Insulation System Considerations for MCA

Quantum Mechanics and Motor Diagnostics

ALL-TEST Pro
A Division of BJM Corp

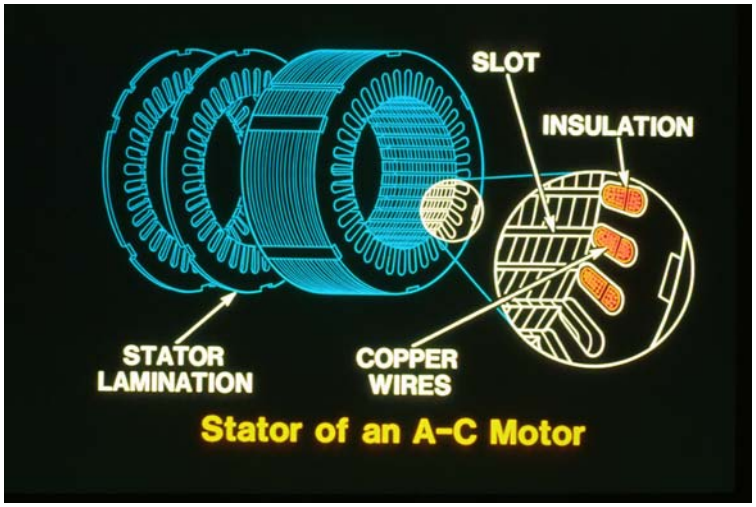
Welcome to part 8 of our 2004 series.

ALL-TEST Pro is a division of BJM Corp, a submersible pump manufacturer. The ALL-TEST Pro division manufactures the ALL-TEST line of motor diagnostics equipment which includes motor circuit analysis and electrical signature analysis instruments.

My name is doctor Howard W Penrose and I will be your guide through this presentation. My background includes many years of direct, hands-on work related to motor systems, design and repair. My personal area of interest, since 1986, has been the study of estimating time to failure in electric motor systems. I joined ALL-TEST Pro in 1999 to study motor diagnostics, an area, that I believed, held the final key to this elusive problem. Over the past several years we have released papers on this study and, in September of this year, at our motor diagnostics level 1 course, we released our time to failure estimator software. Over the next several months, I will be your guide in presenting how this is done using motor diagnostics techniques.

The basis for the understanding of time to failure estimation is to understand how the insulation system generally works within an electric machine. We will then discuss how the major test methods work with the insulation system at the atomic level. This is necessary in order to assist you in understanding what you are observing in the field with your instrumentation and the strengths and limitations of those instruments. Armed with this understanding, we will be able to discuss field observations of the time to failure estimation study.

STATOR LAMINATIONS



For this presentation, we will be focusing on the stator insulation system, although the same insulation activity exists in rotors which have windings.

The stator core consists of many layers of insulated magnetic steel. In an AC motor, this steel is designed to be able to change polarity rapidly as line frequency power is introduced through each phase. The laminations are thin, usually 19 to 49 thousandths of an inch, in order to reduce eddy currents, or circulating currents within the steel. If you did not separate the laminations, you would have induction heating of the core which would rapidly reduce the age of the insulation system and the motor would not be especially efficient for its very short life. The type of steel, laminated annealed in older machines and silicone steel in most modern machines, is selected to reduce hysterisis losses. This type of loss is directly related to the resistance of the changing magnetic fields. In effect, magnetic dipoles, similar to the insulation dipoles we are about to discuss, must be able to switch direction rapidly. If they do not change easily, the resistance shows as heat due to the amount of energy needed to force the change.

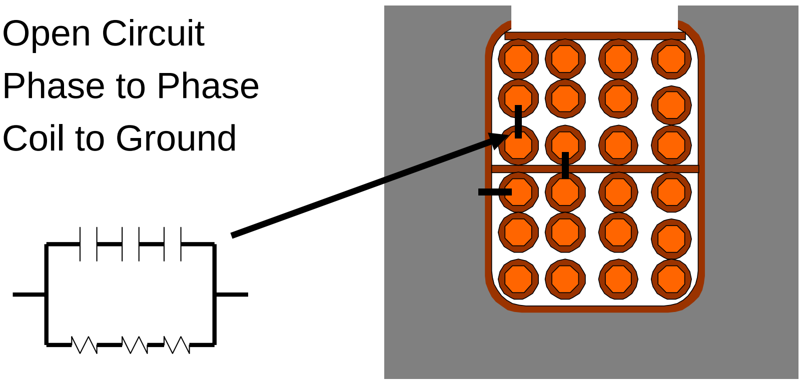
The back iron of the core is used to direct the magnetic fields efficiently into the interior of the core so the fields are denser within the air gap and rotor windings.

The stator coils are mounted within the core in ‘slots’ or ‘slot cells.’ There is a ground-wall insulation system, which is inserted into the cells before the coils. These are meant to both reduce abrasion to the coil conductors and to provide dielectric strength between the conductors and ground. The ground-wall insulation only exists within these slots.

The conductors of the coils also have an insulation system coating which provides dielectric strength between the conductors of the coils. There are slot insulators which separate the coil sides in each slot and phase insulation which separates the coils of each phase from each other. Finally, there is the varnish insulation whose primary purpose is mechanical strength with secondary purposes of mechanical strength and heat conduction. It also adds insulation integrity to the system.

Stator Failure Modes

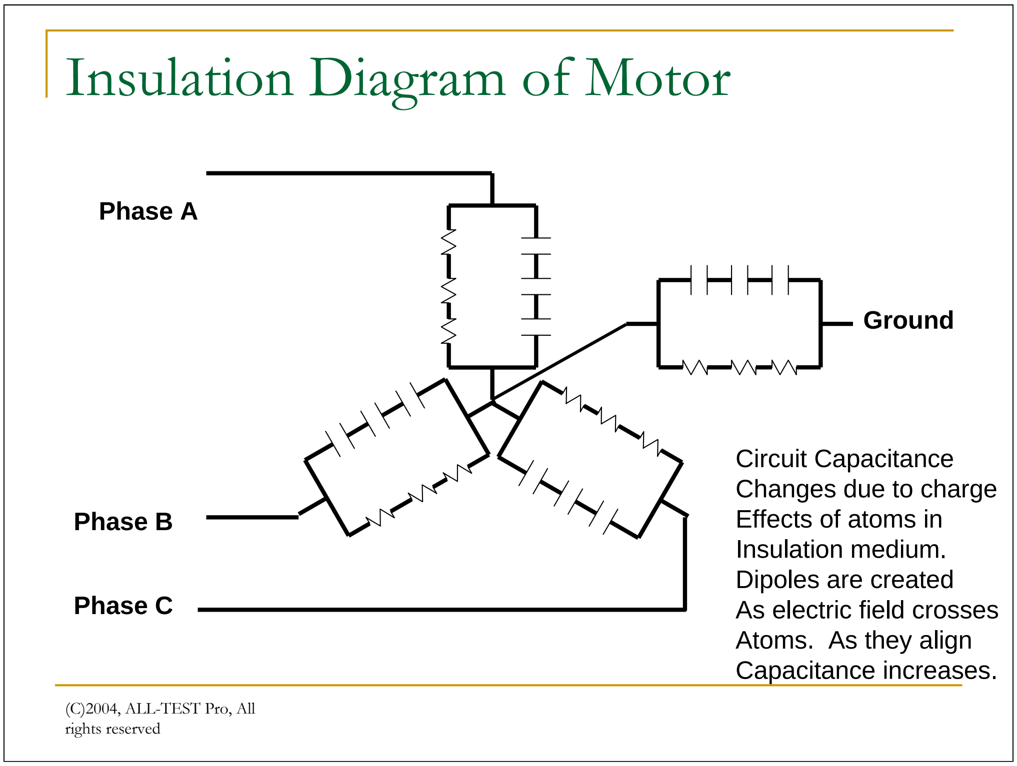
- Turn to Turn
- Coil to Coil
- Open Circuit
- Phase to Phase
- Coil to Ground



When everything is in place and operating as designed, there should be a relatively even heat distribution through the stator core and insulation system. However, when things go wrong…

The simplest description of an insulation system shows that it is not a true insulator. Instead, it can be modeled as parallel capacitances and resistances. These values, in an AC system, are referred to as the capacitive and resistive impedances of the insulation system. Changes to these values generate the problems that we commonly refer to as winding failure, or shorts. The changes can result from contamination or degradation of the insulation system.

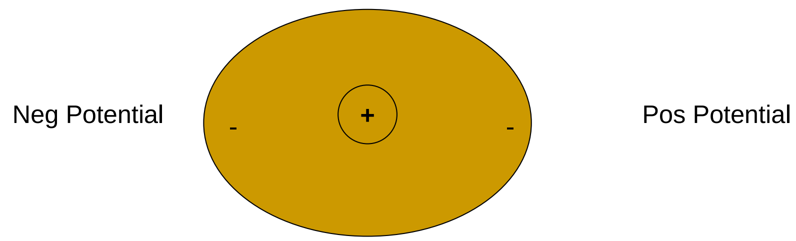
The most common insulation fault, within a winding, is the short. Insulation to ground faults, or faults through the ground wall insulation system, amount to 1/6th of your winding faults. This then translates into 1/18th of your electric motor faults, including mechanical. Winding shorts between turns, coils or phases, actually make up about 1/3rd of motor faults which may, occasionally, end up as insulation to ground faults.



The complete insulation system of an electric machine, in this case a wye connected machine, can be modeled as these resistive and capacitive impedances. This is where the mechanics of the insulation system end and the physics, at the atomic level, begin.

In the insulation system, the circuit capacitance is directly due to the electric field's effect on the atomic structure of the insulation system. An insulation system is actually a dielectric and not a true insulator. Dielectrics, themselves, are defined as materials whose atoms contain four valence electrons which allows them to easily polarize and allow some current to flow. The dielectric builds a charge across its surface and the system increases in resistance to current flow as the atoms of the dielectric material polarize.

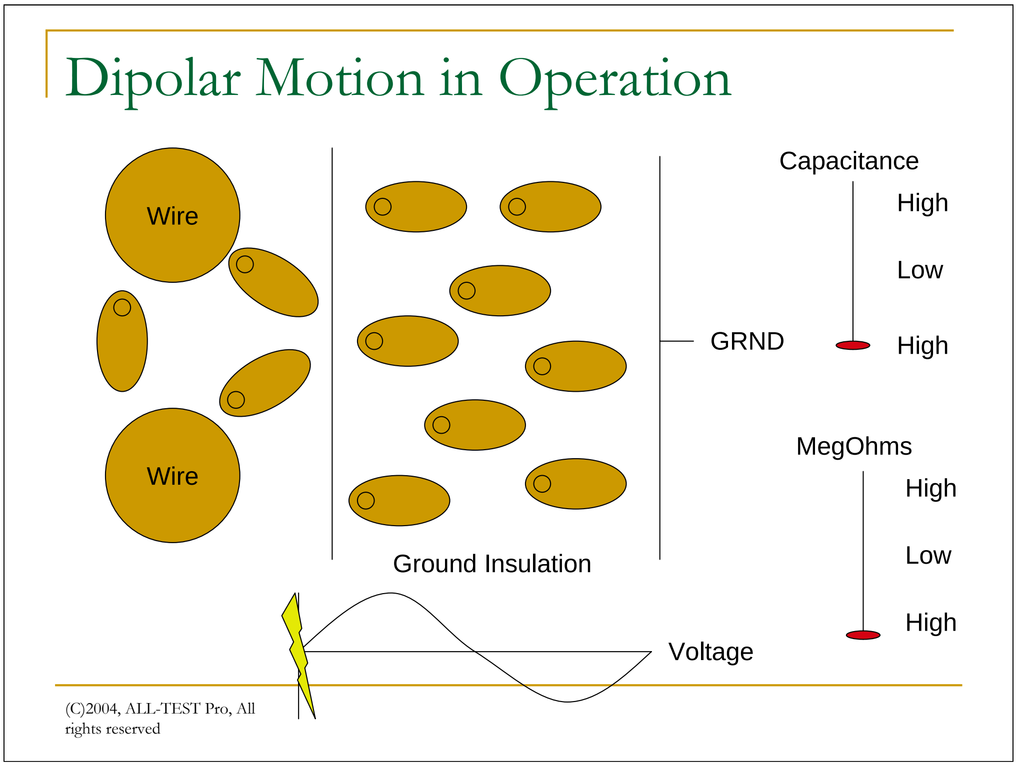
The Dipole



Polarization occurs as the electric field across an atom becomes more positive in one position and more negative in the other position, creating a potential. The effect can be visualized as a shift in the orbit of the electrons causing one side of the atom to be more positive and one to be more negative. This causes the insulation system to become more capacitive as more and more atoms polarize over time. When the field is removed, the polarized atoms relax and release the stored energy, that keeps them polarized, back into the system.

You can observe this effect when you place a DC insulation to ground tester across an insulation system to ground. Following the test, if you bring one of the test leads against the frame of the motor or, if you are unlucky, touch one of the leads of the motor, you may note a static discharge, or spark. This is a result of the dipoles relaxing, or returning to their neutral state.

The dipole effect is different than ionization in a very direct way. As the field increases, in a dielectric, it will become more resistive to current flow until it achieves a dielectric strength limit and breaks down, or ionizes. Ionization occurs when a material loses electrons, or adds electrons, becoming more positively or negatively charged. When this happens, the material becomes conductive, versus resistive, allowing current to flow freely.

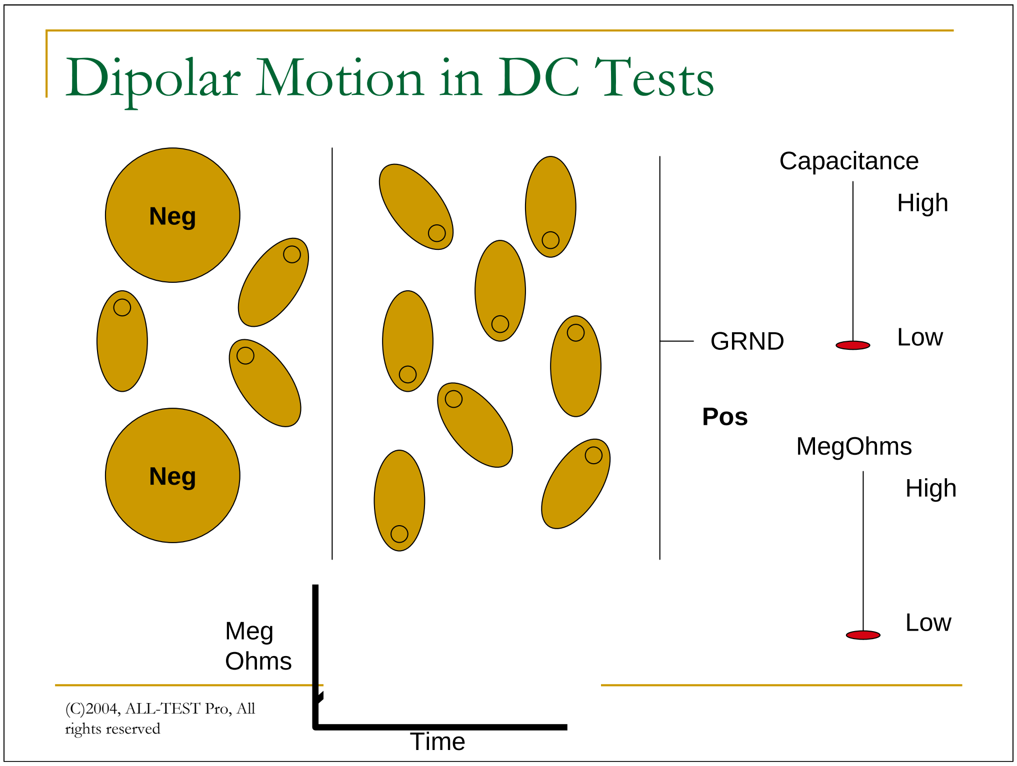


In an operating AC machine, the electric fields are constantly changing polarity and strength between conductors, coils and conductors and ground. This results in a constantly changing circuit capacitance and, therefore, a constantly changing insulation to ground resistance.

The dipole action is more along the lines of a ‘piston’ affect. However, in order to more easily stay with quantum mechanic descriptions, we will refer to it as ‘dipole spin.’

In an operating machine, the insulation system is quite active with the insulation system dipole spin occurring rapidly due to the amount of applied voltage to the motor. The strong alternating electric field masks minor changes to the insulation system by forcing defective insulation medium to polarize. This means that minor changes to the capacitance of the circuit are masked by the higher field potential of the motor at operating voltage.

What it also means is that a small capacitive defect will become hotter as the field forces the atoms of the dielectric to polarize. This causes a further breakdown of the insulation medium, sometimes referred to as carbonization, carbon, of course, being a dielectric. As the temperature and stress across the insulation increases, with time, the fault point becomes less resistive until the insulation, itself, finally becomes conductive. This will normally cause the motor to trip. Depending on the severity of the short, the insulation cools quickly, becomes more resistive and may allow the motor to re-start, in a sinusoidal voltage environment.



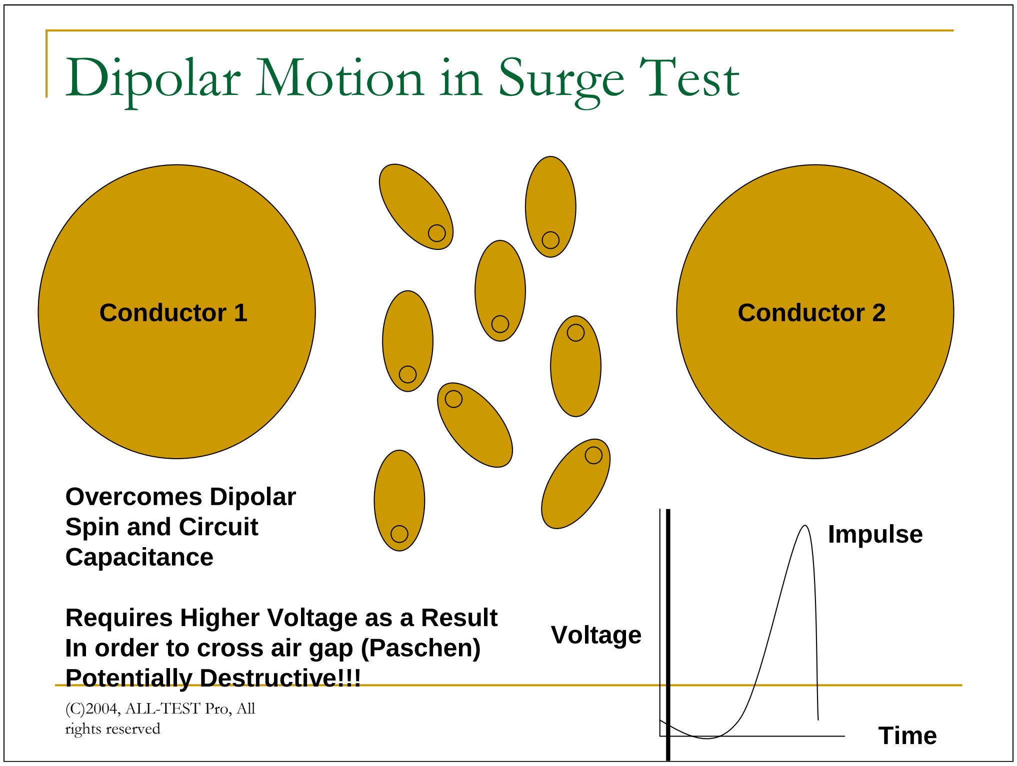
An insulation to ground DC test is a measurement of the amount of current flowing across the ground-wall insulation between the conductors at the ground-wall insulation through the slot cell insulation and to ground. This current value, normally in the milli or micro amp range, is then converted to MegOhms for display.

The atoms in the insulation system do not all polarize at once. It takes time. This can be observed on your insulation to ground tester as an increase in MegOhms over time, which, depending on the insulation system and conditions, may be very rapid or relatively slow.

Winding contamination, such as water, will molecularly polarize with a different value and may effect the rate at which current passes from the conductors to ground. Temperature also has an effect in that the higher the temperature, the more current flows.

In the past, the polarization index and dielectric absorption values were used as ratios in how rapidly the dielectric material polarizes, or how quickly the atoms polarize. However, with new insulation systems that polarize very rapidly, the polarization index values are normally very low and may fail the old ratio recommendations. Temperature and humidity, issues that could be ignored in pre-1974 insulation systems for polarization testing, must now be accounted for. The newest version of IEEE Standard 43-2000 states that in insulation systems over 5,000 MegOhms, the polarization index is not a useful test. New insulation systems have a tendency of having values in the high gig-ohms and terra-ohms.

The polarization index is also limited to determining the contamination or embrittlement of the insulation system at the ground-wall boundary in the slot cell and will not detect contamination on the coil ends.



One traditional method of testing inter-turn insulation condition in the manufacturing and repair environment is surge comparison testing. This method is based upon Paschen's law, which is simply defined as a voltage value in which the air and material ionizes and an arc is generated.

This method uses an applied voltage limited to twice the voltage plus 1000 volts in a series of fast rise-time pulses through the winding. The ringing effect of the impedance circuit of the winding is shown on an oscilloscope and phases are compared. If there is a deviation to the waveform, it determines that a potential fault exists.

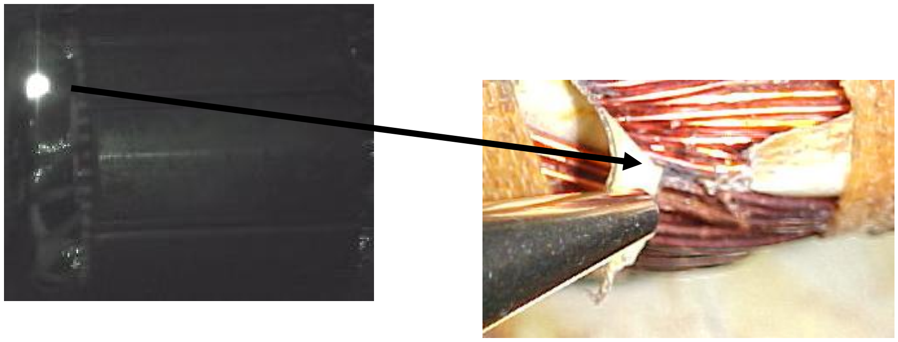
The system becomes less effective in assembled motors as the rotor will have an effect on the waveforms and the rotor position will cause a visible difference in the wave shapes from phase to phase. This may cause a false positive, meaning that the operator may claim the motor as failed, even though it has not.

The fast rise-time pulse of this technology causes the energy to dissipate rapidly through the first few turns of wire in the first coil of each phase. This limits the detection ability to this area of the winding such that faults deeper in the winding, say a VFD related short or end-turn damage, may be missed unless higher voltages are applied.

The size of this technology is also an issue due to the high energies and voltages required, as well as a nearby power source.

The final concern is that, if a defect exists, the detection of the insulation defect, itself, will cause rapid degradation of the winding. This means that the motor may operate prior to the test, but not after.

Accelerated Insulation Degradation

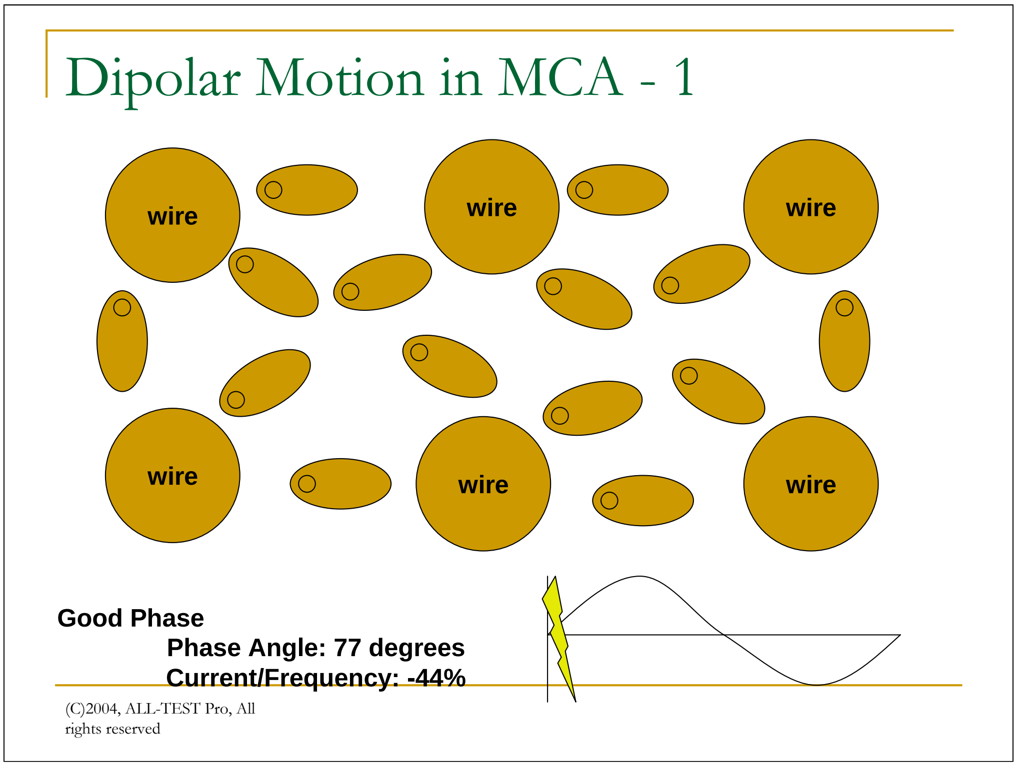


Arc during fault detection using surge test.

The separated insulation is the result of the arc (burned). The grey area on the copper is carbonized insulation.

The resulting arc from a contamination defect will cause rapid degradation of the insulation in the windings. This fault, between phases, resulted in damage to the phase paper insulation and carbonization of conductors between coils. The 20 horsepower stator shown was from an operating BJM Submersible pump. Repeated testing showed a rapidly decreasing voltage threshold.

Great care should be taken if considering this technology for field testing.



Motor circuit analysis is a technology designed primarily for field testing of assembled machines. It utilizes a very low, AC, sinusoidal voltage. The test voltage is such that the effect of circuit capacitance is dominant over voltage. The sinusoidal voltage excites the dipole spin of the insulation system between turns. Note that any other type of voltage output, such as a pulsed or saw-tooth output, will not work.

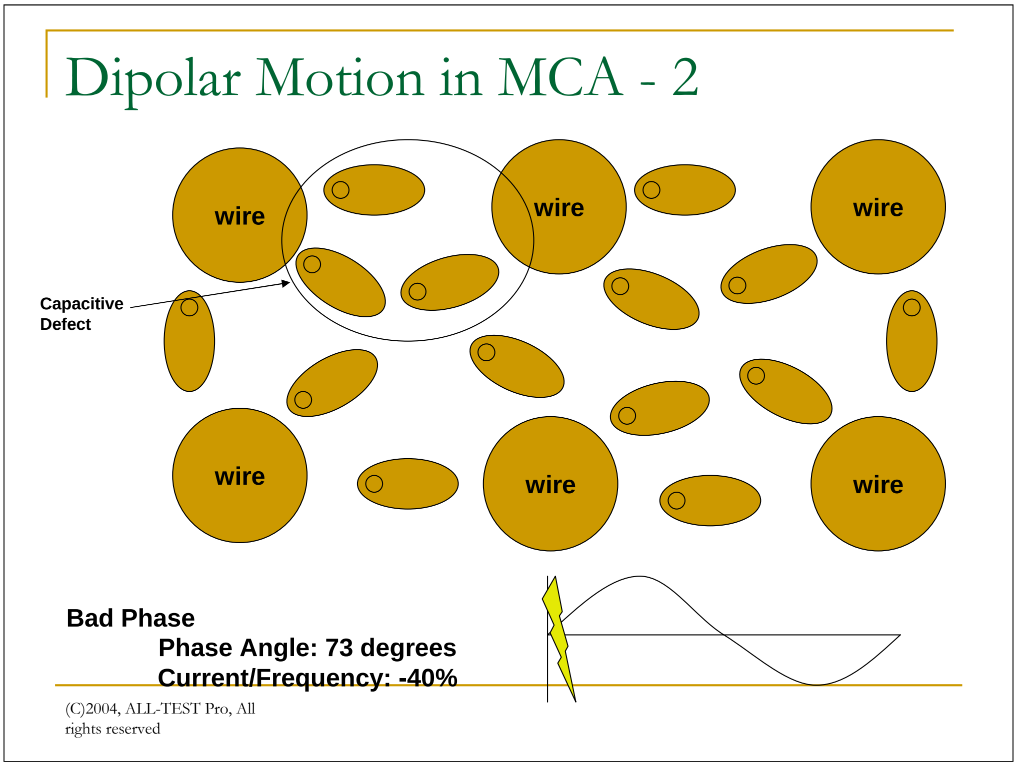
This allows for a direct comparison of the dielectric system between phases as a small change to the capacitance of the circuit will generate a significant change to the values of phase angle, or how far current lags voltage. In addition, a second test involving taking a current reading before and after doubling the instrument frequency, known as current/frequency response, or I/F, causes changes to the inter-turn capacitance to change. The value between the phases should be very close. The tolerance for both results are +/- 1 digit between phases, regardless of machine size.

Impedance and inductance are used together in order to detect winding contamination. As inductance will not change until a direct short has occurred, it is used as a baseline. Inductance will also be affected by rotor position, and will produce an unbalance value that is dependant upon the motor design and where the rotor is positioned. As such, when performing predictive maintenance testing, if the rotor cannot be moved, the inductive unbalance cannot be used to pass or fail a motor. Instead, the impedance, which is effected by such things as contamination or winding degradation, can be used along with it.

Contaminants cause an increase in circuit capacitance and have a particularly significant effect on this value when using low voltages by causing it to decrease. Therefore, when comparing phases, if an inductance reading shows a low, medium and high value, the impedance, which must be higher than inductance, should show a low, medium and high value. If they do not, then insulation degradation has occurred.

Resistance is used in MCA testing, but primarily for broken conductors and loose connection detection.

Insulation to ground testing is also included, in order to detect those 1 in 18 ground wall insulation defects.



As a fault progresses and carbonizes over time, a larger and larger number of dipoles become difficult to align. In an operating machine, the dominant voltage overcomes any small changes to the insulation capacitance. The defect does not become apparent until there is a significant current unbalance or the machine trips off line.

However, the low voltage application of MCA will detect those changes very quickly. In fact, the changes will be found early enough to trend developing defects in the insulation system over a relatively long period of time in a majority of cases.

Due to the simple physics of fault detection using MCA, it has also been determined that the phase angle and current frequency response patterns can discern the type of developing, or existing, defect. If both are out of range, it is related to turns within a coil, if phase angle is effected, it is coil to coil in the same phase, and if current frequency is effected, it is phase to phase. Historically, these have been seen in most field cases.

Before and After Defect

	1-2	1-3	2-3
Resistance	0.6821	0.6798	0.6865
Impedance	21	21	39
Inductance	8	8	7
Phase Angle	77	76	76
I/F	-47	-45	-47
Ins Resist	>99		

MCA Result on
20 hp with contamination and slight phase to phase defect. Still running.

	1-2	1-3	2-3
Resistance	0.6786	0.6797	0.6819
Impedance	21	21	39
Inductance	8	8	7
Phase Angle	77	77	76
I/F	-47	-43	-47
Ins Resist	>99		

MCA test results following surge test from previous example. Trips on start.

In this example, the previously described 20 horsepower stator was tested, disassembled, surged and then reassembled and re-tested.

The contamination issue and a slight phase to phase defect were detected prior to disassembly. Following high voltage testing, the test results in current frequency changed and degraded further. The motor was operable prior to the high voltage test, but not after.

This was part of a larger study meant to duplicate, using real stators with real defects from our pump division, not lab induced faults, observations from the field so that they could be studied in detail. All instruments used were factory calibrated and used per instructions.

Insulation Test Method Overview

- Electrical Insulation is a dielectric
- Electric fields cause atoms to polarize with a change to capacitance as they polarize
- DC Insulation tests measure change to capacitance as charge crosses in *one direction*
- Surge test uses a high voltage impulse in order to detect defects by causing an arc. Voltages too high to detect small changes in capacitive reactance defects in insulation systems. Requires over-stress.
- MCA causes full excitation of the insulation system with low voltage. Small changes will effect circuit capacitance which will not be ‘masked’ by high voltage.
- MCA method also allows early detection of faults and, as a result, can trend winding faults over time.

In conclusion, the following observations come from this presentation:

Electrical insulation is a dielectric. As such, electric fields cause the atoms of the material to polarize and change capacitance as they polarize.

DC insulation tests measure change to capacitance as the charge crosses in one direction versus generating dipole spin. The tested area is also limited to just the ground-wall insulation.

High voltage surge testing uses a high voltage impulse in order to detect defects by causing an arc. The applied voltages are too large to detect small changes in capacitance between conductors in an insulation system and instead relies upon stressing the insulation system.

MCA involves fully exciting the insulation system with low voltage. Small changes to the circuit capacitance will not be masked by higher voltages, allowing for early detection of changes to the insulation system. The small changes can be trended, providing a method of estimating time to failure when a defect is detected.

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Contact Dr Penrose for information on how to obtain copies of this series and the 2003 motor diagnostic series.