THEORY OF STATIC WINDING CIRCUIT ANALYSIS

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ABSTRACT

Static winding circuit analysis describes the electronic method of evaluating the condition of rotating machinery, coil windings and transformer windings. The method requires test instruments that utilize a combination of alternating and direct current measurements, frequency and phase angle – based tests. Through a review of the patterns resulting from static winding circuit analysis (SWCA) tests.

INTRODUCTION

Existing electronic test methods can be applied to the evaluation of the condition of electrical windings. The machines that can be evaluated include: AC/DC rotating machines of virtually any size and voltage; Electro-Magnetic coils of virtually any size and voltage; and, Transformers of virtually any size and voltage. The analysis requires a specific strategy of electronic bridge measurements, de-energized equipment and software. The purpose of this paper is to outline the test methodology, provide brief application theory, and to provide testing limits and criteria for new, repaired or existing equipment.

DEFINITIONS

The following definitions are provided for application within this paper:

- Ohms Law: The basic definition of Ohms Law is current = voltage divided by resistance. For AC measurements, the law is extended as $I_1\angle = E_1\angle / Z_1\angle$.
- Mutual Inductance (L_m): Is the flux linkage between the current flow through one loop into a second loop.
- Internal Inductance (L_i): Is the flux linkage within the same circuit.
- Inductive Reactance (X_L): The $X_L = 2\pi f L$ where f is the applied frequency and L is the total circuit inductance in milli-Henries (mH).
- Capacitance (C): Is a property of conductors and dielectrics when potential differences exist between conductors and conductors and ground. The result is a series of stored charges.
- Capacitive Reactance (X_C): The $X_C = 1/(2\pi f C)$ where f is the applied frequency and C is the total circuit capacitance in micro-Farads (μF).
- Circuit Impedance (Z_c): The circuit impedance of a winding includes the overall DC resistance, inductance, capacitance and applied frequency. $Z_c = \sqrt{}(R^2 + (X_L - X_C)^2)$.
- Phase Angle (Fi): Is the relative angle of current to voltage in an inductive circuit. The phase angle is impacted by the circuit impedance, inductance and capacitance.
- Current/Frequency Response (I/F): The current/frequency response is the ratio of current in a winding when the frequency is doubled.

MAGNETIC CIRCUITS

Electrical coils and machines are made up of a combination of coupled electro-magnetic circuits. The magnetic circuits are developed as a result of electrical current passing through conductors and guided through magnetic materials.

First, consider a conductor of length *l* placed at right angles to the poles of a magnet while carrying a current I. The result is a force of level F, where B is the magnitude of the magnetic flux density (in Tesla, or T) and magnetic flux is the measurement of the strength of magnetism. The resulting formula is found as:

Formula 1: Force (Newtons)

$$F = BI\,l$$

Based upon the arbitrary position of a conductor with l being a vector of magnitude *l* in the direction of the current.

Formula 2: Force with Arbitrary Conductor Position

$$F = Il \times B$$

Assuming B is constant in magnitude with area A:

Formula 3: Magnetic Flux (Φ, Webber)

$$\Phi = BA \text{ or } B = \Phi/A$$

B is expressed as Webber(Wb)/m

The relationship between I and B is as follows:

Formula 4: Ampere's Circuital Law

$$A/m * d * l = I$$

Where A/m is the magnetic field intensity H

When a closed circuit is passed by the current N times, such as in a coil, then the resulting magnetomotive force (mmf or $\Im$) is as follows:

Formula 5: MMF

$$\Im = NI$$

NI is also known as the Ampere turns (At). An N of one will be known as one 'turn.'

The Inductance (L) is defined as the flux linkage per unit of current shown as units of Henry (H).[1]

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[1] Electric Machines and Electromechanics, Syed A Nasar, Schaum's Outline Series, 1981

Formula 6: Inductance

$$L = (N\Phi)/I$$

For a toroid wound with 'n' distinct coils, the inductances may be defined:

Formula 7: Toroid Fields[1]

$$L_{pq} = (N_p(k_{pq}\Phi_q))/i_q$$

The energy stored in an inductance can be calculated, carrying a current (i):

Formula 8: Inductive Energy

$$W = (1/2)Li^2$$

Frequency impacts the fields within a conductor. As the applied frequency is increased, the current, and resulting fields, travel closer to the surface of the conductor (skin effect). "This is due to the fact that there are induced emf's in a conductor in which there is alternating flux. These emf's are greater at the center than at the circumference, so the potential difference tends to establish currents that oppose the current at the center and assist it at the circumference. The current is thus forced to the outside of the conductor, reducing the effective area of the conductor."[2]

INSULATION SYSTEMS

"Electrical insulation is a medium or a material which, when placed between conductors at different potentials, permits only a negligible current in phase with the applied voltage to flow through it. The term dielectric is almost synonymous with electrical insulation, which can be considered the applied dielectric. A perfect dielectric passes no conduction current and only capacitive charging current between conductors."[2]

The simplest circuit representation of a dielectric is a parallel resistor and capacitor. The capacitance between conductors (in a vacuum) is 0.0884×10^{-12} A/t where A is the area of the conductor in square centimeters and t is the spacing of the conductors in centimeters. "When a dielectric material fills the volume between the electrodes, the capacitance is higher by virtue of the charges within the molecules and atoms of the material, which attract more charge to the capacitor planes for the same applied voltage. The capacitance with the dielectric between the electrodes is:"[3]

Formula 9: Capacitance Between Parallel Circular Conductors

$$C = (2\pi\epsilon'\epsilon_o L)/\cosh^{-1}(D/2r)$$

[2] Standard Handbook for Electrical Engineers, Fourteenth Edition, Donald G Fink, Wayne Beaty, McGraw Hill, 2000.

The permittivity of insulation systems decrease downward (dispersion region) with an increase in applied frequency, as does the ionic-interface polarization and the molecular dipolar polarizations. In polymers, dipolar dispersion occurs in very low frequencies.

INSULATION BREAKDOWN

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

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

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

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

Table 1: Max Insulation Temperatures

Insulation Rating	Temperature
A	105^oC
B	130^oC
F	155^oC
H	180^oC

Other environmental factors also impact the thermal life of the insulation system including: Winding contamination; Moisture; Electrolysis; and, Other electrical stresses.

Mechanical faults in the electrical insulation system include stress cracking, vibration, mechanical incursion, and mechanical faults. The forces within a coil during various operations, will cause mechanical movement and may end in the fracturing of insulation materials. Electrical and mechanical vibration cause undue stress on the insulation system resulting in stress fractures and looseness of the insulation system. Mechanical incursion includes the movement of materials into the insulation system either between conductors and/or insulation system to ground.

Mechanical faults include failures such as bearing faults, in rotating machines, that cause the bearing to come apart and pass through the moving components of the system. These faults may end as shorts between conductors, coils, or coil to ground.

TEST MEASUREMENTS

In an integral winding (greater than 746 Watts), a series of specific measurements can be analyzed in order to determine the condition of a winding. These measurements are to be the overall results of the circuit, such as a combination of all mutual and internal inductance of a circuit. Enough measurements are required in order to compare them to each other in ORDER to discern patterns. The instrument outputs must be Direct Current (DC) for resistance and insulation resistance measurements and Alternating Current (AC) for impedance, inductance, phase angle and current/frequency tests. The AC output must be a clean sine-wave and output frequency of at least 100 Hz.

The test instruments must be able to test at least:

- Resistance (R) – 0.001 Ohms using a balanced bridge method.
- Impedance (Z) – At least 3 Ohms impedance
- Inductance (L) – At least 1 mH inductance
- Phase Angle (Fi) – From 0 to 90 degrees
- Insulation Resistance (MegOhms) – From 0 to at least 100 Meg-Ohms
- Current/Frequency Response (I/F) – Frequency doubling test with a range of –15 to –50% reduction in current

Circuit resistance is the overall DC current resistance measured through a bridge such as a Wheatstone or Kelvin bridge. Other variations are available of this bridge type but must have an accuracy to at least one milli-Ohm.

The circuit impedance test method is also read through an impedance bridge. Impedance is frequency, resistance, inductance and capacitance dependant. Resistance has a relatively small impact on the overall impedance and the applied frequency impacts the inductive and capacitive reactance components. Increases in inductance have an additive effect to the impedance values while capacitance has a negative effect on the impedance. For instance, an increase in the overall circuit inductance will generate a roughly parallel increase in impedance, an increase in the overall circuit capacitance will cause the impedance to decrease at a nonlinear rate in opposition to the circuit inductance.

Inductance is a function of geometry and permeability. It is independent of voltage, current and frequency. The overall inductance measured is a combination of the mutual and internal inductances of the circuit, known as the circuit inductance. Fault detection is possible in winding shorts only when the capacitances of dielectric insulation systems become resistive and a shorted circuit exists, resulting in mutual inductance between the good part of the coil and the shorted turns. This can be determined as the advanced stage of winding shorts.

The circuit phase angle is a measurement of the lag time between voltage and current presented as degrees of separation. It is directly impacted by the circuit impedance, voltage and frequency applied.

Insulation resistance is a measurement of capacitance between the conductors, through the insulation then to ground.

The current/frequency response test is a percentage reduction in current as a direct result of doubling the applied frequency. The initial circuit impedance and applied voltage presents a current of the first value (I_1). The applied frequency is doubled and the change in frequency results in a change to the electro-magnetic properties of a coil, causing current to flow nearer the surface of the conductors (skin effect), and changing the leakage between conductors and coils. The resulting impedance changes based upon the circuit capacitance (resistance and inductance remains the same) and a second current is presented (I_2). The ratio (I/F) is presented as the reduction in current resulting from the change in frequency (for instance, if the initial current is 1mA and the second current is 0.5 mA, then there is a reduction in current of 50% or -50%, as presented).

COIL ANALYSIS

An electric coil, defined within this paper, includes coils used as solenoids and electro-magnets as individual coils that may interact with other materials, but not other coils. Effects of core material and metallic objects in close proximity will be considered operating stress.

A coil is wound in such a method as to create a magnetic field of sufficient strength to perform an operation such as pulling in a plunger, lifting or fastening materials to a table, acting as a coil on the rotor of a synchronous motor, fields in a DC machine, and a great many other applications. The following effect the test readings:

- Resistance: Wire size; Connections; Directly shorted turns and feet of wire in the circuit; Open parallel connections.
- Inductance: Internal inductance; Mutual inductance of either multiple wires or if there is a material close by that is permeable – such as another coil, steel, etc.; Direct shorts between conductors.
- Impedance: Circuit resistance; Circuit inductance; Capacitance between conductors; Contamination.
- Phase Angle: Will be impacted by the circuit impedance of the coil.
- I/F: Circuit impedance; Capacitance.
- Insulation Resistance: Breakdown of insulation between conductors and ground.

Testing coils requires similar coils to be evaluated, or a single coil to be evaluated over time. The key to winding circuit analysis is a comparison between windings that have the same electro-magnetic properties including core materials and any other magnetic materials in close proximity. The primary cause for coil circuit failure is temperature impacts on the magnetic center of the coil conductor path. Internal forces and heat conduction principles cause the greatest thermal stress deep within a coil. Therefore, while the outer appearance of a coil may appear to be in good condition, the area that is not visible may have thermally broken down. This type of failure results in a change in the capacitance and resistance between conductors. These measurements can also be used to evaluate the accuracy of a new or rewound coil.

Detecting faults in a coil is straight forward. The rule for fault and similarity detection of faults in a coil include patterns that fall within the scope of Table 2.

Table 2: Coil Limit Guidelines (With limited mutual inductance with outside materials)

Measurement	Limits
Resistance	2%
Impedance	2%
Inductance	2%
Fi	+/- 1 Degree
I/F	+/- 1 Digit
Ins Resistance	> 100 M-Ohms

Early turn faults will be detected as changes to the Fi and I/F in the circuit. As a fault progresses, the impedance and inductance will begin to change, possibly followed by the resistance and the insulation resistance. Coils should be scheduled for replacement or rejection once the Fi and I/F begin to change and replaced immediately should the impedance, inductance and/or resistance change.

Table 3: Fault Patterns in Coils

Fault	R	Z	L	Fi	I/F	Ins
Open turns	X	S	S	S	S	-
Incorrect Wire Size*	X	-	-	-	-	-
Shorted conductors	S	S	S	X	X	-
Grounded Windings	L	L	L	L	L	X
Early turn shorts (used when trending)	-	-	-	X	X	-
Incorrect number of turns*	X	X	X	S	S	-

*New or repaired coils only

X identifies fault readings; S indicates when a fault is severe that these readings will change; and, L means that only a little change may be noticeable

TRANSFORMER ANALYSIS

Single and three phase transformers produce an interesting test challenge. During off-line testing, the sine-wave introduced into the transformer may cause circulating currents in the side opposite the side of the transformer being tested (ie: if testing on the primary, circulating currents will be found on the secondary). The circulating currents then induce current back into the primary, causing a dramatic increase in inductance and impedance, while generating erratic results in the I/F and phase angle. Therefore, the best method of evaluating the condition of the windings is to shunt the circulating currents directly to earth ground by shorting all of the leads on the side opposite of the side being tested to ground.[4]

Single phase transformers are evaluated in the same way and with the same limits as coils with both the primary and secondary being evaluated separately. This analysis method also counts for control transformers.

The three phase transformers covered include, but are not limited to, control transformers, dry-type transformers and transmission and distribution transformers. Principles and theory of transformer operation can be found in Motor Circuit Analysis: Theory, Application and Energy

[4] For details on transformers, testing and applications, see Chapter 3.3 and Chapter 13 in Motor Circuit Analysis: Theory, Application and Energy Analysis, Penrose, 2001, SUCCESS by DESIGN, ISBN: 0-9712450-0-2

Analysis[5], and "Single and Three Phase Transformer Testing Techniques Using Static Motor Circuit Analysis Techniques"[6].

The following effect the test readings:

- Electro-Magnetic Induction (EMI): Outside electrical sources induce currents within the windings causing changes to the test results.
- Resistance: Same as coils; and in cases where the resistance is non-repeatable it is most likely EMI related current problems resulting from incorrect test ground connections or open terminal connections on the side opposite the side being tested.
- Inductance: Same as coils and resistance; Inductive unbalances are more critical in transformers where they should be balanced from phase to phase.
- Impedance: Same as coils and resistance; Impedance unbalances are critical in transformers where they must be balanced from phase to phase.
- Phase Angle: Will be impacted by the circuit impedance of the coil
- I/F: Will be impacted by the circuit impedance and capacitance. This measurement will provide the earliest indicator of winding faults in transformers.
- Insulation Resistance: Breakdown of insulation between conductors and ground and between conductors of the primary to secondary.

Testing transformers results in a comparison of each phase, in a three-phase transformer, to each other, or trending of the comparison results over time. The primary causes for faults in transformers include: Overloading; Unbalanced Loads; Mechanical vibration impact on insulation; Electrical harmonic distortion; and, the Environment. Each of these result in a breakdown of insulation that can be detected using winding circuit analysis. Once a fault is determined, a root-cause-analysis should be performed in order to evaluate the cause.

One difference in testing transformers, as opposed to coils and motors, is to perform an insulation resistance test between the primary and secondary. In severe faults, a breakdown in the insulation system may occur between these points.

Table 4: Transformer Test Limit Guidelines

Measurement	**Limits**
Resistance	5%
Impedance	5%
Inductance	5%
Fi	+/- 1 Degree
I/F	+/- 2 Digit
Ins Resistance	> 100 M-Ohms

One difference between transformer testing and other test methods is that early insulation breakdown will be detected first with the current/frequency response test. This may be detected as a small shift between phases, ie: -44/-44/-43.[7]

[5] Motor Circuit Analysis: Theory, Application and Energy Analysis, Penrose, 2001, SUCCESS by DESIGN, ISBN: 0-9712450-0-2

[6] "Single and Three Phase Transformer Testing Techniques Using Static Motor Circuit Analysis Techniques", Penrose, 2001, BJM Corp ALL-TEST Division White Paper

[7] IEEE Std 388-1992: IEEE Standard for Transformers and Inductors in Electronics Power Conversion Equipment, IEEE Standards Committee.

THREE PHASE INDUCTION MOTOR ANALYSIS

Over 47% of electric motor failures occur due to electrical faults. Ten percent are due to rotor faults, the rest are due to stator winding faults.[8] Contrary to popular belief, insulation to ground faults (insulation resistance) account for the least number of initial faults. The primary causes, such as insulation (thermal) breakdown, contamination, moisture incursion, transients, and mechanical stress, first result in a breakdown of insulation between conductors within the same coil, between coils in the same phase or between coils of separate phases. These winding 'shorts' may, but not always, end up as an insulation resistance fault when the winding actually fails. Detection of changes between conductors provides a greater chance of early repair or replace action before equipment actually stops operating (failure), reducing unscheduled downtime costs.

The anatomy of a winding fault between conductors is:

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

Through a series of readings that include simple resistance, inductance, impedance, phase angle and current/frequency response, these faults can be detected in the first stage of failure. The rate of fault between the stages will depend upon the motor voltage, size of fault and severity of fault. In the present operating environment, most corrective measures are applied in the second or third stage, in which the equipment is having a financial impact on production, or the mission of the equipment. High voltage test equipment will detect some stage 1 issues, however, once detected, will cause a rapid move towards stage 3. Current signature analysis will only detect faults that are progressing from stage 2 to stage 3.

Rotor fault detection has become more popular at the turn of the 21st Century. This is the result of two issues: 1) Marketing and papers presented by manufacturers of equipment who relyon mutual inductance measurements; and, 2) Marketing and papers presented by manufacturers of current signature analysis equipment, who are limited to rotor and air gap fault detection. In both cases, these technologies can only detect, within strict limits, the later stages of winding faults.

The types of faults common to electric motor rotors are:

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[8] See Motor Circuit Analysis: Theory, Application and Energy Analysis for details on electric motor operating theory and test methods specific to motor types. This paper will focus on three phase induction motors only, but the test results fit any three phase stator. Rotor field coils, for synchronous motors, and other coil equipment should be evaluated as coils in the coil section of this paper.

- Air gap (Rotor Eccentricity): Which is normally not a progressive failure, unless there is looseness in the rotor, or a fault within either the motor shaft or bearings has become severe. Looseness, bearings and motor shaft issues can be detected faster, and safer, using vibration analysis techniques. Manufacturing and repair air gap issues can be detected with static winding circuit analysis during acceptance testing or at the manufacturer/repair shop prior to time lost installing the equipment. This type of acceptance testing is used to determine if the air gap has been set properly (+/- 10% of average airgap reading taken at either end of the rotor during installation).[9]
- Casting Voids and Rotor Bar Connections: Which may progress to 'broken rotor bar' faults over time. There are always casting voids in cast aluminum rotors, variations in the aluminum alloy and variations in the joints of copper alloy bars that will effect inductance. The faults can be detected by taking a series of readings as the shaft is rotated 360 degrees. These readings can be graphed as a waveform and viewed for faults by looking at the position of inductance and/or impedance changes of the waveform. A small change on the incline or slope of the waveform indicates a small, usually non-intrusive defect, while a significant change at the peak of the waveform indicate severe rotor faults. Severe faults will interfere with the operating characteristics of the motor.
- Broken Rotor Bars: Are progressive faults that normally occur due to incorrect operation of the electric motor. As an electric motor is started, heat builds up in the rotor due to high currents and high frequency, requiring a cool-down period. In other cases, a rotor may be stalled, causing high currents and high rotor frequencies. The expansion rate of the copper alloys (or aluminum) and the rotor materials are different, putting mechanical stress on the bars themselves. Under extreme stress, the rotor bars may crack, reducing the ability of the motor to produce torque. As rotor bars fracture, the surrounding rotor bars carry additional current, causing a further increase in rotor bar temperatures and possibility that additional cracks will occur.

The ability of test equipment to detect faults through inductance and impedance is due to changes in the mutual inductance of the circuit as the rotor position changes. As an electric motor is a transformer with a rotating secondary circuit, when the rotor position changes the effective primary (stator windings) to secondary (rotor windings) ratio changes and the overall mutual inductance and resulting circuit impedance changes. Because of the nature of rotating equipment, the changes over time will be sinusoidal (or some variation) and symmetrical.

Table 5: Electric Motor Limit Guidelines

Measurement	Limits
Resistance	5%
Impedance	~5%[10]
Inductance	~15%[10]
Fi	+/- 1 Degree
I/F	+/- 2 Digit
Ins Resistance	> 100 M-Ohms

[9] IEEE Std 1068-1990: IEEE Recommended Practice for the Repair and Rewinding of Motors for the Petroleum and Chemical Industry, IEEE Standards Committee.

[10] The resistance and impedance unbalance readings can only be counted if the rotor position is accounted for. The readings must be taken at either a peak or valley of the sine wave from the change of rotor position.

Early turn faults will be detected as changes to either phase angle or current/frequency response as a 'shift' in readings. A shift can be indicated, for example, as Fi: 77/76/77 and/or I/F: -44/-46/-44.

Table 6: Fault Patterns in Electric Motor

Fault	**R**	**Z**	**L**	**Fi**	**I/F**	**Ins**
Loose/Open Connections	X	S	S	S	S	-
Grounded Windings	U	U	U	U	U	X
Incorrect Wire Size	X	X	-	S	-	-
Turn to Turn Shorts in the Same Coil	S	S	S	X	X	S
Coil to Coil Shorts in the Same Phase	S	S	S	X	-	S
Phase to Phase Shorts	S	S	S	-	X	S
Contaminated/Overheated Windings	-	NP	NP	S	S	S
Rotor Position (Winding OK – Rotor may be OK as well, this test does not give rotor condition)	-	P	P	-	-	-
Winding Fault With Winding Contamination or Overheated Windings	S	NP	NP	B	B	B

X – Fault; S – When fault is severe; U – Good Possibility; NP – Z and L not parallel;
P – Z and L parallel; B – May be the bad reading

Following are a few examples of rotor test results:

Figure 1: Good 200 Horsepower, 3600 RPM Motor

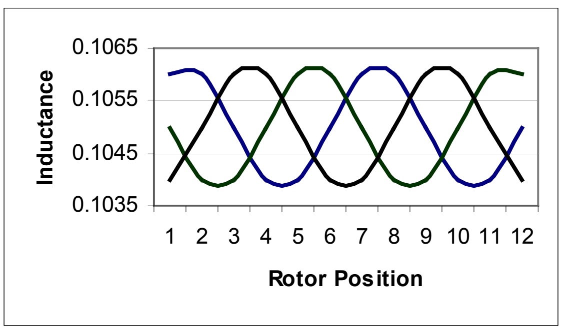


Figure 2: 200 Horsepower, 3600 RPM Motor with Casting Void that Effects Operation

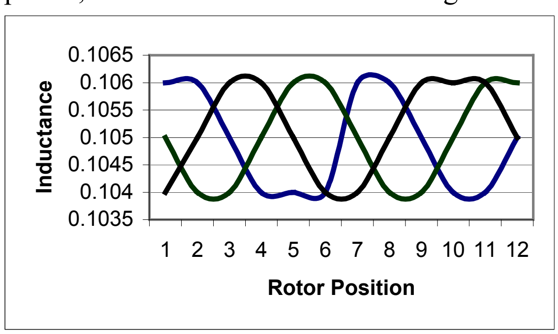
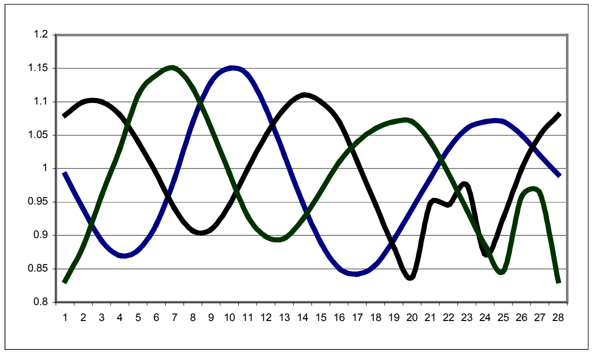


Figure 3: 400 Horsepower, 1800 RPM Motor With Casting Void and Rotor Eccentricity



The 400 Horsepower example shows a casting void (note the sine-waves on the right side) and the sine-waves arc as the readings go from left to right.

CONCLUSION

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 tests 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.

Traditional test methods rely upon either high voltage testing or ohmmeters with insulation resistance tests. As shown in this paper, high voltage testing has the potential to damage the insulation system and ohmmeter/insulation resistance testing will almost always miss faults. Alternative test methods that detect changes to the insulation (resistance and capacitance) circuit and their response can detect the first stages of winding failure. Circuit inductance and impedance readings can also be used to detect the condition of electric motor rotors through a series of tests.

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