

INFLUENCE OF ROTOR RESIDUAL FLUX ON THE MEASUREMENT OF INDUCTANCE AND ITS POSSIBLE USE AS AN IMPENDING FAULT INDICATOR

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Abstract--During normal operation of a three-phase AC induction motor, the magnetic flux in a healthy rotor forms a sinusoidal pattern. Typically, in healthy rotors, little residual flux will remain after the motor is de-energized. However, as rotor anomalies such as cracked or broken bars develop, a net residual flux may be established. This additional flux appears as a variation in the residual flux after the motor is de-energized. To analyze these variations, a modified version of the standard practice inductance measurement is used. Plotting all three phases of inductance as the rotor is rotated will show any variations, and thus, anomalies associated with the rotor. This paper will discuss how residual flux influences the waveforms generated by plotting inductance and suggests, by analyzing changes in them, impending faults in induction motors may be detected.

Index Terms--Air Gap, Eccentricity, Flux, Inductance, Induction Motors, Rotor Influence Check (RIC), Rotor Fault, Stator Fault, Motor Testing, and Measurement.

I. INTRODUCTION

Much research has been done in the area of non-intrusive online and intrusive offline testing of induction motors for rotor anomalies. In contrast, there has been very little research done in the area of non-intrusive offline detection for rotor anomalies. Intrusive offline tests such as the growler and core loss tests require the rotor to be removed from the motor, rendering their use in the field impractical. Non-intrusive offline tests on motors typically include phase-to-phase resistance, inductance, resistance-to-ground, and capacitance-to-ground. In recent years, a modification to existing phase-to-phase inductance tests has proven to be of value in motor health assessment. Instead of a single inductance measurement as previously had been the standard, plotting the inductance and inductive imbalance as the rotor is rotated in discrete increments may now be used to detect many faults. These faults include turn-to-turn and phase-to-phase shorts, eccentricity, bowed rotors, misalignment, porosity, and cracked or broken rotor bars.

A. Inductance Measurements on Motors

Inductance testing of motors, a standard practice, measures the total impedance of the motor, which includes the impedance of the stator windings and the reflected rotor impedance. To measure the inductance, impedance is measured on each phase by applying a low-voltage AC signal of known frequency to the winding and measuring the current that is passed through the windings. Resistance of the windings is measured by applying a DC voltage to the windings and measuring the current. From these measurements, inductance is then calculated using:

$$L = \frac{X_L}{\omega} = \frac{\sqrt{\left(\frac{V_{ac}}{I_{ac}}\right)^2 - \left(\frac{V_{dc}}{I_{dc}}\right)^2}}{2\pi f} \quad (1)$$

Where:

L is the inductance in Henries.

X_L is the inductive reactance in Ohms.

ω is $2\pi f$

V_{ac} is the voltage of the AC test signal in Volts.

I_{ac} is the current of the AC test signal in Amps.

V_{dc} is the voltage of the DC test signal in Volts.

I_{dc} is the current of the DC test signal in Amps.

f is the frequency of the test signal in Hertz.

B. Physical Parameters That Affect Inductance

Several physical parameters affect inductance; these include the area of the core, the number of turns, the length of the air gap, the length of the magnetic circuit, and the incremental permeability of the steel, as indicated in equation (2) below. In a motor, the number of turns, the area of the core, and the length of the magnetic circuit are constant. The primary parameter that will affect the inductance is the length of the air gap. Another parameter that will affect the inductance to a far lesser degree than the air gap is the incremental permeability of the steel. It is of importance for the reader to note that although effects from fringing flux

affect inductance, they are not included in this formula for simplicity.

$$L = \frac{3.19N^2 A_c \times 10^{-8}}{l_g + \frac{l_m}{\mu_\Delta}} \quad (2)$$

Where:

- L is the inductance in Henries.
- N is the number of turns.
- A_c is the area of the core in square inches.
- l_g is the length of the air gap in inches.
- l_m is the length of the magnetic path in inches.
- μ_Δ is the incremental permeability.

C. Inductive Imbalance

From the inductance measurements, percent (%) inductive imbalance is calculated using:

$$\%L_{imb} = \frac{\Delta_{max}}{L_{avg}} \times 100\%$$

Where:

- $\%L_{imb}$ is the inductive imbalance in percent.
- Δ_{max} is the maximum deviation of inductance from the average inductance in Henries.
- L_{avg} is the average inductance in Henries.

Percent inductive imbalance is used to determine how well windings between phases are balanced. Although there are no specific standards, in a healthy motor it is generally accepted there should be less than a 7% inductive imbalance for form wound motors, and less than 12% for random wound motors.

Several factors affect inductive imbalance. One factor is whether the motor is concentric or lap wound. Some concentric wound motors exhibit differing inductances between each of the coils. The total core area coupled by each coil causes differing inductances between coils. In addition to core area in concentric windings, the coupling (leakage reactance) between the stator coils and the rotor cage will cause slight imbalances between the coils. Other factors that will affect inductive imbalance are the rotor design and eccentricity. To simplify manufacturing, yet create a skew, some rotors have half of the cage shifted at the center of the rotor. It has been our experience that this shift in the cage tends to create an inductive imbalance of approximately 8 to 15% between phases.

D. Influence of the Rotor on the Measurement of Inductance

It is well known that the rotor can influence the measurement of inductance. This influence comes from three main factors: the air gap, the reflected impedance of the cage back into the stator windings (Lenz's law), and the residual magnetism on the rotor.

Seen in the past as a nuisance, the influence of the rotor on the measured inductance offers advantages in detecting the health of a motor. Plotting measured inductance with respect to rotor position (rotation) has opened a world of opportunity to determine the health of the motor. To perform this test, the rotor is rotated in discrete increments, and the inductance is measured at each point. With the exception of some rotors, the resulting graph of inductance will typically display waveforms sinusoidal in shape. These waveforms may then be analyzed to determine the overall health of the rotor and stator.

When analyzing inductance graphs, there are two main factors to consider, the amplitude of the inductance waveforms and repeated variations in the waveforms throughout all three phases. The amplitude of inductance waveforms depends on the type of motor, its construction, the residual flux on the rotor, and the overall health of the motor. Low amplitudes with very little sinusoidal activity of the inductance waveforms indicate the rotor is of "low influence." Low influence rotors are typically of higher quality, have copper bars, and have no defects (see Fig. 1).

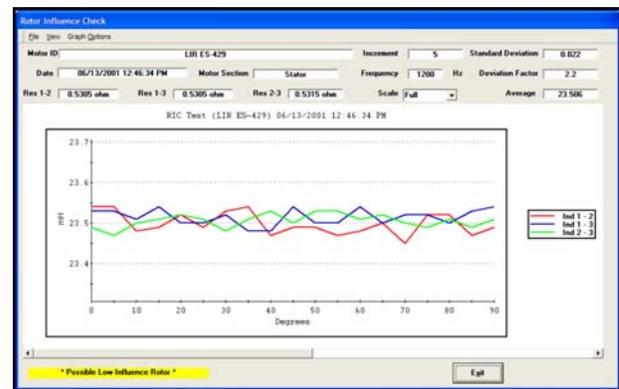


Fig. 1. Inductance test of a rotor with "Low Influence."

An increase in the amplitude of the inductance waveforms often indicates a developing fault in the motor, especially in rotors that initially have low influence. It has been our experience that, due to porosity, cast aluminum rotors will typically produce inductance waveforms "with influence," i.e., with an increase in amplitude of the waveforms. However, adverse conditions such as broken or cracked rotor bars

will also produce these effects; the amplitudes of the waveforms increase and the waveforms will become sinusoidal in shape as the severity of the fault increases (see Fig. 2).



Fig. 2. Inductance test of a rotor “with Influence.”

An increase in amplitude in the inductance waveforms is caused by two primary factors. One factor is the reflected impedance from the cage back into the stator windings. When a bar breaks, the “short circuit” effects of the cage are reduced, i.e., as the cage inductance increases, the reflected impedance into the stator windings increases. Another factor that increases the amplitude of the inductance waveforms is the increase in residual flux associated with rotor anomalies.

As rotor anomalies occur, the residual flux on the rotor increases. Two factors cause this increase; one of these is the decrease in flux cancellation from adjacent bars. Another factor that causes the increase in residual flux is the case of shorted laminations or decreasing quality of steel (from severe overheating conditions, for example). Shorted laminations or decreased quality of steel increases the retentivity point of the steel, and thus, the residual flux. In healthy rotors, large residual flux on a rotor indicates lower quality steel used in the construction, or higher stray losses from fringing effects, and thus, higher core losses when the motor is operating.

As shown in Fig. 3, repeated variations throughout all three phases of inductance waveforms are a very good indicator of developing faults in the rotor.

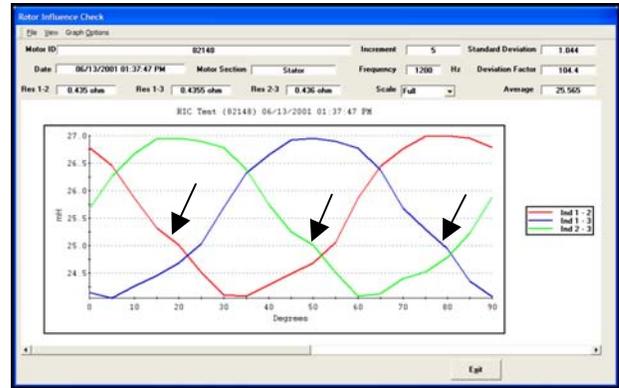


Fig. 3. Inductance test of a rotor with anomalies.

Repeated variations are caused by the same factors that affect the amplitudes of the inductance waveforms: reflected impedance of the cage and the increase in residual flux on the rotor.

II. DISCUSSION

To determine that residual flux influences inductance measurements, all variables except the residual flux have to be made constant or tested to verify they do not influence or abnormally distort the residual flux or the inductance.

For purposes of this paper, in all of our experiments we used a completely healthy rotor (except for a slight porosity). A rotor with any faults would negate our ability to show the residual flux influences the inductance measurements.

In our experiments, the air gap was made to be constant through meticulous design of experiment procedures. When taking measurements, the rotor was always returned to the same position (keyway up). To eliminate air gap variances, the end bell was marked so that it too was oriented the same every time the rotor was removed from the motor. Meticulous repetition of our setup ensured that the air gap was constant for all experiments.

In reference to the physical inductance formula (2), several variables need consideration. These variables include the number of turns, line frequency, and core area. Although the number of turns and core area are variables in design, once the motor is designed and constructed these are constants unless a fault develops in the motor.

In reference to the measurement of inductance (1), the last variable to consider is the frequency at which the tests are made. The test frequency was created using a stable frequency generator, and thus became a constant for our experiments.

With these variables now as constants for our experiments, we have to ensure that our inductance test, which is performed at 1200 Hz at a voltage of

approximately 10 volts, does not influence the residual flux on the rotor. As seen in Fig. 4, before the inductance measurement test, the average residual flux density on the rotor was -0.26 gauss. After the inductance measurement, the average residual flux density had changed to 0.18 gauss. The average change in the residual flux density was 0.44 gauss. Residual flux on the rotor is typically less than 5 gauss; a change of 0.44 gauss represents a change of approximately 8.8% in typical residual flux levels on the rotor. Although the inductance measurement had a slight effect on the magnitude of the residual flux on the rotor, the pattern was unaffected and was not distorted by the inductance measurement.

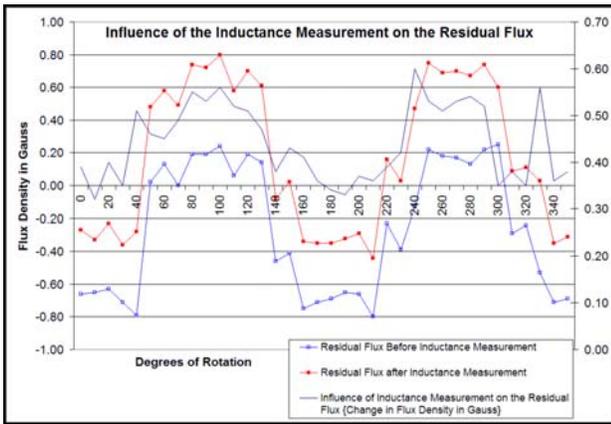


Fig. 4. Experimental data to show the influence of the inductance measurement on the residual flux.

With air gap, number of turns, line frequency, and core area now constants in our experiments, and the fact that it was determined that the inductance test had little influence on the magnitude of the residual flux and no effect on its pattern, we focused on the residual flux of the rotor as the only variable.

To show residual flux varied the inductance, the rotor was degaussed, and the residual flux was measured to verify the degaussing procedure (see Fig. 5).

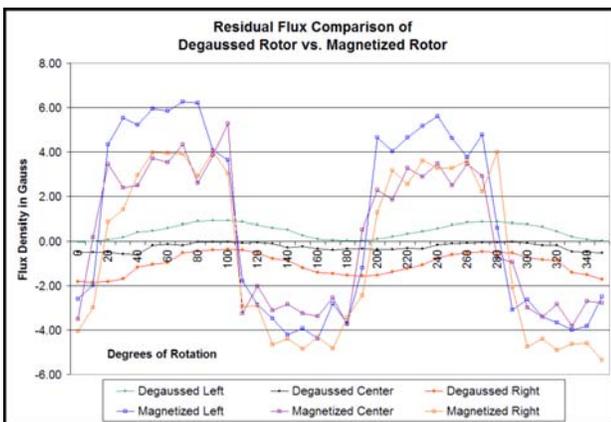


Fig. 5. Residual flux measurement to compare the residual flux density of magnetized rotors versus degaussed rotors.

An inductance test was performed on the rotor in 10 degree increments (see Fig. 6).

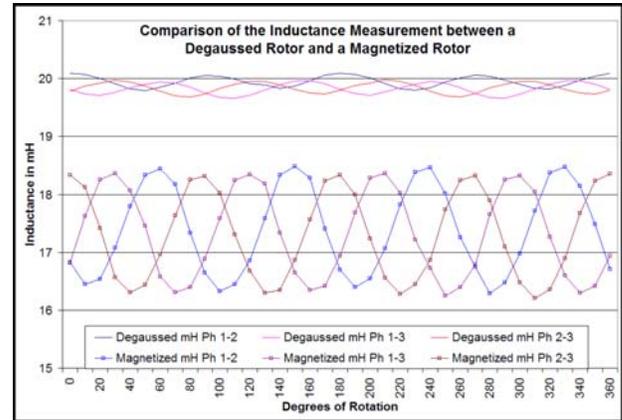


Fig. 6. Inductance measurements of a degaussed rotor versus a magnetized rotor.

The motor was then supplied DC current on one phase without rotating the rotor. This developed a residual flux on the rotor as shown in Fig. 5.

Another inductance test was performed on the motor as shown in Fig. 6. The amplitude and average value of the inductance changed from the previous value. The average inductance level fell from 19.87 mH to 17.34 mH due only to a change in the level of residual flux on the rotor. Also associated with the change in the residual flux, the amplitude of the inductance waveforms increased from 0.43 mH to 2.27 mH peak-to-peak.

Experiments were also performed on a 100 HP motor in which rotor bars could be removed and replaced as desired. The motor was single phased, and the shaft rotated, with all bars in place to establish a residual flux pattern associated with a healthy rotor cage. Once the field was established, the inductance was measured. Next, the motor was then single phased with one bar removed. With the bar removed, a residual flux was created around the missing bar. The bar was then replaced and an inductance was performed. As shown in Fig. 7, the inductance measurement changed solely due to the change in the residual flux level on the rotor.

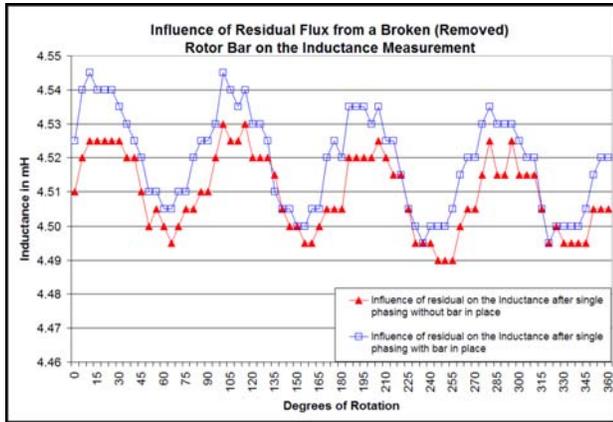


Fig. 7. Inductance test to show the influence of the residual flux from a broken (removed) rotor bar on the inductance measurement.

Another possible indicator of impending faults due to residual flux is a change in the inductive imbalance. From equation (3), as the residual flux on the rotor increases, the amplitude of the inductive waveforms increases (Fig. 8.). Thus, conditions conducive to influencing the residual flux on the rotor may be detectable by plotting the inductance waveforms as the rotor is rotated.

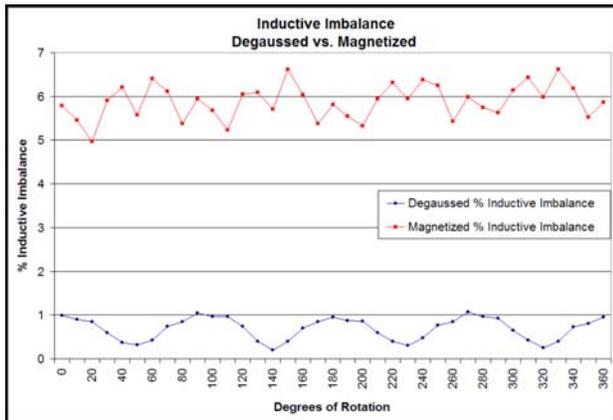


Fig. 8. % Inductive Imbalance of degaussed rotor versus % Inductive Imbalance of a magnetized rotor.

III. RELATED FIELD OBSERVATIONS

A. Field Observation #1

A screw motor from a plastic injection molding machine was removed from service due to a mechanical fault (bearings). A Rotor Influence Check (RIC) test was performed on the motor to evaluate its condition (see Fig. 9).



Fig. 9. Inductance test of a rotor in which the residual flux had been distorted by external influences.

The RIC test shows a highly distorted pattern of inductance. The motor was then run for approximately 30 minutes (in an unloaded condition).

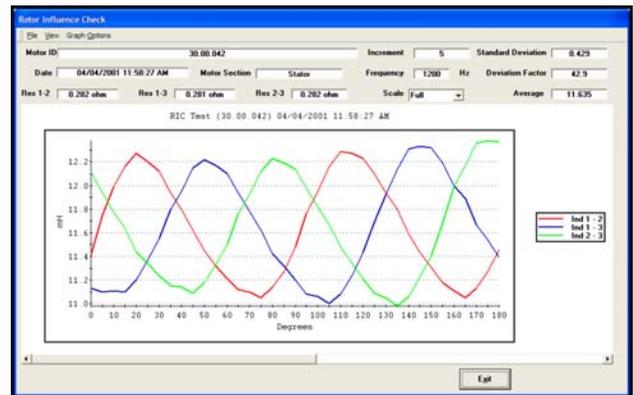


Fig. 10. Inductance test of the same motor as shown in the previous figure after the motor had been run for approximately 1/2 hour.

Another RIC was then performed on the rotor. As seen in Fig. 10, the inductance measurements have returned to a “normal” signature (although there are rotor anomalies associated with this particular rotor). After further study as to the cause of the difference, it was learned that during mechanical repairs requiring arc welding, the welding leads had been placed on top of the motor and the high current DC used in the welding process distorted the residual flux field.

B. Field Observation #2

Two motors of the same manufacturer and model number were tested. The motor shows sinusoidal activity in the inductance measurement (Fig. 11). In addition to the sinusoidal activity, tests performed on motor 30-00-035 show an average inductive imbalance of 5.08% (Fig. 12). In contrast, tests performed on motor 30-00-008 show little sinusoidal activity (Fig. 13) and a low inductive imbalance of 0.57% (Fig. 14).

The motors were pulled from service for investigation into the possible differences between the motors. It was discovered there was significant core loss in the motor with the LOWER inductive imbalance. Investigations are continuing as to the cause of a decreasing, rather than, increasing inductive imbalance.

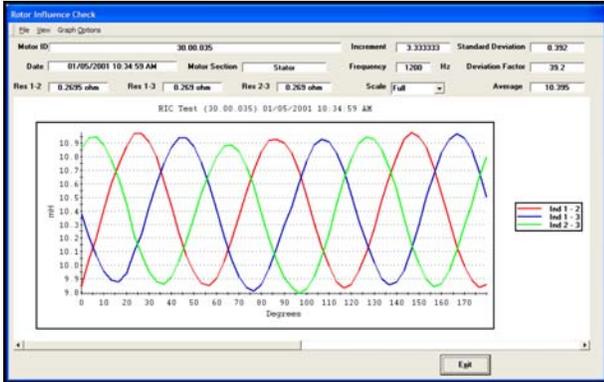


Fig. 11. Inductance test of motor 30-00-035.

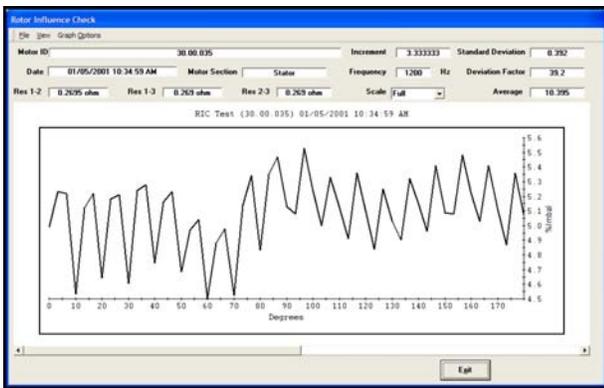


Fig. 12. Inductance Imbalance of motor 30-00-035.

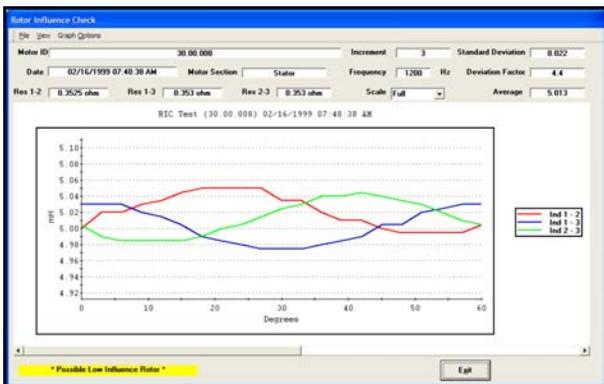


Fig. 13. Inductance test of motor 30-00-008.

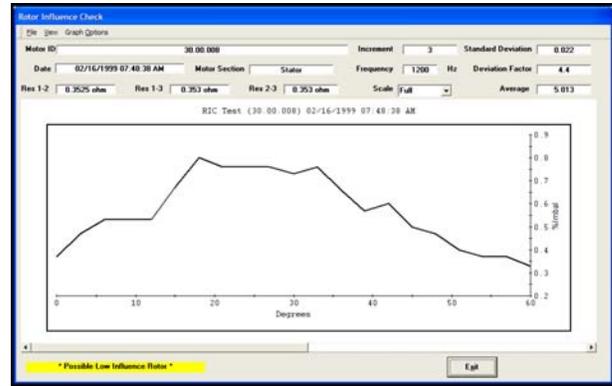


Fig. 14. Inductive Imbalance of motor 30-00-008.

IV. CONCLUSIONS

Our research has shown that using a modified version of the standard inductance measurement on an induction motor may provide additional valuable information. By plotting the measured inductance of each phase as the rotor is rotated in discrete increments, variations in inductance may indicate developing faults that may be overlooked using the standard practice inductance measurement.

Our research has shown that the residual flux may affect inductance measurements. Although the primary factors affecting inductance measurements are the air gap and the reflected impedance from the rotor cage into the stator, residual flux may affect the average inductance, the amplitude of the inductance waveforms, or the inductive imbalance. Trending these over time may provide an indication of a developing fault in the motor. As with all tests, cross correlation between tests is imperative in the decision making process.

Consistent with the objectives of motor testing, the work reported in this paper is very applied, with little theoretical basis presented. It is the intention of the authors to follow this paper with another that will result in test guidelines of interest.

V. REFERENCES

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