Time to Failure Estimation™ Using Motor Circuit Analysis

Howard W Penrose, Ph.D., CMRP
President, SUCCESS by DESIGN

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 motors systems. In fact, the real question should be: When will the probability of failure become unacceptable?

In this article, 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 article will include low voltage (<600Vac), standard, integral, three phase motors. This article 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.

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 article.

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."[1]

The simplest circuit representation of a dielectric is a parallel resistor and capacitor. The capacitance between conductors, in a vacuum, is 0.0884×10^{-12} 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."[2]

Insulation Breakdown

Insulation breakdown, termed as 'faults' or 'shorts' within this article, 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 non-secured portion of the coil, such as the end turns of a rotating machine (which is also the highest stress point of the windings), and the highest mechanical stress point, such as the point the coils leave the slots of a rotating machine.

---

[1] IEEE Standard 120-1989, Section 5.4.2
[2] Fink, Beaty, et.al., Standard Handbook for Electrical Engineers, Fourteenth Edition, McGraw Hill, 2000.

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^oC increase in operating temperature. The insulation system 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 modulation 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. If the same motor control is placed in by-pass, there is a good chance that the motor will run, but will not when returned to inverter service. 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 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 conductors;
3. Type and amount of insulation; and,
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 the 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 involve the following tests:

1. Resistance (IEEE Std 118-1978, IEEE Std 389-1996) – Used for detecting variations in wire size, connections and open/high resistant circuits.
2. Inductance (IEEE Std 388-1992 Inductance and Impedance Unbalance, IEEE Std 120-1989) – 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 dependant. Resistance has a relatively small impact on the overall impedance and the applied frequency impacts the inductive and capacitive reactance components. Increases with 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 inductance 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 (i.e.: 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 389-1996) – 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 of 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 capacitance 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.

All of these tests, including pass/fail criteria, have been introduced in IEEE P1415, “Draft Guide for Induction Machinery Maintenance Testing and Failure Analysis,” presently in the voting stages of the IEEE Standards Authority.

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. 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) and Condition-Based Monitoring (CBM) for AC/DC motors and transformers. The concept of MCA induction motor testing for trending. A definition of schedule-able findings and immediate action findings shall be described.

Trending Fault Descriptions

The ability of 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) may develop and fail 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 the 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 long-term trending of bearing failure. It is the same with MCA, infrared and most other PdM/CBM 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 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 (i.e.: between 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. 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. It the relative unbalance values between inductance and impedance 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 of more than 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, which would represent a change in readings as follow:

Table 1: Reading Change Table for AC Rotating Machinery

Reading	Change from Baseline	Severity
R, Z, L	< 3%	Green
R, Z, L	>3%, <5%	Yellow
R, Z, L	>5%	Red
Fi, I/F	<1 point (pt)	Green
Fi, I/F	>1pt <3pts	Yellow
Fi, I/F	>3pts	Red

Time to Failure Estimation (TTFE™) Using MCA

The purpose of PdM and CBM 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 that 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 the fault. Cycling loads, overloaded equipment, phase unbalances and unusual supply power and loads make life estimation extremely difficult. For the purpose of this article, a constantly loaded motor at 75 to 100% load, balanced voltage, operating 4,000 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.

Winding contamination 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.

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 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 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 field best 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. MCA provides an immediate method of evaluating the winding condition, in a single test. If the winding fault does exist, the motor will not be able to operate with a variable frequency 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 and stages of winding shorts determined. This may occur over a significant length of time in applications under 600 Vac and issues leading up to a fault can be detected in systems over 600 Vac.

About the Author

Howard W Penrose, Ph.D., CMRP, is the President of SUCCESS by DESIGN, a reliability and maintenance services consultant and publisher. He has over 20 years in the reliability and maintenance industry with experience from the shop floor to academia and manufacturing to military. Dr. Penrose is a past Chair of the Chicago Section of the Institute of Electrical and Electronic Engineers, Inc. and is presently the Founding Executive Director of the Institute of Electrical Motor Diagnostics. For more information, or questions, related to this article or SUCCESS by DESIGN services, please contact Dr. Penrose via phone: 860 575-3087 or email: howard@motordoc.net.

Bibliography

1. IEEE Std 43-2000: IEEE Recommended Practice for Testing Insulation Resistance of Rotating Machinery;
2. IEEE Std 56-1977: IEEE Guide for Insulation Maintenance of Large Alternating Current Rotating Machinery (10,000 kVA and Larger);
3. IEEE Std 118-1978: IEEE Standard Test Code for Resistance Measurements;
4. IEEE Std 120-1989: IEEE Master Test Guide for Electrical Measurements in Power Circuits;
5. IEEE Std 388-1992: IEEE Standard for Transformers and Inductors in Electronic Power Conversion Equipment;
6. IEEE Std 389-1996: IEEE Recommended Practice for Testing Electronics Transformers and Inductors;
7. IEEE Std 1068-1990: IEEE Recommended Practice for the Repair and Rewinding of Motors for the Petroleum and Chemical Industries;
8. Penrose, Howard W., Ph.D., Motor Circuit Analysis: Theory, Application and Energy Analysis, SUCCESS by DESIGN, 2001;
9. Penrose, Howard W., Ph.D., "Estimating Electric Motor Life Using Motor Circuit Analysis, Part 1," 2003 IEEE Electrical Insulation Conference Proceedings, IEEE, 2003;
10. Penrose, Howard W., Ph.D., "Estimating Electric Motor Life Using Motor Circuit Analysis, Part 2," 2004 IEEE-ISEI Conference, IEEE, 2004;
11. Fink, Donald and Beaty, Wayne, Standard Handbook for Electrical Engineers: Fourteenth Edition, McGraw-Hill, 2000;
12. Sarma, Mulukutla, Electric Machines: Steady-State Theory and Dynamic Performance, Second Edition, PWS Publishing Company, 1996;
13. Mazur, Glen and Proctor, Thomas, Troubleshooting Electric Motors, Second Edition, ATP Publishing, 1997;
14. Nasar, Syed, Electric Machines and ElectroMagnetics, McGraw-Hill, 1981.