

Evaluation of Electric Motor Condition Using Motor Circuit Analysis

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Abstract: Winding field evaluation of new, repaired or in-process electric motors has traditionally required expensive equipment and extensive equipment and instrument knowledge. Research into advanced motor circuit analysis techniques have allowed analysts to view and determine electrical condition and faults that are relative regardless of motor size and manufacturer. Motor circuit analysis methods for three phase induction motors and cases will be presented in this paper.

INTRODUCTION

Motor Circuit Analysis (MCA) instrumentation is a relatively recent technology (dedicated MCA instrumentation has been available since the mid-1980's). Technological innovations have made such instrumentation portable and hand-held through the 1990's.

The concept of MCA technology is the application of a relatively low amount of energy with amplified responses in electrical terms. These responses allow the analyst to evaluate the condition of both the windings and rotor through comparative readings, either trended or phase to phase.

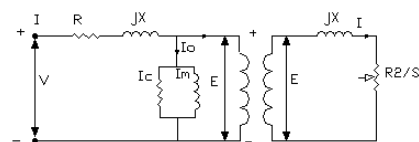
The data provided within this paper represent the output from a specific MCA device, the ALL-TEST IV *PRO*™ 2000 (ATIV), which provides resistance, impedance, inductance, phase angle, current/frequency response (I/F) and insulation resistance readings. This data can be used to provide detailed information on the condition of an electric motor winding and rotor with very little training. Winding unbalances, in assembled equipment, can be determined by how the data relates between phases without having to rotate the motor shaft. As a result, machine tool equipment, compressor motors, and similar equipment can be evaluated without having to uncouple the motor.

MOTOR CIRCUIT

The basic motor circuit, as represented in Figure 1 (one phase of three phases), provides a

representation of winding resistances, impedances, capacitance (between conductors and to ground), inductances (mutual and internal), and, when an AC signal is applied, phase angle.

Figure 1: Per Phase Circuit Diagram



Each phase should be separated 120° electrically from each other. This allows the development of a rotating magnetic field within the stator as the incoming power increases then decreases the north and south electrical poles.

Figure 2: Stator Field



The rotor is made up of a series of bars (aluminum or copper alloy) shorted at either end with a shorting ring.

Figure 3: Rotor Cage



The stator rotating magnetic fields interact with the rotor bars. As a magnetic field is passed over the bars, they induce a current flow that generates a second magnetic field.

Figure 4: Rotor Interaction



Both the rotor and stator magnetic fields interact in the air gap between the rotor and stator.

When an electric motor is started, the fields within the rotor are at line frequency (ie: 60 Hz), which causes a high current within the rotor which is reflected back through the stator windings. As the rotor comes up to speed, the frequency drops and the operating current drops until the motor operates at the load speed (ie: the heavier the load, the more the rotor reduces speed, causing a change in rotor frequency resulting in higher stator current).

In a theoretical motor, all three phases of the stator are electrically balanced and the rotor is free of rotor bar faults and located centered within the motor air gap. In reality, this is normally not the case. The purpose of MCA is to provide a means to determine the variations within the motor, identify defects that would hamper the motor's mission, and to assist in pin-pointing those defects.

APPLICATIONS OF MCA

Motor Circuit Analysis has any number of applications. From evaluating motors in the manufacturing process, verifying condition upon receipt of new or rebuilt motors, to evaluating existing electric motors and root-cause-analysis investigations. MCA devices can be used from a Motor Control Center or disconnect, or right at the motor terminations.

During the manufacturing or rebuilding process, the objective is to identify defective motors, or motors that have correctible defects prior to application. For electric motors in service, the

objective is to provide accurate and repeatable readings that can be trended in order to avoid unplanned outages. Within this paper, we shall review several case studies depicting these purposes.

CASE 1: NEW MOTOR PHASE UNBALANCE

A 50 horsepower, 3600 RPM, delta connected electric motor was installed and rotation checked on a generator cooling pump motor. When the motor was brought online, there was an 11% (p-p) current unbalance with a less than 0.5% (p-p) voltage unbalance. The motor had a 120Hz vibration (electrical) and an excessive operating temperature, although the peak current was under the nameplate full load value.

An MCA meter was used to determine the phase unbalance, with results of 000, -016, and -016 (% unbalance) phase to phase when the rotor was shifted to the peak unbalance on each phase. Two consecutive motors of the same model and similar serial numbers were selected for review and tested using both the ATIV and individual bridges of different manufacture for impedance and inductive unbalance. The resulting phase unbalances and rotor tests were evaluated.

Table 1: Phase Unbalance Test Data

	T1-T2	T1-T3	T2-T3
Resistance	0.163	0.175	0.168
Impedance	30	49	44
Inductance	6	9	8
Phase Angle	77	77	77
I/F	-44	-44	-45
Insulation	>99M		

Figure 5: Inductive Unbalance/ Rotor Test

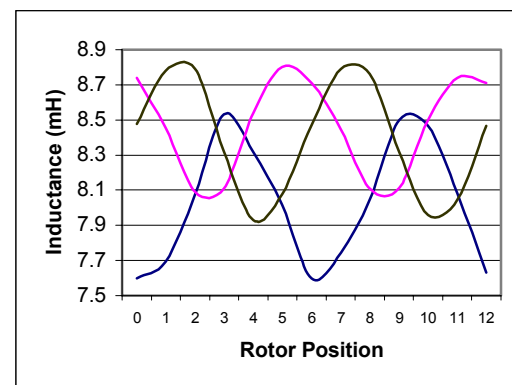
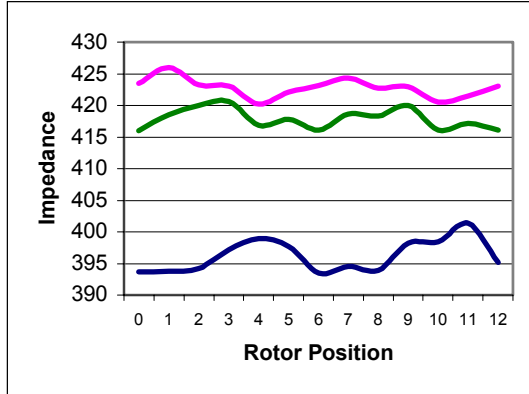


Figure 6: Impedance Balance Test Using Alternate Impedance Tool at 1200 Hz



The unbalance was found to be striking, and related to the unbalanced current, vibration and overheating of the motor. Possibilities were explored ranging from power quality to test equipment calibration. All were satisfactory. When interviewed, the manufacturer noted that process changes were made at a particular location for larger concentric wound machines. In a motor of this size and speed, the first set of concentric coils (one phase) curls under the following phases, reducing the equipment's winding appearance and mechanical strength. In order to combat that issue, the manufacturer made a decision to significantly increase the size of the first set of coils in their automated process (first phase) that also happens to be the furthest from the rotor. This allows the coil ends to appear without having to make post-winding modifications to the coils. No dynamometer testing, full load testing, or otherwise was performed on the motor design other than an applied voltage impedance test that 'met design requirements.'

During the interview, a statement was made that any equivalent manufactured motor would exhibit the same results. Many other motors of the same frame size, other manufacturers, etc. were evaluated at the facility, with similar winding configurations. None resulted with the same findings.

Table 2: Alternate Motor

	T1-T2	T1-T3	T2-T3
Resistance	0.223	0.225	0.225
Impedance	36	35	36
Inductance	7	7	7
Phase Angle	70	69	70
I/F	-39	-39	-39
Insulation	#.#		

Figure 7: Inductive Unbalance/ Rotor Test, Alternate Motor

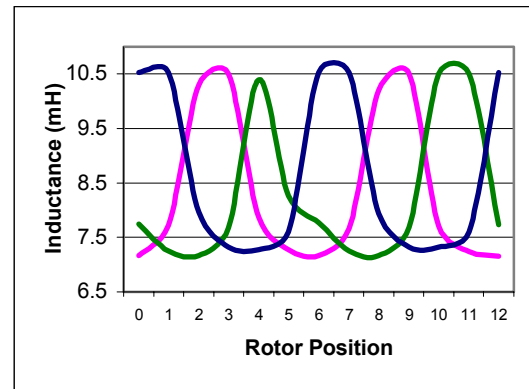
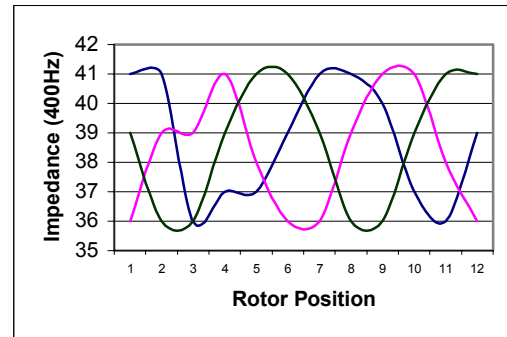


Figure 8: Impedance Unbalance, Alternate Motor



It is interesting to note that on the 'alternate' motor example, while the general phase balance is common to other motors in this frame size, with the same concentric winding type (with the exception that all coils are equivalent in size) a defect in the waveform is identified. As it turns out, this particular defect is common to this particular manufacturer, and is identified as a casting void defect, which alters the smooth curvature of the sine-wave. Through experience, it has been found that casting voids that impact the sides of an inductive waveform have a minimal impact on the reliability of a motor. However, if the deformity is at the crest, it will significantly impact the motor's ability to produce torque.

The result of this study concluded that the particular motor design was not acceptable to the user for the critical application. As a result of these findings, the power plant now performs MCA testing on all new critical motors to check for winding and rotor defects that may impact equipment reliability.

CASE 2: BRUSHLESS DC SERVO

The following Brushless DC Servo motor tested coil-to-coil short on a test bench:

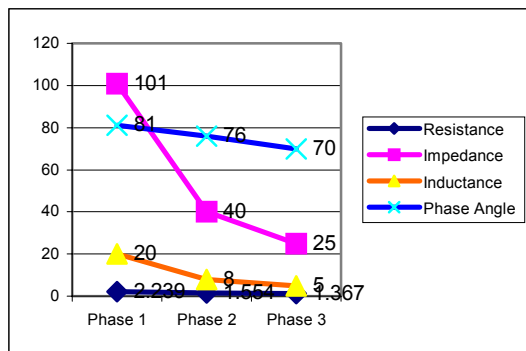
Table 3: Shorted DC Brushless Servo

	T1-T2	T1-T3	T2-T3
Resistance	2.239	1.554	1.367
Impedance	101	40	25
Inductance	20	8	5
Phase Angle	81	76	70
I/F	-47	-47	-46
Insulation	>99M		

Note the slight variation in resistance, significant changes to impedance, inductance, over 5 points of phase angle, with a balanced I/F. The phase angle compared to I/F indicates a coil-to-coil fault.

The relationship between phases, can be visually represented as follows:

Figure 9: Visual Representation of Faulted Brushless DC Servo



In figure 9, note the relationship between impedance and inductance. Because of the resistive, capacitive and inductive components of impedance, the relationship between impedance and inductance can be used to determine the condition of the windings. If the impedance and inductance are parallel, then the winding is in good condition and any inductance or impedance

unbalances are due to rotor position. Should impedance dramatically differ from inductance, then the most likely cause is contamination or overheated windings (insulation issues showing in capacitance).

CASE 3: SUBMERGED MOTOR

The following 100 Horsepower, 1800 RPM motor was found to have seized bearings and had been submerged during operation. One concern was whether the motor was salvageable.

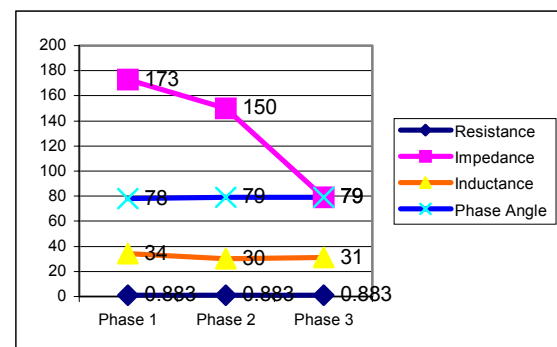
Table 4: Winding Condition - Dirty Windings

	T1-T2	T1-T3	T2-T3
Resistance	0.883	0.883	0.883
Impedance	173	150	79
Inductance	34	30	31
Phase Angle	78	79	79
I/F	-43	-44	-44
Insulation	>99M		

The following information can be gathered from the above data and the following visual data:

- All but the impedance and inductance are fairly balanced.
- The steep angle found as the difference between impedance and inductance is due to leakage to ground from contamination that has effected the insulation.
- The small 'shift' in phase angle and I/F indicates that some minimal damage may have occurred due to contamination. However, the windings may be salvageable.

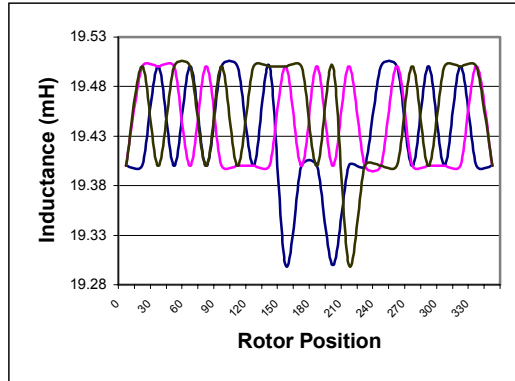
Figure 10: 100 HP Visual Data



CASE 4: 3000 HP WITH BROKEN ROTOR BAR

The following data was taken with the 3000 horsepower, 1800 RPM motor assembled. Inductance readings were taken every 15 degrees.

Figure 11: Broken Rotor Bar Data



Particular issues found with this rotor data are:

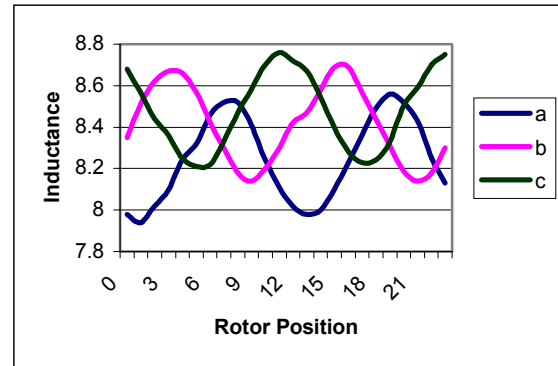
- In smaller electric motors there will be one 'sine-wave' for each pole of the motor. For instance, a 3600 RPM motor would have two sine-waves. On a larger motor this will double (ie: medium voltage motors), so that a two pole motor will have four sine-waves. This is because the instrument puts out enough power to only read the influence of the rotor bars above each coil side, whereas it will influence the complete coil on smaller motors. In the above case, the motor was a 3000 Horsepower, 4160 V_{AC} motor, 1800 RPM.

As the rotor position is changed, the broken rotor bars will cause a dramatic change to the inductance between the stator and rotor.

CASE 5: NEW 50 HP, 3600 RPM COMBINED FAULTS

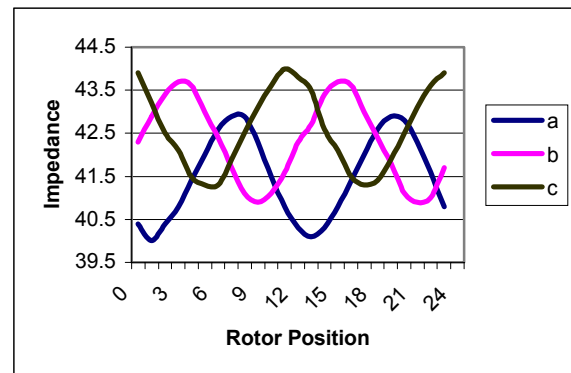
The following information was gathered on a new 50 Horsepower, 3600 RPM electric motor prior to shipment to a customer for a critical application. The combined problems found within this motor caused its rejection prior to shipment and installation. The faults were confirmed using vibration analysis.

Figure 12: Combined Rotor and Stator Faults, Inductance



- The shift of inductance and impedance indicate that there will be an inherent current unbalance.
- The slight indentations in the sides of the sine-waves indicate casting voids within the rotor shorting rings and possibly the rotor bars.
- The casting voids are serious enough that they impact the impedance of each phase.

Figure 13: Combined Rotor and Stator Faults, Impedance



CONCLUSION

Motor Circuit Analysis plays an important roll in the development of a reliability based maintenance program and through the application of final manufacturing tests. The cases within this paper provide a basic understanding of the implication of MCA in the detection of electric motor faults quickly and reliably. Of particular importance is that the criteria for pass/fail of winding faults, using the methods outlined in this paper, are applicable

whether the motor is a small servo motor, pump motor or 13.8 kV alternator. Each phase is compared and balanced against each other to indicate the condition of the equipment involved.

ABOUT THE AUTHOR

Howard W. Penrose, Ph.D is the General Manager for the BJM CORP ALL-TEST™ Division, a manufacturer of Motor Circuit Analysis equipment. He has over 15 years in the electric motor and reliability industry starting as an electric motor repair journeyman in the US Navy to leading Motor System Maintenance and Management programs within the industry for service companies, the US Department of Energy, utilities, states, and many others. Dr. Penrose spent one year with the University of Illinois at Chicago teaching Industrial Engineering and performing energy, reliability, waste stream and production industrial surveys in a variety of industrial facilities as part of the UIC Energy Resources Center. Dr. Penrose is the Treasurer of the CT Section of IEEE, a past Chair of the Chicago Section of IEEE, past Chair of the Chicago Section IEEE Power Electronics and Dielectrics and Electrical Insulation Societies, has numerous published research papers, and is a trained vibration analyst, infrared analyst, and motor circuit analyst.

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