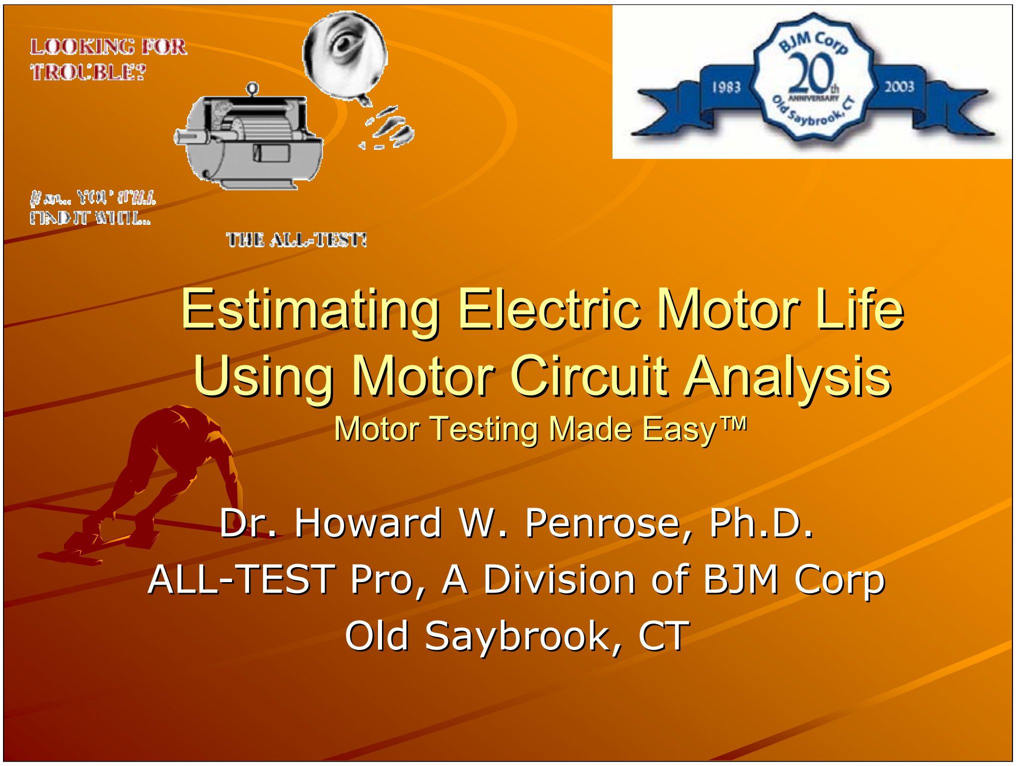
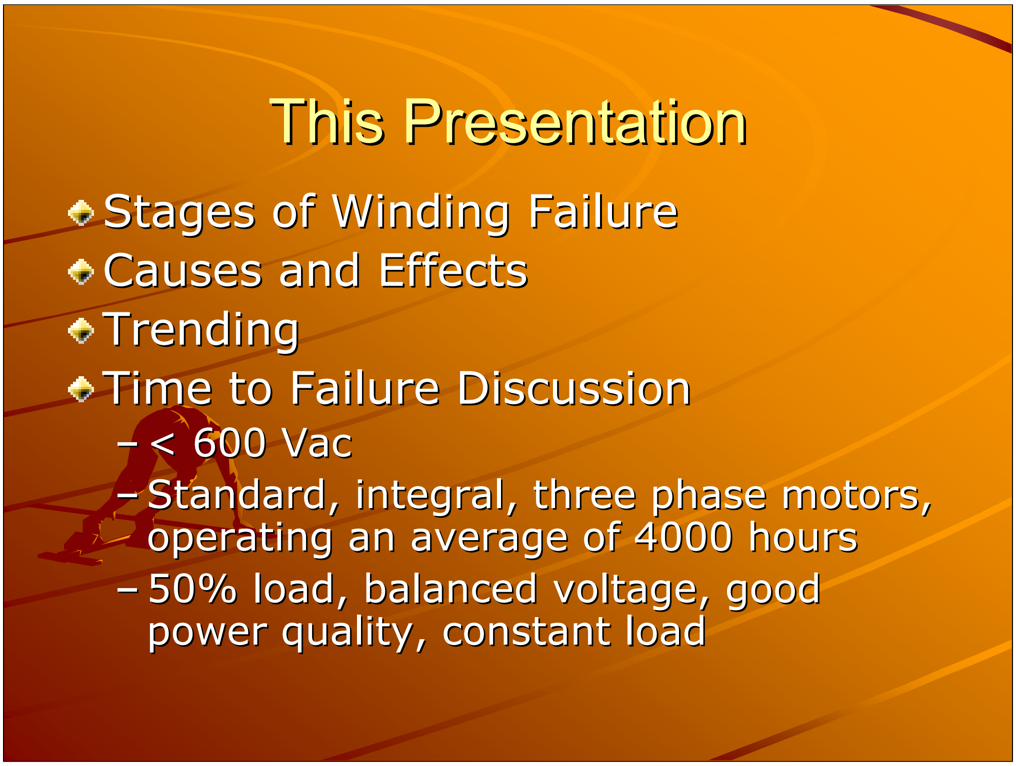


Estimating Electric Motor Life Using Motor Circuit Analysis is part 3 of Motor Testing Made Easy.

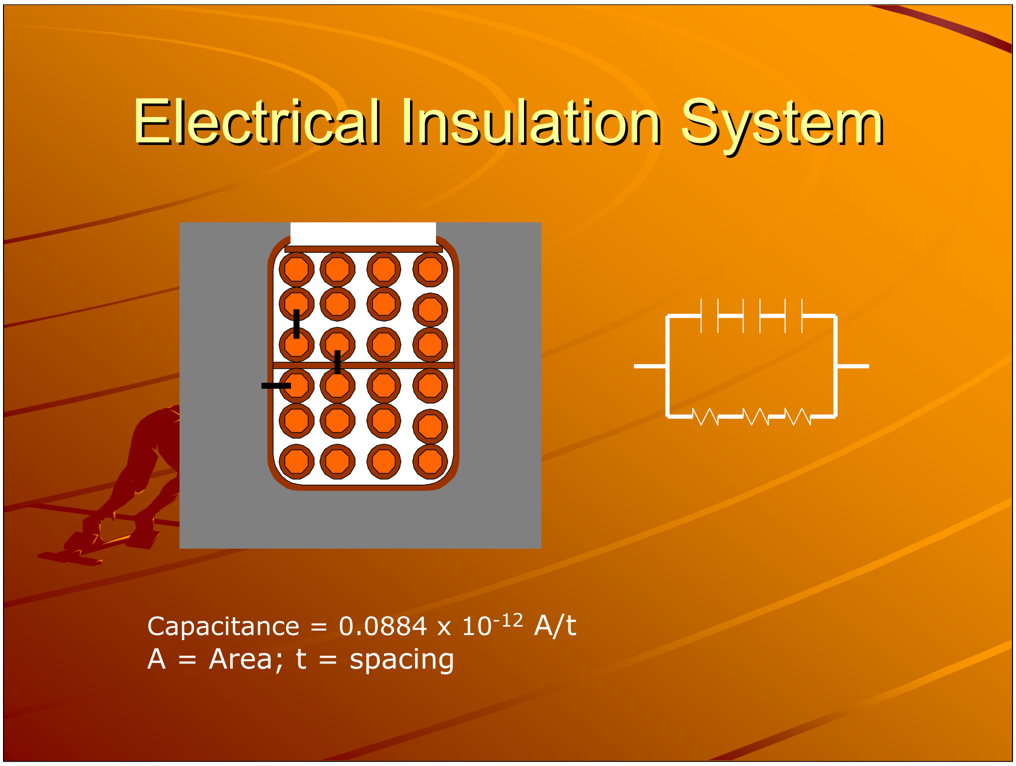
This presentation is brought to you by BJM Corp’s ALL-TEST Pro division. BJM Corp is a premier manufacturer of electrical submersible pumps and ALL-TEST motor circuit analysis equipment.

Dr. Penrose is the General Manager of the ALL-TEST Pro division and is considered a top motor system troubleshooting, energy and repair expert. He serves in a variety of capacities with professional organizations including standards and certification development.



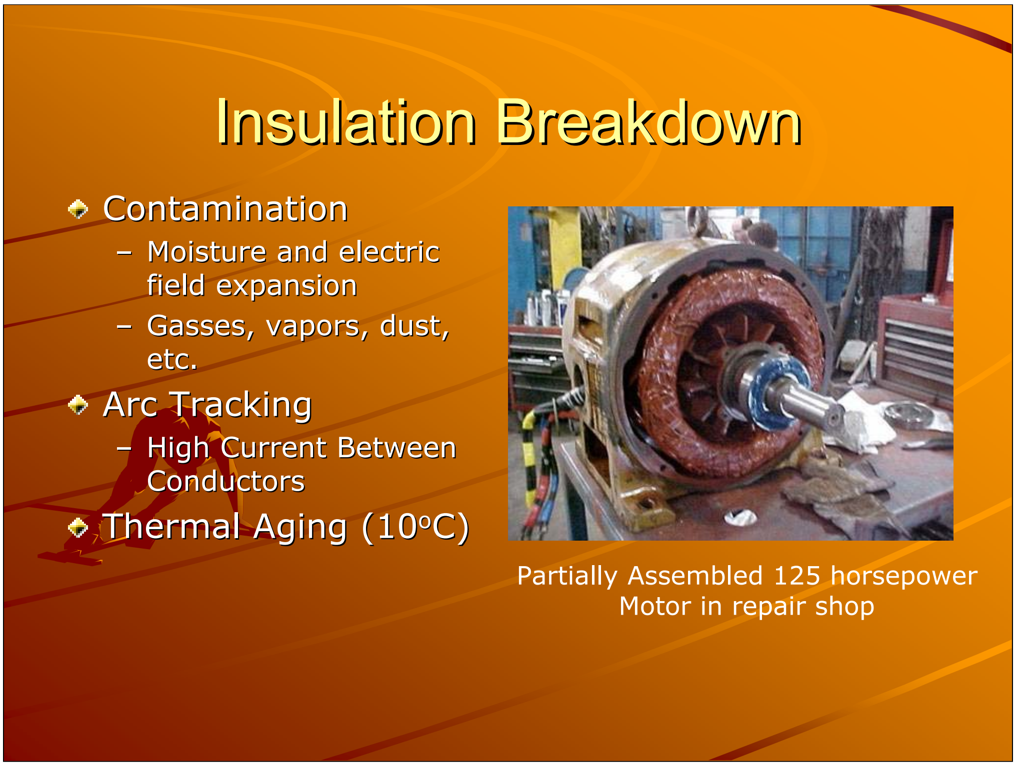
In this presentation, we shall review the stages of winding failure, causes and effects of winding faults, and how motor winding and rotor system faults can be trended. The presentation shall be concluded with the first stage of a time-to-failure discussion following the detection of a winding fault using motor circuit analysis.

This presentation builds upon the first two presentations and is the initial presentation of a long-term ALL-TEST Pro R&D project on electric motor predictive maintenance. It sets the groundwork for future presentations including an IEEE Dielectrics and Electrical Insulation paper to be presented at the Electrical Insulation Conference and Electrical Manufacturing and Coil Winding Association Conference to be held at the Indianapolis Convention Center in September, 2003 and the IMC Conference in Florida in December, 2003.



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 develops 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.



•Electrical Insulation breaks down over time for a variety of reasons.

•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.

•Arc tracking can be caused by high energy discharges between conductors. Carbonization occurs, weakening the winding insulation system or destroying it.

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.

Insulation Breakdown

- VFD Applications
  - Partial Discharge
- Mechanical Faults
  - Stress cracking
  - Parts Faults

Stators awaiting assembly after rewind

•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.

•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 rotor moves during operation and 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.

The time before the failure becomes catastrophic depends on:

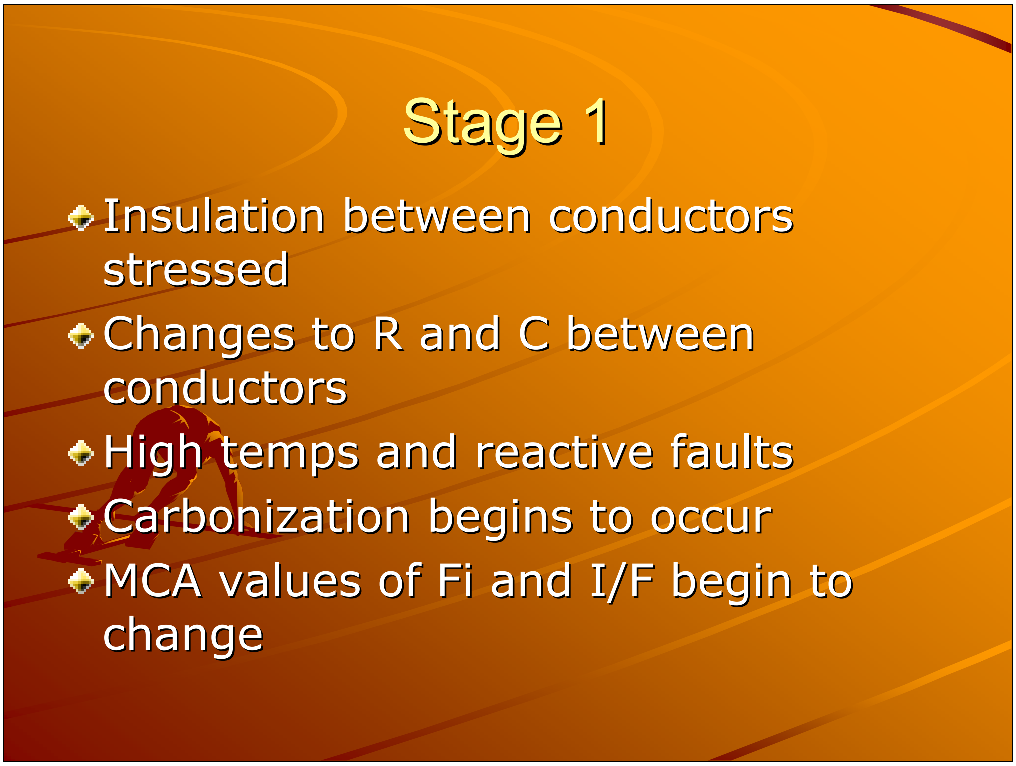
•The severity of the fault – how many conductors and the cause of the fault

•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.



In a Stage 1 winding failure:

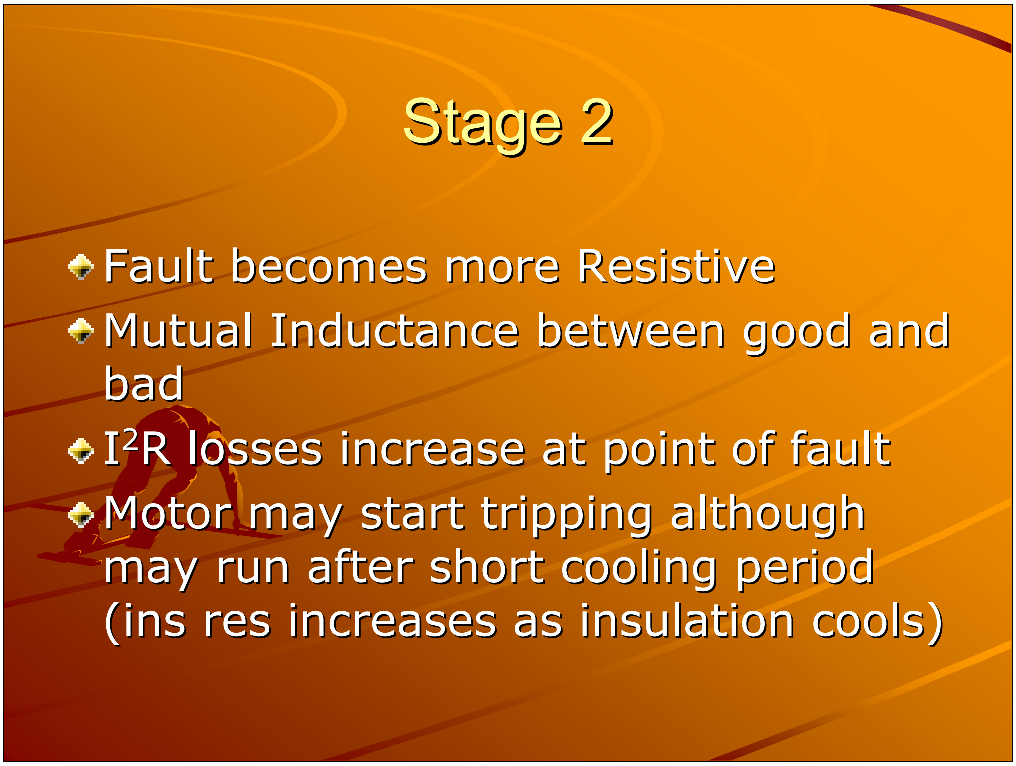
•Insulation between wires in the motor are stressed, electrically or mechanically.

•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.



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.

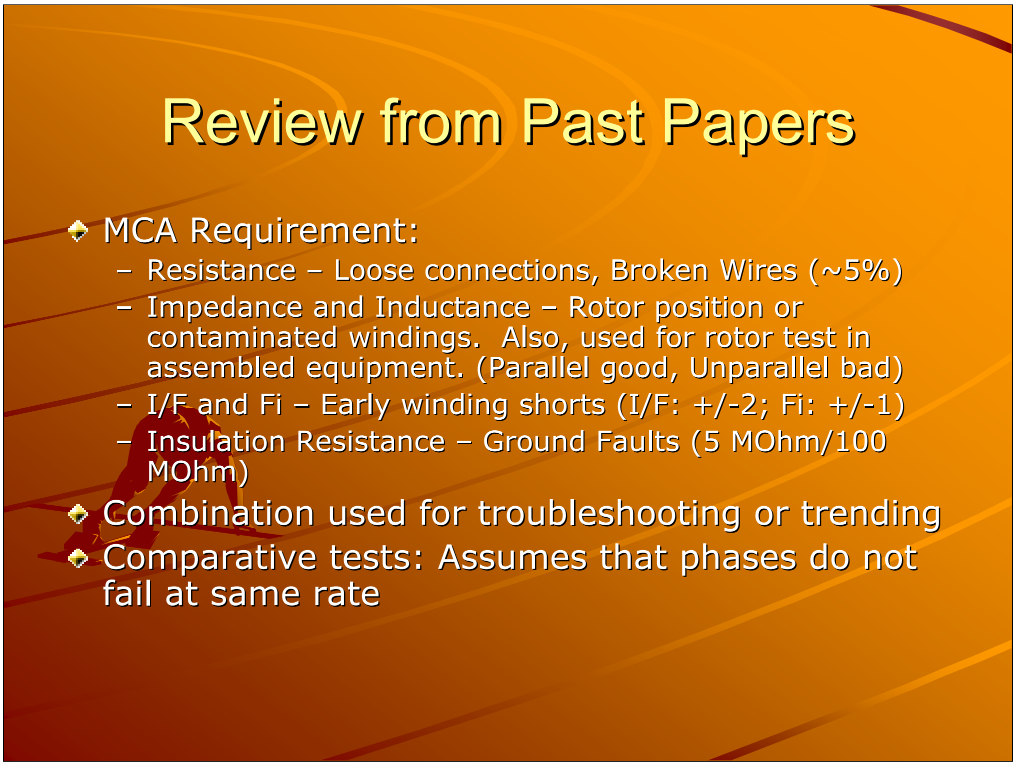
In Stage 3 winding failure:

•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.



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.

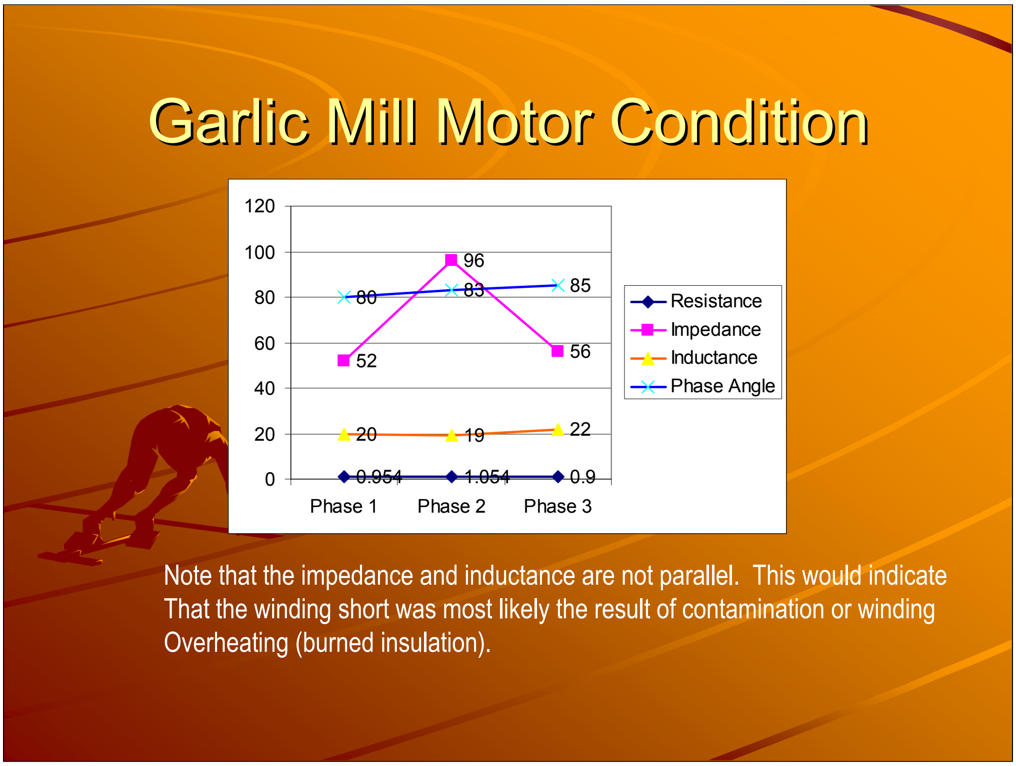
Bad 15 HP (Garlic Mill)

	T1-T2	T1-T3	T2-T3
R	0.954	1.054	0.9
Z	52	96	56
L	20	19	22
Fi	80	83	85
I/F	-44	-39	-39
Megger		>99M	

Note that both Fi (Phase Angle) and I/F (Current-Frequency Response) are bad. This Motor was still operating but tripping intermittently. The test results show that this Winding is shorted (most likely turn-to-turn shorts).

In this case, a 15 horsepower, 1800 RPM standard motor was in operation in a dust-contaminated environment (even better, garlic dust!). The motor operates but nuisance trips on a 60 Hz supply.

You may note the following: Greater than +/- 1 digit on both the phase angle (Fi) and current/frequency test (I/F), which indicate a turn to turn short. The impedance reads low, high, medium and the inductance reads medium, low, high, indicating winding contamination.



The visual of impedance and inductance again shows that they do not follow each other.

When this motor was disassembled, it was found that the winding was completely coated in grease and garlic dust and a small blackened area at the end of one coil showed the turn to turn short.

Using motor circuit analysis when trending electric motors, the following criteria is followed:

•The peak to peak maximum % unbalance is tracked for resistance, impedance and inductance. Evaluation of the % unbalance eliminates the need for temperature correction, reducing data collection time and improving accuracy.

•The actual points difference in phase angle and current/frequency response are tracked over time. These measurements are not temperature dependant and will provide an early detection of impending winding faults.

•Insulation resistance testing is primarily used to detect continuity to ground.

•A computerized evaluation using the rotor grading system allows a numerical method for trending condition of the rotor bars.

AC Rotating Machine Testing

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

The above criteria outlines the limits of change allowed over time for low voltage electric motors.

For resistance, with impedance and inductance the % change from the baseline reading is tracked over time.

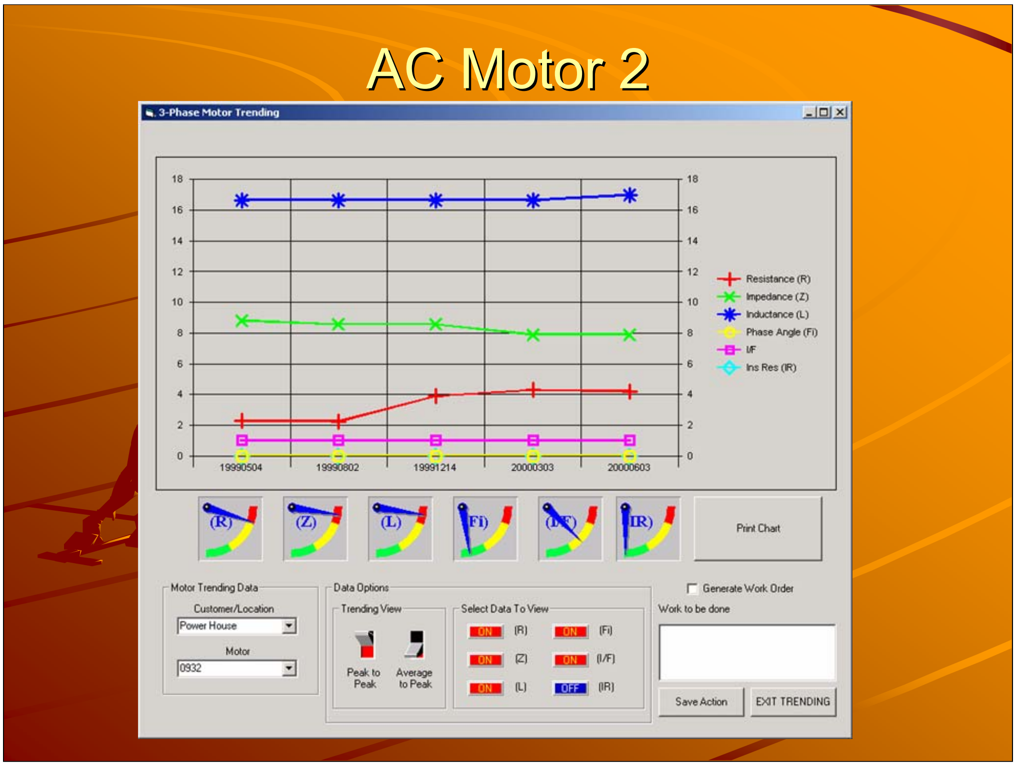
For phase angle and current/frequency testing, a less than 1 point change is considered normal. Changes over 1 point indicate that an electrical fault is occurring and should be tracked closer.

‘Green – Good and Red – Bad’ A reading that changes from green to red between PdM tests should be considered severe and action should be taken immediately.

Example of a severe change requiring immediate action.

Note the ‘fuel guage’ indicator change in phase angle and current/frequency. This motor was still operating but was causing trouble during operation. The resistance, impedance and inductance had not changed significantly. However, when viewing the ‘raw data’ it was noted that a change in the relationship between impedance and inductance had occurred, indicating a winding contamination or overheating winding issue.

When investigated further, the indication was that the motor had been single-phased for a period of time then put back into operation. This indication allowed the user to plan a motor replacement.



In this case, a change to resistance over time indicated a loosening connection in the electric motor connection box.

While the impedance and inductance show ‘red’ in the fuel guages, review of the individual readings show that the tests are running in the same direction, indicating that the unbalances are due to rotor position and not a fault. Note that while the readings are taken with the rotor in random positions, the changes in readings are not significant.

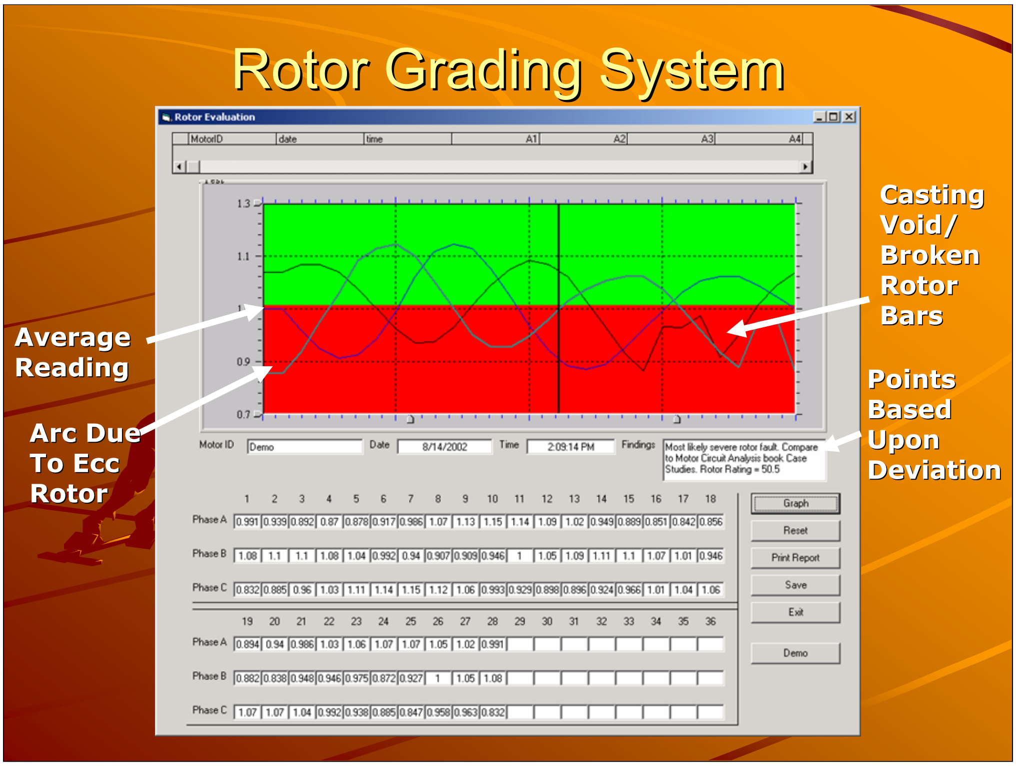
Rotor Grading System (RGS™)

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

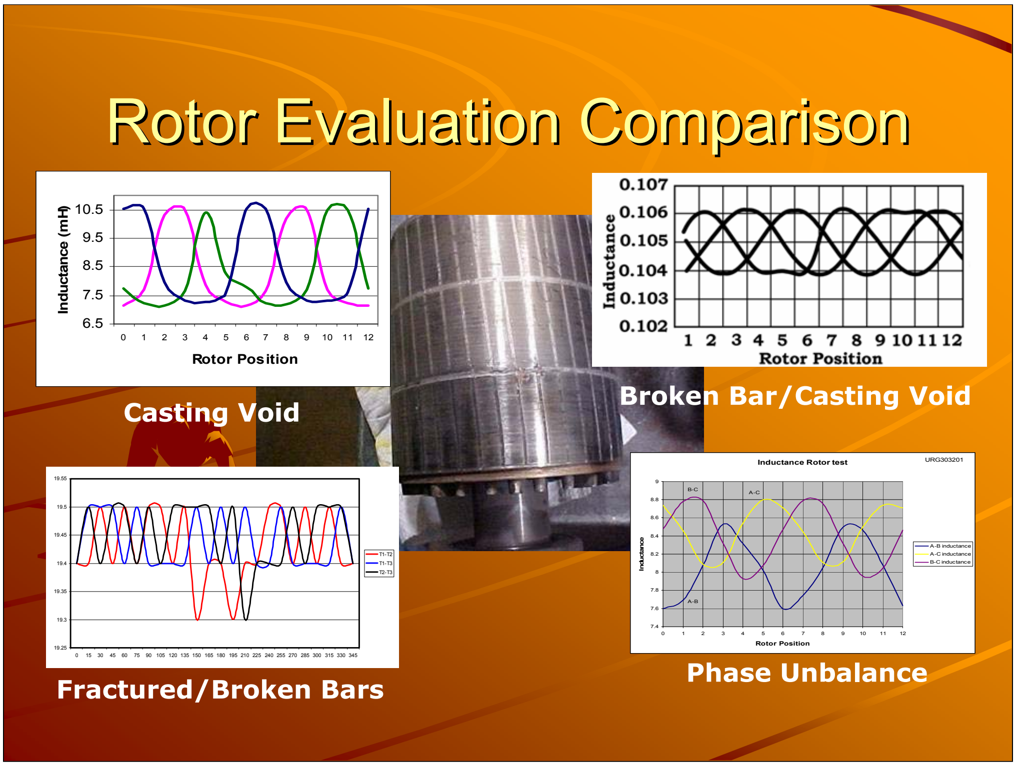
Using the rotor grading system, which evaluates the variations in the rotor inductance signature, a trend-able value may be obtained.

Values under 5 indicate no significant variations between phases through rotation; values between 5 and 15 may indicate slight fractures, rotor eccentricity or significant casting voids; values over 15 indicate significant issues.

A baseline reading can be taken and compared when possible rotor problems need to be evaluated.



In this case of the Rotor Grading System being used in the Electric Motor Circuit Analysis Tool (EMCAT) software, The arc from left to right 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.



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.

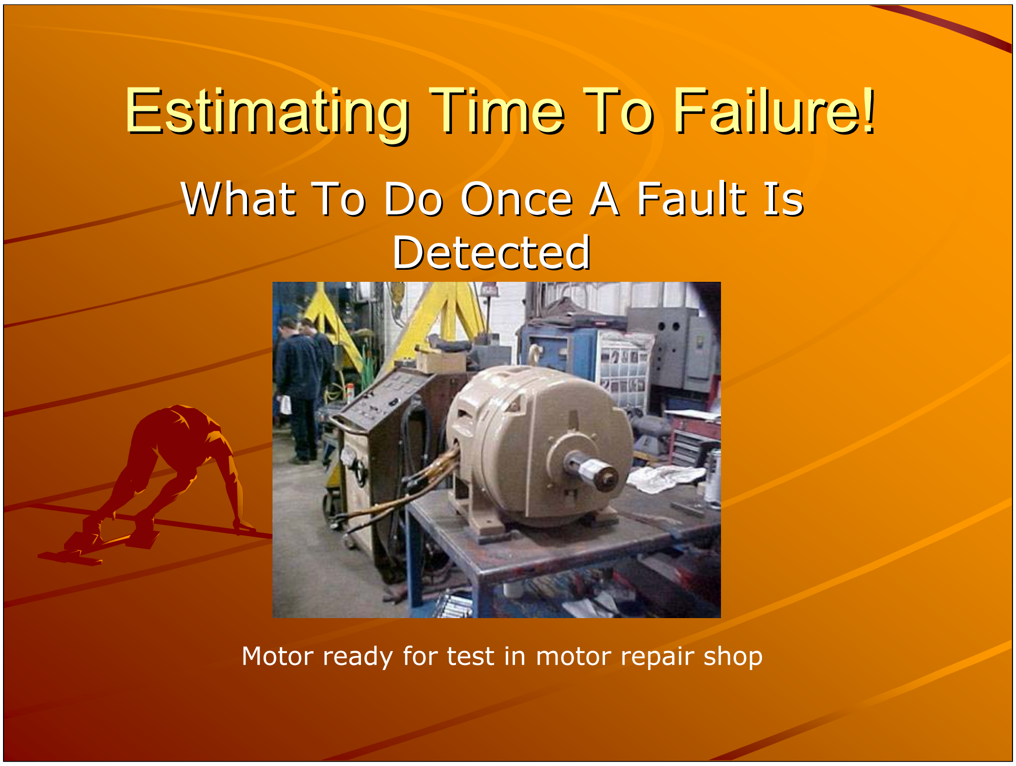
PdM Testing Frequency

Motor Type	Clean/Dry Environment	Moderate Environment	Dirty/Wet Environment
3-Phase Non-Critical	12 Mo	9 Mo	6 Mo
3-Phase Production	6 Mo	6 Mo	3 Mo
3-Phase Critical	3 Mo	2 Mo	1 Mo
DC Motors	6 Mo	6 Mo	3 Mo
Transformer	12 Mo	9 Mo	6 Mo

In order to evaluate the condition of the winding and receive an accurate time to failure, the above table indicates the minimum recommended times between tests.

For example: An electric motor operating in a clean/dry environment, used in critical production equipment, should be tested at least once each quarter.

If an electric motor is used for a critical pumping application in a wet or contaminated environment, testing at least once per month will allow a significant amount of time from detection to failure in order to correct the problem.



Estimating time to failure is critical in any operation. Caution should be taken with critical equipment during this evaluation for time to failure. The findings estimate the time to catastrophic failure following early fault detection.

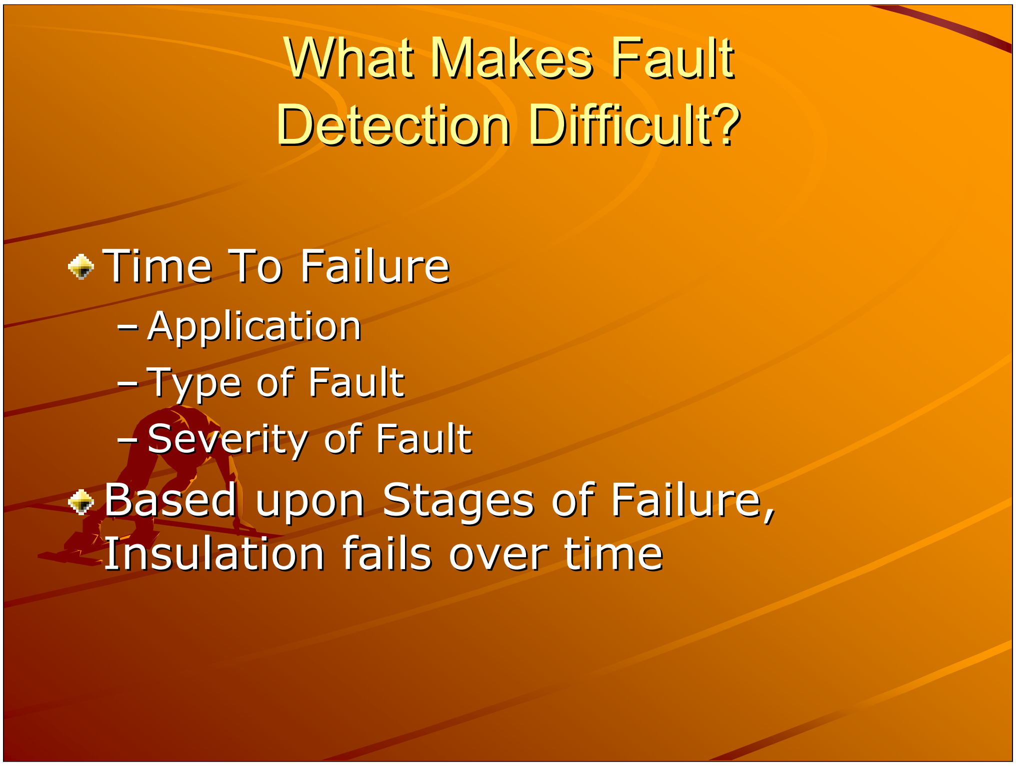
Through estimating the time to failure (not a prediction, contrary to the term ‘predictive maintenance’), you have the opportunity to review the application in order to determine:

•What is the root-cause of the fault and what can be fixed when the motor is repaired or replaced.

•Electric motor right-sizing or energy improvements.

•Other system corrections or improvements during scheduled downtime.

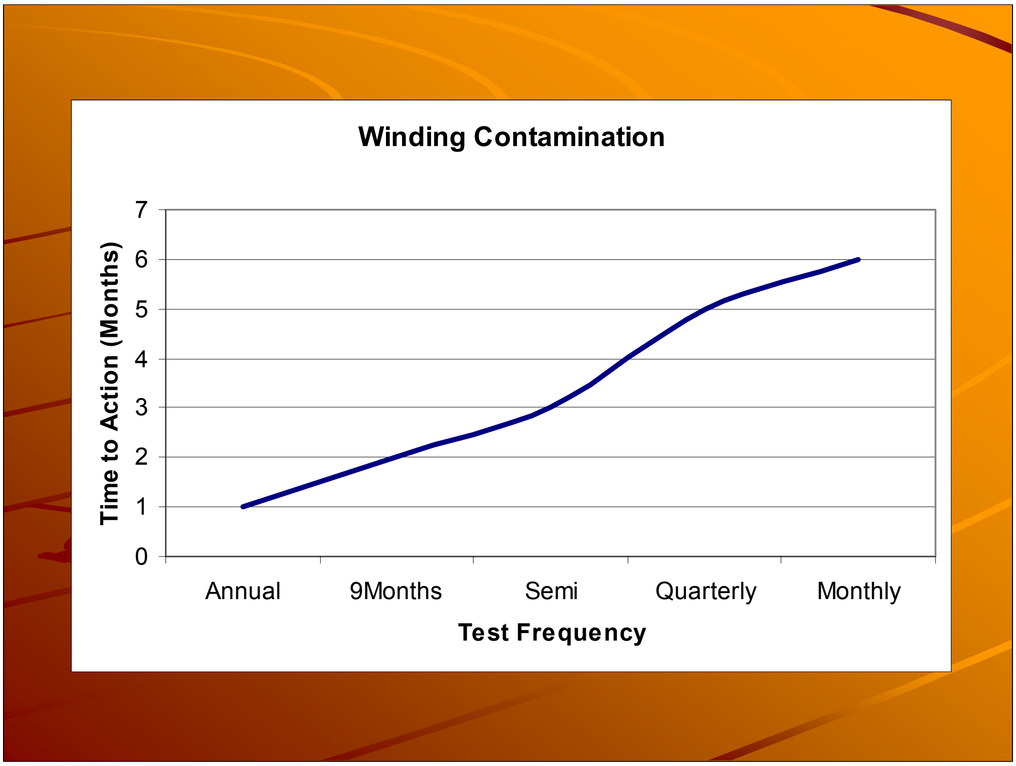
•How much time will be required to correct the trouble.



In the case of this presentation, we shall estimate a lightly loaded motor running in a clean/dry environment, under constant load, clean power and operating constantly 4000 hours per year. Changes to these criteria will have a significant impact on time to failure and will be covered in future presentations.

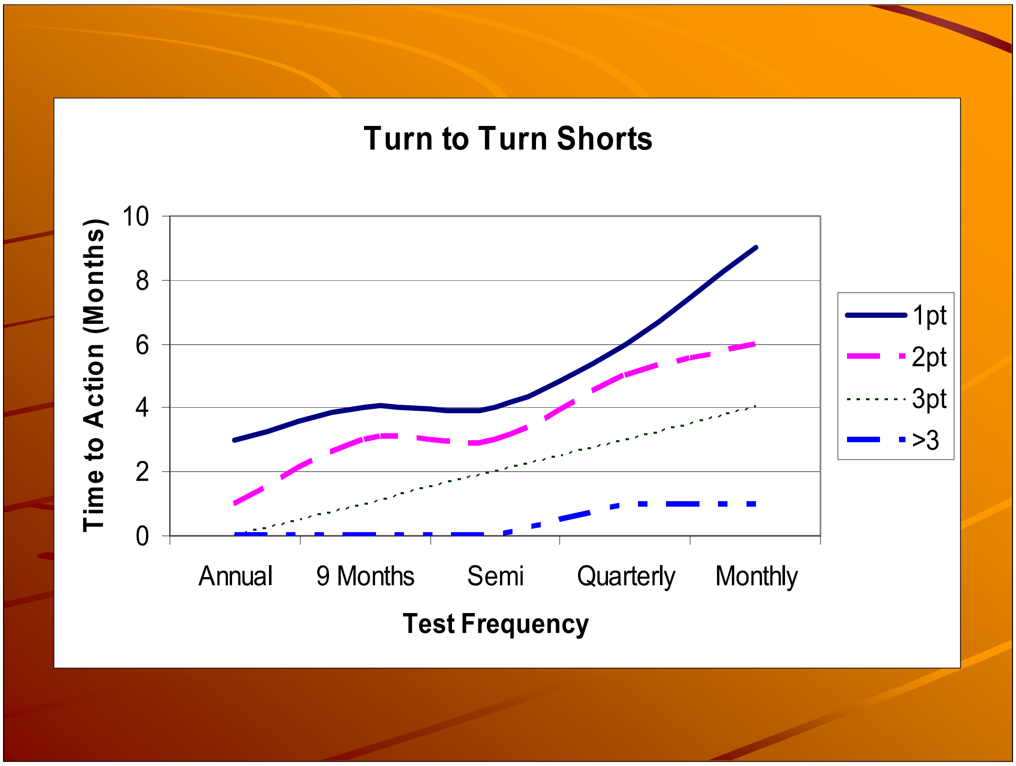
The true time to failure will depend upon the application, type and severity of the fault.

The concept is based upon stages to failure and the fact that insulation fails over time. The data is compiled from real data provided by MCA users from September 1999 to December 2002. Data was isolated to motors rated less than 600 Vac. Additional work is underway reviewing motors rated to 13,200 Volts and what faults can be trended over time.



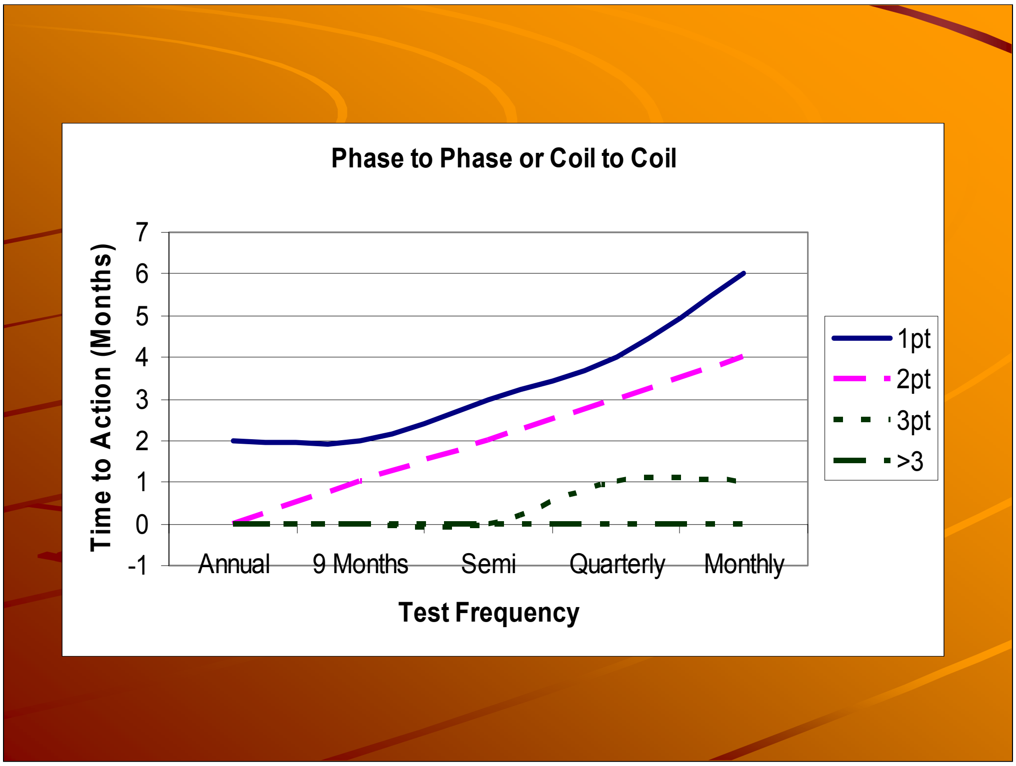
This table estimates time to failure once impedance and inductance readings begin to diverge from each other. For instance, once winding contamination is detected when testing quarterly, it can be estimated that the winding will survive up to 5 more months.

Winding contamination detection is a correctible problem that may only require a clean, dip and bake at the repair shop. However, the contamination issue will have to be addressed fairly quickly to take advantage of the less costly repair.



The ability to determine the type of short through a comparison of phase angle and current/frequency response allows you to determine how long you will have to failure. A turn fault in a single coil has less energy crossing the fault than a coil to coil or phase to phase fault.

Once a fault is detected, the trending period should be increased if you are attempting to operate to failure or to the next downtime period. For instance, a 2 pt change occurs in phase angle or current/frequency testing and you are testing quarterly, you will have up to 5 months before catastrophic failure. You may wish to increase the test frequency to monthly or bi-weekly during the time the equipment is still being operated. If the motor begins nuisance tripping, the decision to correct the problem will have to be re-evaluated.



In this case, a phase to phase or coil to coil fault is detected during quarterly testing, by two points. The problem should be addressed within no more than three months.

BJM Corp strives to provide leading research and development in the area of motor circuit analysis. This presentation is being made available to assist the users with an initial guideline for time to failure. Additional details on this research project will be made available throughout 2003.

For more information on ALL-TEST Pro instruments, contact us at:

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Contact us for pricing, information, a CD ROM demonstration and more. The ALL-TEST is available and in use world-wide!