in trouble, faults may show when the winding is hot, but not show when the winding is cool. Insulation system resistance is inversely proportional to temperature. Therefore, there may be enough continuity between conductors to cause a current spike, and resulting trip, when the winding is hot, but will have enough of a resistance to prevent current flow when the winding is cool.

When a winding nuisance trips, testing must be performed to determine if a winding fault exists. If so, the motor will not be able to operate with a VFD due to possible damage to the drive.

Conclusion

Winding problems can be detected and trended using Motor Circuit Analysis techniques. Once a fault is detected, the winding insulation life can be estimated in constant operating machines. Stages to winding shorts can be determined and evaluated using MCA, which may occur over a significant length of time in low voltage (< 600 Vac) electric motor systems.

About the Author

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. 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.

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