

## Motor Circuit Analysis Concept and Principle

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### Abstract

Low voltage Motor Circuit Analysis (MCA) techniques involve the collection and analysis of resistance, impedance, inductance, phase angle, current/frequency response and insulation to ground faults. Output voltage of the test instruments are less than 9Vac, sinusoidal output. The resulting low level alternating magnetic fields excite the dielectric dipoles and surrounding magnetic steel dipoles, in both the stator and rotor. Winding defects, including developing shorts, cause changes to the dielectric and resulting dipolar action (spin), which changes the capacitance of the winding circuit at the point of defect. The resulting change effects the phase angle and current/frequency response in the corresponding phase, causing a difference when comparing phase, or coil grouping, to phase. As the defect progresses, the changes to the insulation system continue, allowing trending of the defect over time. The purpose of this paper is to cover the concepts and principles in the physical changes to the windings in winding short and winding contamination faults. The concepts will be supported with a series of experiments performed with MCA and traditional test methods.

### I. INTRODUCTION

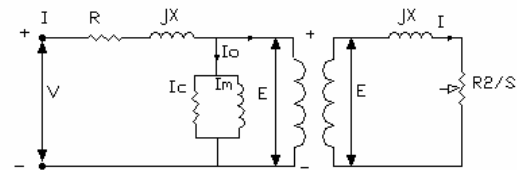
Motor Circuit Analysis (MCA) techniques utilizing Resistance (R), Impedance (Z), Inductance (L), Phase Angle ( $\Phi$ ), current/frequency response (I/F) and insulation resistance have been in practice since 1985. The technique has been successfully applied for the detection of winding defects (shorts, resistive unbalances and insulation to ground), cable defects and rotor defects. It has also been found to be able to trend and estimate winding failures with a high degree of accuracy.<sup>i, ii</sup>

In this paper, we will discuss the physical properties that allow for the detection of these motor electrical circuit faults using MCA. We

will then support the concepts by presenting a series of experiments performed using MCA techniques and comparing to existing technologies.

### II. THE MOTOR CIRCUIT

Figure 1: Single Phase Equivalent Circuit



The three phases of a three phase induction electric motor are separated by  $120^\circ$  electrical. The supply voltage phases are also, optimally, separated by  $120^\circ$  electrical. Within each phase, as the voltage increases, current increases due to the impedance of the motor circuit (See Figure 1). As the current increases, the two magnetic poles increase (or sets of poles), then decrease as current decreases. The stator back iron acts to strengthen and direct the magnetic fields within the air gap between the stator and rotor. As the fields pass through the rotor bars (conductors) of the rotor, a second current develops in the rotor which interacts with the rotating fields in the air gap. The rotor follows the rotating fields, although lags behind the synchronous speed of the stator (slip) in order to maintain a rotor current, and resulting rotor magnetic fields.

As this is occurring, changes also occur to the insulation system and back iron steel. As the current increases in each phase:

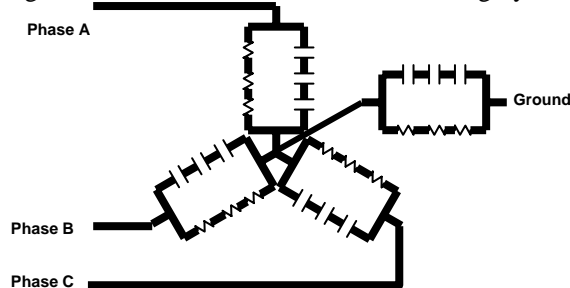
- ✓ There is a skin effect within the copper conductors that forces more current towards the surface of the conductor.

- ✓ Insulation dipoles polarize between conductors as the phase voltage and current increases and decreases, causing constantly changing capacitance within the circuit between conductors.
- ✓ Insulation dipoles polarize between conductors and ground as the phase voltage and current increases and decreases, causing constantly changing capacitance between the winding circuit and ground.
- ✓ Magnetic dipoles polarize in the area of effect of each pole within the stator core steel. The reluctance to realign, with a change in magnetic field, is termed as hysteresis.

Operating voltages force the changes to occur fairly rapidly. Changes to the circuit, or to the dielectric or magnetic properties of the motor effect its operation and the force of the operating voltage causes the defective areas of the insulation or steel to heat. Continued breakdown of the dielectric occurs based upon the severity of the fault.

## III. INSULATION AND MAGNETIC FIELD EFFECTS

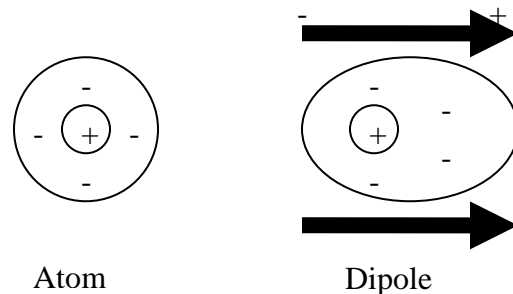
Figure 2: Insulation Model of Motor Winding System



The electrical insulation circuit is modeled as a series of parallel RC circuits between conductors and conductors and ground. As changes occur to the insulation system, the values of R and C change. The values of the insulation in each phase are the sum of the turn to turn and coil to coil RC values of each phase. Insulation to ground values are the sum of the insulation between conductors and ground for the complete circuit.

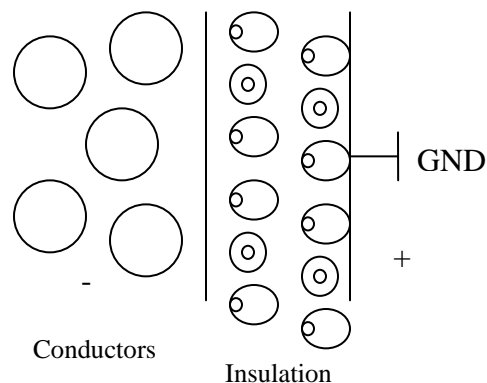
The capacitance of the electrical insulation is a direct function of the generation of dipoles within the insulation system. As a field is generated across an atom, or molecule, of a dielectric, it will polarize, meaning that the electron orbit of an atom will shift slightly, making one side of the atom more positive and one more negative.

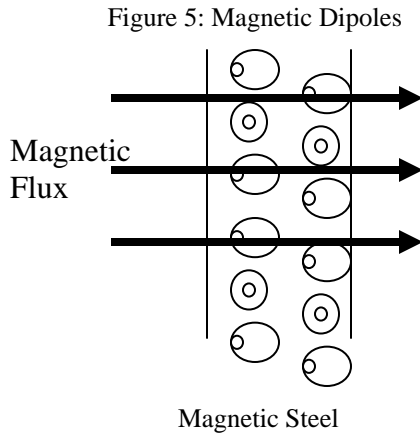
Figure 3: Generation of a Dipole



As current passes through conductors near electrical insulation, the insulation reacts by polarizing the atoms (dipoles) within the insulation. As the dipoles polarize, there is less leakage (capacitance) between the conductors and ground. This also occurs in the insulation system between conductors when there is a difference in potential. In a good insulation system, the polarization of the insulation system occurs in a larger number of atoms. Once the potential is removed, the atoms return to their original state (dipoles randomize).

Figure 4: Dipolar Effect of Insulation





The same effect occurs in a magnetic field. The magnetic dipoles of the backiron and teeth of the stator core line up in the direction of the magnetic field. This helps direct the magnetic flux and adds to the strength of the fields within the airgap. The reluctance of the steel to change polarity shows up as hysteresis losses from the field. Once the field is removed, the magnetic dipoles of the steel quickly randomize.

The above descriptions for the polarization of electrical insulation and core steel represent the steady-state application of an applied voltage potential. In an operating three phase system, the effects get far more exciting. As each sinusoidal phase of voltage is impressed across the windings:

- ✓ As the voltage starts from zero, the beginning of the coil energizes, the insulating dipoles between the insulation to ground and the conductors within the coil are forced to polarize.
- ✓ As the voltage continues to rise, the potential at the beginning of the coil is higher than the end of the coil, insulating dipoles continue to polarize and the magnetic dipoles begin to polarize in the direction of the magnetic flux generated by the coils.
- ✓ As the voltage hits its peak at the beginning of the coil, a majority of the magnetic and insulating dipoles associated with the start of the coil have polarized and the ones at the end of the coil continue to polarize. There is a lag in the fields between the beginning and

the end of the coil, which causes a potential between conductors to exist.

- ✓ As the voltage begins to decrease, the insulating and magnetic dipoles begin to randomize (move to neutral) at the beginning of the coil and release energy back into the system as the fields collapse. The fields at the end of the coil hit their peak then start to decrease.
- ✓ The voltage approaches zero, then passes into the negative sequence of the sine wave. The dipoles and fields continue to react, but align in the opposite direction (as in a piston action). We will define this action as 'dipolar spin' of both the electrical insulation and magnetic steel dipoles.

The high potential of most electric motors force the changes to the fields and dipoles to happen quickly. As a result, work is performed and heat is generated.

The Capacitance of each portion of the circuit is given, at any time, as:

$$[1] \quad C = \frac{Q}{Q - q} \frac{\epsilon^o S}{l}$$

Where an insulator exists between the conductors and conductors and ground. The induced charge,  $q$ , increases the capacitance by the ratio  $Q/(Q-q)$ . The dimensionless ratio  $q/(Q-q)$  is a property of the polarizability of the material and is referred to as the electric susceptibility,  $\chi_e$ .<sup>iii</sup> At the boundary of each insulation system (conductors, slot, phase, etc.), the boundary conditions are such that:

$$[2] \quad \tan \theta_2 = \epsilon_r \tan \theta_1$$

Where  $\epsilon_r$  represents the relative permittivity of the boundary of the insulation surface.

By dividing each phase into tubes and slices,<sup>iv</sup> the total capacitance for  $m$  slices and  $n$  tubes through the system would be:

$$[3] \quad C = \sum_1^n \left( \sum_1^m \frac{\delta l}{\epsilon \delta S} \right)^{-1}$$

The inductance of the circuit can be figured as the flux linkage per unit of current, and is represented by the unit Henry (H):

$$[4] \quad L = \frac{N\phi}{i}$$

For a motor with n coils, the inductance may be defined:

$$[5] \quad L_{pq} = \frac{N_p(K_{pq}\phi_q)}{i_q}$$

Where  $K_{pq}$  is referred to as the coupling coefficient between two coils (p and q). When p and q are equal, the inductance is termed as self-inductance, when unequal, it is termed mutual inductance.<sup>v</sup>

The total impedance per phase as viewed from the stator input terminals is given as [6] where X refers to the leakage reactance (capacitive).<sup>vi</sup>

$$[6] \quad Z_t = R_1 + jX_{l1} + \frac{jX_M \left( \frac{R'_2}{s} + jX'_{l2} \right)}{\frac{R'_2}{s} + j(X_M + X'_{l2})}$$

In simpler form, impedance can also be viewed as:

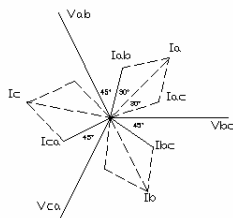
$$[7] \quad X_L = 2\pi fL = \text{Inductive Reactance}$$

$$[8] \quad X_c = \frac{1}{2\pi fC} = \text{Capacitive Reactance}$$

$$[9] \quad Z = \sqrt{R^2 + (X_L - X_c)^2}$$

When looking at a balanced system, a wye circuit should appear as in Figure 6.

Figure 6: Balanced Wye System



The circuit impedance would appear:

$$[10] \quad Z_{AB} = \frac{V_{AB}}{I_{AB}}$$

For example:

$$32.9 \angle 45^\circ \Omega = \frac{650.5 \angle 120^\circ V}{19.8 \angle 75^\circ A}$$

Armed with this information, we can now review the effects of winding related faults on the operation of the motor.

## IV. WINDING FAULTS

When a defect occurs in a winding due to a developing short, winding contamination or severely damaged core steel, it effects the electrical properties of the insulation system. In the case of a winding defect, changes to either capacitance or resistance within the insulation system will cause a reactive problem due to changes to the makeup of the insulation system. For instance, in a developing short, the changes to the insulation system cause changes to the capacitance due to changes in how the dipoles are excited (dipole spin). As a result, there are changes to how the insulation reacts in that area, causing a leakage reactance variance and heating due to forcing the insulation to polarize with high applied potential (operating voltage). Winding contamination causes changes to the resistive and capacitive reactance between insulating surfaces, as well.

At design voltage, most defects do not become apparent until a distinct change occurs, which may be represented by a severe current unbalance, nuisance tripping or a direct short circuit. In the case of winding contamination, the end result is the same as a winding short: Either a short between conductors or across the insulation system to ground.

As a result, as faults occur due to thermal deterioration, contamination, moisture absorption or other reactive faults, the circuit impedance will change, slightly, at first, then more dramatic as the fault progresses.

### V. TRADITIONAL TEST METHODS

Most of the traditional test methods require a significant voltage application in order to work. The purpose is to stress the insulation system by forcing a reaction of the insulation dipoles, or ionization of air and insulation medium defects in order to force a potential across a resistive or capacitive fault. In this section, we will review a few of the test methods in brief, including: Insulation to ground testing; Polarization Index; Resistance Testing; and, Surge Comparison Testing.

#### A. *Insulation to Ground Testing (Meg-Ohm meters)*

As described in Figure 4, a DC potential is placed across the motor winding conductors and ground. The applied potential is set and a value of current (leakage) crosses the insulation boundary. This value is converted to resistance, usually in meg-ohms. It is, in effect, a method of measuring leakage across the insulation boundary, but only between the surfaces of the conductors and ground. As the insulation dipoles are only excited with DC, some time is required for them to polarize. Standards normally indicate a winding charging time of one minute and, as insulation resistance is directly affected by temperature and moisture, normalization for temperature.

#### B. *Polarization Index*

The Polarization Index (PI) test is a measurement of leakage at one minute then at ten minutes. The results are shown as a ratio of the ten minute to one minute readings. It is assumed that a fault will polarize slowly (high ratio) or rapidly (low ratio) due to contamination and changes to the ground wall circuit capacitance.

#### C. *Resistance Testing*

Resistance tests use a low voltage DC output and bridge. The primary purpose is to detect high resistance joints, loose connections, broken connections and direct shorts.

#### D. *Surge Comparison Testing*

An older method of evaluating windings for shorts. A series of steep-fronted higher voltage pulses are sent from the instrument to the stator. The higher voltages occur too fast to properly polarize the insulation system, instead relying upon higher voltage to ionize gasses leaving the ability to detect a reactive fault as creating enough potential to cross the barrier (Paschen's Law) with the test ending prior to twice the nameplate voltage plus 1000 Volts or once an arc is drawn. This method of testing causes a change to the properties of the insulation at the point of defect either accelerating the fault or completing the fault. In order to force slight defects, a greater potential must be applied in order to stress the complete system. Due to the steep fronted surges, however, the applied voltage is normally applied on the first 2-3 turns in the first coil of each phase.

"The situation is quite different for detecting the breakdown of the turn insulation in a winding (parallel or phase) having many coils. The breakdown of the turn insulation in a single coil in a winding of many coils produces a very small relative change in the characteristics (L, C, R) of total load impedance seen by the surge generator. Hence, the change in the VWF [voltage wave form] shape produced by the breakdown of the turn insulation somewhere in a winding of many coils is relatively very small. Hence the surge tests may not reliably verify the presence of one shorted turn in a single phase and may probably lead to wrong conclusions. Perfectly intact windings may appear to have a turn short. More importantly, a turn short induced by the surge test by breaking down the weakened turn insulation may not be detected. In such a case, the stator winding would likely fail after the machine is put back into service.

"In view of the above facts, caution is advised in surge testing of the turn insulation in complete windings. These tests carry very significant risks, which should be carefully considered. Such caution is more important for diagnostic tests on machines in service as such tests are carried out quite infrequently in contrast to

frequent tests on new, or refurbished, or repaired machines in a manufacturer's plant."<sup>vii</sup>

As shown, traditional testing has specific flaws in the ability to detect faults, and the ability to detect these faults in a non-destructive manner.

### VI. MODERN LOW-VOLTAGE TESTING: MOTOR CIRCUIT ANALYSIS

Modern MCA devices use a low voltage sine-wave output designed to excite the insulation system dipoles and surrounding magnetic steel dipoles with low current. There are several key benefits to this approach: Size and voltage rating of the machine being tested do not matter; Specific pass/fail criteria can be applied to phase comparison; and, Degradation can be trended over time without any adverse effects to the existing condition.

"Based upon the physical and electrical properties of coil windings, insulation, systems, transformer theory and electric motor theory, a set of electronic measurements can provide the necessary information to determine the condition of electrical equipment. The measurements must include circuit DC resistance, circuit inductance, circuit impedance, phase angle, current/frequency response and insulation resistance readings. Resistance readings are used for open or poor connections, inductance and impedance are used to evaluate winding condition in electric motors and phase balance in all other applications, phase angle and current/frequency response tests evaluate windings for shorts and insulation resistance readings are used to detect winding to ground shorts."<sup>viii</sup>

#### A. Detection of Winding Contamination

Due to the fact that one of the last measurements to change due to a turn short fault is inductance (L), a test result of L can be used as a comparative baseline. This is important as the relative position of the rotor in an assembled machine will effect the reading due to mutual inductance.

$$[11] \quad a^2 = \frac{m_1}{m_2} \left( \frac{k_{w1} N_1}{k_{w2} N_2} \right)^2$$

Where 1 represents the stator winding factors and phases and 2 represents the rotor bar factors and bars per phase. The result is a ratio, the same as a transformer ratio. When a rotor is stationary in an electric motor, the ratios are different for each phase.

Winding contamination causes small changes to the capacitance of the winding circuit. In most cases, the capacitance increases within the circuit. When referencing the simple impedance formula, earlier in this paper, it identifies that an increase in capacitance will have a negative impact on impedance. Also, as the applied voltage is very low, capacitive reactance has a more significant impact on the impedance (Ohm's Law) as the capacitive value is more dominant. The result, using a relatively low frequency and sinusoidal output, is a collapse of impedance towards inductance in the phase which has capacitive effects from the contamination or water absorption. In cases of high humidity, the insulation has to have fissures or defects in order to cause the change.

#### B. Overheated Windings

Overheated windings have a similar impact as winding contamination. The difference is that the insulation is thermally degrading causing increased resistance to dipolar action. In this case, the capacitance may decrease, causing an increase in impedance in one, or more, phases.

In both winding contamination and overheated windings, the end result would be a winding short. Winding contamination can be corrected if detected in its early stages. However, once changes occur that allow for the detection of a winding fault, the winding will have to be replaced.

#### C. Winding Shorts

One of the keys to proper MCA testing is that inductance is not used as a primary method of detection for developing shorts. Instead, two

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specific measurements are used in combination to determine the type and severity of the defect. These measurements are: The circuit phase angle; and, A Current/Frequency response method.

When a defect occurs in the winding, it changes the effective capacitance of the complete circuit. The change in capacitance will directly effect how the low level current lags behind voltage with the usual result being an increase in capacitance and a reduction of the phase angle in the effected phase. Once the fault becomes more severe, it will begin to effect the surrounding phases. This normally occurs when the defect exists in once coil or between coils in the same phase. A very small change to capacitance within the circuit can be detected, allowing the detection of single turn faults and pinhole shorts when using very low frequencies.

A second method of fault detection uses a current ratio, similar in method to the frequency response method used for transformer testing. However, the low voltage current is measured, then the frequency is exactly doubled and a percentage reduction in the low-level current is produced. When the frequency is doubled, small changes to capacitance between turns or between phases are amplified, causing a change to the percentage reduction when compared between phases.

The combination of phase angle and current/frequency response allow for the detection of winding shorts and the type of short being detected in any size machine. Also, due to the use of low voltage and the result that only a small change to circuit capacitance is required to detect the faults, early winding defects can be detected quickly and trended to failure.

### D. Additional Tests

In combination with the above tests, MCA utilizes resistance readings and insulation to ground tests. This allows the technology to detect approximately half of the potential faults in the overall motor system and allows for the comparison of any two sets of insulated coils.

Faults and defects can be detected in cables, coils, transformers, motors and rotor defects.

### E. Rotor Testing and Back Iron Effects on MCA

The effect of being able to evaluate the condition of the motor rotor is “based upon Faraday’s law of electromagnetic induction, according to which a time-varying flux linking a coil induces an emf (voltage) in it.”<sup>ix</sup>

$$[12] \quad e_1 = \omega N_1 \phi_m \cos \omega t \text{ for the primary emf}$$

$$[13] \quad e_2 = \omega N_2 \phi_m \cos \omega t \text{ for the induced secondary emf}$$

$$[14] \quad \frac{e_1}{e_2} = \frac{N_1}{N_2} \text{ for the turns ratio}$$

$$[15] \quad \frac{Z_1}{Z_2} = \left(\frac{N_1}{N_2}\right)^2 = a^2$$

Which is the ratio of the primary and secondary impedances of the circuit.

The motor circuit analyzer excites the core steel based upon the amount of current available to the circuit and reacts across the airgap:

$$[16] \quad nI = \frac{Bl_{iron}}{u_r u_o} + \frac{Bl_{gap}}{u_o}$$

The direct relationship to the ability to detect the rotor across the airgap depends upon the distance across the airgap, the area of the steel magnetized and the length of the stator core. In longer cores, the effect will carry across the airgap and excite the rotor core and induce the instrument frequency into the rotor circuit. In very short cores, the fringing effect the magnetic field from the stator has a similar effect. In large machines, the amount of energy available from an MCA device allows for the detection of rotor defects only above the area immediately surrounding each coil side.

This produces multiple effects:

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- A. The mutual inductance changes as the rotor position changes as a direct result of the change to the transformer ratio between the primary (stator) and secondary (rotor). A good rotor will show as a repeating pattern, a bad rotor will change the transformer ratio and a defect will appear as a non-repeating pattern.
- B. Fractures will be readily detected as the induced energy is relatively low and the oxides on the surface of the defect will change the transformer ratio. Whereas, in higher voltage rotor tests, the energy may be significant enough to pass through the defect.
- C. In rare instances, the airgap may be too significant and very little to no variation of the mutual inductance occurs. In this case, larger defects, such as multiple fractures or a broken bar, will show as a variation in a straight line.
- D. MCA technology has the ability to detect wound rotor, synchronous rotor field and other wound-rotor defects across the airgap. Because of the impedance ratio between the primary and secondary, rotor winding defects will show as a change to phase angle and current/frequency response and will vary based upon rotor position.

### *F. Armature and Commutator Contamination Detection*

One of the unique abilities of MCA is the ability to detect carbon buildup in DC motor armatures. Due to the dielectric (capacitive) properties of carbon, capacitance values of the circuit become unstable. This causes test results of impedance, phase angle, current/frequency response and insulation to ground to become unstable and non-repeatable. As a result, armature circuit contamination is detected by noting non-repeatable test results. This is important in that, if detected early, this type of defect may be corrected by blowing out the armature with low pressure air.

## VII. SUMMARY OF MCA THEORY

Based upon the engineering principles of motor and transformer design, utilizing low voltage

testing technologies allow for the detection of incipient defects in the electric motor circuit including cable insulation, coils, transformers, connections, motor and rotor windings, armatures, air gap issues and squirrel cage rotor defects, covering over 50% of all potential motor system faults of any size or voltage machine through the motor circuit and cabling or directly at the machine. This is achieved by utilizing a low potential sinusoidal output from the instrument which excites the insulation and magnetic dipoles of the circuit. The low potential allows defects to become more readily apparent at early stages as it does not force, but excites, dipolar spin, causing changes to the circuit impedance, phase angle and current at varying frequencies (current/frequency response), depending on the type of fault. These properties of the technology allow for long term trending of developing defects from insulation breakdown and contamination without any harmful testing effects due to insulation breakdown nor winding contamination.

## VIII. DEVELOPMENT OF EXPERIMENTS

In the first part of this paper, a number of fault detection capabilities and the method for how faults are detected, using MCA methodology were outlined. A series of controlled experiments were developed, based upon this paper and previously developed tolerances, using MCA and surge comparison testing. The experiments were developed to provide the following:

1. Experiment 1: A used 20 horsepower, 3600 RPM, 460 Volt stator only from a BJM Pump, model KZN 150 (submersible) was selected from the BJM Corp repair center discard area. A visible winding fault, caused from what appeared to be mechanical damage, was identified. The original cause of failure for the pump was seal failure, resulting in bearing failure with the bearing causing damage to the winding. The winding was still operational when the pump was sent for repair and was pulled due to detection of the fault by MCA, then visual detection:



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- 1.1. Use MCA to detect fault using standard fault detection rules;
- 1.2. Apply surge comparison voltage value until the visible fault was detected and note voltage value. Determine if the fault was detected in the same phase;
- 1.3. Note effect of both test methods, during fault detection.
2. Experiment 2: Performed in three parts:
  - 2.1. A  $\frac{3}{4}$  horsepower, 3-phase, 1750 RPM, 460 Volt, used, complete Dayton motor was selected. The motor was disassembled and inspected, then reassembled. Testing was performed before and after using both an ALL-TEST IV PRO 2000 (AT4) and ALL-TEST PRO 31 (AT31). Surge comparison testing was performed to 1800 Volts for 3-5 seconds. The purpose was to detect and determine field observed changes to impedance, inductance, and other test results following surge comparison testing in the field.
  - 2.2. A Baldor, 1 horsepower, 1725 RPM, 460 Volt, new, assembled motor with a rotor fault generated, involving the removal of two rotor bars from the rotor circuit. The purpose was to detect the condition of the winding and determine the capability of detecting rotor bar faults, and the effect of rotor position on test methods using the AT4, AT31 and surge comparison tester. Confirmation of winding condition was determined by applying 12,000 Volts using the surge comparison tester.
  - 2.3. A 1 horsepower SPV style, 3600 RPM, 460 Volt, BJM Submersible Pump stator with grey water contamination was selected from the repair discard pile. A coil-to-coil fault within the same phase, between individual turns, was observed during selection. The stator was selected due to a low (0.98 MegOhms) insulation test value, representing severe winding contamination conditions. The stator was to be evaluated using the AT4 and AT31 for purposes of contamination detection, surge tested to 1800 Volts,

then re-tested using MCA. The purpose was to determine the ability of MCA to detect the faults and impact of surge comparison testing on winding contamination.

3. Experiment 3: Insert rotor in the stator from Experiment 1 in order to determine the impact of the rotor on the original test results and to identify severity of the faults. Surge comparison testing was used to degrade the fault condition and the results monitored using MCA. The dielectric strength was trended following each test. The differences between a running equipment fault and progressive degradation from the surge tester used are to be noted.

The MCA devices were factory calibrated, as was the surge comparison tester, prior to test evaluation. Testing was performed over three separate days with variations to temperature and humidity (dew point) in which the differences were noted between Experiment 1 and Experiment 3.

Through each experiment, the theories presented in the first part of this paper were supported and winding tolerances confirmed. Testing and results were recorded within instruments and via a video log of critical test results. Variances in test results between the AT4 and AT31 involve the use of different test frequencies ranging between 25 Hz and 800 Hz.

## IX. TEST TOLERANCES

### A. MCA Tolerances

MCA Test tolerances for the technologies presented in this paper are well established:

Table 1: Assembled Motor Tolerances

Test	Tolerance
Resistance	< 5%
Z and L	Similar Pattern in Both Results (phase comparison)
Fi and I/F	+/- 1 Digit from Average Result (phase comparison)
Insulation Resistance	> 5MegOhm for <600V motor >100 Mohm for >600V motor

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Table 2: Disassembled Motor Tolerances

Test	Tolerance
Resistance	< 5%
Z and L	< 3% and <5% respectively
Fi and I/F	+/- 0 From Average Result (phase comparison)
Insulation Resistance	> 5MegOhm for <600V motor >100 Mohm for >600V motor

### B. Surge Testing Tolerances

Requires a visual tolerance between phases. Separation of waveforms indicate a fault in the windings, such as a short. Theoretically, surge testing will provide a 'shift' in the right side of the waveform prior to arcing.

## X. EXPERIMENT TEST RESULTS

### A. Experiment 1

The 20 horsepower stator was selected and placed on a wooden crate to ensure no interference from other surrounding materials. Testing was performed using MCA and following the rules for motors tested without rotors, as shown in Table 3.

Table 3: Pre-Test Results with MCA

	1-2	1-3	2-3
Resistance	0.7209	0.7207	0.7206
Impedance	41	40	40
Inductance	8	8	8
Phase Angle	83	83	83
I/F	-49	-50	-49
Ins Resistance	>99		

Surge testing was performed. All three phases were, initially, limited to testing to 2,000 Volts (Figure 7, 8 and 9).

Figure 7: Surge Results T1-T2

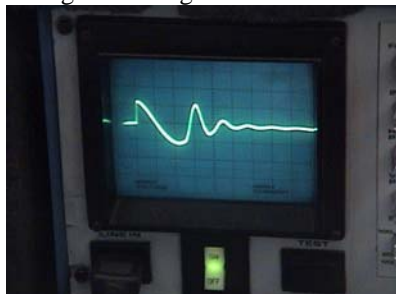


Figure 8: Surge Results T1-T3



Figure 9: Surge Results T2-T3



The MCA test identified the phase to phase fault in test leads T1-T3. To ensure detection across T1-T3, the stator was surge tested to failure (Figure 10).

Figure 10: Fault Detection (Night Vision Video)



The fault was detected on leads T1-T3 at 6,000 Volts. In confirming tests, it was noted that the voltage decreased to 4,500 Volts. No shift, or other pre-arc conditions, were noted prior to distortion and concurrent arcing at the fault point. Smoke was noted at the fault point, which was found to be the arc burning through the remaining insulation during surge testing (Figure 11). In the follow-up MCA, it was noted that the impedance measurements across leads T2-T3 increased significantly (doubled) due to a change in the applied frequency as a result of a change to the condition of the circuit.

Figure 11: Arc Damage (Night Vision Video)



The conclusion was that MCA testing was able to detect the fault sooner, between phases, than the surge comparison test. Due to the location of the fault, this was expected as it was a 'deep winding' fault in the center of a coil.

## B. Experiment 2a

One occasional observation, in the field, has been changes to MCA results following fast  $dV/dt$  high voltage testing, such as surge comparison testing, including inductance, impedance and other results. An assumption has been the dipolar alignment of the magnetic steel and dielectric insulation following the motor being at rest for some length of time. If this were to be the case, then it would have to be assumed that: a) Surge comparison testing would generate dipolar action and alignment; and, b) The core steel would maintain the dipolar action, assuming magnetic domains would be generated, which would cause some level of retained magnetism. Therefore, a used motor with a good winding, that was estimated to show evidence of this effect, was selected and surge tested to 1,800 Volts.

Figure 12: Disassembled Test Motor



Table 4: Before and After AT4 Test Results with Differences

	Before	After	Diff
Resistance	85.422	85.402	-0.02
Impedance	300	287	-13
Inductance	458	437	-21
Phase Angle	79	78	-1
I/F	-41	-41	0
Ins Resistance	>99		

Table 5: Before and After AT31 Test Results and Differences at 200 Hz

	Before	After	Diff
Impedance	525	504	-21
Fi	72	72	0
I/F	-44	-45	+1

The after tests were performed as quickly as possible following the surge test. Each result was performed twice to ensure repeatability (all results were repeatable within 1%). The motor was quickly disassembled, a metal piece placed against the stator, which did not attract, then placed in front of a fan and reassembled and re-tested. All tests returned to the original test findings.

The original concept of dipolar action discounts the following considerations: a) Paschen's Law requires ionization of air and materials; b) As noted in the first part of this paper, the fast rise time does not allow for significant polarization of materials; and, c) The assumption that there would be remaining magnetic flux would require steel with high magnetic retention properties, which would result in extremely high hysteresis losses in the machine.

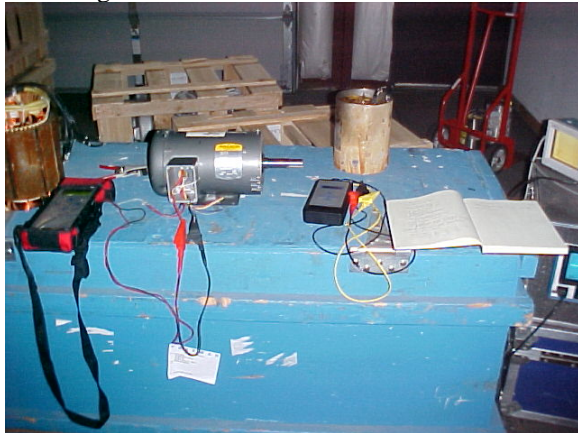
The observations provide the preliminary conclusion that the cause of change has to do with ionization of the air within the stator, in these instances. Ionized air and ozone (detected as an ozone 'odor' when the motor was disassembled) results in conductivity of the atmosphere between the conductors of the motor. Changes to the readings, during follow-up testing with MCA, indicate that this condition lasts a short period of time. This may also identify the result of partial discharge in VFD applications. The exchange of air supported the conclusion as well as the lack of retained

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magnetism following the test. Finally, none of the tests noted in this paper, and other tests performed for support of the findings of this paper, performed on stator-only conditions showed any of the same results, regardless of the amount of time not used. This particular area has been noted for additional research for its value in MCA.

### C. Experiment 2b

Figure 13: Rotor Position and Rotor Test



The motor was set up and isolated. The AT4 and AT31 were both used to analyze the condition of the windings, the AT31 was used to analyze the condition of the rotor. The surge comparison tester was used to evaluate the condition of the windings and rotor. Following all tests, the surge comparison tester was increased to 12,000 Volts to ensure condition of each phase.

Table 6: AT4 Test Results on Motor

	1-2	1-3	2-3
Resistance	20.368	20.336	20.334
Impedance	186	183	154
Inductance	147	144	122
Phase Angle	80	79	79
I/F	-43	-44	-45
Ins Resistance	> 99		

Table 7: AT31 Test Results on Motor (60Hz)

	1-2	1-3	2-3
Impedance	79.6	78.3	71.8
Fi	57	57	56
I/F	-38	-38	-38

As outlined in the first part of this paper, the impedance and inductance of MCA followed the same pattern, showing the insulation system was clean and dry. MCA identified a good winding in both instances. The AT31 identified bad rotor bars using a visual inductance rotor test. Each of the surge waveforms followed the same pattern, but required rotor position movement in order to determine condition of the windings, but did not identify two missing rotor bars. The surge test to 12,000 Volts identified the new winding was in excellent condition.

### D. Experiment 2c

A stator was selected with winding contamination from grey water in the windings. The test results identified as 0.89 MegOhms to ground. The motor was tested with the AT4 and AT31, before and after the surge comparison test. Surge comparison was limited to 1800 Volts, max. A visible coil to coil fault was identified and detected using the MCA instruments.

Table 8: AT4 Test Results on Stator

	1-2	1-3	2-3
Resistance	0.6400	0.5577	0.6189
Impedance	27	26	27
Inductance	5	6	5
Phase Angle	79	80	79
I/F	-49	-49	-49
Ins Resistance	0.89		

Table 9: AT31 Test Results on Stator (60Hz)

	1-2	1-3	2-3
Impedance	2.12	2.08	2.12
Fi	25	29	25
I/F	-20	-20	-20

Figure 14: Effect of Surge Comparison Testing on Winding Contamination





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Table 10: AT4 Test Results on Stator Post Test

	1-2	1-3	2-3
Resistance	0.6400	0.5577	0.6189
Impedance	27	26	27
Inductance	5	6	5
Phase Angle	79	80	79
I/F	-49	-49	-49
Ins Resistance	0.0		

Table 11: AT31 Test Results on Stator Post Test

	1-2	1-3	2-3
Impedance	2.12	2.08	2.12
Fi	25	29	25
I/F	-20	-20	-20

The MCA tests identified the winding contamination and coil to coil short. There were no changes to the surge comparison waveform until the stator arced to ground at 1,600 Volts. The stator was in a condition to clean dip and bake prior to high voltage testing, but had a visible hole to ground following 3-5 seconds of applied test voltage.

### E. Experiment 3

Figure 15: Virtual Motor with Spacers to Hold Airgap



Part of the purpose for the exposed 'virtual' motor is to reduce the influence of ionization on the test results. The stator was tested with MCA, then re-tested until the applied voltage was less than 1,000 Volts before fault detection.

Table 12: AT4 Test Results on Virtual Motor

	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 Resistance	> 99		

Figure 16: Surge Values on Each Test

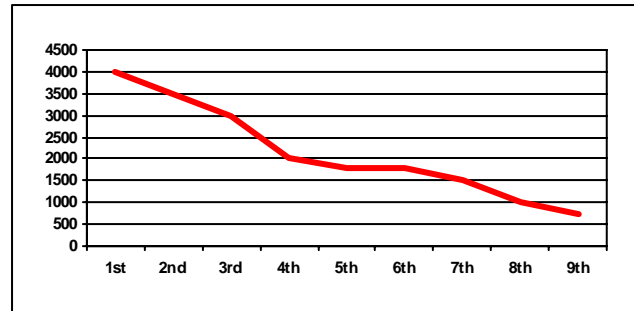


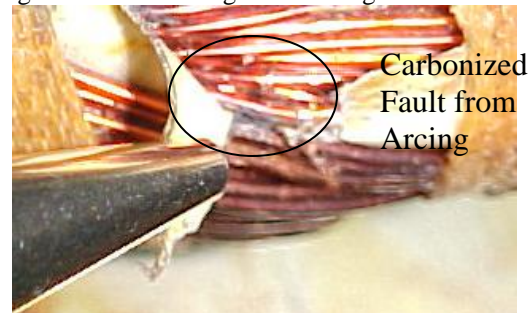
Table 13: AT4 Test Results After Test 6 and Before Test 7 on Virtual Motor

	1-2	1-3	2-3
Resistance	0.6604	0.6592	0.6569
Impedance	21	21	40
Inductance	8	8	7
Phase Angle	77	77	77
I/F	-47	-45	-47
Ins Resistance	> 99		

Table 14: AT4 Test Results on Virtual Motor After High Voltage Tests

	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 Resistance	> 99		

Figure 17: Arc Damage to Winding and Insulation



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While this experiment proved that high voltage testing will degrade defects in windings, MCA will detect the fault and identify changes to the condition of the winding, and leads to an observation of the ability to detect and trend degradation, it represents a fault different from an operational fault. In an operational fault, the defect will overheat and a greater area of insulation will be effected, causing a more significant change to the phase angle and/or current/frequency test result as the insulation degrades. However, the test does provide evidence that the prediction of the first part of the paper, concerning changes to results, due to a progression of winding degradation, does occur. It is observed that the final change to the current/frequency reading came from a point where additional conductors, other than the original two, were effected and the area of carbonization of the insulation increased.

It is noted, in Figure 18, that the separation of the phase paper around the fault point is a direct result of the surge comparison arc, evidence of Paschen's Law in action. Low voltage test methods had no impact on the existing condition of the insulation system.

### XI. CONCLUSIONS

The purpose of this paper, and the experiments contained within, has been to provide additional supportive evidence for papers, research and field conclusions using MCA.

#### *Experiment 1 Conclusions*

It has been determined that MCA is capable of detecting a phase to phase deep-winding defect before traditional test methods as it does not require a steep dV/dt. An arc is often formed when high voltage surge comparison testing detects a defect. The high energy involved degrades the remaining insulation life of the insulation defect.

#### *Experiment 2a Conclusions*

Variations in MCA test results following high voltage testing appear to be due to ionization and not polarization. Additional work is being

conducted to determine how best this effect can be used for fault detection, in particular in applications involving partial discharge.

#### *Experiment 2b Conclusions*

A number of important conclusions concerning condition based monitoring resulted from this experiment. It was determined that MCA is capable of evaluating the condition of the stator insulation system without having to move the motor shaft. This makes MCA an excellent method for Predictive and Condition Based Maintenance of motors in-place. MCA was also found to be able to detect defective rotor bars using inductive-based rotor tests and movement of the shaft.

High voltage surge comparison testing was incapable, during this experiment, of detecting rotor condition and required movement of the shaft in order to detect any winding defects. This makes it less capable as a method for PdM and CBM programs. It was noted that new insulation systems should be capable of withstanding high voltage surge comparison testing, including accidental over-potential. However, it is noted that in all aged systems that showed any defect, including minor, correctable defects, the high voltage surge comparison test degraded the insulation system significantly further than before testing. This presents the conclusion that any defect that could provide an estimated time to failure using MCA would represent a near-immediate fault in high voltage surge comparison testing. This further supports the conclusion that it is less capable as a method for PdM and CBM programs.

#### *Experiment 2c Conclusions*

MCA was determined to have the capability to detect winding contamination without a negative impact on insulation condition. This provides for an excellent ability to evaluate system condition during predictive maintenance or condition based monitoring. High voltage surge comparison testing was determined to destroy correctable insulation system conditions in contaminated winding conditions. This supports the EASA (Electrical Apparatus Service

Association) ANSI/EASA AR-100 Motor Repair Standard recommendation to clean insulation systems prior to applying high voltage tests. Also, it provides evidence of risk in using high voltage test methods in predictive maintenance applications.

### *Experiment 3 Conclusions*

It was determined that MCA has the ability to detect changes to the insulation system over time, providing the ability to estimate time to failure following fault detection. High voltage surge comparison testing was found to significantly degrade the insulation system after each successive test following fault detection, rendering it less capable of estimating remaining insulation life following fault detection.

### *Summary*

Each of the experiments supported the theory and conclusions of the first part of this paper. However, it has been determined that additional experiments are to be planned, with an expansion to include Electrical Signature Analysis. The purpose of the additional work will be to prove further the original intent of Experiment 3 by generating an insulation defect, with the surge comparison tester, in a used submersible pump motor. The pump will then be run in normal operating conditions, with periodic MCA tests and periodic ESA tests in order to provide evidence of trending using MCA and to determine the point at which ESA can detect a winding short.

Some of the conclusions of this study were surprising to the investigators including the repeated condition of the fault not showing until an arc was drawn, although the arcs were sometimes only visible with the lights out. In each case, there were no 'waveform shifts,' nor other warnings, prior to waveform distortion and arcing on the stators and assembled motors selected with real-life, versus laboratory induced, faults.

## XII. REFERENCES

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## XIII: BIOGRAPHY

**Howard W Penrose** (M'93) received the BS, MS and Ph.D. degrees in General Engineering from Kenedy-Western University in 1996, 1998 and 2000, respectively.

Most recently, he is the General Manager and Technical Director of the ALL-TEST Pro Division of BJM Corp in Old Saybrook, CT. Prior to that he was a Senior Research Engineer (Energy Research) and Adjunct Professor of Mechanical and Industrial Engineering with the University of Illinois at Chicago following 12 years in the electric motor industry as a Navy trained Electric Motor Repair Journeyman and Field Service Engineer. He is currently involved in motor diagnostic technology research and development and training.

Dr Penrose is a Past Chair of Chicago Section IEEE (1998-1999), Vice Chair of Connecticut Section IEEE (2002-2004), Past Chair Chicago IEEE DEIS and PELS (1996-1999) and has published numerous articles and books related to electric motor systems.