Static Motor Circuit Analysis: An Introduction to Theory and Application

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With the introduction of modern electronics, advances in electrical circuit analysis, and a close view of basic electromagnetic circuits, methods have been developed to measure the static electrical/electromagnetic properties of rotating machinery. A number of hand-held and portable motor circuit analyzers (MCA) have been introduced to the world market since 1985 providing several methods for viewing the basic properties of rotating machinery electrical components. Analysis methods can include simple resistance and inductance testing through resistance (milli-Ohms), impedance, inductance, phase angle, and more complex proprietary testing methods, taken on rotating equipment that has been de-energized. In the past the test methods had been very complex but are now relatively simple, requiring little training for operation but increased knowledge of electromagnetic circuits for complex analysis.

For the purpose of the analysis results presented within this paper an ALL-TEST IV *PRO*™ 2000 motor circuit analyzer was selected as it provided resistance to one milli-Ohm, impedance, inductance, phase angle, and a special test that measures current response at measured variable applied frequencies. Test voltage and frequencies were applied at less than 10 V RMS, true sine wave, at applied frequencies from 100 to 800 Hz. The electric motors tested were provided at a number of locations and included either planned failures or failures that were first analyzed then investigated using alternate methods. Histories of MCA were analyzed from data collected over a period of approximately 15 years.

Within this paper we shall present the basic theory of analysis on wye and delta connected electric motors, then the results of applied testing on several electric motors. Basic limits of unbalance shall be presented; however, while analysis and research continues, these limits should be considered guidelines and not absolutes as the range of electric motors that can be tested have included fractional horsepower electric motors to machines over 10,000 horsepower, 13.8 kV. The results of the studies presented provide a view of the application of static MCA for testing three-phase induction electric motors. Troubleshooting, reliability, and predictive maintenance have been successfully applied to single-phase motors, direct current motors, generators, and transformers, as well.

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Basic Theory

The concept of static MCA is to provide a simple method for measuring the electromagnetic properties of an electric motor in order to determine the condition of the electric motor as an electrical circuit. For the most part electric motors are tested while assembled, such that the applied testing includes the complete motor circuit (stator and rotor windings) as presented in Fig. 1.

In the past, simple resistance testing or high-impact surge testing were the only accurate methods of testing for turn-to-turn and coil-to-coil faults and weakened interturn insulation problems. The challenges presented were two-fold: simple dc resistance testing could only identify direct shorts or opens in the motor windings and, surge testing provides a potentially destructive high voltage [(2 V + 1,000 V) × 1.44 in new windings]. However, surge testing does provide a view of the ac components of the circuit, in particular the impedance balance of the motor winding.

Accurate electric motor circuit analysis requires the study of ac electrical basics including milli-Ohms of dc resistance, impedance, inductance, and phase angle. As a three-phase electric motor circuit is expected to have three sets of equiva-

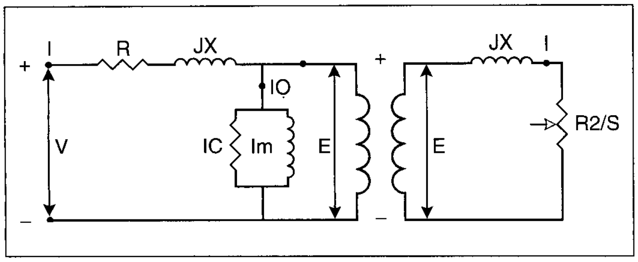

Fig. 1 Three-phase couple circuit.

lent windings separated by 120° electrical, the detection of faults and analysis will include the balance between each circuit (Figs. 2 and 3). For example, a 460 V, 3-phase, 60 Hz, 10 horsepower electric motor has a full load current of 14 Amps; the vectors of voltage and current may appear as in Fig. 4. The resulting expected impedance of each phase measured line to line, assuming balanced input voltage, would be

$$Z_{AB} = {V_{AB}}\Big/{I_{AB}}$$

$$32.9\angle 45^\circ\,\Omega = 650.5\angle 120^\circ\,V\Big/19.8\angle 75^\circ\,A. \tag{1}$$

The resulting impedance is broken down as follows:

$$Z = \sqrt{R^2 + \left(X_L^2 - X_C^2\right)} \tag{2}$$

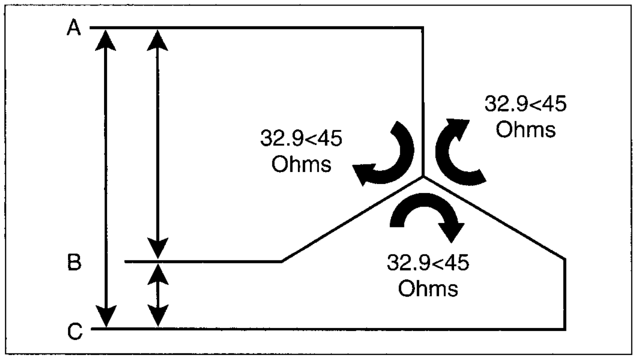

Fig. 2 Wye connect circuit.

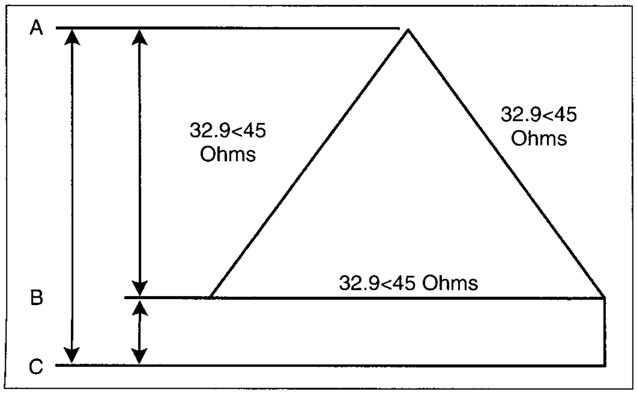

Fig. 3 Delta connect circuit.

$$X_L = 2\pi f L \tag{3}$$

$$X_C = 1\big/2\pi f C. \tag{4}$$

The inductance (L) of the electric motor circuit is directly impacted by a number of factors, including:

- The position of the rotor windings in relation to the location of the stator windings and type of stator winding design.
- The quality of the rotor windings, including casting voids and broken rotor bars, and the position of the rotor windings in relation to the stator windings, such as with an uneven air gap.
- The type of stator windings. A lap wound stator has the windings and phases evenly distributed in relation to the core and each phase. A concentric wound stator will have each phase evenly distributed throughout the core but each phase will be positioned differently in relation to the core. Due to the relationship of the flux path through the core, the inductance of the lap winding should be equal between phases while the concentric winding may have a slightly unbalanced inductance due to the distance of each set of phase windings from the core.
- Mutual and internal inductance between turns. With evenly distributed coils and properly layered turns, the inductance and resulting impedance should be balanced. With shorted turns or coils, the mutual and internal inductance will change causing unbalanced impedance between phases and a change to the phase angle. Insulation defects, such as insulation breakdown and voids, will also have an impact due to changes in the permeance through the defect (will change the concentration of magnetic flux at the defect point; see Fig. 5).

As a direct result of the fact that the inductance between phases in an assembled electric motor will vary, a method must be used to identify potential defects in the rotor or

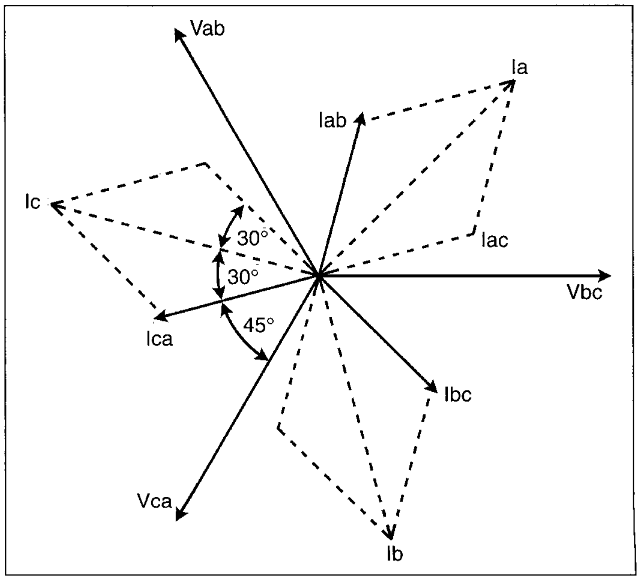

Fig. 4 Good winding balance wye.

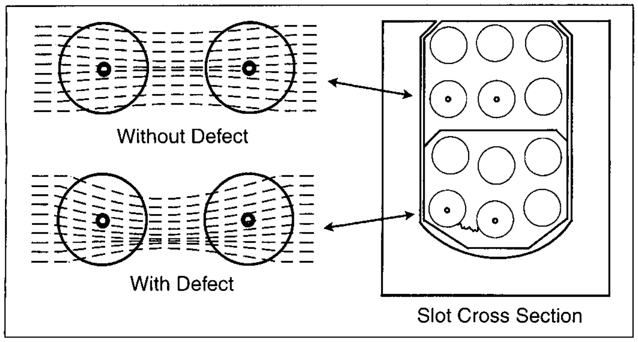

Fig. 5 Turn-to-turn flux interaction.

stator windings. This can be done by setting a phase reference with an applied frequency, then by doubling the frequency and viewing the ratio in each phase, separately. The result will be a true view of the balance between phases (readings are often found in a reduction in the resulting current of between 15 and 50%).

In a winding that has a defect, such as a shorted coil, the phases will become unbalanced (using the same 10 horsepower example. Please note that the wye and delta connection figures are for demonstration only; the impedance values and angles would change otherwise.). For instance, test readings should be found as follows: T1 – T2 = $30\angle 20^\circ\ \Omega$; T1 – T3 = $32\angle 30^\circ\ \Omega$; T2 – T3 = $33\angle 46^\circ\ \Omega$. Basic analysis would indicate a possible short in the phase containing T1.

$$
\begin{aligned}
I_{AB} &= \frac{650.4\angle 120^\circ\ V}{30\angle 20^\circ\ \Omega} = 21.7\angle 100^\circ\ A_{AB} \\
I_{AC} &= \frac{650.4\angle 0^\circ\ V}{32\angle 30^\circ\ \Omega} = 20.3\angle -30^\circ\ A_{AC} \\
I_{BC} &= \frac{650.4\angle 240^\circ\ V}{33\angle 46^\circ\ \Omega} = 19.7\angle 194^\circ\ A_{BC}. \qquad (5)
\end{aligned}
$$

Two things occur at this point:

- The resulting unbalance current causes uneven heating within the electric motor and windings themselves (5% impedance unbalance is similar to 5% voltage unbalance). Should the defect actually be caused by improper distribution of windings, the reliability would be decreased due to a dramatic increase in operating temperature rise (50% at full load) and the thermal impacts on both the windings and bearings.
- In both cases (shorts and improper winding distribution), localized heating will result. The localized heating will have a limit that is directly impacted by the mutual inductance between the energized portion of the winding and the shorted turns as high current will pass through the defect. The expected life of an electric motor due to shorted turns or coils is very short due to the extreme heat generated at the defect point.

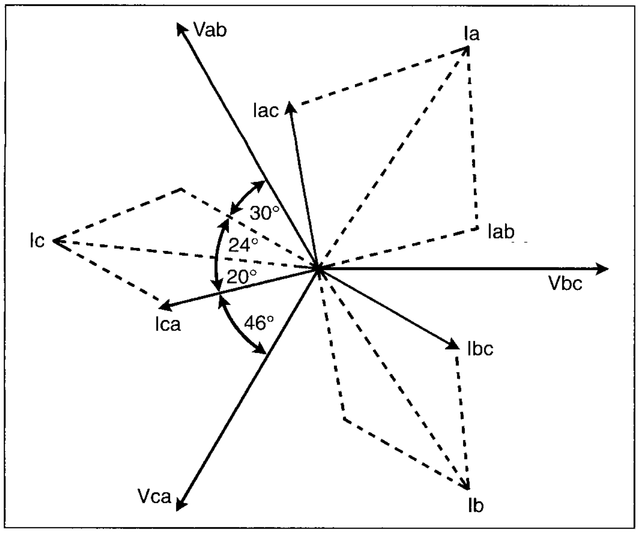

Fig. 6 Defective winding vectors wye connected.

Electric motor rotor windings can be tested by rotating the motor shaft to change the rotor to stator winding position. If readings are evenly spaced (i.e., 1 through 12 o'clock positions), the result will be three sine waves 120° out of phase, which should be similar. Defects in the rotor or airgap will be identified, as a result.

Field Testing Using MCA

A number of electric motors have been tested over time. Three examples using electric motors ranging from 10 horsepower to 200 horsepower will be presented with findings. The motors had planned faults introduced to the windings as part of a study comparing motor circuit analyzers.

200 Horsepower Electric Motor with Rotor Casting Defect

A 200 horsepower electric motor was selected for testing. The motor was reported to have low starting and running torque, which was confirmed with dynamometer testing. Testing was performed first on the windings (Table I), then a rotor inductance test was performed (Figs. 7 and 8).

The winding tests were satisfactory, however, the impedance showed an unbalance that was not directly related to the other readings and the I/F remained equivalent, which called for a rotor test. Once the rotor test was performed, a defect was detected. The rotor defect was determined to be either a casting void or broken rotor bar, which was confirmed on a dynamometer with vibration testing.

10 Horsepower Single Bad Rotor Bar

A 10 horsepower, 1800 RPM electric motor was selected and a single rotor bar opened by drilling the rotor bar at both ends of the rotor. Several test methods were used to detect the rotor problem including: vibration analysis, current

Table I: 200-hp Winding Test

	T1-T2	T1-T3	T2-T3
R	.867	.872	.870
Z	266	264	261
Phase Angle	85	85	84
L	106	105	103
I/F	-47	-47	-4

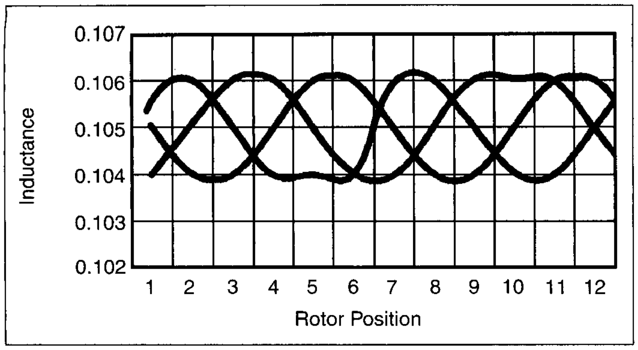

Fig. 7 Bad rotor readings.

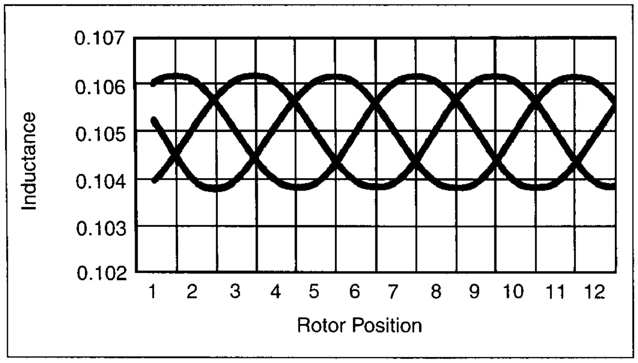

Fig. 8 Good rotor readings.

analysis, and three MCA tests. Vibration and current analysis did not detect the fault as the values were too low and only two of the MCA tests detected the problem. The test instrument used for the study detected the fault both through inductance, impedance, phase angle and the rotor test.

It was noticed that the resistance, phase angle, and I/F (current response when applied test frequency doubled) remained constant while the inductance and impedance changed dramatically, as was expected. As two of the three MCA units tested this failure as a severe problem, a comparison was performed on the MCA units. It was determined that the output of the two units that detected the failure used true sine waves, while the third used square wave pulses. This also explained why comparison testing performed between the MCA instruments at an Illinois based motor repair shop showed greater accuracy in the sine-wave output instruments overall. The other instrument did not determine impedance, phase angle, nor had an equivalent test to I/F.

Table II: 10 Horsepower with Bad Rotor Bar

	T1-T2	T1-T3	T2-T3
R	1.511	1.533	1.535
Z	168	280	265
Phase Angle	81	80	80
L	66	55	52
I/F	-44	-44	-44

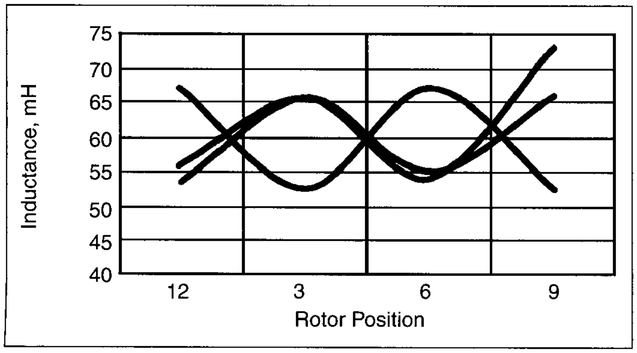

Fig. 9 Horsepower rotor test.

10-hp Delta Connected Motor with Broken Wire

A 10 horsepower delta connected electric motor was set up with a single broken wire. Each coil had three wires per conductor. A single wire in one conductor was cut at the beginning of the stator coils in one phase.

All of the readings had shifted slightly, in this case. The simple resistance was greater than 10% unbalanced. This value should be less than 5% unbalanced. In this case, due to the shift of all of the readings, it was determined that one of the wires between T1 and T3 at T3 was damaged.

Testing Limits

An EPRI study indicated that 53% of electric motor failures are due to mechanical means, while 47% are due to electrical problems (10% rotor and 37% coil failures). Motor circuit analysis provides a unique method for determining and trending electrical failures. As part of the consideration for trending and failure analysis, recommended limitations for electrical unbalance need to be set. The following unbalance recommendations are for reference and are based upon 15 years worth of data. Further study and analysis is in progress.

Inductance test limits are found in the *E-Source Drivepower Manual*, chapter 12. During the course of our study, we were unable to determine whether these limits were conclusive or not. Because of the various designs of electric motor windings and rotors, we have determined that inductance measurements alone for troubleshooting are arbitrary.

Impedance measurements were found to be far more accurate in detecting winding and rotor faults. Where reliabil-

Table III: 10 Horsepower with Broken Wire

	T1-T2	T1-T3	T2-T3
R	1.162	1.157	1.273
Z	156	154	154
Phase Angle	74	74	75
L	31	30	30
I/F	-42	-43	-43

Table IV: Testing Reference

Test	Good	Poor	Failure
Inductance	<5%	<15%	>15%
Impedance	<1%	2%	>5%
I/F	0	+/-1	>2

ity measurements are concerned, per Ohms Law (I = V/Z), voltage and impedance unbalance are similar. In cases of troubleshooting, as can be evidenced in the delta connected 10 horsepower fault, where one wire was broken, the impedance unbalance was under 1%. Therefore, impedance testing alone can be considered arbitrary.

I/F readings were found to be an excellent indicator of whether a fault was due to the stator or rotor windings. A significant sampling of motor winding failures have indicated that I/F readings that show variations between coils of greater than 1 point of I/F will indicate early signs of failure and can accurately detect single turn insulation breakdown in electric motors from 25 horsepower and up.

Conclusions

The findings of the MCA study indicate that a combination of testing measurements are required in order to detect and determine winding faults. It was found that simple measurements of just resistance or inductance alone are extremely anomalous while a complete combination of standard engineering measurements of resistance, impedance, phase angle, and inductance provide a highly accurate view of the electric motor condition. The addition of a test that allows the analyst to determine whether faults are rotor or winding related allows for an excellent method for testing electric motors in an industrial or commercial environment. In the case of the testing methods used, all units could be used to detect potential faults from the nearest motor control center or disconnect within the instrument's accuracy. All of the instruments provided a nondestructive and intrinsically safe method for testing the electric motors using a low-voltage higher frequency signal. Test output (sine wave), portability, and accuracy are all important aspects of MCA.

While MCA has been available for over 15 years, more research is required and is presently underway. FEA and Tubes and Slices analysis combined with field studies have been used to determine testing reference limits. However, it has been determined that a basic understanding of the motor circuit and trending readings over time provide the best method of determining electric motor condition.

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Dr. Penrose has 15 years in the electric motor and service industry leading PdM and Root-Cause-Analysis initiatives in a large variety of commercial and industrial locations from steel and commercial buildings to power plants and agriculture. Starting as an Electric Motor Repair Journeyman on aircraft carriers in the US Navy to research into energy efficient electric motor systems and reliability, Dr. Penrose has repaired, troubleshot, retrofitted, installed, or researched a broad variety of systems that are, or will be, used in industry. He has also consulted to the US Department of Energy, various state energy programs, engineering firms, and the Canadian Electrical Association concerning electric motor systems, repair and reliability.

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Mr. Jette has over 18 years of hands-on electromechanical and electronic testing and repair experience both in repair shops and in the field. His experience includes pumping systems, technical support, and motor testing for industries from marine to wastewater and from chemicals to mining. Mr. Jette developed the testing and submersible pump quality control programs for BJM CORP since 1994.

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