MOTOR CIRCUIT ANALYSIS (MCA) MANUAL FOR ALL-TEST PRO 5™

ALL-TEST Pro, LLC

MCA™ MANUAL
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Understanding Motor Diagnostics using Motor Circuit Analysis (MCA™)

Introduction

MCA is a very simple and safe method to test electrical windings while the winding is de-energized. The basic premise of MCA:

> *In equipment with three phase windings all phases should be identical (same # turns, same wire size, coil diameter, etc.).Consequently, all characteristics of the windings should also be similar. If a change occurs in any one of these characteristics, the change is never for the better, (windings do not repair themselves) as degradation is taking place. By analyzing the amount and relationships of the change it is possible to identify the cause of the degradation. Once the cause and the severity of the degradation are known it is now possible to determine the necessary action*.

Use of this Manual

The purpose of this manual is to provide users of MCA technology tips and guidelines to follow when performing Motor Diagnostics using the ALL-TEST Pro line of MCA instruments. This manual is intended primarily for use with the ALL-TEST PRO *5*™ (AT5). However, some of the information is applicable to the ALL-TEST PRO 33IND™ (AT33IND). If the user only has an ALL-TEST PRO 33IND™, it is designed to only test AC induction with squirrel cage rotor motor less than 1kV.

ALL-TEST Pro Instrument Philosophy

- Easy and safe to use for both the user and item under test
- Battery operated, light weight and portable
- Effective tests for motors regardless of design, size and construction
- Show fault(s) immediately
- Show changes over time
- Produce multiple measurements for comprehensive analysis

ALL-TEST Pro Analysis Philosophy

Testing and analysis of electrical motors, transformers or any winding is not "black magic art". In reality it is very straightforward, if sufficient and proper measurements are performed.

It has been the experience at ALL-TEST Pro that the most accurate and comprehensive method of determining the true condition of motor windings is by controlling the testing parameters while the motor is de-energized. This method removes errors and conflicting results from stray or unknown sources used by other methods.

By injecting a known, low voltage AC sinusoidal, ***non-destructive*** signal through the motor windings, winding faults or weaknesses are not driven to failure. In many cases, potentially destructive faults can be easily corrected before total winding failure occurs.

Winding faults are indicated by variances in the response to the signal injected through the windings. These variances cause unbalances in the measured response to the injected signal. Using MCA faults appear the same regardless of the size or type of the winding. Motors as small as automobile windshield wiper motors as well as 300 Megawatt Generator windings have been successfully tested.*

*Very large equipment testing may require the user to perform the measurements to individual coils. I.e. Coil to coil testing.

Through additional investigation and measurement of these variances in the winding, faults can be quickly and easily identified, and corrected prior to energizing the winding; which can lead to total destruction of the motor.

Examples:
A deteriorating Insulation to Ground situation, will normally require immediate attention. This type of fault can be very dangerous (safety hazard) and lead to immediate machine failure.

On the other hand a *developing* turn-to-turn or coil-to-coil fault, especially in low voltage motors, may degrade over a longer period of time and provide the opportunity to correct the fault before it becomes a catastrophic failure, thereby, requiring a complete rebuild or costly replacement.

MCA injects an AC signal through the windings and measures the response of the item-under-test to this signal to identify any unbalances in the windings that indicate either a current or a potential fault.

Motor Diagnostic Theory

ALL-TEST Pro **MCA** instruments are based on proven electrical theory. The motor system can be represented by developing the basic motor circuit, which is nothing more than a simple RCL circuit. This circuit represents the various components of the motor system. Each basic circuit represents one phase of the three phase motor system. Since each phase of the motor system is identical, each basic circuit should respond the same way to an applied signal.

To allow the user to obtain the most benefits from ALL-TEST Pro instruments and this manual, a brief review of electrical theory as applied to Motor Diagnostics is presented below. A review of this section will help in understanding the results obtained from ALL-

TEST Pro instruments. Additional information is available in any electrical textbook. ALL-TEST Pro also offers on-site and public training courses to further the user's knowledge. For dates and locations of these courses please visit us on our website www.alltestpro.com.

Basic Electrical Theory & Definitions of Measurement and Calculation Values

R -Resistance is the Direct Current resistance measured in Ω (Ohm). The resistance should be the same across all phases or fields. Any difference may indicate a potential problem. Difference can be due to "over-winding", corrosion, faulty connections, etc.

Z- Impedance is the complex resistance in a coil or winding. Impedance includes resistance, inductive reactance and capacitive reactance. Impedance is measured in Ω (Ohm).

Zero impedance in a winding indicates "a shorted" winding. Also, see I/F below.

Note: A coil or winding can have a severe turn-to-turn or coil to-coil fault, but show "good" when using a MegOhm meter. It can also show a severe Ground Insulation fault but shows perfectly OK turn-to-turn.

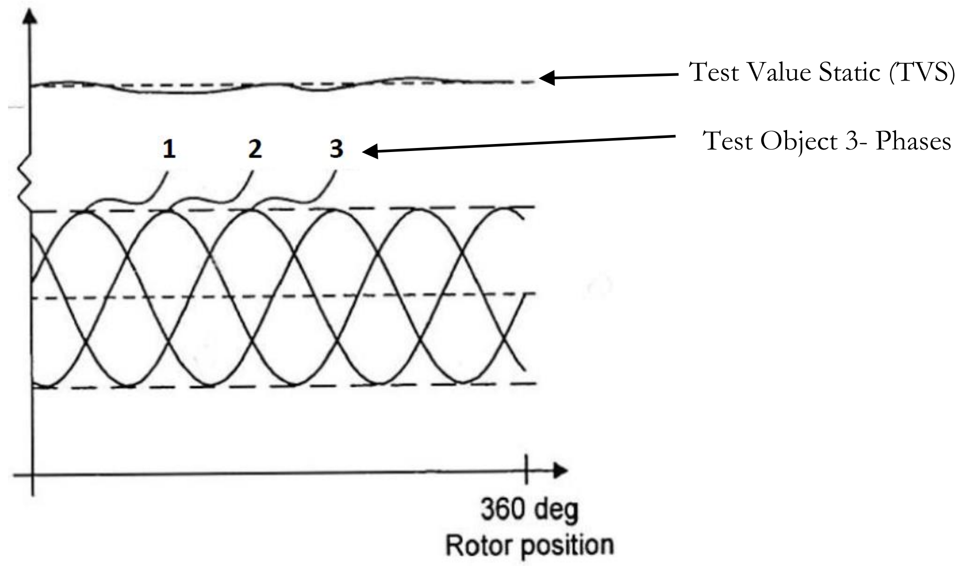
L- Inductance is the property of a changing magnetic flux to create (or induce) a voltage in a circuit. Inductance is dependent on the number of turns, diameter of the coil, length of coil, number of the layers and the material in a spool or coil core. Inductance opposes any change in the current flow through a conductor. The value is a measurement of the ability of a coil to store magnetic energy. It is measured in Henry (H).

> **Self-Inductance** is the property of a circuit where a change of current in the circuit creates/induces a voltage in the same circuit due to the magnetic field created by the changing current.
>
> **Mutual Inductance** is the concept that current flow through one conductor or circuit can induce a voltage into a nearby circuit or conductor.

Note: In a three phase induction motor with the rotor in place, inductance unbalances when performing a static test (rotor in a fixed position) can be the result of unbalanced mutual inductance due to the rotor angular orientation (More commonly referred to as rotor position).

Test Value Static (TVS) An AC induction motor is a "Symmetric Alternating Current Machine", i.e. the three phases are designed and manufactured to be identical. When a fault occurs it creates an asymmetry in the AT5 (AT33) measured data. All common types of faults in the Rotor and in the Stator windings break the symmetry of the machine (motor), therefore, asymmetry in test data indicates winding and/or rotor fault.

For a Symmetric Alternating Current Machine (motor), the rotor position influences the inductances (L), impedances (Z), or Phase Angles (Fi) of each stator winding differently since the rotor position influences the coupling of the L, Z, and Fi between stator windings and rotor winding.



However, due to the Symmetry of the motor the measured/calculated Test Value Static (TVS) of the stator windings is independent of the rotor position. *Note: In practice, TVS may be slightly influenced by the rotor position, due to inaccuracies during assembly of the motor or motor parts (manufacturing tolerances), slight differences between stator windings, flaws in the rotor, measurement inaccuracies, etc.* The figure above shows some measurement on three phases for a “Symmetric Alternating Current Machine” and the top line illustrates that TVS stays relatively constant with slight deviations at different rotor positions.

All common types of faults in the Rotor and in the Stator windings break the symmetry of the motor. As a result, the TVS will change and no longer be independent of the rotor position. Consequently, a second TVS will no longer be equal to the first TVS ($TVS_2 \neq TVS_1$).

Static – Testing Sequence

The AT33/AT5 outputs a low voltage sinusoidal signal at frequencies of 50, 100, 200, 400, & 800Hz. The following is true:

- Calculates Test Value Static (TVS) in the “first” rotor position (TVS_1).
- Rotor position has little influence on TVS value in a good motor.
- TVS is a motor specific parameter.
- TVS can be used as a Reference (REF) value for detecting fault conditions.
- TVS can be used as a REF value for that specific motor or other motors of exact same type, manufacturer and manufacture tolerances. (Refer to the figure in

previous page). Just because two motors have the same nameplate specifications, it does not necessarily mean the two motors are exactly the same.

- A subsequent test with the AT33/AT5 calculates a new TVS (at any rotor position).
- TVS_1 can be compared to TVS_2.
- If $TVS_2 \neq TVS_1$ this indicates that a change has occurred in the condition of the stator and/or rotor.

Dynamic Test

An AC induction motor is a “Symmetric Alternating Current Machine” and when a fault occurs it creates Asymmetry in the AT33/AT5 measured data. All common types of faults in the Rotor and in the Stator windings break the symmetry of the machine (motor), therefore, asymmetry in measuring data indicates winding and/or rotor fault.

All three phases of the motor are connected to the AT33/AT5 and dynamic testing requires that the user manually rotate the shaft of the motor while the instrument goes through the testing process. The motor shaft must be turned in a slow and steady manner without stopping or reversing the rotation. We recommend that a tool should be used to facilitate a smooth rotation. For this purpose ATP can provide a rotation strap wrench, which is wrapped around the rotor shaft with a convenient handle for a user to rotate. The left picture below shows an example of strap wrench and the right picture shows the strap wrench attached to the motor shaft.

As with the Static test, the AT33/AT5 will test all phases in real-time while the shaft is moving and current, inductance, impedance, phase angle, current/frequency response, and other measurements/calculations are made. From these measurements and calculations two important **“Signatures”** are presented at the end of the test: **Stator** and **Rotor**.

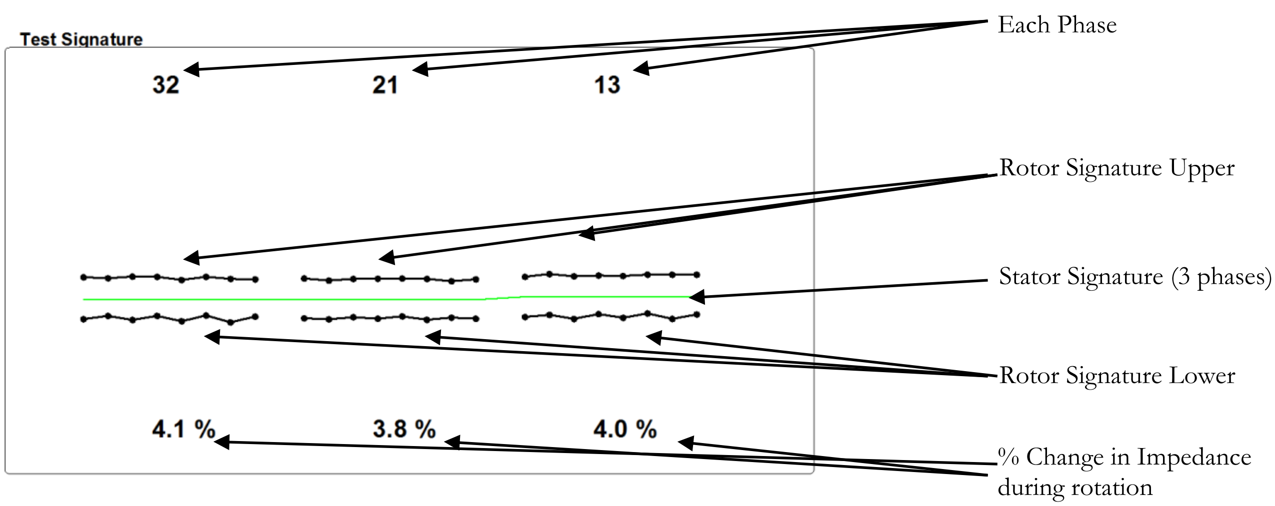
The following are the recommended rotating speeds when performing dynamic test with AT33/AT5. However, when testing a motor for the first time, we suggest that the user perform the dynamic test at a few different speeds to find the optimal one for the specific motor under test. I.e. the speed which results in relatively smooth and uniform data points for dynamic test signature.

Maximum recommended rotor shaft rotational speed for 2-pole motor = 100 RPM
Maximum recommended rotor shaft rotational speed for 4-pole motor = 50 RPM
Maximum recommended rotor shaft rotational speed for 6-pole motor = 33 RPM
Maximum recommended rotor shaft rotational speed for 8-pole motor = 25 RPM
Maximum recommended rotor shaft rotational speed for 10-pole motor = 20 RPM
Maximum recommended rotor shaft rotational speed for 12-pole motor = 17 RPM

One way to help perform good dynamic test is to look at the dynamic test bar displayed on the screen. If the bar moves back and forth uniformly, chances are the dynamic test will be performed well. However, the users still need to see the final dynamic signature to determine if the test is good.

The Dynamic test provides the **OK**, **Warn**, or **Bad** alarms for the Stator and Rotor. Moreover, it provides the valuable Stator & Rotor Signatures. At the end of the Dynamic test the results can be viewed, stored, or uploaded to the appropriate computer software.

Note: The image below is generated using the computer software.



Dynamic Signature Analysis

The Green line is the Stator signature and represents the deviation of the mean values during rotation for each phase. Note that for Phase 1-3, the Stator signature is slightly elevated above the other two phases. This indicates the mean values for Phase 1-3 are slightly higher than the other two phases, but are within acceptable limits and this stator is considered to be in good condition.

The two black dotted lines represent the Rotor Signature and include an upper and lower signature. This represents the deviation of the peak values during rotation. As the output of the instrument is sinusoidal and the response of the motor will be sinusoidal, there will be peak values both high and low. There are 8 dots for each phase and if this were an 8-pole motor then this represents 1 full revolution of the motor shaft. If this were a 2-pole motor then it represents 4 revolutions of the motor shaft. If this were a 12-pole motor then it represents ¾ of a revolution of the motor shaft. With this Rotor signature there is a slight variation in the distribution of the peak values, but as they are within our limit, this rotor is in good condition.

The % change in impedance represents the change in impedance during rotation of the shaft for that particular phase.
Phase Angle is a relative measurement that indicates the angular difference between two waveforms of the same frequency. The results are expressed in degrees angular difference (0 – 90^0). In the electrical circuit the phase angle expresses the relationship of the AC current to the applied voltage. This test is included in **IEEE Std 1415™-2006 sec 4.3.20** as an effective method to identify winding shorts.

Basic Electrical theory states that:
In a purely **Resistive** circuit, current & voltage are in-phase. I.e. they both reach the same point in the waveform at the same time.

In a purely **Inductive** circuit voltage leads current by 90 degrees. I.e. Voltage reaches it maximum & minimum value 90 degrees before current.

In a purely **Capacitive** circuit current leads voltage by 90 degrees. I.e. Current reaches it maximum & minimum values 90 degrees before voltage.

If the Voltage leads the current the phase angle is positive, if the voltage lags the current the phase angle is negative.

With **MCA** testing the phase angle expresses the relationship of the measured current to the AC voltage applied by the ALL-TEST Pro instruments.

Note: MCA phase angle should not be confused with the 120 degrees electrical separation between electrical phases in a three-phase system.

I/F- Current/Frequency Response is a test designed primarily to test for coil-to-coil or turn-to-turn faults. This test is included in **IEEE Std 1415™-2006 sec 4.3.33** as an effective method to identify winding shorts.

For the I/F test the low voltage AC signal is applied to the connected winding/windings, at a specific **frequency** and the resultant current is measured. Then the **frequency** of the applied AC signal is then doubled and the resultant current is again measured.

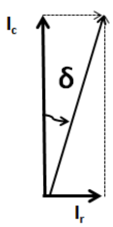
The I/F reading is the ratio of the current at the doubled frequency to the current at the original frequency. This result is displayed as a ratio. I.e. an I/F reading of -50 indicate that the current at the doubled frequency is 50% lower than the current at the original frequency.

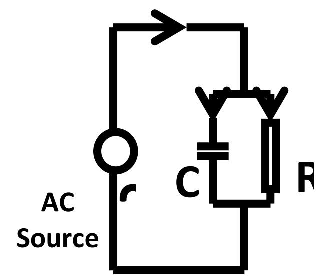
C- Capacitance is the capability of a body, system, circuit, or device to store electric charge. It is a measure of the amount of electrical charge stored for a given applied potential. The unit of capacitance is the Farad (F). The capacitance of a circuit opposes any change in voltage in the circuit.

The capacitance of a circuit is dependent on the geometry of the system and the material of the dielectric.

Any capacitors in the motor circuit should be tested separately from the motor.

DF: The Dissipation Factor (DF) is the ratio between the resistive power loss and the reactive power loss of the insulation material. This is used to detect contaminated or overheated windings.





Since the insulation material forms a capacitor, an AC voltage applied across the insulation will cause the system to react as a capacitive circuit. Ideally the electrical equivalent circuit would be a simple capacitive circuit, and all of the current through the circuit would be capacitive. However, in real life the equivalent electrical circuit will be a parallel RC circuit. Some of the current will be capacitive I_c, while some of the circuit will be resistive I_r. The two currents have a phase difference of 90^0. The DF is the ratio of the resistive current to the capacitive current. DF = I_r / I_c. It is also referred to as the tan **δ.**

DF testing is widely used on electrical equipment such as power transformers, circuit breakers, generators and cables. Also, DF values, trended over time, can help in detecting problems like contamination, high moisture content and the presence of voids in the insulation.

When the insulation system begins to degrade or becomes contaminated, the DF will increase. In addition, the DF is temperature dependent. Measuring DF at too high or too low temperature can introduce errors and the IEEE recommends performing DF tests at or near 68 ^{0}F (20 °C).

INS- Insulation (to Ground) Test. Measured in Meg-Ohm.
A motor can have a good insulation to ground but fail other phase-to-phase tests and vice versa. IRG is the most common electrical test performed on electrical systems. The IRG test is performed by applying a high dc voltage between de-energized current-carrying conductors (windings) and the machine casing or earth.

According to IEEE Std 43, the insulation resistance is measured after applying DC high voltage for 1 minute. The motor should be above dew point temperature before testing, if possible. It is important to correct values to a reference temperature (typically 40 °C) so that trends and changes in insulation resistance can be readily detected. To correct the insulation resistance to 40 °C, use the following equation

$R_c = K_T\, R_T$

R_c is the insulation resistance normalized to 40 °C.

K_T is the insulation resistance temperature coefficient at temperature of T

R_T is the insulation resistance measured at temperature of T.

According to the IEEE Std 43, for the thermoplastic insulation systems

$K_T=(0.5)^{(40-T)/10}$

For the thermosetting insulation systems

$$K_T = exp\left[-4230\left(\frac{1}{(T+273)} - \frac{1}{313}\right)\right] \qquad 40\ ^oC < T < 85\ ^oC$$

$$K_T = exp\left[-1245\left(\frac{1}{(T+273)} - \frac{1}{313}\right)\right] \qquad 10\ ^oC < T < 40\ ^oC$$

Contamination, humidity, temperature, and other factors affect insulation resistance values.

The standard recommends choosing test voltages for insulation resistance testing:

Winding rated voltage (V)[a]	Insulation resistance test direct voltage (V)
<1000	500
1000–2500	500–1000
2501–5000	1000–2500
5001–12 000	2500–5000
>12 000	5000–10 000

[a]Rated line-to-line voltage for three-phase ac machines, line-to-ground voltage for single-phase machines, and rated direct voltage for dc machines or field windings.

The AT5 instrument offers two test voltages: 500V and 1kV. For windings rated over 5kV, a higher test voltage will be needed according to the guidelines above. The standard also recommends minimum insulation resistance value at 40 ºC as shown below. “kV” is the rated line-to-line rms voltage of 3-phase motor, line to ground voltage of single phase motor, or rated DC motor voltage.

Minimum insulation resistance (megohms)	Test specimen
$IR_{1\ min} = kV + 1$	For most windings made before about 1970, all field windings, and others not described below
$IR_{1\ min} = 100$	For most ac windings built after about 1970 (form wound coils)
$IR_{1\ min} = 5$	For most machines with random-wound stator coils and form-wound coils rated below 1 kV and dc armatures

Note: The IEEE guidelines above provide the recommended voltages and Minimum Insulation Resistance to ground values. If these procedures or values differ from your equipment manufactures' recommendations, follow their guideline.

Applying MCA

ALL-TEST Pro has four instruments designed to perform **MCA testing.**

ALL-TEST PRO 5™ (AT5) is a Motor Circuit Analyzer for de-energized testing used for predictive maintenance and troubleshooting winding and rotor faults in motors and transformers of virtually all sizes and types: Single and 3-phase, AC and DC, even traction motors and machine tool servos. It performs automated measurements, performs calculations and comparisons, and gives immediate feedback regarding the condition of the motor under test using an OK, Warn, or Bad result. When an initial baseline test is performed a Reference Test Value Static (TVS) can be saved for that induction motor. Subsequent test results can be immediately compared to the Reference TVS to instantly show developing problems or changes with the stator or squirrel-cage rotor (view comparison right on the large, easy to read display). A Reference TVS can also be established from the starter or motor drive, thereby, making it easy to detect changes with connections and cables, along with the motor. No need to access computer software while in the field. It stores over 600 motor and Reference test records.

ALL-TEST PRO 33IND™ (AT33IND) is a Motor Circuit Analyzer for the de-energized testing of AC Induction, squirrel-cage rotor motors <1000V for: contamination, winding faults such as turn to turn & coil to coil, open connections, ground faults, and also evaluates the condition of the rotor. An initial baseline test is performed and a Reference Test Value Static (TVS) is saved for that motor. Subsequent test results can be immediately compared to the Reference TVS to instantly show you developing problems or changes within the stator or rotor (view comparison right on the AT33 easy to read display). A Reference TVS can also be established from the starter or motor drive, thereby, making it easy to detect changes with connections and cables, along with the motor. No need to access computer software while in the field. It has internal memory storage for over 800 motor and Reference test records.

ALL-TEST PRO 33EV™ (AT33EV) is used to test the special permanent magnet motor and motor/generator used in electric and hybrid vehicles. Contact ALL-TEST Pro for details.

ALL-TEST IV PRO (ATIV) is a Motor Circuit Analyzer for de-energized testing that will test virtually any motor, generator, transformer, or coil based device. It can be used not only for incoming inspection and trouble-shooting, but also for PdM or CBM testing purposes (data trending and time to failure estimation). Use our MCA Analysis Manual 2008 Rev B for analysis assistance.

ALL-TEST PRO 31™ (AT31) is a de-energized motor circuit trouble-shooting tool that will test a wide variety of motors and some transformers. It will test most AC motors under 600V and can also be used to test higher voltage motors, depending upon their resistance, inductance, and impedance. The AT31 should be used in conjunction with an ohmmeter, as it does not measure resistance (it does perform an insulation to ground resistance test) – use our MCA Analysis Manual 2008 Rev B for analysis assistance.

Motor Testing Procedure
It is important to note that a "perfect" 3-phase motor is very difficult to find based upon manufacturing tolerances, etc. In other instances, motors may have a particular difference in design in order to meet special operating applications.

IND

Used to test AC three-phase squirrel cage induction motors with rated voltage less than 1000 V. It performs the Static, Dynamic, Insulation resistance to ground, DF & capacitance tests.

Z/φ

Used to test all types of AC/DC motors, generators and transformers. It performs the Static, Insulation resistance to ground, DF & Capacitance, Phase Angle, I/F, Impedance and Inductance tests. It may be necessary to perform additional steps to isolate rotor or stator faults.

1 Phase AC Test

Applicable to AC single-phase motors or other single coil devices. It performs the Static, Insulation resistance to ground, DF & Capacitance, Phase Angle, I/F, Impedance and Inductance test.

DC Test

Applicable to different types of DC motors as well as individual coils. Each test option includes Insulation Resistance to Ground, Phase Angle, I/F, Impedance and Inductance test. DF & Capacitance are only available when the test is performed directly at the motor connections.

Initial Readings

In a few cases, some motors may exhibit unusual levels of unbalance(s) with respect to Fi, I/F, L, and/or Z results. This can occur for a number of reasons, including:

1) Stator winding to rotor bar ratio and position.
2) Stator winding design (lap versus concentric coil).
3) Other tolerance-related issues including rotor casting voids.

If unusual unbalances are detected with the instrument, there are several ways of isolating the cause including:

- For AC induction squirrel-cage rotor motor <1000V use the Dynamic test mode.
- Make a short series of additional tests using the AT5 (see Rotor Reposition Test in the Motor Troubleshooting Section).

Performing Motor Diagnostics Using MCA

Motor/Winding Analysis

Performing motor/winding analysis has been greatly simplified with the development of advanced diagnostic tools such as the AT33IND and AT5 with their comprehensive internal analytics coupled with easy-to-use computer software for analysis, reporting, and data storage. However, even as good as these tools are, sometimes additional information and testing may be required before the final condition of a machine can be accurately assessed.

To help maximize the data obtained from the ALL-TEST Pro tools, the next few sections will provide the analyst the procedures, techniques, suggestions and methods necessary to help the analyst properly and accurately diagnose most winding faults using Motor Circuit Analysis (MCA).

The basic rule for **MCA** is: If the data indicates a good winding then the winding is generally good. However, if **MCA** indicates a fault then additional testing should be performed before condemning a winding.

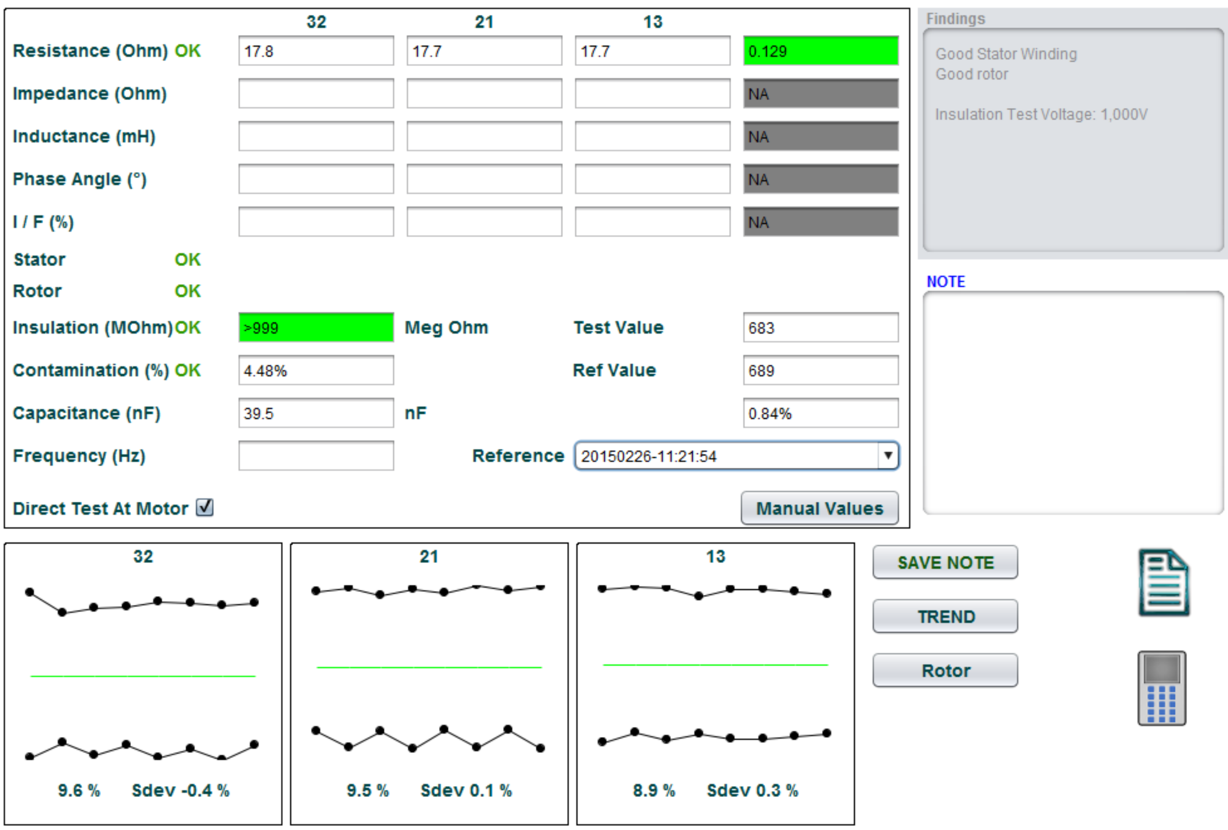
1) The test leads that are supplied with the AT5 instrument are customized Kelvin leads. If a different size of Kelvin clips is needed, please contact ALL-TEST Pro. **Note:** The repeatability of the resistance readings can be improved by using a small wire brush to clean surface oxidation from connection points and by lightly

squeezing the test jaws together while lightly twisting the clips on the connection point to ensure as solid a connection as possible.

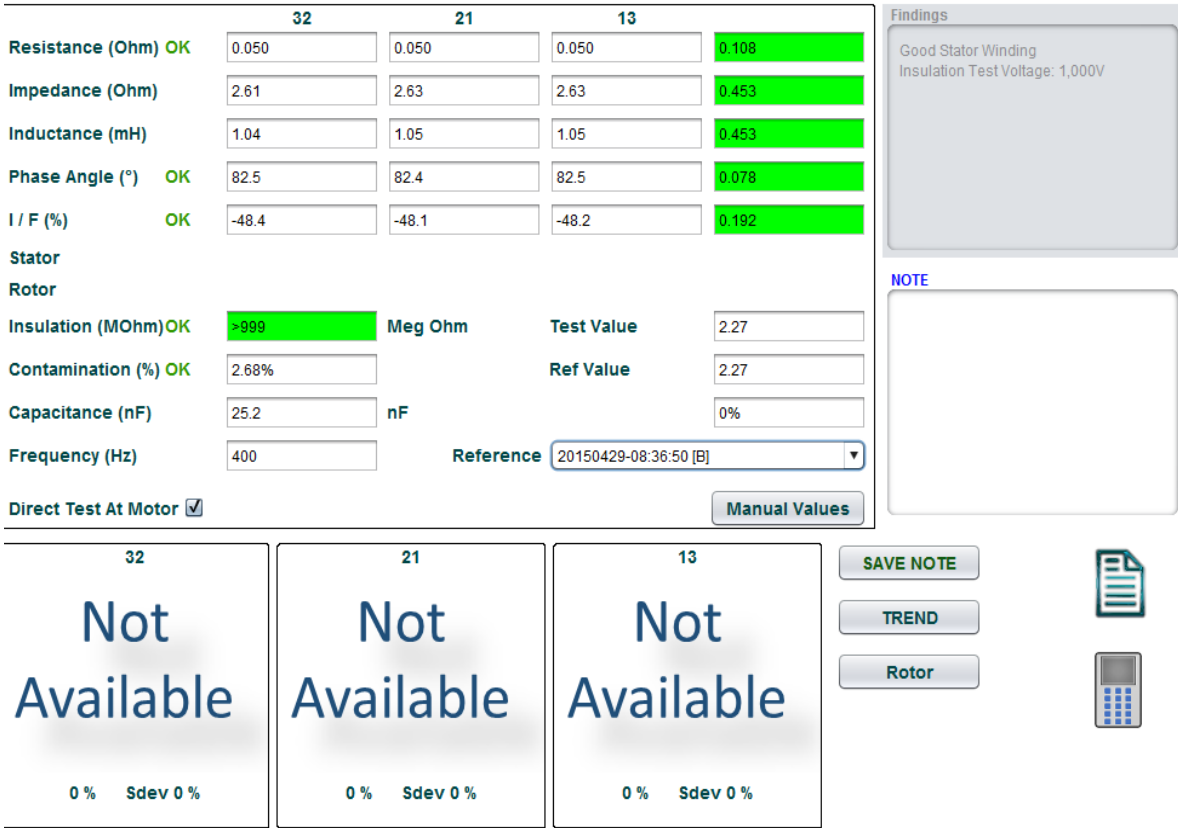
2) The AT5 uses a Kelvin bridge ohmmeter for making the DC resistance measurement with a resolution of 0.01 mΩ. **Note:** For **MCA** purposes the DC resistance measurements are used to detect problems related to connections and are not used to detect winding faults (TVS, Dynamic Test, Fi and I/F are much better indicators for winding faults).

Sample Test Results AC Induction

IND Test Mode



Z/φ test mode



Note: In Z/φ test mode computer software will only state "Good Stator Winding" when all values are "Green".

Condemning Criteria

This information pertains to testing 3-phase, AC induction motors. How to properly test and analyze for other motor types, transformers, etc. is covered in other sections of this manual.

Data Analysis Tips

When a motor testing program is first implemented it is expected that between 20- 40% of the motor systems tested may exhibit some alarm condition. When a motor is in an alarm state, this does not necessarily mean that the motor will fail or that it should be stopped immediately, but that the measured values have exceeded pre-determined limits established for most common motors. The software alarm limits of the MCA BASIC™ and MCA PRO™ are established for standard 3-phase squirrel-cage induction motors. Some motors may have a special design, which can cause the measured values to be normally outside of these standard limits. In fact, many new motors will have an unbalance in inductance and impedance, due to rotor bar winding ratio. Therefore, it is virtually impossible to establish limits for all possible design configurations. Of these cases, it is necessary for the analyst to evaluate these readings on a case-by-case basis. The software and AT5 instrument will flag any motor test that exceeds these limits to inform the analyst that they are outside of the generic alarm limits. The following analysis tips provide a method for more closely evaluating these special circumstances. Following the Analysis tips are various Scenarios using actual readings. Reviewing these scenarios will provide additional insight into determining how to evaluate the test data.

NOTE: It is highly recommended that users and analysts review this information carefully. ***There may be circumstances were more narrow alarm limits are appropriate and please contact our technical support team for further information.***

Condemning Priority

The MCA BASIC™ and MCA PRO™ software simply generate the alarms when the measured values exceed pre-determined limits. However, not all faults are the same. The guidelines provided below will help the analyst place priority upon the alarms generated by the software.

One of the first considerations regarding winding faults should always be motor criticality. Obviously, the most critical motors should be afforded a higher priority than less critical motors. The second consideration is the type and location of the fault (connection, winding, rotor, etc). Additional considerations include availability of spares, maintenance schedules and other plant operations. These priorities assume that the test data is valid and good connections were made during the testing process. Bad test lead connection can negatively impact all readings. ***Non-repeatable test results should be considered suspect and investigated further.***

1) Winding shorts are generally more severe than contamination or rotor faults, therefore, motors with TVS warning and/or unbalances in I/F & Fi should be evaluated first, to determine the condition of the winding.
2) Motors with alarms in TVS, Fi & I/F as well as inductance and/or impedance should be evaluated next. It may be necessary to perform a rotor reposition or rotor compensated test to separate rotor from winding faults. For AC induction squirrel-cage rotor <1000V and the rotor shaft is accessible the dynamic test should be performed.
3) Motors exhibiting small Resistance unbalances alone generally have the lowest priority (If you have company or equipment manufacturer condemning criteria and procedures then follow their guidance).

Condemning Tips

1) Never condemn a motor from the Motor Control Center. Faults in the cabling or connections between the test point and the motor itself can cause unbalanced readings or changes in readings. Before condemning a winding always perform a confirming test at the motor with **the motor leads disconnected from the supply cabling**.
    a) To determine whether the fault is in the motor or the cabling retest the motor at the next connection point between the motor and the starter or motor drive.

b) A rotor reposition test may be necessary to separate rotor from winding faults when evaluating the motor using unbalances of Fi and/or I/F (Refer to the Troubleshooting section of this manual for the Rotor Reposition Test).

2) Generally, never condemn a motor based just on an unbalanced inductance or impedance alone (may require additional testing). The Rotor Bar/Winding Ratio can cause a large unbalance in mutual inductance, as well as small unbalances in the I/F & Fi readings.
3) Always verify the reading before condemning a motor. Stored energy in a motor system can corrupt the data set. Remember, it is much easier to take readings again than it is to remove the motor.
4) Winding shorts are first indicated by unbalances in TVS comparison, Stator Signature, or unbalances with Current/Frequency response (I/F) and/or Phase Angle (Fi).
5) Loose connections are indicated by unbalances in winding resistance measurements.
6) Winding contamination or overheated windings are indicated with the dissipation factor measurement.
7) Problems of stator or rotor can be separated by performing the dynamic test, assuming the motor is an AC induction squirrel-cage rotor motor <1000V. If different motor type then additional testing may be required to identify the exact problem. Details are provided within this manual.
8) Never condemn a motor if the readings are not repeatable. EMI (induced voltages from adjacent energized conductors) or the motor shaft turning will also give inconsistent readings.

Unassembled Motor Analysis

If the rotor is removed from the stator the mutual inductance created by the stator magnetic field inducing a voltage into the rotor will no longer create an inductance unbalance. Therefore, the only part of the basic motor circuit that is responding to the injected AC signal from the instrument is the stator winding and stator iron. Any unbalances caused by rotor bar/winding ratio error are eliminated. Therefore, the fault criteria are much tighter for motors tested when the rotor is removed. Below are the tolerances for motors stators only (motors with the rotor removed).

Note: *Experience has proven that these tolerances hold true regardless of the size of the motor. MCA software alarms are only designed for motor with rotor assembled. For a test with an unassembled motor, the following is the guideline to get the conclusion.*

Test Result	Tolerance
Resistance (R)	<5%
Impedance (Z)	<3%
Inductance (L)	<3%
Phase Angle (Fi)	+/- 0*
Current frequency Response (I/F)	+/- 0*

TVS, Stator & Rotor Signatures	Not Applicable
Insulation Resistance	See INS section as previously described

This table is *only* applicable to motors with the rotor removed

*Small variations may be acceptable. I.e. Fi 76.1°, 76.0°, 75.9°

Data Interpretation Basic Rules and Tolerances

There are specific rules that encompass virtually all test applications of three phase motors in which the motors are assembled and a rotor is installed. The common method for testing is from an MCC or disconnect with the rotor stationary.

Assembled Motor Analysis

If the rotor is installed in the stator the mutual inductance of the rotor may cause large inductance unbalances which will result in a large impedance unbalance. The Rotor Bar/Winding ratio may also cause small unbalances in I/F and Fi.
Note: The guidelins for "BAD" warning of R, Z, L, DF, Fi, I/F and Insulation Resistance also apply to transformer test and coil test under the DC test menu.

Test Result	Tolerance	Detail
Resistance (R)	<5%	Likely loose or faulty connections
Impedance (Z) and Inductance (L)	<5%	If random wound <1000V, unbalance might be due to rotor position or motor design. If form wound then a fault may have occurred.
Dissipation Factor (DF)	>6%	Likely winding contamination or overheated windings
Phase Angle (Fi)	+/- 2 digits (degree) from average	Indicates a winding short: 74, 75, 76 OK; 74, 74, 76 suspect; 73, 73, 76 failed
I/F	+/- 2 digits (%) from average	Indicates a winding short: -44, -45, -46 OK; -44, -46, -46 suspect; -42, -45, -45 failed
TVS	>3%	Likely change in condition of the winding or rotor
Dynamic Test	Stator: >1.5%	Likely stator winding issue
	Rotor: >15%	Likely rotor issue
Insulation Resistance	See INS Guide	Indicates poor insulation to ground (I.e. ground fault)

Resistance (R): Unbalances in resistance are an indicator of loose connections, pitted contactors, cold solder joints, etc. In some cases the resistance unbalance can be the result of test lead clip placement. Always retake the resistance measurements if a resistance unbalance exists. Changes in the resistance measurements with repetitive readings indicate test lead or test lead connection issues. Attempt to clean the connection location and then retake the resistance readings. If the readings were taken at the motor control center taking reading progressively closer to the motor will normally locate the high resistance connection(s).

Inductance (L) and/or Impedance (Z) Unbalance: When a squirrel cage rotor is installed in the motor, inductance unbalances are possible, especially with smaller less expensive motors. If this does occur these unbalances are usually the result of the unbalanced mutual inductance created by the unequal rotor bar/winding ratios resulting from rotor position. To verify that this unbalance is the result of the rotor position, the rotor reposition test should be performed (See section on Rotor reposition test).

Dissipation Factor (DF): Dissipation factor is used to indicate the capacitive property of the insulation materials used in the motor. When the insulation degrades over time and becomes less resistive due to the contamination or overheating, the dissipation factor will increase. Along with dissipation factor, capacitance is measured which can help trend the insulation property changes in the long term. As DF and capacitance are directly related to one another, when either one returns an invalid test result, e.g. out of range, then it means the other test result is not valid either.

IRG – Insulation Resistance to Ground: IRG is the most common electrical test performed on electrical systems to test the insulations capability to withstand voltage. The IRG test is performed by applying a high dc voltage between de-energized current-carrying conductors and the machine casing or earth. The insulation resistance value is proportional to the insulation material thickness and inversely to the conductor surface area. In addition, the physical and chemical properties of the insulation materials play a critical role in terms of resistance, for example, resistivity of the insulation, void distribution inside the material, resistance to being oxidized and thermal expansion/shrink all play important roles in overall insulation resistance and the capability of the insulation system to withstand voltage.

Phase Angle (Fi): The amount of lag between the applied voltage and the resulting current in the basic motor circuit is one of the most sensitive of measurements used to detect winding faults in the motor circuit. Fi is usually one of the first measurements to change when the insulation system degrades (Winding short). Unbalances of >1 degree from the average indicate a winding short. The Fi readings should be ≥ 15° and < 90°.

Current Frequency Response (I/F): Degraded winding insulation systems respond differently at different frequencies. The I/F measurement are also one of the first indications of winding system degradation. The I/F readings should be between -15 to -50. All I/F reading should be balanced within 2 digits (percent). Unbalances of >2 digits from the average indicate winding shorts. A spread of ≥4 digits between maximum and minimum I/F measurements, also indicates winding faults. These readings are for non-compensated rotor position at the motor. However, if a winding fault is indicated additional testing may be necessary to verify the winding fault.

TVS (Test Value Static): Makes measurements on all three phases and calculates a "Test Value Static", which when compared to a baseline "Reference Value Static", becomes a powerful combined fault indicator for Rotor and Stator faults. The "Reference Value Static" is normally saved from the first time the motor is tested (a baseline test) or can be saved from a known good motor of the exact same motor type (manufacturer, model, manufacturing tolerances, ect.).

Dynamic Test (Test Signature): Measures, in real time during manual rotation, a number of values in all three phases which together forms the “Test Signature” for the rotor and stator. The "Test Signature” is then automatically analyzed in the AT5/AT33 and gives the user immediate results for Stator and Rotor status. The “Test Signature” can also be uploaded to the MCA software and evaluated further.

Analyzing Measurements and Change

Data interpretation of collected AT33 or AT5 data can be performed through the MCA software.

Troubleshooting Rules

Following are the basic rules for troubleshooting with the AT33 and AT5:

Shorted Windings:

Developing windings faults, as well as shorted windings, are evaluated by viewing the TVS as well as Fi and I/F readings of similar coils or between phases:

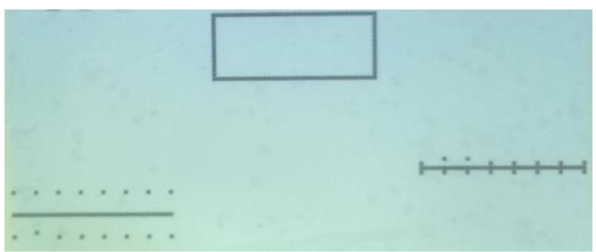
> **Dynamic Test (Stator Signature)** – Experience show that the stator signature is more sensitive in detecting the problem with the stator. This proprietary and patented method provides WARN or BAD warnings once winding faults exist in stator windings. Moreover, as the Dynamic test also evaluates the rotor we recommend that this test is done as a final confirming test before condemning a motor. Assuming of course, the motor is an AC induction squirrel-cage rotor motor <1000V.
>
> **Test Value Static (TVS)** – When a new TVS value is compared to the Reference TVS acquired previously, if the difference is greater than 3% then it’s most likely that a winding fault has occurred (rotor fault can also cause a change in TVS). *A Warning limit of >1.5% may be appropriate for form wound squirrel-cage rotor motors.* A narrower limit can be determined by static testing the motor in several different rotor positions. I.e. if TVS varies <1% in multiple rotor positions then a more narrow alarm may be appropriate.
>
> **Phase Angle (Fi)** – The maximum phase angle difference between any two phases should be within 2 digit of the average reading. For example, a reading of 76/75/76 would be good because the maximum difference is 1. A reading of 77/75/76 would be bad.
>
> **Current Frequency Response (I/F)** – The maximum difference of the current frequency response between any two phases should be within 2 digits. For example, a reading of –45/-45/-46 would be good. A reading of -44/-45/-46 would be bad.

In certain cases, if only TVS provides warning while phase angle and/or I/F are "Green", or if TVS is "Green" while phase angle and/or I/F are in alarm, it is suggested to do the following:

1) If AC induction squirrel-cage rotor motor <1000V perform the Dynamic test.
2) If AC induction above 1000V then perform a rotor compensated winding test to determine if the stator winding has a fault.

As the dynamic test result can be sensitive to the specific operation, i.e. how the rotor shaft is rotated, in case of a warning is provided, the user should check the dynamic test result immediately on the instrument display by pressing "Stator" or "Rotor". A valid dynamic test always comes with solid lines of stator signature with rotor signature data distributed above and below the line. When any "strange" test results show up, for example, the image below shows an example that looks like the 1st phase test is OK while the other two tests are not valid. The reasons that this happens include:

1) Rotor shaft is rotated at significantly different speed, for example, the rotation changes abrupt from slow to fast or from fast to slow.
2) The shaft is turned at uniform speed; however, it is not the right speed for testing a particular motor. Therefore, the user needs to try several different speeds to determine the best speed appropriate for testing.
3) Due to certain time constant issue, the instrument cannot respond timely and correctly on the signals reflected back from the object under test.



In some situations when the rotor is rotating too fast, the instrument may display the message that disconnection is happening and stops working. In such case, the user needs to turn the shaft at relatively uniform speed. If it still happens, then the speed needs to be reduced.

If the dynamic test produces a warning, the user should try multiple times at different speed to see if the warning results from rotation error. If the user can get good results with one dynamic test then likely the motor is good. To study it further, it is suggested to perform a detailed rotor test assuming the user has already confirm the stator is in good condition, or best to apply energized ESA test which is the most reliable means to detect rotor problems.

Winding Contamination Dissipation factor is the major indication of winding contamination. DF measurement over 10% indicates a serious contamination issue. Sometimes high contamination can also point to a low insulation resistance to ground measurement.

Rotor Reposition Test To verify that the Impedance (Z) and/or Inductance (L) unbalance is the result of rotor bar/winding ratio unbalances it is necessary to evaluate the relationship of the Z & L unbalances. If the unbalances are related to the rotor, they will change relationship by changing the position of the rotor.For example, if there are inductances of 17/18/19 and values of impedances are 24/26/29 with the rotor at its existing position. Then rotate the shaft approximately 90 degrees (1/4 turn) the values should change relationship, such as inductances of 16/19/17 and impedance values of 23/30/25. This indicates that the unbalances are due to rotor position.

Insulation Resistance The insulation resistance (Meg-Ohm reading) will show a breakdown of insulation between the winding conductors and ground. According to IEEE Std. 43, the insulation resistance is measured after applying DC high voltage for 1 minute. The motor should be above dew point temperature before testing if possible. It is important to correct values to a reference temperature (typically 40 °C) so that trends and changes in insulation resistance can be readily detected. Contamination, humidity, temperature, and other factors affect insulation resistance values. The standard recommends choosing these test voltages for insulation resistance testing:

Winding rated voltage (V)[a]	Insulation resistance test direct voltage (V)
<1000	500
1000–2500	500–1000
2501–5000	1000–2500
5001–12 000	2500–5000
>12 000	5000–10 000

[a]Rated line-to-line voltage for three-phase ac machines, line-to-ground voltage for single-phase machines, and rated direct voltage for dc machines or field windings.

The AT5 and AT33 instruments offer two voltages: 500V and 1kV. For windings rated over 5kV, an instrument capable of producing a higher test voltage will be needed according to the guidelines above.

The standard also recommends minimum insulation resistance value at 40^{o}C as shown below. “kV” is the rated line-to-line RMS voltage of 3-phase motor, line to ground voltage of single phase motor, or rated DC motor voltage.

Minimum insulation resistance (megohms)	Test specimen
$IR_{1\ min} = kV + 1$	For most windings made before about 1970, all field windings, and others not described below
$IR_{1\ min} = 100$	For most ac windings built after about 1970 (form wound coils)
$IR_{1\ min} = 5$	For most machines with random-wound stator coils and form-wound coils rated below 1 kV and dc armatures

Note: The IEEE guidelines above provide the recommended voltages and minimum Insulation Resistance to ground values. If these procedures or values differ from your equipment manufactures' recommendations, follow their guideline. AT5 and AT33 adopt different insulation resistance diagnostic rules. Please refer to the user manuals, respectively.

Loose Connections Loose connections or glazing on contacts will show as resistance unbalances. The maximum resistance unbalance should be 5%.

Predictive Maintenance

As early as the 1960's, many companies realized that by routinely monitoring the operating condition of rotating equipment it is possible to obtain an advanced warning of operational or other problems that would impact continued efficient operation. This early warning provides time to remove the machine from operation and affect minor repairs and adjustments before catastrophic failures occur.

This maintenance philosophy, referred to as Predictive Maintenance (PdM), has escalated since the early 1980's, with the introduction of microprocessor based *data-collectors.* Many of the machines' operating characteristics, such as temperature, pressure, oil condition, vibration and performance can be trended to identify changes. However, one of the glaring holes in predictive maintenance has been the inability to easily & accurately identify faults within electrical equipment, such as motors, transformers, solenoids and other like equipment. One of the main reasons for this was the lack of available easy-to-use predictive maintenance instruments for testing motors or other electrical equipment.

Predictive maintenance instruments should be:

- Hand-Held
- Easy to use
- Provide output in Conventional Units

Implementing Predictive Maintenance

Implementing a successful predictive maintenance program requires more than purchasing an instrument and taking data. Predictive maintenance programs when successfully implemented require a complete understanding of the PdM process.

Successful predictive maintenance consists of three phases - **Detection**, **Analysis** and **Correction**. Each one of these phases is important in its own aspect. Problems are created when short cuts are taken and phases are skipped or combined.

> **Detection** The detection phase involves periodically monitoring the operating characteristics of the selected equipment. These values are trended, compared to previously recorded data from that machine or similar machines, then compared against pre-determined or published standards and/or reviewed for any change.

During the detection phase, the data collection process should be done quickly and carefully, with the intent of monitoring as many machines as possible. When a change is detected, additional data may be necessary, to determine the cause of the machine's condition change. This is done during the analysis phase.

In most cases, the MCA data taken during the detection phase may be sufficient to identify developing shorts or other winding issues. But at times, additional data or testing needs to be performed to more accurately identify the problem.

It is usually a waste of time to perform these tests for a more detailed analysis during the detection process, as it slows down the detection process. Most experienced predictive maintenance departments have recognized the importance of separating these two processes.

Analysis The analysis process involves taking additional and perhaps different types of tests than the detection process. This additional testing may require disconnecting the motor from the load, turning the shaft or separating the motor leads and requires more time to take the data. Since usually only a few machines during the detection inspection exhibit any significant change, it is usually more time effective to only take the data necessary to identify a change during the detection process, and then go back for a more detailed look once a change is detected.

However, if the plant site is remote or has other access limitations, these may justify more detailed data be taken during the detection process.

Correction The correction phase involves correcting and eliminating the problem that triggered the analysis. This may require cleaning a motor, tightening connections, or a complete motor rewind. The exact type of correction and repairs are determined by the analysis. Details for correcting and eliminating these problems are outside the scope of this manual.

Predictive Maintenance Hints

The following recommendations are from over 30 years experience with MCA using the ALL-TEST Pro line of motor testers. It should be remembered that these are recommendations only and are designed as suggestions to provide for the optimum program. It may not be possible to implement each and every suggestion in all applications:

1) When performing Predictive Maintenance (PdM) on three phase induction squirrel-cage rotor electric motors, comparison of a new TVS to a REF TVS is the preferred method to detect changes in the condition of the stator. If a TVS REF is not available then evaluating the unbalance of Fi and I/F is desired. However, if a non-form wound motor and specific to analysis of Fi and I/F, it is desirable to try and place the rotor in the same position each time (I.e. Place the shaft key at the 12 o'clock position) as this will minimize changes from

data collection to data collection due to rotor position *(Specific to evaluation using unbalances of Fi and/or I/F you may want to use AT31 in conjunction with the AT5 to perform a rotor compensated test).*

2) Specific to evaluation using unbalances of Fi and/or I/F when the initial test is performed, if variations in the inductance measurements >5% between phases, perform a rotor reposition test in order to determine if the variation is due to the rotor bar/winding ratio or if there is a rotor fault. These variations may be normal or the unbalance may be due to rotor position. Review the rotor position section of this manual for further clarification.
3) The upper limit of equipment size that can be successfully tested is primarily dependent on the DC resistance and impedance of the windings. For best accuracy the winding’s DC resistance needs to be between 0.01 and 999 ohm in each phase. The windings capacitance & inductance, plus cable length can also impact the range of equipment that can be tested. Additionally, with large machines separating coils and testing individually can improve detection accuracy.
4) Always mark your motor leads and collect data in the same order so that MCA software records and analyzes the data in the same order. Establish a pattern when numbering the leads for example left to right, front to back, or top to bottom. This also provides consistency in readings.

This consistency also helps identify in which phase the fault occurred, i.e. if an increase in resistance in 1-2 and 1-3 occurs, then you should check the phase 1 connections.

Data Collection and Test Result Issues

There are issues inherent with faulty motors and with data collection process of motors in an industrial environment. Following are some of those issues when collecting data with the AT5/AT33 and their resolution:

Bad Results Including Non-Repeatable Measurements

EMI (**E**lectro-**M**agnetic **I**nduction) can cause problems with test results. This usually only occurs when testing from the MCC. EMI can come from heavily loaded cables located directly next to the cables from the motor that is being tested. The values are normally in the milli-Volt range and not always detectable with a multi-meter or voltmeter. Use the EMI feature of the AT31 to measure the EMI level. If the EMI cannot be removed then the motor must be tested directly at the motor connection point.

Motor Rotor Turning. If the shaft in the machine being tested is rotating, it will induce a voltage into the basic motor circuit. This will affect all of the readings.

Note: To determine whether the bad result is caused by EMI or rotating shaft, use the Rotor feature of the AT31. If the shaft is rotating the bar graph on the screen will move back and forth across the display screen of the AT31. If the bar graph moves erratically across the screen check the EMI level using the EMI feature of the AT31.

No Connection (Beeping) In case of an open circuit, AT5/AT33 will start beeping. Test closer to the motor to find the open circuit. The open circuit may be in the test leads. Check them for continuity.

Capacitors or Lightening Arrestors in the motor circuit will filter the test results and create incorrect readings which can provide false positives or false negative results. Always disconnect any capacitors or lightening arrestors connected to the motor circuit.

Non-Repeatable Resistance Measurements EMI interference will cause non-repeatable resistance values (see Bad Results above). Contamination in the motor or cabling can cause non-repeatable resistance readings. So can carbon buildup or heavy contamination in cabling. Disconnect the motor leads at the motor connection box and retest. Poor connections at the test clips will normally affect the resistance only, but it may affect other readings also, depending upon severity. If a resistance unbalance exists from the MCC always retake readings directly at the motor with incoming phase leads disconnected before condemning the motor (as the source of the unbalance). If resistance phase measurements are repeatable from one test to another the resistance unbalance is most likely in the motor or cabling. If resistance measurements do change from one test to another the fault is most likely the result of poor connections at the test leads. Clean the connections thoroughly until repeatable readings are obtained.

Servo-motors & Machine tool Motors Some machine tool and servo-motors have permanent magnet rotors which may affect the I/F & Fi measurements. The I/F & Fi readings will be repeatable but outside standard tolerances. Testing permanent magnet rotors may require special procedures (See Appendix 4). Trending the differences in the highest and lowest I/F & Fi readings will provide additional indication of winding degradation. *Rotor faults can also cause the difference between the I/F & Fi readings to increase, it is suggested that a rotor reposition test be performed to verify a rotor fault.*

Synchronous Motor Testing Synchronous motors windings will also test for shorts in the rotor windings. If the Auto test indicates winding shorts, the short could be either in the stator or in the rotor windings. To determine which winding is shorted rotate the shaft approximately 90^0 and retake the readings (large multiple-pole synchronous motors may only require that the shaft be moved a small distance- 5°). If the fault remains in the same phase as the original test the short is most likely in the stator winding. If the fault shifts to another phase the fault is most likely in the rotor. The synchronous motor rotor winding are a single winding, evaluating them is done by trending or comparing current reading to a baseline. Large salient-pole synchronous motors may require special testing considerations. See the addendum found later in this manual or contact our technical support team for further information.

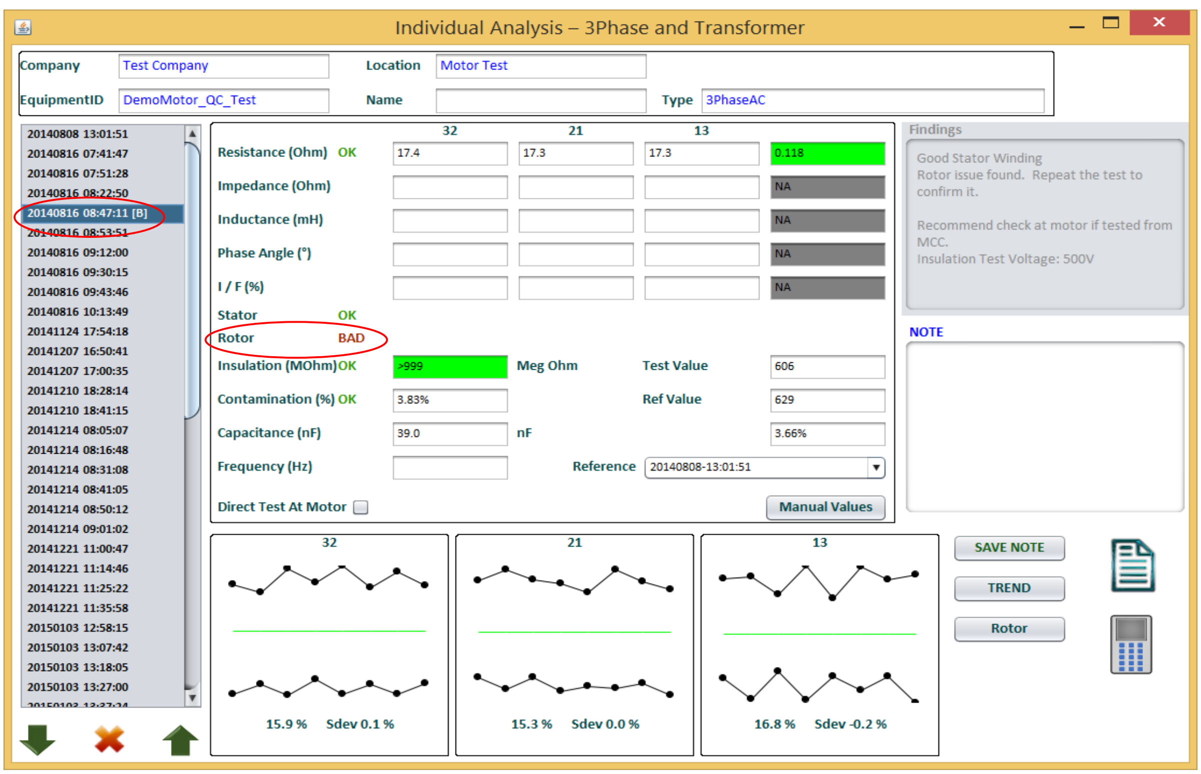
Transformers Testing transformers can identify winding shorts, high resistance connections, open windings, and insulation to ground fault detection; as well as internal circuit impedance unbalance. By using MCA you can compare readings to similar windings or transformers and look at variations and patterns between phases. Testing different types of transformers may require a special procedure (See Appendix 2:).

Wound Rotor Motor Testing wound rotor induction motors will also identify shorts in the rotor windings. If the Auto test indicates winding shorts, the shorts could be either in the stator or in the rotor windings. The windings of a wound rotor motor are tested using the slip rings. The same tolerances apply to the 3 phase rotor windings as to the stator. If the rotor tests good, the fault is in the stator.

Data Trending

Trending test data collected over a period of time is another powerful tool for predictive maintenance. To perform the trending analysis in MCA, a minimum of 2 data points is required. And the comparison is performed between the first test data and the baseline. The trending analysis depends on the baseline the user has chosen. By default, the baseline is the earliest test data which is located on the top of the data group and marked with "B". The user can use up or down arrow to choose the baseline they prefer.

Note: the trending curves displayed on MCA software may not be the values for alarm calculations.



Trending Analysis for 3 Phase AC Motor and Individual Coil Test

Test Result	Alarm Limit	Troubleshooting	Detail
Resistance (R)	5%	Check for loose connection.	For each test data, find the maximum difference between each phase and the average value. Then compare the ratio difference.
Impedance (Z)	5%	Special care should be taken before condemning a motor only due to Z unbalance.	For each test data, find the maximum difference between each phase and the average value. Then compare the ratio difference.
Inductance (L)	5%	Special care should be taken before condemning a motor only due to L unbalance.	For each test data, find the maximum difference between each phase and the average value. Then compare the ratio difference.
Phase Angle (Fi)	2º	If L or Z unbalance is >5% then perform rotor compensated winding test to confirm the issue. If AC induction squirrel-cage rotor motor <1000V then perform the Dynamic test.	First find the maximum difference between any two phases for each test data. Then compare the difference.
I/F	2%	If L or Z unbalance is >5% then perform rotor compensated winding test to confirm the issue. If AC induction squirrel-cage rotor motor <1000V then perform the Dynamic test.	First find the maximum difference between any two phases for each test data. Then compare the difference.

TVS	5%	Either stator or rotor may have a problem. If AC induction squirrel-cage rotor motor <1000V then perform the Dynamic test to determine cause for this change. If >1000V induction squirrel-cage rotor then follow testing procedures for winding and rotor analysis.	Change in percentage of the latest data over the baseline
Dissipation Factor (DF)	10%	Contaminated or overheated windings.	The latest test data is analyzed.
Insulation Resistance	5 MΩ	Grounded windings.	The latest test data is analyzed.

Trending Analysis for DC and 1 Phase AC Motor

Test Result	Alarm Limit	Troubleshooting	Detail
Resistance (R)	5%	Check for loose connection.	For each winding, the relative change of the latest data over the baseline.
Impedance (Z)	5%	Non-repeatable measurements when testing armature circuit can indicate excessive carbon dust buildup.	For each winding, the relative change of the latest data over the baseline.
Inductance (L)	5%	Non-repeatable measurements when testing armature circuit can indicate excessive carbon dust buildup.	For each winding, the relative change of the latest data over the baseline.
Phase Angle (Fi)	2º	Potential Winding faults.	For each winding, the absolute change of the latest data over the baseline.
I/F	2%	Potential Winding faults.	For each winding, the absolute change of the latest data over the baseline.
Dissipation Factor (DF)	10%	Contaminated or overheated windings.	The latest test data is analyzed.
Insulation Resistance	5 MΩ	Grounded windings.	The latest test data is analyzed.

Troubleshooting Motors

Rotor Compensated Test

When there is an alarm from TVS, phase angle or I/F, and the motor is an AC induction squirrel-cage rotor <1000V then perform the Dynamic test. On other types of equipment and Z or L unbalance is >5% then to determine if change relates to the winding and not rotor position we suggest a rotor compensated test be performed. This requires both an AT31 (or an instrument that measures in real-time inductance or impedance) and an AT5 instrument.

1) Find rotor positions of maximum impedance corresponding to every two phases.
    a) Connect the AT31 to two phases, e.g. Phase 32, then turn shaft until the maximum impedance value is obtained.
    b) Mark the rotor position.
    c) In the same way, mark the rotor positions for Phase 21 and Phase 13 where maximum impedance occurs.
2) Start Z/φ menu test. Skip the DF/C test and insulation test. The yellow test lead is not connected.
3) Go directly to the 3-phase static test.
4) Ignore the instructions on the instrument display. Instead, do the following:
    a) Connect Kelvin test leads 32 from AT5 to the Phase 3 and Phase 2 terminals on the motor.
    b) Leave Test lead 1open. I.e. not connected.
    c) Turn the rotor to the marked position of maximum impedance for Phase 32.
    d) After the measurement of Phase 32, AT5 will start beeping due to test lead 1 not connected.
    e) Ignore the beeping; turn the rotor to the position of maximum impedance for Phase 21. Keep test lead 2 connected, disconnect test lead 3 (do not connect it to anything), connect test lead 1.
    f) AT5 stops beeping and starts the measurement. Once it's completed, AT5 will start beeping again.
    g) Ignore the beeping; turn the rotor to the position of maximum impedance for Phase 13. Keep test lead 1 connected, disconnect test lead 2 (do not connect it to anything), and connect test lead 3.
    h) AT5 stops beeping and starts the measurement.
    i) Then the rotor compensated test is completed. Save the test results.
    j) Run MCA software to upload the test data and perform the 3 Phase AC individual analysis. If no Yellow or Red alarm is indicated for the parameters of impedance, inductance, phase angle and I/F, it means the motor is in good condition.

Note: the time interval between every two measurements (the time AT5 keeps beeping) should be limited to less than 5 minutes.

Rotor Reposition Test

Using the AT5 instrument Z/φ test menu, a short series of tests may be performed in order to determine whether the unbalanced readings are due to the rotor or to the stator design. The steps are simple:

1) Note the position of the rotor after saving the original readings. Slightly rotate the shaft about 10 degrees from its original position and remeasure the motor windings with the connections as they were originally taken.
2) Reference the previous reading and note if the unbalance has shifted with the rotor movement. If it has or if the readings are inconclusive, retake the measurements at 90 or 180 degrees from the present position.
3) If the readings remain unbalanced in the original position, the stator windings are most likely faulted; if the readings shift with the rotor position, perform a rotor test as outlined in the motor troubleshooting guide.

Shifting Readings Example

	T1-T2	T1-T3	T2-T3
Impedance 0º	47	53	58
Inductance 0º	9	10	11
Impedance 10º	53	58	47
Inductance 10º	10	11	9
Impedance 10º+90º	58	47	53
Inductance 10º+90º	11	9	10

Note: The readings will not be exact, this is just an example

Maintained Readings Example

	T1-T2	T1-T3	T2-T3
Impedance 0º	47	53	58
Inductance 0º	9	10	11
Impedance 10º	47	53	58
Inductance 10º	9	10	11
Impedance 10º+90º	47	53	58
Inductance 10º+90º	9	10	11

Note: The readings will not be exact, this is just an example

Rotor Test

One of the important features of the AT5 is the ability to perform a complex analysis of a three phase motor rotor.

> **Note:** If AC induction squirrel-cage rotor motor <1000V then evaluate the condition of the rotor using the Dynamic test mode.
> Rotor test is only performed for a 3 Phase AC induction with squirrel-cage rotor motor >1000V after stator is determined to be fault-free. The rotor test is also a detailed study for the rotor issues after the dynamic test reveals possible rotor problems. For motors with 4 poles or less, inductance measurements for 3 phases are collected at

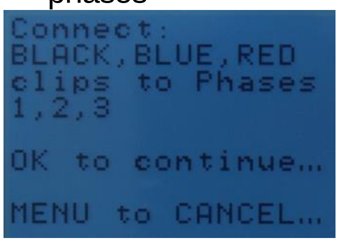
a minimum of 48 different positions for one complete rotation (360°). In other words, one test has to be performed for every 7.5° of rotation. For motors with 6 poles or more, a minimum of 72 tests must be performed, i.e. one test every 5°.

Note: if the motor can be run coupled to a load then Electrical Signature Analysis (ESA) using the ALL-TEST PRO On-Line II ™ instrument is the best means of analyzing the rotor when testing squirrel-cage rotor AC induction motors of any voltage.

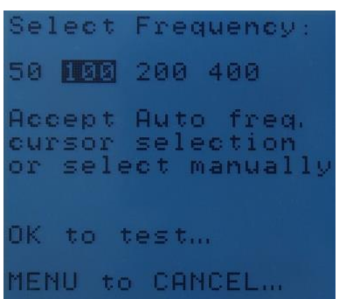
To precisely determine every test position, an angle gauge can be attached to the rotor to determine each rotation angle step. Or the users can find polar graph chart online and print it and attach it to the motor frame with rotor shaft going through the center. An example is provided at the end of this section.

Rotor Test steps

1) Select Rotor Test option, then connect the three test leads to the motor's three phases



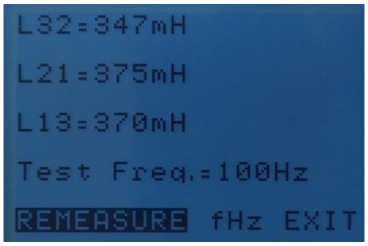
2) The instrument starts the measurement, then will show the frequency determined. The user can choose this frequency or select another frequency at their discretion.



Note: the frequency can be changed during the testing process. However, the same frequency should be used for all phases and positions.

3) Each time, the test is performed on three phases the results are displayed as shown below.
    a) When the rotor is turned to the next position, press the "REMEASURE" and it will perform another measurement. The results of each measurement must be hand recorded and then entered into the optional MCA PRO software or into some other spreadsheet application (Microsoft Excel or similar).
    b) To change frequency, choose "fHz", highlight the desired frequency, then press "OK" key.

c) When all rotor tests are completed, choose “EXIT”.



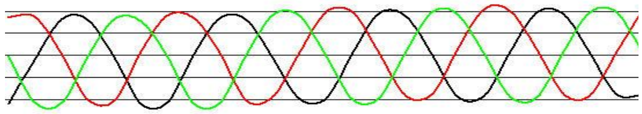
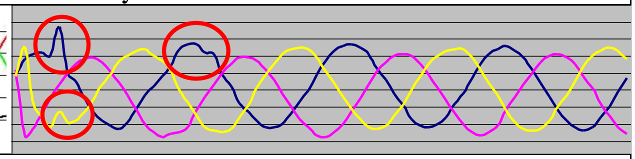
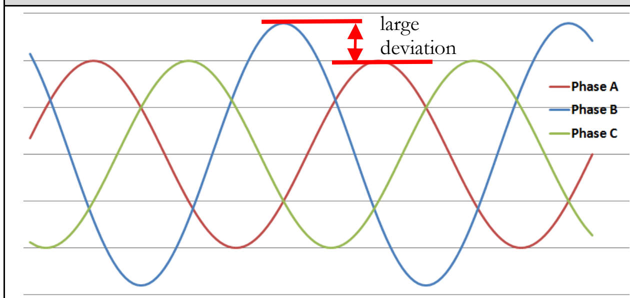
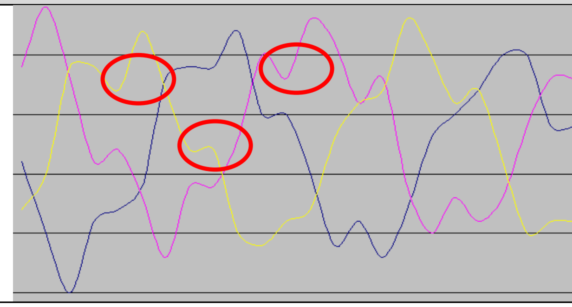
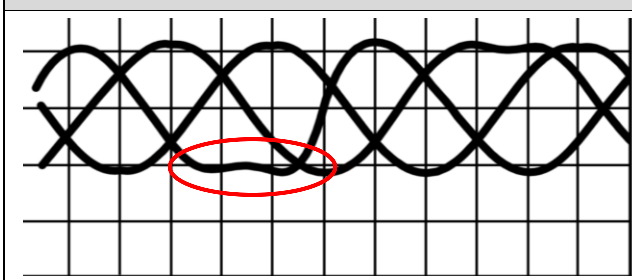
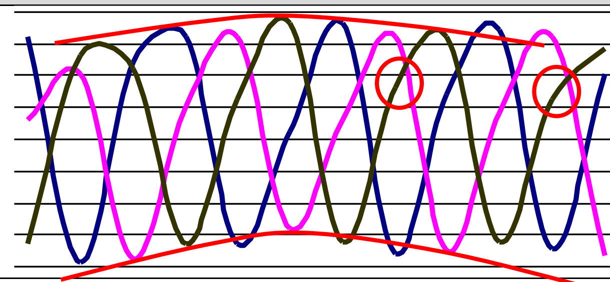
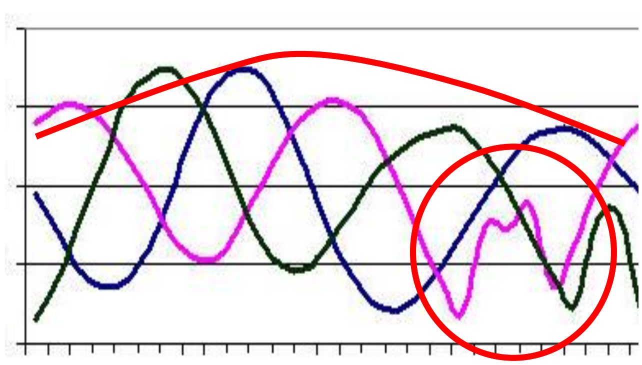
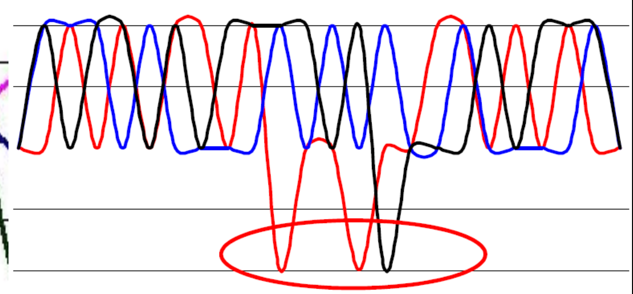
NOTE: The more accurate the positioning of the rotor the more accurate the analysis will be. It is recommended to attach a rotating protractor or use a piece of circular graph paper attached to the shaft to provide maximum accuracy.

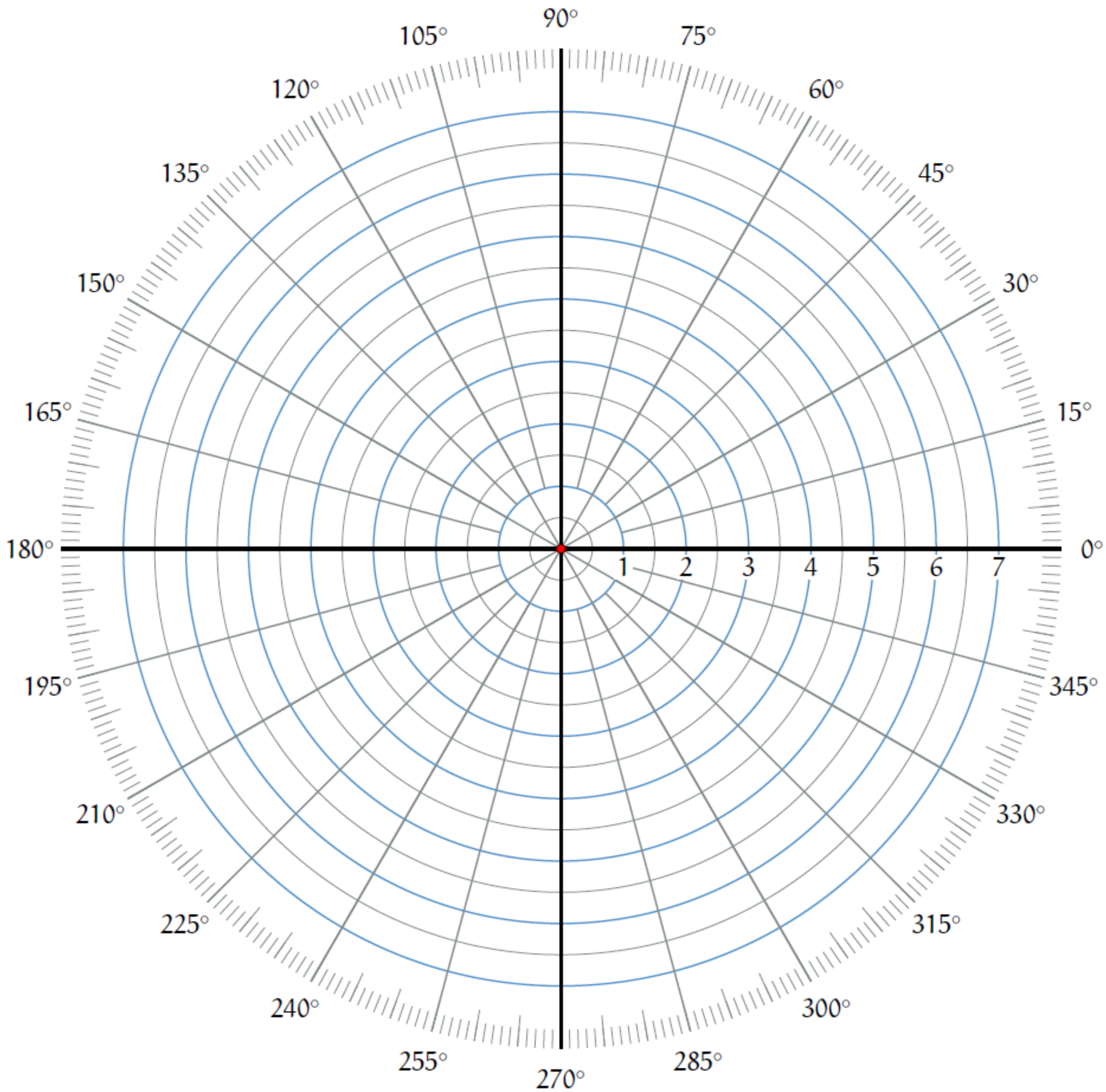
4) When a complete set of data has been taken the results should be graphed using the Rotor Test feature either of the MCA PRO software or by using some other spreadsheet or graphics program such as Microsoft Excel.

Analysis

1) The readings will not be identical but should result in a repeating pattern as the shaft is rotated. If the pattern varies, there is rotor, casting, or air gap problems.
2) Rotor and casting problems show as a sudden change in one location on the motor while air gap problems change consistently around the rotor.
3) The resulting waveforms should be even and 120 degrees out of phase from each other. There are a number of cases where these readings will deviate:
    a) Large deviations at the peak or valley of at least one waveform will identify high resistant points in copper rotor bars, possibly where the bar is welded to the shorting ring.
    b) Similar deviations will indicate broken rotor bars or in small inexpensive aluminum rotors, the rotor laminations may not be set properly, leaving variations in the resistance of each rotor bar (low quality motor).
    c) A more common problem in many electric motors (some manufacturers have more challenges than others) is casting voids. This is usually found as a flat point at the incline or decline on at least two of three sine waves.
    d) Eccentric rotor problems are normally found when the inductance tapers off or the waveform moves higher or lower (arcs from right to left).

In addition to the internal analysis, the MCA also requires users’ input to help make accurate diagnostic conclusions. A table listing common rotor problems is provided in the optional MCA PRO software, which is listed below.

Examples of Different Inductance Waveforms for Rotor Analysis	
	
Good Rotor - curves need to be symmetrical but not necessarily "perfect" sine waves.	Bad Rotor Example
	
Bad Rotor Example	Bad Rotor Example
	
Bad Rotor Example	Bad Rotor Example
	
Bad Rotor Example	Bad Rotor Example



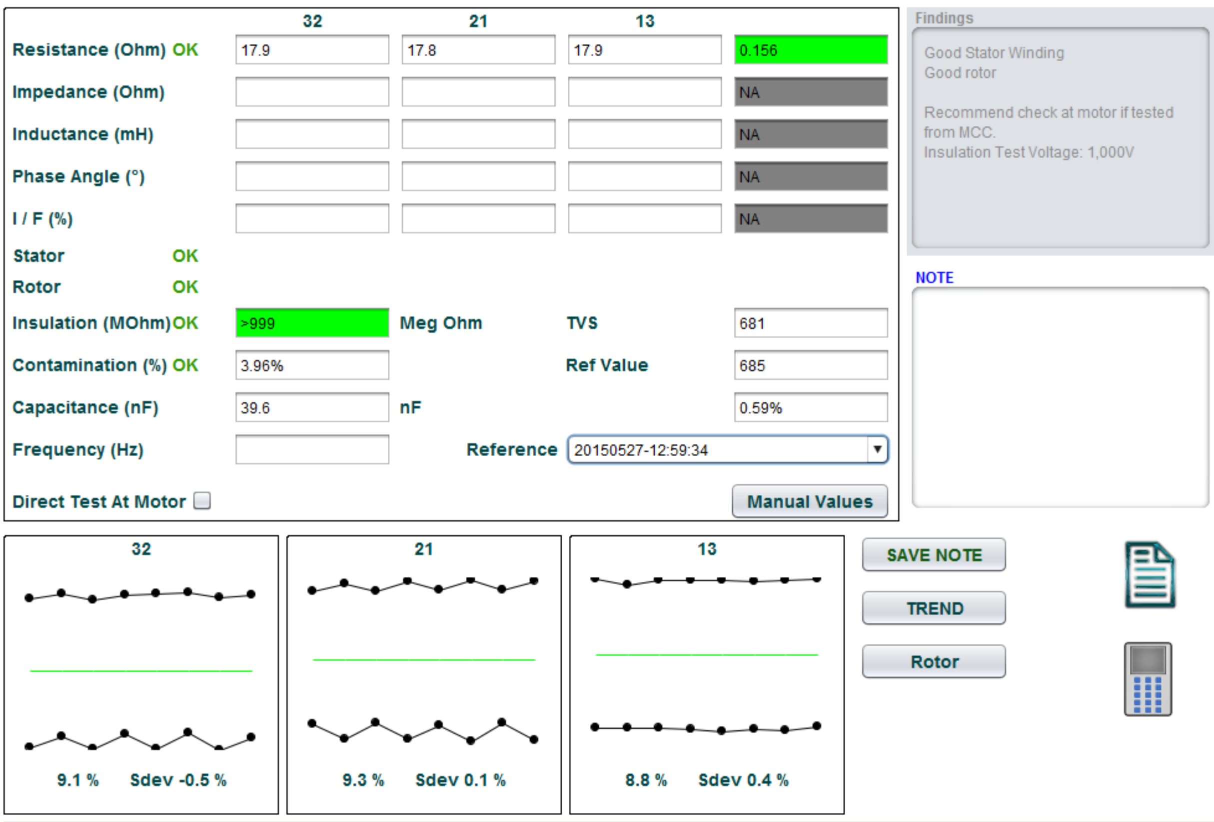
A Sample of Polar graph

Appendix 1:

Different Test Scenarios

Over 30 years experience in conducting motor testing using MCA has identified these common scenarios. The section below provides a sample display and brief write up of each scenario.

Scenario 1: A good motor test results



This is a typical complete test performed by AT33 or AT5 **IND** test mode for a 3 Phase AC induction motor with squirrel-cage rotor <1000V. Both static tests and dynamic tests show "OK" in green.

An example of a good motor tested by AT5 Z/φ mode is shown below.

	32	21	13	
Resistance (Ohm) OK	17.8	17.9	17.9	0.047
Impedance (Ohm)	229	235	236	1.89
Inductance (mH)	364	373	375	1.90
Phase Angle (°) OK	68.8	68.7	68.8	0.075
I / F (%) OK	-40.3	-40.1	-39.9	0.175
Stator				
Rotor				
Insulation (MOhm) OK	>999	Meg Ohm	TVS	701
Contamination (%) OK	3.96%		Ref Value	685
Capacitance (nF)	39.8	nF		2.25%
Frequency (Hz)	100		Reference	20150527-12:59:34
Direct Test At Motor ☐				Manual Values

Scenario 2: Unbalance in Impedance and Inductance

	32	21	13	
Resistance (Ohm) OK	17.5	17.5	17.5	0.1237
Impedance (Ohm)	230	232	219	3.50
Inductance (mH)	365	368	347	3.52
Phase Angle (°) OK	68.0	68.2	68.0	0.1275
I / F (%) OK	-40.1	-40.1	-40.5	0.2637
Stator				
Rotor				
Insulation (MOhm) OK	>999	Meg Ohm	TVS	681
Contamination (%) OK	4.54%		Ref Value	
Capacitance (nF)	39.4	nF		
Frequency (Hz)	100		Reference	
Direct Test At Motor ☐				Manual Values

A complete AT5 **Z/φ** test mode shows all parameters are balanced except impedance and inductance. Never draw any conclusion simply based on inductance and/or impedance unbalance alone. In such case, a rotor reposition test should be performed first to determine if the unbalance is due to influence from rotor. Depending on the situation, compensation test may be needed.

Rotor Reposition Test Results – I

The rotor is rotated by 10º from the initial position with the test results shown above.

		32	21	13	
Resistance (Ohm)	OK	17.5	17.5	17.5	0.1238
Impedance (Ohm)		234	227	220	3.01
Inductance (mH)		371	361	350	3.03
Phase Angle (°)	OK	68.0	68.6	68.1	0.3990
I / F (%)	OK	-40.0	-40.3	-40.4	0.1910
Stator					
Rotor					
Insulation (MOhm)	OK	>999	Meg Ohm	TVS	682
Contamination (%)	OK	4.12%		Ref Value	
Capacitance (nF)		39.9	nF		
Frequency (Hz)		100		Reference	
Direct Test At Motor ☐					Manual Values

Rotor Reposition Test Results – II

The rotor is rotated by additional 90º from the last position with the test results shown above.

		32	21	13	
Resistance (Ohm)	OK	17.5	17.5	17.5	0.1216
Impedance (Ohm)		222	224	238	4.46
Inductance (mH)		352	356	378	4.48
Phase Angle (°)	OK	68.2	68.5	68.0	0.2475
I / F (%)	OK	-40.6	-40.2	-39.8	0.4313
Stator					
Rotor					
Insulation (MOhm)	OK	>999	Meg Ohm	TVS	684
Contamination (%)	OK	4.28%		Ref Value	
Capacitance (nF)		39.9	nF		
Frequency (Hz)		100		Reference	
Direct Test At Motor ☐					Manual Values

Summarization of the three tests are shown below,

Shifting Readings Example

Motor Phases	32	21	13	Pattern of Values
Impedance 0°	230	232	219	Med → High → Low
Inductance 0°	365	368	347	
Impedance 10°	234	227	220	High → Med → Low
Inductance 10°	371	361	350	
Impedance 10°+90°	222	224	238	Low → Med → High
Inductance 10°+90°	352	356	378	

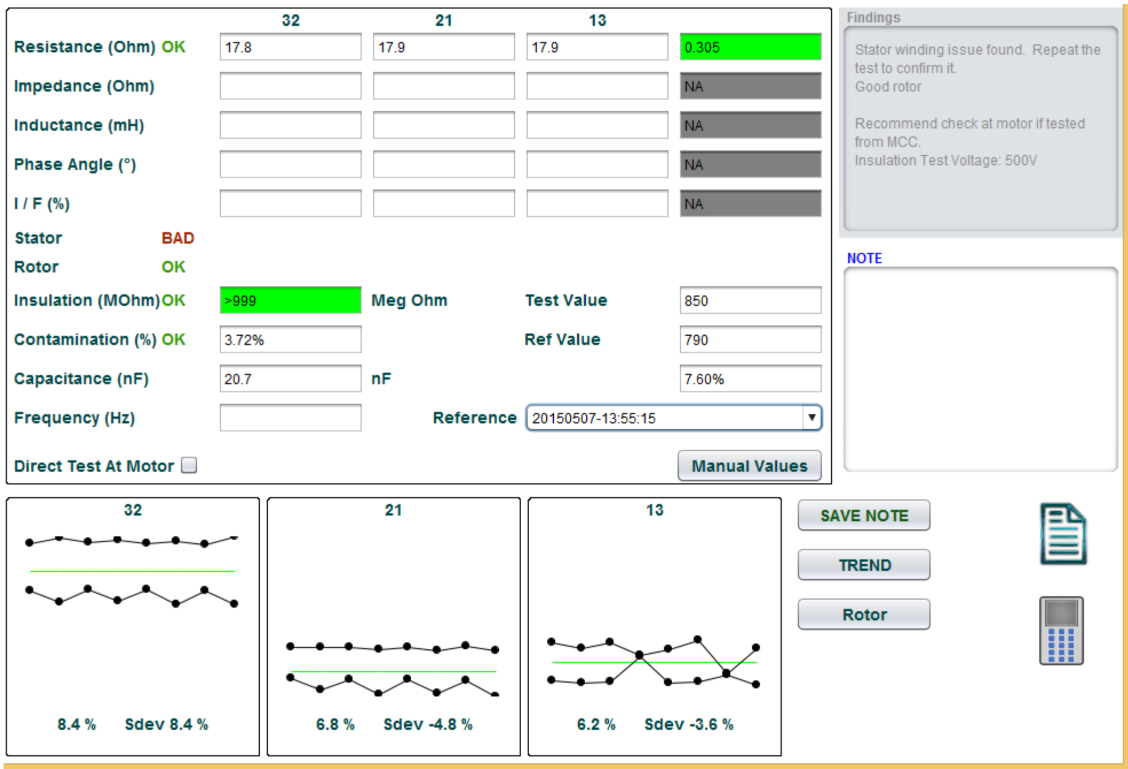
Since the pattern of the three phases' impedance and inductance changes when the rotor shaft is rotated, it means the unbalance comes from the rotor. As an example, a rotor compensated winding test is still performed as shown below.

Rotor Compensated Winding Test Result for Good Windings

		32	21	13	
Resistance (Ohm)	OK	17.6	17.6	17.6	0.0920
Impedance (Ohm)		236	238	239	0.5854
Inductance (mH)		375	377	380	0.5889
Phase Angle (°)	OK	67.9	68.0	67.9	0.0690
I / F (%)	OK	-40.0	-39.9	-39.8	0.1237

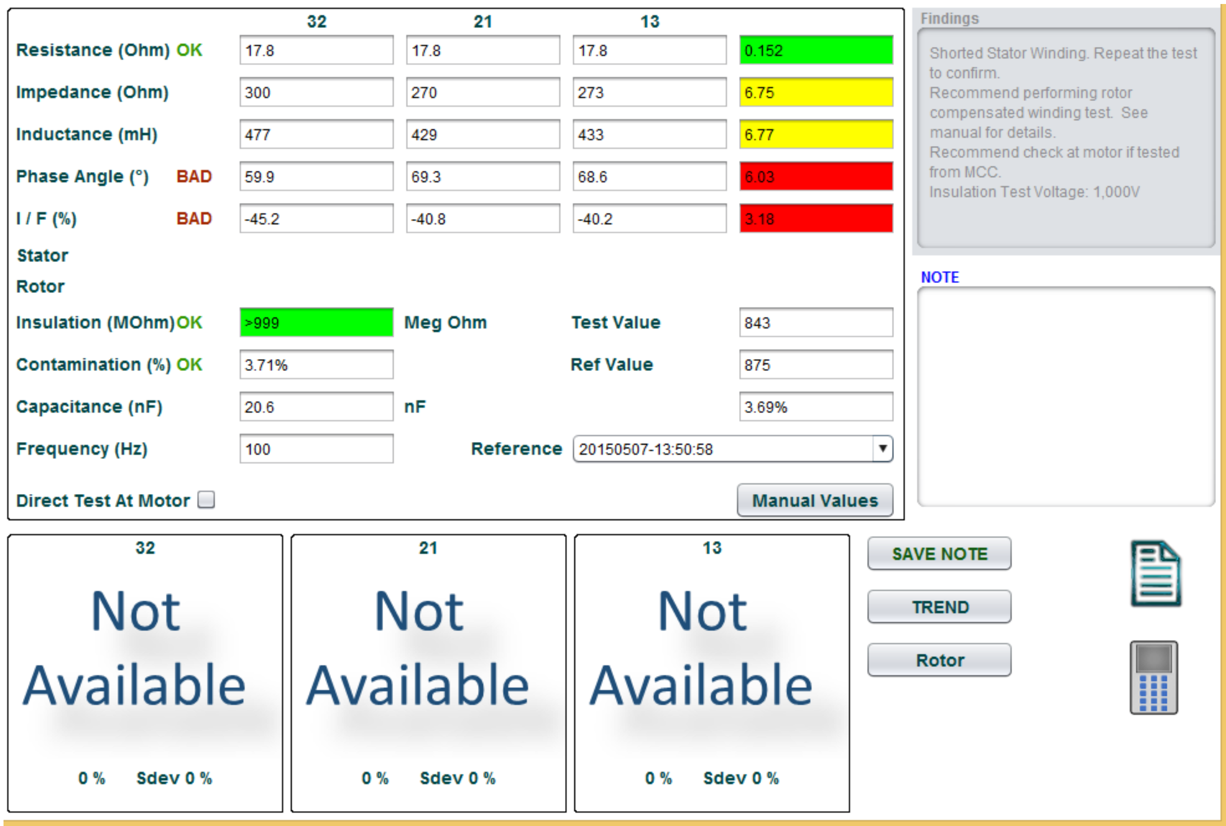
The rotor compensation test results show the impedance and inductance are well balanced. Therefore, it is confirmed the unbalance comes from the rotor influence. **Note:** for rotor compensation test procedures, please refer to AT5 user manual.

Scenario 3: Shorted winding AT33 or AT5 IND Test

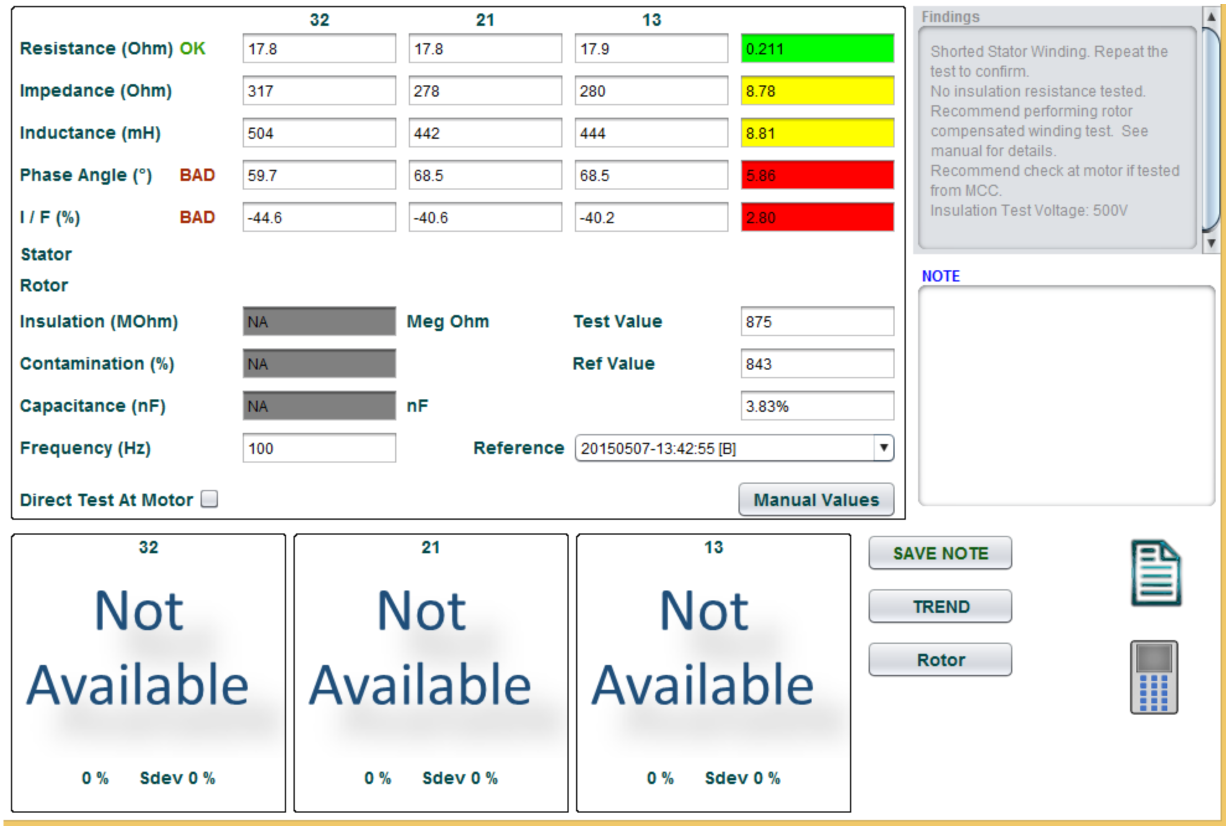


With the AT33 or the AT5 **IND** test mode, the fact that one of the stator signature lines is significantly higher than the other two signatures means the problems are with the stator windings. At the same time, the TVS shows 7.6% deviation from the original reference TVS value, which is also an indication of the shorted winding.

AT5 Z/φ Test

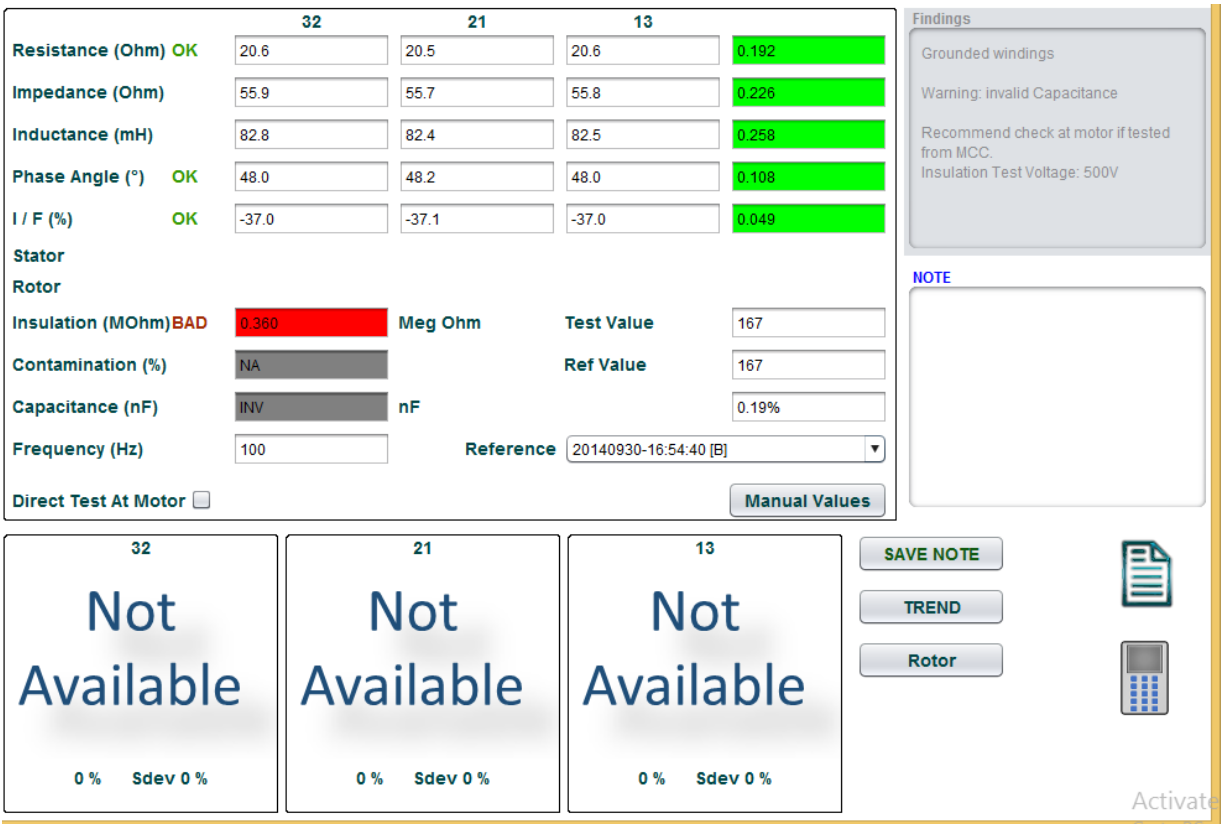


In a similar situation, a full AT5 Z/φ test shows unbalance in Phase Angle and I/F.



If only the **Z/φ** test mode is performed and alarm is provided by Phase Angle and/or I/F, then a rotor compensation test is required. The test above shows the results which confirms the winding is shorted since a rotor compensation test also provides the alarm, i.e. the unbalance in Phase Angle and/or I/F is not due to rotor influence only, but largely from problematic stator windings.

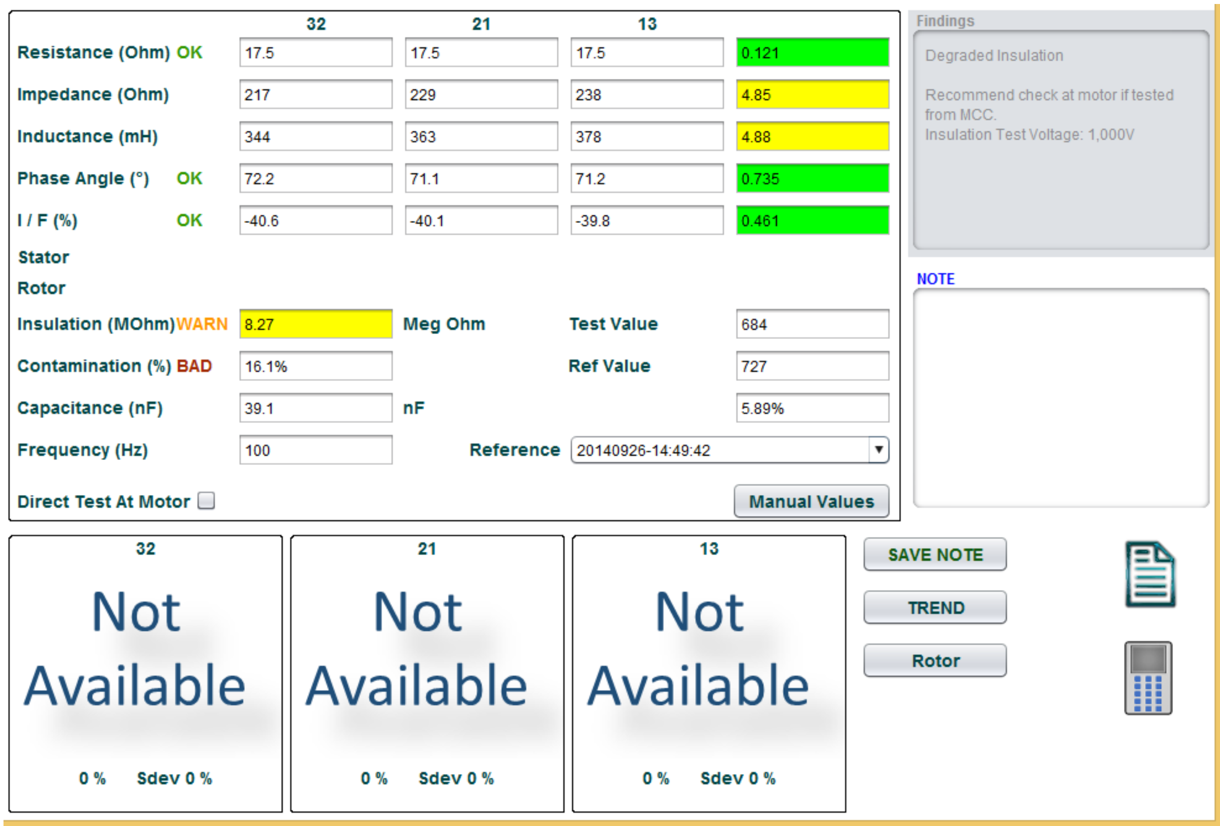
Scenario 4: Grounded Winding while all other parameters are OK



An example of grounded winding test using the AT5 **Z/φ** test mode. Note: *The insulation test diagnostic rule is different between the AT5 and AT33. The insulation resistance diagnostic rule provided in this manual is for AT5. If you are using an AT33 please refer to the user manual for details.*

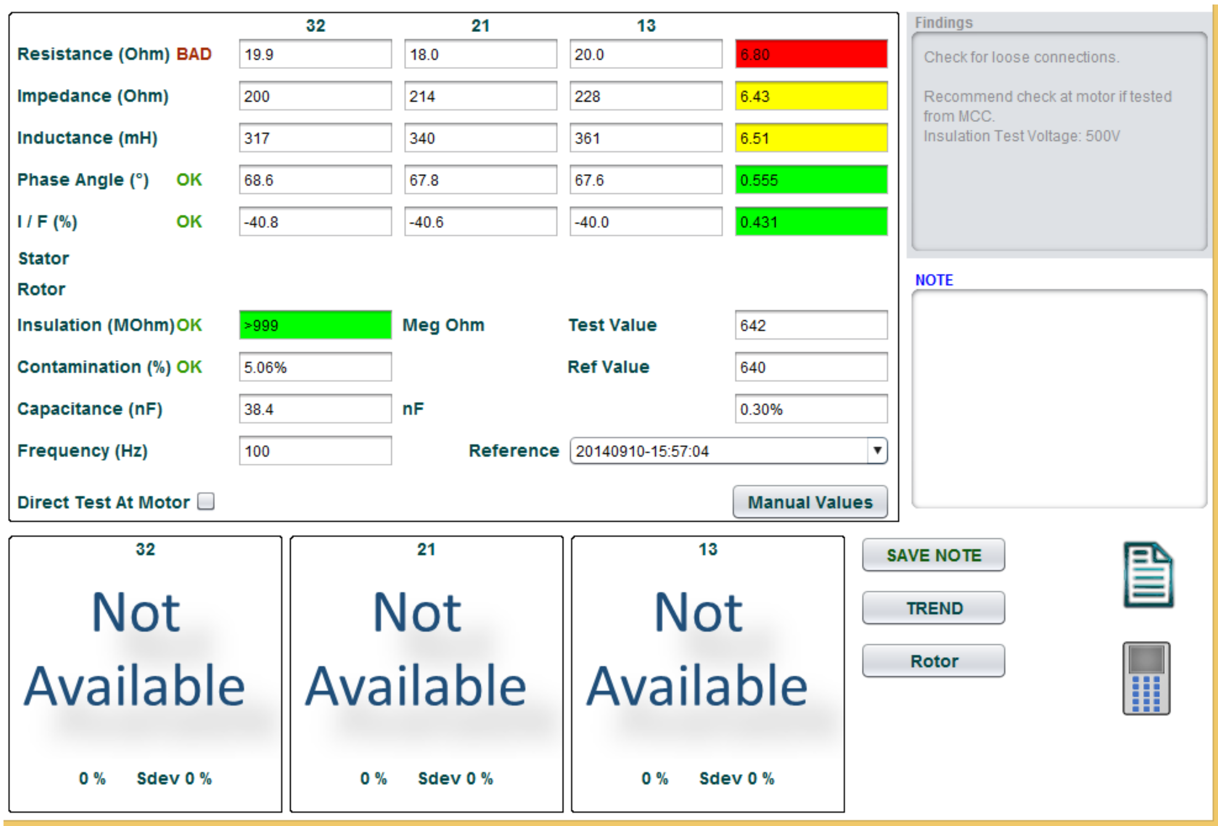
Note: if the user has different insulation resistance test equipment, the measurements and diagnostics can be manually input by clicking on “Manual Values” in the MCA software, which will override the instrument test results.

Scenario 5: Low Insulation Resistance and High Dissipation Factor



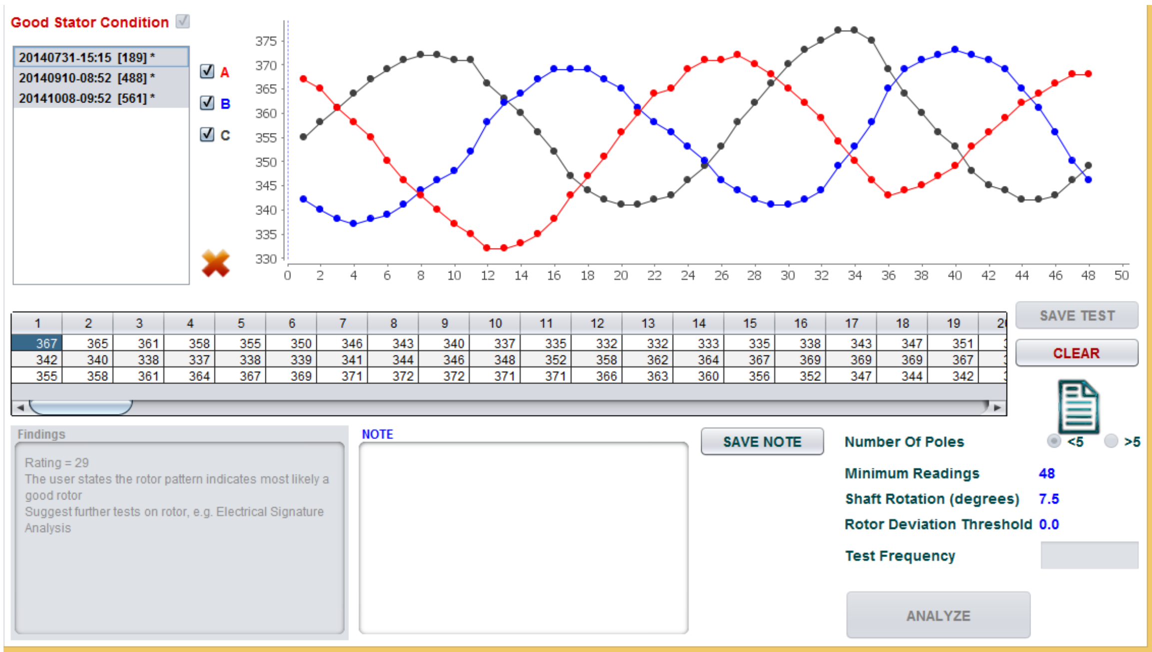
Low insulation resistance combined with high dissipation factor is a strong indicator of the seriously degraded winding insulation.

Scenario 6: Resistance Unbalance

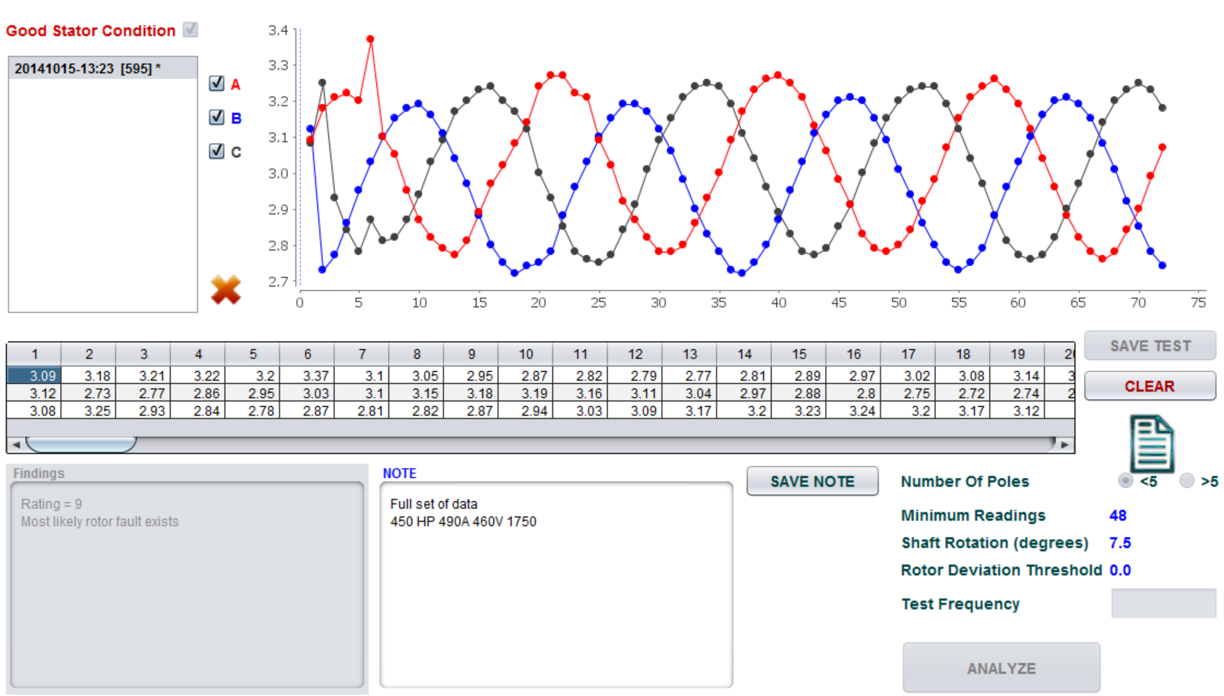


A typical case of resistance unbalance resulting from loose connection which lies in Phase 3 and causes the increase in resistance when measuring Phase 3-2 and Phase 1-3.

Scenario 7: Rotor Test

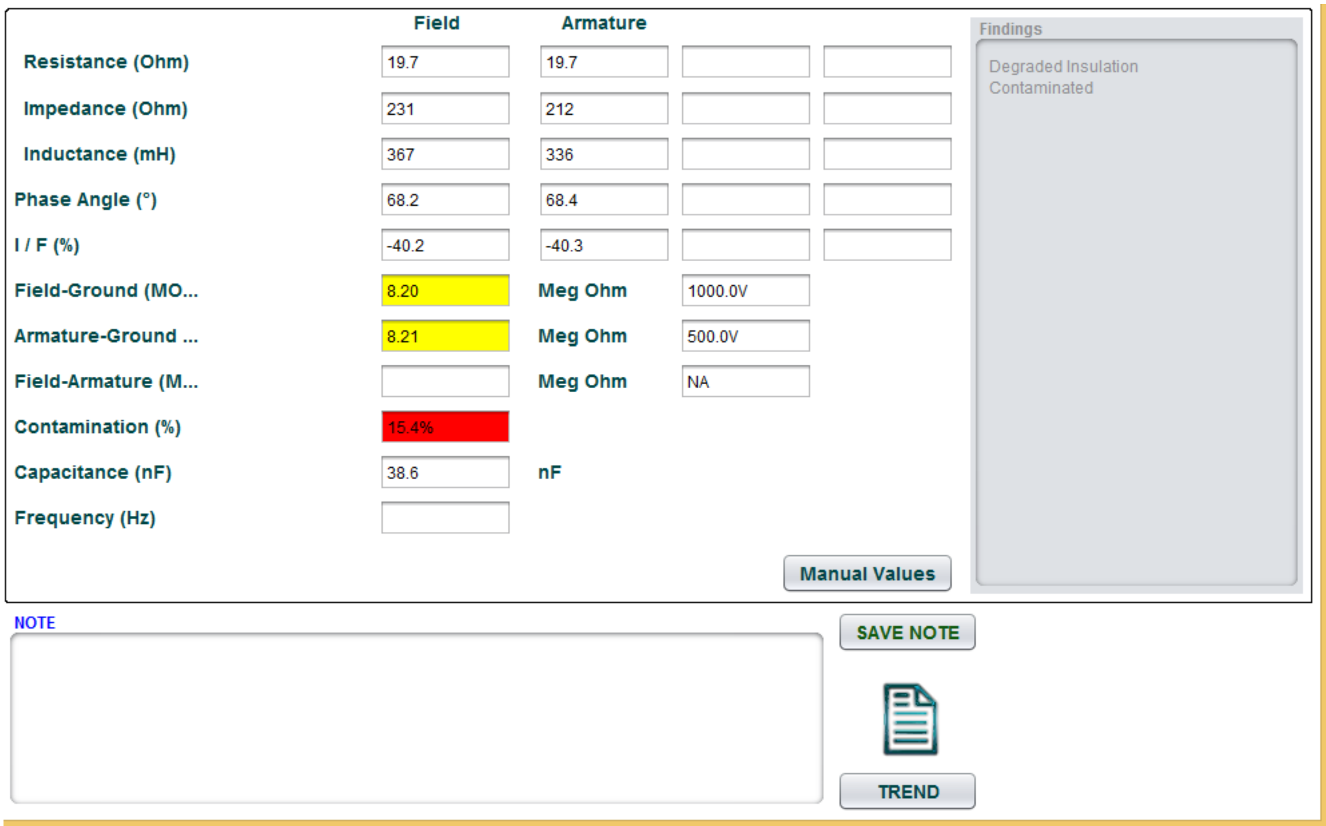


There are two steps for rotor test analysis: the user's input and the analysis performed by the software. The example above shows the case that the user believes the motor is good while the analysis shows there is a likely rotor faults because the three curves are not symmetrical.

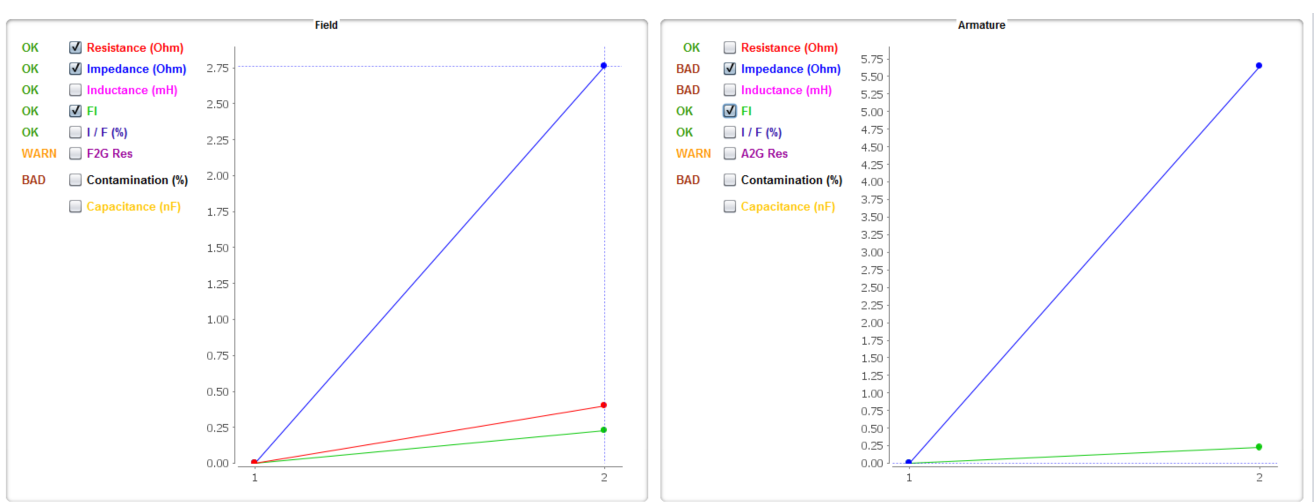


Above is a rotor test example that both the user and the software analysis show the rotor fault exist.

Scenario 8: DC test and Trending



A direct test on a DC series motor. The individual diagnostic are only performed on the insulation resistance and contamination since the theory of phase balance does not apply to DC motor. A useful tool for DC motor diagnostics is the trending, as shown below.



The trending of the armature shows alarms due to the significant increase of impedance and inductance trended over time.

Appendix 2:

Single and Three Phase Transformer Testing; Using Static Motor Circuit Analysis Techniques

Howard W. Penrose, Ph.D (original author)
Edited by ALL-TEST Pro, LLC 2015/2016

Introduction

Field and shop testing of pole and pad mount transmission and distribution (T&D) transformers can be costly and time consuming. With the onset of utility generation deregulation across the country, T&D becomes a greater issue due to varying power demands and power quality. A simple test method for quickly and accurately testing the condition of T&D equipment is a necessity as, if a transformer fails, both the end user and generating facility will complain. Through the use of an existing technology, originally designed for motor winding testing, an initial transformer evaluation can be performed (ATP MCA instrument testing is not intended to replace other industry standard testing including Tan Delta/TTR, etc).

For conceptual reasons, consider that an AC induction electric motor is a transformer with a rotating secondary. In this way, the capabilities that static Motor Circuit Analysis (MCA) provides an electric motor can be extended to a transformer. These include detecting winding shorts, high resistance connections, open windings and insulation to ground fault detection as well as preliminary internal circuit impedance balance. Specific information on the transformer is not required for most applications of MCA because the test equipment is used as a winding comparator.

An MCA device which provides readings of resistance, impedance, inductance, phase angle and a special test called current/frequency response (I/F) has been applied to transformers, for the purposes of this paper. Because the test method is off-line (de-energized), the MCA device generates its own voltage and frequency output. Therefore, the ALL-TEST IV PRO™ motor circuit analyzer (ATIV) was selected (*Editor- ALL-TEST PRO 5 is the recommended replacement for the ATIV*). This unit weighs less than 2 lbs, is handheld, and has a proven track record with AC/DC motors and generators from fractional to over 10 MW (See AT5 specifications to determine if the transformer you are testing resistance, inductance, and impedance is within the testing range of the instrument).

The first set of transformers tested included pole and pad mount transmission and distribution transformers from a few kVA to over 2500 kVA with primary voltage ratings of 480 Volts to 28.8kV. Following initial testing and analysis, procedures were developed to allow for general testing of any type of pole and pad mount transformer with a simple resistance greater than 0.001 Ohms. The results included the capability of testing the primary and secondary of any type of transformer in about 5 to 10 minutes (after proper grounding procedures are followed).

Basic Transformer Concepts

To understand the basic concepts of a transformer, we shall start with an "ideal transformer," or a theoretical transformer that has no losses. The purpose of the transformer is to convert one level of voltage and current to another level of voltage and current for distribution and application purposes. This is achieved by having a primary winding located close to secondary winding and allowing for mutual induction to occur between the windings.

When a sine-wave voltage is applied to the primary windings a magnetic field is established that expands and contracts based upon the applied frequency. This field interacts with the secondary winding producing a voltage within the secondary that is directly proportional to the turns ratio, while current is inversely proportional to the turn's ratio.

Equation 1: Voltage Turns Ratio

$$N1 / N2 = a$$

Where N1 is the number of turns in the primary and N2 is the number of turns in the secondary

Equation 2: Current Turns Ratio

$$N2 / N1 = 1/a$$

For example, an ideal transformer with 100 turns in the primary and 50 turns in the secondary, with 480 Volts applied to the primary and a 100 amp load on the secondary would have: a voltage turn ratio of 2; a current turn ratio of ½; a 480 V_1, 50 A_1 load reflected on the primary and a 240 V_2, 100 A_2 load on the secondary.

Equation 3: Load Impedance

$$Z_L = V_2 / I_2$$

Equation 4: Equivalent Primary Impedance

$$Z^1{}_L = a^2 Z_L$$

Equations 3 and 4 can be used to reference the impedance from the secondary to primary. This can also be used inversely. Internal impedance can be matched to load impedance as found in Equation 5.

Equation 5: Internal Impedance

$$Z_S = a^2 Z_L = Z^1{}_L$$

In a "real transformer" there are certain losses, including core losses (hysteresis and eddy-currents), the magnetizing current, and leakage. In addition, supply voltage and load currents may have harmonic loads and other issues that would impact the effectiveness of a transformer. The purpose of static MCA is to reduce or eliminate these issues to isolate transformer testing.

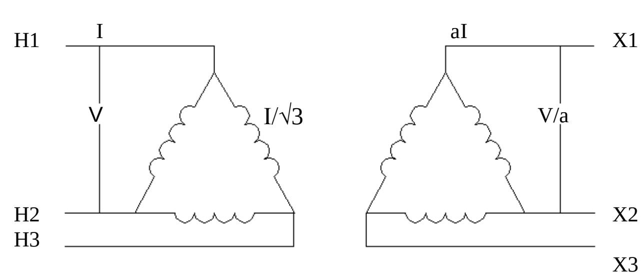
Transformer Types and Connections

Transformers of both single and three phase have a variety of connection types for a variety of loads. In a three-phase circuit, these connections are: Wye-Delta; Delta-Wye; Delta-Delta; and Wye-Wye. Single-phase, pole mounted transformers normally have a single-winding primary with a two-winding or center-tapped secondary.

Three phase transformer connections are developed for a variety of applications:

1. Delta-Delta: Lighting and power applications, normally used when power loads are greater than lighting loads.
2. Open-Delta: Lighting and power applications, used when lighting loads are greater than power loads.
3. Wye-Delta: Power applications, used when stepping power up in voltage (i.e.: 2400 to 4160 Volts).
4. Wye-Delta: Lighting and power applications.
5. Open Wye-Delta: Will allow 57% capacity if one phase is disabled.
6. Delta-Wye: Normally provides a 4-wire on the secondary which allows for balanced single-phase loads between neutral and each phase.

Figure 1: Delta-Delta Transformer



Three phase transformer connections are labeled H1, H2, and H3 on the primary and X1, X2, X3, with X0 as the neutral, on the secondary.

Figure 2: Delta-Wye Transformer

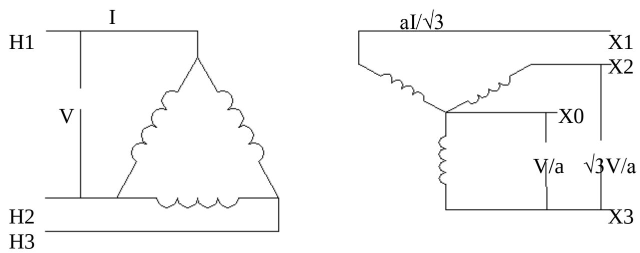


Figure 3: Wye-Delta Transformer

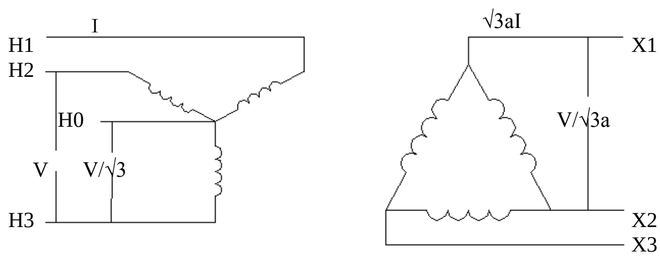


Figure 4: Wye-Wye Transformer

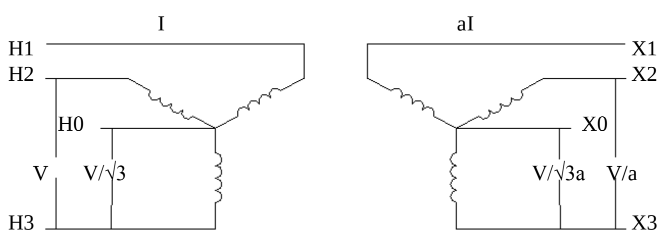


Figure 5: Delta-Wye Transformer Connection

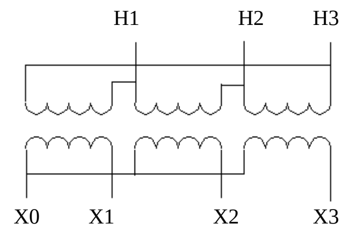
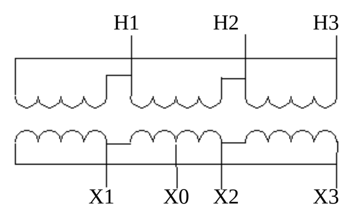
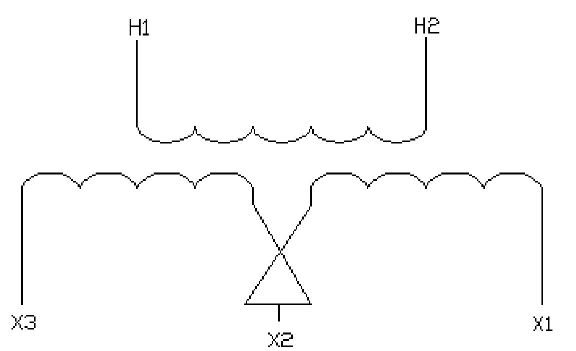


Figure 6: Delta-Delta Transformer Connection



Single-phase pole mounted transformers are often connected and labeled H1 and H2 on the primary and X1, X2 (center tap), and X3.

Figure 7: Single-Phase Transformer Connection



Motor Circuit Analysis Basics

Motor Circuit Analysis (MCA) is used for troubleshooting and pinpointing faults within an inductive or capacitive circuit by using readings of resistance, impedance, inductance, phase angle, current frequency response I/F, and insulation resistance (MCA instruments provide other measurement/calculated values that are not used with tranformer testing). Therefore, MCA is not only applicable to motor testing but also transformer testing. The ALL-TEST PRO 5 static MCA instrument outputs a low voltage, 50 to 800 Hz sinusoidal signal which it then evaluates the response of the device under test. These readings relate as follow:

1. Resistance (R): The simple DC resistance of the circuit.
2. Inductance (L): The magnetic strength of a coil.
3. Inductive Reactance (X_L): The AC resistance of a coil. $X_L = 2\pi fL$
4. Capacitive Reactance (X_C): $X_C = 1/(2\pi fC)$
5. Phase Angle (Fi): The angle of the lag of current to voltage.
6. Impedance (Z): The complex resistance of an AC circuit. $Z = \sqrt{R^2 + (X_L - X_C)^2}$
7. Current/Frequency Response (I/F): Percentage change in current when the frequency is doubled by the instrument, as I = V / Z.
8. Insulation Resistance (Meg-Ohms): Measurement of leakage to ground, ground-wall insulation strength.

When taken as a group, these readings can assist the analyst in determining, first, if a fault exists, then the type of fault. Using the AT5™, these readings can be taken in less than 5 minutes per transformer (after appropriate grounding procedures have been followed). The key to MCA testing is to compare readings between similar windings or transformers and to look at the variations and patterns between phases.

Note: The transformer test option in the instrument AT5 includes the dissipation factor (or contamination) test, however, the DF test is used only for the purpose of comparison between different transformers or trending over the same transformer. While the instrument provides the test results, the diagnostic status of OK/WARN/BAD are only used as a general guideline due to the wide varieties of different types of transformers. Therefore, it should only be used at users' own discretion. The DF test option is not supposed to replace any other DF or tanδ tests for the transformer.

Figure 8: Motor Circuit Analysis Instrument – AT5

Transformer Field Test

The initial set of tests were performed using the same type of procedure that would be used on an electric motor, first for the primary windings, then for the secondary windings. Table 1 represents a sample of one of 30 transformers that were tested over a period of 90 minutes.

Table 1: Initial Transformer Test Data: 2500 kVA Transformer

	Primary			Secondary		
	H1-H2	H1-H3	H2-H3	X1-X2	X1-X3	X2-X3
Resistance	258.5	48.45	153.3	0.198	0.125	0.132
Impedance	15633	11028	11035	566	411	420
Inductance	24878	17552	17562	902	655	669
I/F	-50	-23	-18	-44	-46	-44
Phase Angle	9	90	90	90	85	90
Meg-Ohm	>999			>999		

An issue that became immediately apparent was the unusual and extremely unbalanced readings. All of the tests identified similar results and it was also noticed that resistance varied from test to test and that the impedance and inductance changed from test to test. Upon evaluation of these phenomena, two theories were developed:

1. The sinusoidal voltage output of the instrument was inducing into the opposite set of windings resulting in reflected impedance and inductances that would increase during each test because of a resulting static charge.
2. Electro-Magnetic Interference (EMI) from surrounding operating equipment, transformers, lighting, etc. would cause stray currents because the transformer windings and core would act as an excellent EMI antennae. This scenario would explain varying resistances from test to test.

To resolve both issues, the connections on the side opposite of the side being tested should be grounded to a proper earth ground. The result was predicted to shunt all induced currents direct to ground resulting in the ability to fully test just the winding being tested. This would also allow for tighter testing tolerances. The results are found in Table 2 and test time remained under 5 minutes per transformer.

Table 2: Final Transformer Test Data: 2500 kVA Transformer

	Primary			Secondary		
	H1-H2	H1-H3	H2-H3	X1-X2	X1-X3	X2-X3
Resistance	3.703	3.623	3.648	0.103	0.100	0.096
Impedance	220	217	218	15	14	14
Inductance	87	86	86	2	2	2
I/F	-49	-49	-49	-48	-48	-49
Phase Angle	88	88	88	75	75	75
Meg-Ohm	>999			>999		

These results were found to be repeatable in all cases. Transformers that tested bad tended to have drastic variations in readings.

Table 3: Shorted Transformer

	Primary			Secondary		
	H1-H2	H1-H3	H2-H3	X1-X2	X1-X3	X2-X3
Resistance	116.1	98.2	48.5	0	0.005	0.005

Impedance	4972	1427	2237	0	1	1
Inductance	7911	2267	2237	0	0	0
I/F	-33	-29	-29	0	-20	-20
Phase Angle	23	21	20	0	5	5
Meg-Ohm	>999			>999		

It was found that the 500 kVA transformer had a shorted primary with damage between the primary and secondary windings.

<u>Transformer Testing Procedure</u>

The results of the study produced simple test procedures for both three-phase pad and single-phase pole mounted transformers. The key to testing any type of transformer is to ground all of the leads on all of the connections of the winding opposite of the winding being tested.

A good transformer should have unbalances less than:

1. Resistance: No more than 5% unbalance (<3%?).
2. Impedance: < 5% unbalance
3. Inductance: < 5% unbalance
4. Phase Angle: No more than 1 degree between phases
5. I/F: No more than 2 digits difference and the readings should fall between –15 and –50.
6. A "shift" in readings should be flagged for further testing or trending. For instance, a winding that tests as I/F: -48; -48; -46 and Phase Angle: 70^{o}; 70^{o}; 69^{o}, should be checked further.

Normally, a winding is beginning to experience inter-turn shorts when the Phase Angle and I/F begin to shift. A corresponding unbalance in inductance and impedance indicates a severe fault. A change in Phase Angle with a fairly balanced I/F normally indicate a phase short.

The basic steps for three phase transformer testing are as follow:

1. All of the leads on the side opposite of the side being tested must be firmly shorted together with a comparable wire size of the transformer being tested. Battery cables with clamps are suitable for doing this. Using too small of a wire (like a #10AWG with alligator clips) will give false readings. The wires that are shorted together should be solidly attached to a known Earth ground.
2. Test the primary from H1, H2, and H3 using the AT5 **Z/φ** [Transformer] test mode. Then "retest" to verify that the readings are repeatable. If they are not repeatable, check the ground and continue.

3. Save the results and check condition.
4. Test the secondary from X1, X2, and X3 using the same test mode from the primary side. Be sure that the primary side is shorted together and solidly attached to a known Earth ground. Then "retest" to verify that the readings are repeatable. If they are not repeatable, check the ground and continue.
5. Save the results and check condition.

Single-phase transformers are tested in a slightly different manner and require a known reading for the single phase winding to be used as a point of comparison, such as with a similar transformer or a past test on the same transformer. The basic steps for single phase transformer testing are as follow:

1. All of the leads on the side opposite of the side being tested must be firmly shorted together with a comparable wire size of the transformer being tested. Battery cables with clamps are suitable for doing this. Using too small of a wire (like a #10AWG with alligator clips) will give false readings. The wires that shorted together should be solidly attached to a known Earth ground.
2. Test the primary from H1 to H2 by using the MAN [1-Phase] test mode. Then "retest" to verify that the readings are repeatable. If they are not repeatable, check the ground and "retest."
3. Save the results
4. Test the secondary from X1 to X2 using the same test mode from the primary side. Be sure that the primary side is shorted together and solidly attached to a known Earth ground. Then "retest" to verify that the readings are repeatable. If they are not, then check the ground and "retest."
5. Save results
6. Test from X2 to X3, then save readings. Compare the second and third reading to each other and the first reading to a standard.
7. Save results and check condition.

These procedures can be used on three phase pad mount and single-phase pole mount transformers regardless of connection type.

Conclusion:

Motor Circuit Analysis techniques provide an excellent method for analyzing the primary and secondary windings of both three-phase pad and single-phase pole mounted transformers. A simple procedure incorporating grounding the side opposite of the side being tested allow for very accurate test results. Measurements of resistance, impedance, inductance, phase angle, current response and insulation resistance can be compared for troubleshooting purposes and measurement patterns for pinpointing faults.

Test equipment required for MCA testing transformers must have the following capabilities:

1. Resistance, impedance, inductance, phase angle, I/F and insulation resistance in engineering units.
2. Sine-wave voltage output in a variety of frequencies.
3. Onboard memory with software to upload and download readings.

4. Cost effective and accurate.

The procedures described require about five minutes per transformer with greater than 99% test result accuracy.

Bibliography

Sarma, Mulukutla S., Electric Machines: Steady-State Theory and DynamicPerformance, PWS Publishing Company, 1994.

Nasar, Syed A., Theory and Problems of Electric Machines and Electromechanics, Schaum's Outline Series, 1981.

Edminster, Joseph, et.al., Electric Circuits Third Edition, Schaums Electronic Tutor, 1997.

Hammond, et.al., Engineering Electromagnetism, Physical Processes and Computation, Oxford Science Publications, 1994.

US Department of Energy, et.al., Keeping the Spark in Your Electrical System, US DOE, October, 1995.

Penrose, Howard W. Ph.D, "Static Motor Circuit Analysis: An Introduction to Theory and Application" IEEE Electrical Insulation Magazine, July/August 2000, p. 6.

Appendix 3:

Synchronous Machine Testing With ALL-TEST Pro Instrumentation

Dr. Howard W. Penrose, Ph.D.

Introduction

In order to further understand the application of motor circuit testing and analysis on synchronous electric motors (synchronous machines), it is important to have a brief overview of the operation of a synchronous motor, most common faults, common test methods, how the ALL-TEST IV PRO™ (*Now AT5*) works with large synchronous motors, basic steps for analysis of synchronous stators and rotors, and, expected test results (*Editor- ALL-TEST PRO 5 is the recommended replacement for the ATIV*). In this paper, we will discuss these various aspects, referencing other materials for additional details.

About Synchronous Machines

Large synchronous motors have two basic functions:

- The first is to improve the electrical power factor in a plant. In any plant with large inductive loads, such as motors and transformers, current begins to lag behind voltage (poor power factor). When this becomes severe enough, the plant requires significantly larger amounts of current to perform the same amount of work. This can cause voltage sag and overheating of electrical components. A synchronous motor can be used in such a way as to cause little to no impact on power factor, or can be used to cause current to lead voltage to correct power factor problems.
- The second method of operation is to absorb pulsating loads, such as reciprocating compressors. Once a synchronous motor has achieved synchronous speed, it has coils which 'lock' in step with the electric motor's rotating magnetic fields from the stator. If a torque pulse occurs (such as at the top of a reciprocating compressor stroke), the motor may come out of synch with the rotating fields. When this occurs, a special winding on the rotor called an amortisseur winding (see synchronous construction below) absorbs the energy from the torque pulse, keeping the rotor in synch.

The basic construction of a synchronous motor is straightforward. There are three sets of windings, a stator, a rotor, bearings, and either a generator (brushless) or a 'static exciter' (brush-type). The windings consist of: A standard three phase winding, very similar to a standard induction electric motor; A set of field coils, which are DC coils made of round wire for small machines and rectangular or ribbon wire on larger machines; And an amortisseur winding, which is similar to an induction motor rotor squirrel cage.

The starting methods for both the brush-type and brushless synchronous motors are similar. The starting circuit will be different for both. Following is a description of the basic mode of operation, followed by a brief description of the differences:

During the starting phase of a synchronous motor, it acts much the same as a standard induction motor. The stator receives an electrical current and a rotating magnetic field is developed (the speed = (120 * applied frequency) / # of poles). This field generates a current in the amortisseur winding, which is used to develop starting torque by generating its own magnetic field which interacts with the stator magnetic field in the air gap and causes the rotor to follow the stator magnetic fields. As the rotor starts to catch up to the stator fields, DC current is injected into the rotor field coils, creating north and south magnetic pairs (rotor coils are always found in pairs). These lock in step with the stator magnetic fields and follow at the same speed as the stator fields, whereas a standard induction motor always lags behind.

In a brush machine, the DC source for the rotor fields usually comes from a 'static' (electronic) starter, which converts a supplied AC power to DC. In most cases, the output DC is varied through the starting cycle. The drive may also be set up to short out the field coils of the machine to avoid rotor saturation and the resulting extremely high currents on the stator. Once the rotor begins to turn, DC is supplied to assist the motor in developing torque. The DC voltage is supplied through a pair of slip rings and brushes.

In a brushless machine, a DC generator is installed directly on the shaft of the synchronous motor. As the synchronous motor starts, the generator provides very little DC through its commutator. As the speed increases, the DC voltage also increases, helping the motor generate torque then lock in step at synchronous speed. In this type of machine, the generator is wired directly to the rotor fields.

There are also machines that have a generator mounted on the shaft of the rotor that feeds a separate control. This is used to first short the windings and then control the amount of DC fed to the rotor, just as the brush machine.

Most Common Synchronous Motor Faults

Large synchronous motors tend to be well built and sturdy. They are often overbuilt with material to withstand the severe loads that are applied. The most common failures for industrial synchronous machines, in order, are:

- Bearings due to general wear and contamination
- Rotor fields – due to high temperatures, these will often burn up from the inside out
- Amortisseur windings – mostly in reciprocating loads. Because of the amount of energy absorbed, the winding bars will often crack. In particular if the rotor fields are beginning to fail and short, making it easier for the rotor to fall out of 'synch.'
- Stator windings – general wear and contamination. Stator windings in synchronous machines tend to be 'form wound' and heavily insulated.

Almost all of the winding faults that occur in a synchronous motor start between conductors in the rotor or stator coils.

Common Test Methods, Strengths and Weaknesses

Following are the traditional test methods for evaluating the condition of a synchronous motor:

- Insulation resistance testing: Using applied DC voltages as specified by IEEE 43-2000, a potential is placed between the stator windings and ground. This measures only direct faults between the stator windings and the stator frame. Is also performed through the slip rings on a brush type machine.
- Polarization Index: Is a 10 minute to 1-minute ratio of insulation resistance. This has been traditionally used as a method to gage the condition of the insulation between the stator windings and frame. As with insulation resistance testing, this can also be performed through the slip rings on a brush type machine. As stated in IEEE 43-2000, this test method is only truly valid on pre-1970 insulation systems.
- High Potential testing: Most common on large machines is DC high potential testing which is performed at a value of twice the motor nameplate voltage plus 1000 volts, times the square root of 3. On an existing insulation system, this value is often reduced to 75% of the potential voltage. This test highly stresses the insulation system and is potentially damaging (per IEEE Std's 388 and 389). This type of test should NEVER be applied to the rotor windings of a synchronous motor.
- Surge Comparison testing: Evaluates the turn-to-turn condition of the stator only by comparing the waveforms of two windings when a fast rise time pulse of twice the voltage plus 1000 volts. If there are correctable issues, such as contaminated windings, this test may damage the motor windings.
- Partial Discharge testing: Is a non-destructive test method that measures radio frequencies from discharges in voids within the insulation system of the motor windings. This is effective for trending on machines that are over 6.6 kV and only provide a brief warning from 4 kV. It does not detect any rotor faults.
- Motor Current Signature Analysis: Was designed for rotor testing of induction motors.
- Voltage Drop Test: Requires that the motor is disassembled. A 115 AC voltage is applied to the rotor windings and the voltage drop is measured with a voltmeter across each coil. If there is a short, the voltage drop will vary more than 3%.

The above list does not include equipment for mechanical testing of synchronous motors.

About the ALL-TEST Pro Instrument

The ALL-TEST IV PRO™ (*Editor- ALL-TEST PRO 5 is the recommended replacement for the ATIV)* is a simple electronic instrument that performs in much the same manner as a multi-meter, except that it provides a series of readings that cover the AC parameters of the motor circuit. It is a data collector and tester that sends a low voltage DC signal for simple resistance testing, in the same manner as a milli-Ohm meter, and a low voltage, high frequency AC signal for AC readings. The instrument then measures and calculates test results in engineering units of resistance, impedance, inductance, phase angle, current/frequency response and an insulation resistance test to ground.

The primary differences between electronic testing of power equipment versus traditional power methods are:

- A more complete view of the motor circuit, including influences from changes in the condition of rotor field coil insulation.
- One instrument for a large range of equipment size. The test is limited only to the simple resistance range of the instrument (0.010 Ohm to 999 Ohms).
- Non-destructive – no harmful voltage is applied.
- Easier data interpretation – A few simple rules for data interpretation (See data interpretation below).
- Hand held vs. equipment that may weigh from 40 lbs to well over 100 lbs.
- Internal power source for the instrument.

As an insulation system ages, or if the insulation system is contaminated and it is effecting the integrity of the insulation, the electrical circuit of the motor changes. Because the rotor is an integral part of the circuit, changes to the electrical integrity of the rotor circuit and insulation system are directly reflected through the stator windings, as well. This allows both immediate troubleshooting and long-term trending of the motor.

Unique test information allows the ALL-TEST Pro Instruments to view enough parameters of the insulation system to detect and isolate:

- Shorted stator windings
- Shorted rotor fields
- Broken amortisseur winding bars
- Air gap eccentricity
- Winding contamination (rotor and stator)
- Ground insulation faults

Basic Steps for the Analysis of Synchronous Machines with ALL-TEST Pro Instruments

The steps for testing synchronous machines are similar to those for evaluating the condition of standard induction motors. However, because there are field coils on the motor rotor, a few additional steps are involved when troubleshooting a fault.

When testing a synchronous machine from the motor control center or starter:

- De-energize the equipment. Ensure that secondary sources of power are also de-energized.
- Perform the standard ALL-TEST IV PRO™ (now AT5) tests on the stator following the menu prompts on the instrument.
- Evaluate the test results (See Expected Test Results)
- If a fault is indicated, begin troubleshooting:
  - Adjust the position of the rotor, as much as possible, up to 45 degrees (any movement will do if the rotor is difficult to turn, but no less than 5 degrees)
  - Re-perform the tests and review the readings. If the fault has shifted, or changed by more than a digit, then the fault most likely is located in the rotor.
  - If the fault remains stationary (does not change with rotor position), then disconnect the leads at the motor terminal box and retest. If a fault is still indicated, it is most likely in the stator, if not, it is most likely in the cable.

The average test time, other than troubleshooting, is approximately 3-5 minutes.

When testing a disassembled synchronous machine, it is important to remember that the readings will be very different without the rotor in place:

- Perform the ALL-TEST IV PRO™ Auto test (AT5 **Z/**φ test mode) on the stator and evaluate the test results. This will provide an immediate indication of any faults.
- For the rotor test:
  - Perform the Auto test and compare to a past reading; or,
  - Perform the Auto test and compare to an 'identical' rotor; or,
  - Perform the Auto test across each field coil instead of a voltage drop test.
  - All parameters for all three should meet the evaluation limits.

Because of the style of testing, these results can be trended and compared between like machines.

Other applications for motor circuit testing include evaluation and acceptance, and predictive maintenance.

<u>Expected Test Results</u>

As mentioned in the last section of this paper, the test results are similar to those found in three phase induction machines. Fault patterns are very straightforward and apply regardless of equipment size, within the test range of the ALL-TEST Pro Instruments. Following is a brief overview of the test measurements and their results for basic troubleshooting:

- Simple resistance measurements: Are an indicator of high resistance connections, loose connections or broken conductors in the circuit. This test is important, especially if the resistance problem is in one spot as, based upon I^2R, a resistive spot will put out a great deal of heat energy (in Watts). For instance, a 0.5 Ohm resistance across a point in a circuit that is seeing 100 Amps would give off: ($100Amps^2$)(0.5 Ohms) =

5,000 Watts (5kW) worth of energy. This is about the same energy used to turn 6 horsepower worth of electric motor.

- Inductance measurement: Is an indicator of magnetic strength of a coil and the influence of other coils on one coil. It is impacted by the number of turns in a circuit, the dimensions of the coils and the inductance of other coils. This measurement, by itself, is only a good indicator of the condition of the amortisseur winding and rotor eccentricity. Inductance will only show a shorted winding if it is severe.
- Impedance measurement: Is the measurement of the complex resistance in the circuit. It can be used, much like inductance, for checking the amortisseur winding and rotor condition. However, when used along with inductance, it can be used to detect overheated windings and winding contamination quickly. By viewing the relationship of inductance and impedance between each phase: If the inductance and impedance are relatively parallel, then any inductive and impedance unbalance is in the relationship between the rotor and stator (rotor position); If they are not parallel, this is an indication of an insulation problem such as insulation breakdown or winding contamination.
- Phase angle and I/F (Current/Frequency): Are both indicators of insulation faults between turns in the stator or rotor.
- Insulation Resistance: Evaluates the insulation to ground and will only indicate when the insulation has failed.

The test limit recommendations, as outlined in the "Guideline for Electronic Static Winding Circuit Analysis of Rotating Machinery and Transformers," are as follow:

Table 1: Test Limits (peak-to-peak values)

Measurement	**Limits**
Resistance	5%
Impedance	~ 5%*
Inductance	~5%*
Phase Angle	+/- 1
I/F	+/- 2
Insulation Resistance	> 100 M-Ohms

*Can exceed this value if measurements are parallel.

Following is an overview of the troubleshooting rules:

- Shorted Windings:
  - Shorted windings can be evaluated by viewing the phase angle and I/F readings from the instrument on similar coils or between phases:
  - Phase Angle (Fi) – The phase angle should be within 1 digit of the average reading. For instance, a reading of 77/75/76 would be good because the average reading is 76. A reading of 74/77/77 would be bad.
  - Current Frequency Response (I/F) – The current frequency response should be within 2 digits of the average reading. For instance, a reading of –44/-45/-46 would be good. A reading of -40/-44/-44 would be bad. However, a reading such as -42/-44/-44 should be considered suspect.
- Winding Contamination and Rotor Position
  - The position of the rotor within the electric motor may cause a natural phase unbalance. Winding contamination will also cause phase unbalances. Evaluation of the DF can show if the phase unbalance comes from rotor or contamination.
  - Rotor Position – Rotor position unbalances can be evaluated by looking to see if the inductance and impedance values are fairly balanced. For instance, if there are inductances of 17/18/19 and impedances of values 24/26/29, then the unbalance is due to rotor position. This may also be the case if the inductances are 5/5/5 and the impedances are 8/9/8.
  - Winding Contamination – Can also be found as overheated (burned) windings. These conditions are the result of changes to the insulation due to breakdown of the insulation system.

Conclusion

Through a set of simple rules and instructions, the ALL-TEST IV PRO™ (now AT5) provides an excellent tool for troubleshooting and trending the condition of synchronous machines. The test is performed using simple, non-destructive test measurements that allow for a more complete view of the motor stator and rotor circuit than any other test. Test evaluation is simple and direct, regardless of equipment size or type.

Bibliography

- Guideline for Electronic Static Winding Circuit Analysis of Rotating Machinery and Transformers, BJM Corp, ALL-TEST Division, 2001.
- Penrose, Howard W. Motor Circuit Analysis: Theory, Application and Energy Analysis, SUCCESS by DESIGN, 2001.

Appendix 4:

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Appendix 5:

DC Current Motor Electrical Evaluation Using Motor Circuit Analysis

Howard W. Penrose, Ph.D

Introduction

Electrical testing of Direct Current (DC) electric motors is a challenge within industry, manufacturing and repair centers alike. The key issue has to do with the ability to compare one coil to the next, should exact information not be provided. In this article, the issue of simple tests to increase the confidence of testing and analysis conclusions using Motor Circuit Analysis (MCA) shall be discussed.

The term MCA is derived from a test method that provides information on the basic components of an AC or DC electric motor. These basic components include: resistance, measured in Ohms; impedance, measured in Ohms; inductance, measured in Henries; the induction winding phase angle, measured in degrees; and, insulation resistance, measured in Meg-Ohms. The instrument that will be referred to in this article provides these readings by generating a low voltage, true sine-wave, alternating current (impedance, inductance, phase angle), signal at frequencies from 100 to 800 hertz, a low voltage DC signal for resistance, and 500 or 1,000 volts DC for the insulation resistance test. In addition, a special test called I/F is performed in which the applied frequency is doubled and a ratio results from the change in the winding impedance. This test is introduced to identify early winding shorts that may exist in the winding. Using the applied data, the condition of a DC motor winding can be evaluated through coil comparisons, comparisons to known readings, or by trending changes to the windings over a period of time.

The DC electric motors that will be included in this article are: series, shunt, and compound DC motors. Some of the basic tests described can be performed on permanent magnet, DC servo, DC machine tools, and others (although brushless DC motors are evaluated in a similar fashion to AC motors). The types of DC electric motors can be described by their windings and connections.

DC Motor Theory

Direct Current electric motors operate under a basic principle of electricity: interaction between two magnetic fields positioned at an angle from each other will attract/repel resulting in movement. In the case of a DC electric motor, power is provided to a stator field and an armature creating magnetic fields that are, electrically, about 90 degrees from each other. The resulting attraction/repulsion of the armature from the field generates a torque and the armature turns.

The basic components of a DC electric motor include:

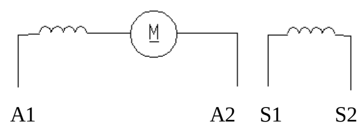
- Frame – Makes up the outer structure of the machine. It is used to mount most of the other components of the motor.
- Fields – Are coils mounted on field pole pieces that generate a stationary magnetic field.
- Interpoles – Are coils that are placed between the field coils that generate a field that is used to prevent excessive sparking of the brushes.
- End shields – Also called bearing housings, are used to house the brushes, brush rigging, and to house the shaft bearings, holding the armature centered in the frame.
- Brush rigging – Holds and positions the brushes above the armature commutator. Usually, a tension device is used to maintain a constant pressure on the brushes.
- Brushes – Are used to provide DC to the armature. The brushes ride on the commutator.
- Commutator – Consists of many copper bars that are separated by mica. Each bar is connected to coils in the armature.
- Armature – Is the rotating portion of the motor that contains coils.

Unlike most AC motors, DC motors require separate power to be provided to both the fields and the armature. The DC provided to the stator fields generate a constant North and South set of fields. DC provided to the armature generates North and South fields that are 90 electrical degrees from the stationary field. As the armature generates a torque and moves towards the appropriate North or South pole, the brushes change position on the commutator, energizing another set of coils 90 electrical degrees from the stationary field. This actually makes the armature an Alternating Current component as the current will travel in one direction, based upon brush position, then in another direction as the motor operates. The brushes are set in such a position that they are electrically "neutral" (no induced current from the stator fields) in order to reduce sparking. In most DC motor connections, by varying the armature voltage, the operating speed may be changed. One general danger that is inherent in DC motors is that if field current is lost while armature current is maintained, the motor may take off and the speed increase until the armature self-destructs.

The three basic winding types that can be used to identify the type of DC motor include:

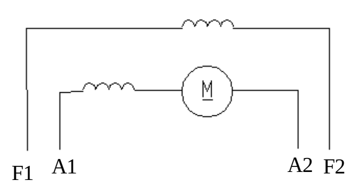
- Series: Normally found in applications that need a high starting torque. They consist of a set of field windings of large wire and relatively few turns, marked S1 and S2, that are connected in series to the interpoles and armature, marked A1 and A2 (See Figure 1). Series connected motors are normally used as traction motors and have a very low basic resistance.

Figure 1: Series Motor



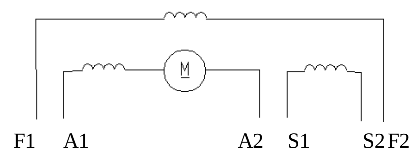
- Shunt: Normally found in applications that require constant speed. They consist of a set of field windings of smaller wire with many turns, marked F1 and F2 for single voltage and F1, F2, F3 and F4 for dual voltage, and A1 and A2 for the interpoles and armature (See Figures 2). Shunt connected motors are normally used as crane and machine tool motors and have a relatively high basic resistance.

Figure 2: Shunt Wound Motor



- Compound: Combine the benefits of both the series and shunt wound motors. They provide a relatively high torque with a basic resistance to a change in operating speed. The connections combine both the series and shunt connections (See Figure 3). Compound motors are the most common and are commonly found in industrial manufacturing.

Figure 3: Compound Wound Motor



As it can be seen, there are few coils to compare to each other in an assembled DC machine. However, procedures can be developed for winding testing that provide a high level of test result confidence.

Common DC Motor Electrical Faults

There are a number of common DC motor electrical faults of which the most common will be described here. These result from issues specific to DC motor design as a result of temperature, friction and internal contaminants such as carbon or graphite.

One of the most common causes of winding faults in a DC motor is from winding contamination from carbon or graphite (carbon) dust from the brushes. The fine powder permeates all of the stationary and rotating windings and will create a path between conductors or between conductors to ground. Carbon is often trapped and problems aggravated further through cleaning and maintenance practices when the carbon is blown with compressed air or the armature is cleaned and baked. In either case, the carbon may become tightly packed in corners, usually just behind the commutator. This will end as a ground fault or shorted turns right at the commutator connection.

Another common fault, that is often not considered, is cooling of the DC machine. This may occur because cooling passages are blocked, the armature is turned too slow with no additional cooling, or from dirty filters (the most common cooling-related fault). Temperature is the greatest enemy of electrical equipment, particularly the insulation system, of which the life will be reduced by half for every 10 degrees centigrade increase in temperature (accepted rule of thumb). As the insulation weakens, its reliability decreases until winding faults between turns occur. In addition to the insulation system degrading, brushes also degrade faster, causing increased wear on the commutator and additional carbon contamination of the windings.

Another fault that is related to heat is generated from practices that have the fields energized with the armature at rest (de-energized). This is a common mode of operation that requires a separate blower to provide cooling to the motor that normally has filters that must be kept clean. This type of fault normally results in shorted shunt coils, reducing the motor's ability to produce torque and may end with the dangerous condition of armature over speed if not maintained properly.

The commutator also provides opportunities for faults, as well as an indicator of motor operation and condition. A properly operating DC motor will have a fine glaze of carbon on the commutator with the bars looking uniform. Burned commutator bars, streaked glazing, heavy carbon, or overheated commutator conditions indicate potential problems that should be addressed.

Armature Testing

DC armatures are the most time consuming but easiest component to test. There are three basic methods that will be introduced: trending; assembled; and, disassembled. In the case of trending, all measurements are used, however, in the case of assembled and disassembled testing a bar to bar impedance measurement will be used. Impedance is viewed because the armature is an AC component and simple resistance measurements may miss some faults including shorts and grounds. Trending will be reviewed in an overall trending procedure for DC motors later in this article.

When testing an assembled DC motor armature, the best method is to perform what's commonly known as a bar-to-bar test using the motor brushes. In the case of a DC motor that has two brushes, none of the brushes needs to be raised, in the case of a DC motor that has four or more sets of brushes, all but two sets 90 degrees from each other need to be raised, which takes them out of the testing circuit. Make sure that good contact is maintained on the commutator by ensuring that 90%+ of the brush is in contact with the commutator bars and that the commutator bars are clean. If they are not clean, polish the armature gently, using an approved method, before testing. If the commutator is badly worn, it will need to be disassembled and the commutator "turned and undercut," in which case a disassembled bar to bar test would be appropriate. Once set, mark the position of one bar on the commutator, then bring the bar to a position where it is just under the leading edge of one of the brushes. In the assembled test, you will probably be covering at least one and a half bars with the brush. Perform an impedance test, mark down the reading, and move the armature so that the leading edge of the brush is over the next commutator bar. Take the next impedance reading and continue until each bar has been tested. A good result will show a consistent pattern, while an inconsistent pattern will identify a poor armature.

Disassembled bar-to-bar testing is similar to assembled testing, other than the armature is out of the frame and the tester has full access to the commutator. In this case, the tester will use an armature fixture or test leads to connect from bar to bar. The spacing between each impedance reading should be constant and about 90 to 180 degrees from each other. The first bar should be marked and testing continues until one leg of the testing fixture or test lead has made it 360 degrees around the commutator. Mark the impedance for each bar-to-bar test then look to ensure that there was a consistent pattern.

Series Motor Testing

Series electric motors are very challenging to troubleshoot as they do not provide sets of fields to compare to. Readings may be taken from S1 to S2 and A1 to A2 then trended over time or compared to other similar machines.

When trending the readings over time, simple resistance readings must be corrected for temperature, usually relative to 25°C. Impedance and Inductance normally has limited change due to temperature while the phase angle and I/F readings will remain constant, regardless of temperature. Variations in the I/F and phase angle will indicate shorted turns, while changes in Impedance and Inductance will normally indicate dirty windings.

Comparing like motors will require additional information. The operator will have to ensure that the motor is of the same manufacturer and design, as well as speed, power, etc. The “model” motor must be new or rebuilt to original manufacturer’s specifications. When performing comparative readings, the testing temperature should be similar from motor to motor, however, the I/F and phase angle readings can be directly compared. These readings should not change more than +/- 2 points for I/F and +/- 1 degree for phase angle. A common error when series field windings are rebuilt, although less common that shunt coils, is an incorrect replacement of wire size, which will impact the ability of the motor to generate torque.

Shunt Motor Testing

Dual voltage shunt motors provide the ability to compare two sets of windings while single voltage motors will have the same test procedure as testing series motor windings, using F1 to F2 as opposed to S1 to S2. With dual voltage, the shunt windings are labeled F1 to F2 and F3 to F4 allowing the analyst to test and compare these two sets of windings.

When testing and troubleshooting the readings over time, simple resistance readings must be corrected for temperature, usually relative to 25°C. Impedance and Inductance will change more than a series wound motor because of the higher simple resistance of the circuit. The phase angle and I/F will remain constant, within 1 to 2 points, regardless of temperature. Variations in the I/F and phase angle will indicate shorted turns, while changes in Impedance and Inductance will normally indicate dirty windings. Comparisons between F1 to F2 and F3 to F4 should be less than 3% in resistance, inductance and impedance and no more than 1 point different in I/F or phase angle.

Like motors can be tested and compared the same as series wound motors. When possible, the motors should be tested, when trending readings, at the same temperature as the previous tests. For instance, within minutes of shutting down operating equipment or before starting equipment, this allows for the tests to be performed at like temperatures.

Compound Motor Testing

In place testing, trending and troubleshooting is much simpler with a compound motor. Single voltage compound motors are normally labeled A1 to A2, S1 to S2 and F1 to F2, dual voltage compound motors are normally labeled A1 to A2, S1 to S2, F1 to F2 and F3 to F4. A key additional point to a compound wound motor is that the series winding is normally wound on top of the shunt winding, allowing for possible faults between these two windings.

Trending a compound motor, the tests are normally taken from the DC drive terminals. Standard MCA tests using the ALL-TEST PRO 5 involve low voltage, higher frequency signals that will not harm the output electronics of the equipment, reducing the need to disconnect the leads from the drive while testing. However, if the analyst wishes to check insulation resistance between the series and shunt windings, the leads must be disconnected from the drive. When trending from the DC drive, test A1 to S2 and the two field leads then perform a 500 Volt insulation resistance test between the S2 and F1 leads and compare to previous tests or similar motors, in either case, insulation resistance readings should remain above 100 Meg-Ohms. As mentioned in series and shunt motor testing techniques, the I/F and phase angle readings should not change more than 1 point between tests, over time, the series and field windings will vary dramatically from each other, however.

Troubleshooting compound motors should be performed at the motor, itself. Disconnect all motor leads and separate them. Test the series and field windings as outlined in the series and shunt winding instructions, then perform an insulation resistance test between the series and shunt windings, the insulation resistance should be greater than 100 Meg-Ohms.

General DC MCA Testing Notes

Several key points can be made using MCA testing on any type of DC motor:

1. Any I/F reading outside the range of –15 to –50, for instance, -56, indicates a winding fault.
2. If the test shows an infinite resistance between leads of the same circuit indicates an open winding.
3. An increase in simple resistance between tests, when corrected for temperature, indicates a loose connection, in particular when impedance and inductance readings change. A reduced simple resistance, when corrected for temperature, may indicate a short, usually accompanied by changes in impedance, inductance, phase angle and I/F.
4. When testing like motors, the I/F and phase angle should not change more than 2 points, any difference greater than this should prompt a full analysis.
5. Changes when testing through the armature circuit should prompt a bar to bar test.

By following these simple instructions, using an MCA device, will allow you to capture early faults long before the equipment fails during operation. If performing tests as part of a predictive maintenance program, the interval should be at least those shown in Table 1.

Table 1: DC Motor Test Frequency

Test Type	Non-Critical	General	Critical
General Maintenance	1 year	6-9 months	3-6 months
Predictive Maintenance	6 months	3 months	1 month
Armature Test	1 year	6 months	3 months

General maintenance tests are those that are not trended over time. Usually accompanied with vibration, bearing greasing, commutator inspection and brush inspection. Predictive maintenance testing normally involves trending readings over time looking to detect potential faults then to determine the best time to remove the motor for corrective maintenance. Once a potential fault is detected, the testing frequency should increase until it is determined that the motor needs to be removed. A complete armature test should be performed either in conjunction with a general or predictive maintenance test due to the high stresses at the commutator and carbon contamination.

Conclusion

General electrical testing of direct current electric motors is made much easier with new techniques available with static motor circuit analysis. For the first time, early turn faults can be detected in series, shunt and armature windings before they take equipment out of operation. Predictive maintenance tests can be performed from the drive with troubleshooting tests being performed at the motor. In general, the tests are relatively quick, requiring less than five minutes per motor for predictive maintenance testing, with additional time required for troubleshooting. Overall, MCA testing dramatically improves DC motor testing over the traditional methods of continuity tests.

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