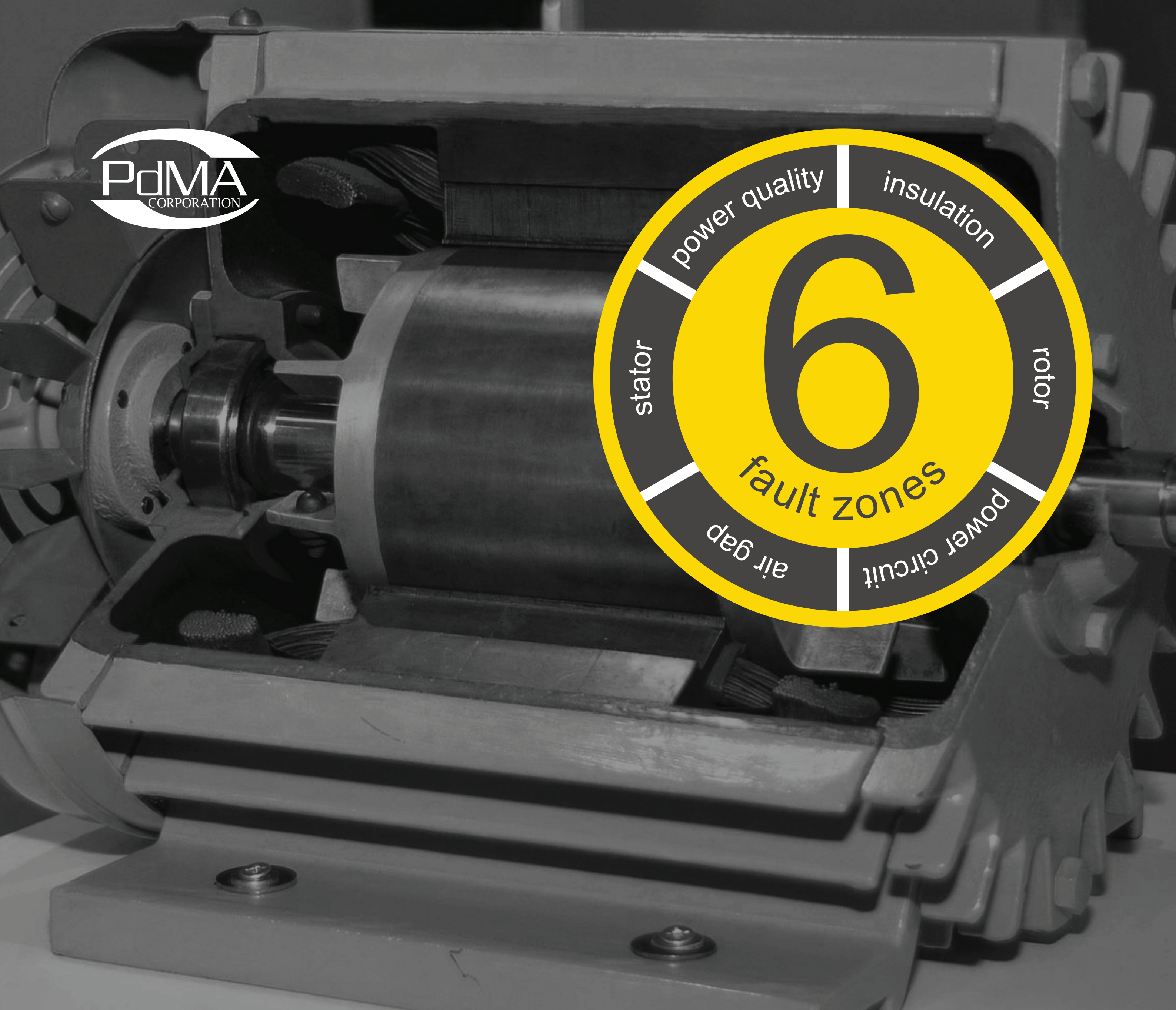

Using A Six Fault Zone Approach For Predictive Maintenance On Motors

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USING A SIX FAULT ZONE APPROACH FOR PREDICTIVE MAINTENANCE ON MOTORS

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Abstract: A comprehensive analysis of motor health may be accomplished by combining online and offline test results into fault zones. These fault zones are Power Quality, Power Circuit, Stator, Insulation, Rotor, and Air Gap. Power Quality focuses on the quality of the voltage and current. Power Circuit focuses on the power circuit supplying power to the motor. The Stator Fault Zone focuses on the turn-to-turn insulation and internal coil connections. The Insulation Fault Zone refers to the winding to ground insulation. The Rotor Fault Zone refers to the health of the rotor cage and laminations. The Air Gap Fault Zone refers to the quality of the air gap between the rotor and the stator. Each fault zone should be analyzed to accurately assess the overall health of a motor. This paper will provide a brief introduction to a six fault zone approach for predictive maintenance on motors.

Key Words: Motor Testing, Current Signature Analysis, Fault Zone, Power Quality

I. POWER QUALITY

The Power Quality Fault Zone focuses on the quality of the voltage and current. The power system determines the quality of the voltage, and the load determines the quality of the current. Power Quality is analyzed using Voltage and Current, Harmonic Voltage Factor (HVF), Crest Factor (CF), and Total Harmonic Distortion (THD).

Low Voltage

When a motor is operated below nameplate rated voltage, some of the motor's characteristics will change. Starting, pull-up, and pull-out torque of induction motors all change based on the applied voltage *squared*. For example, a 10% reduction from rated nameplate voltage (100% to 90%) reduces the starting, pull-up, and pull-out torque by a factor of 0.9 x 0.9. The resulting torque would be 81% of the rated torque (Figure 1).

High Voltage

Typically, motors may tolerate a slight overvoltage condition; however, extremes above 105% of rated voltage may cause the full load amperage to go up (Figure 1).

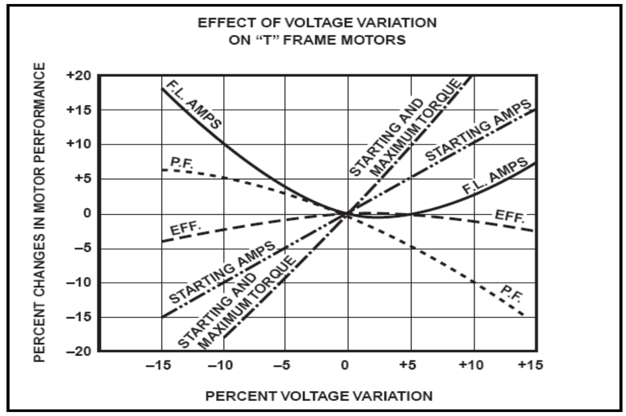

Figure 1. Effect of Voltage Variation on Motors.

Harmonic Voltage Factor

Harmonic Voltage Factor (HVF) is calculated as follows:

$$HVF = \sqrt{\sum_{n=5}^{\infty} \frac{V_n^2}{n}}$$

Where:

n	=	order of odd harmonics, not including those divisible by three (triplen)
V_n	=	the per unit (p.u.) magnitude of the voltage at the n^{th} harmonic frequncy
∞	=	infinity

The HVF curve was developed based on the assumption that even harmonics are negligible and that only odd harmonics, except triplen harmonics, may be present in the system. A motor should be derated according to Figure 2 as the HVF increases. NOTE: The curve *does not apply* when the motor is operated at other than rated frequency or when operated from a variable voltage or frequency source (VFD).

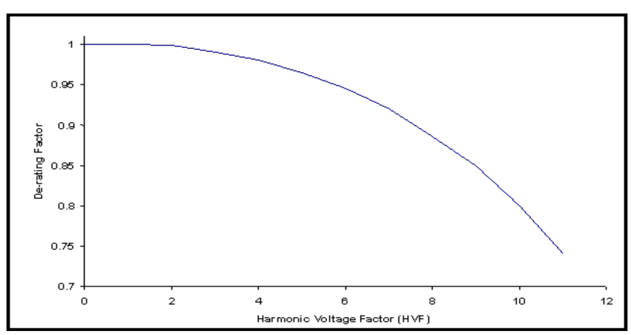

Figure 2. Derating vs. Harmonic Voltage Factor.

Crest Factor
Crest Factor (CF) is the ratio between the voltage's peak-to-peak voltage and the RMS value. A distortion-free voltage waveform (pure sinusoid) has a CF of 1.414. As the signal becomes distorted this ratio changes based on the type of distortion. CF is primarily used for indication of voltage spiking caused from contact chatter, solid-state switching equipment, load switching, and transients.

Total Harmonic Distortion (Voltage)
Total Harmonic Distortion (THD) or Distortion Factor (DF) is calculated as follows:

$$THD = \frac{\sqrt{\sum_{h=2}^{50} V_h^2}}{V_f} \times 100\%$$

Where:

V_h = amplitude of each harmonic voltage
V_f = amplitude of the fundamental voltage

For most applications, there is no need to derate motors if the voltage distortion is within IEEE 519-1992 standard limits of 5% THD and 3% for any individual harmonic (Table 1).

Table 1
Low Volage (<600 VAC) THD limits

	Special Applications*	General System	Dedicated System**
THD (Voltage)	3%	5%	10%
Notch Depth	10%	20%	50%

* Special Applications include hospitals and airports
** A Dedicated System is exclusively dedicated to the converter load

For voltages greater than 600 VAC and less than 69 kVAC, the voltage THD limit is 5%. For any individual harmonic, the limit is 3% (General System). There are more stringent limits for voltages higher than 69 kVAC, but they are outside the scope of this paper.

IEEE 519-1992 standard also places limits on Notch Depth (Table 1). Notch Depth refers to the commutation notch created in a voltage waveform when current is switched from one set of diodes to the next. Notch Depth is measured from the bottom center of the notch straight up to a point that intersects where the voltage waveform would have been if the notch were absent. This voltage difference in a general system should be less than 20% of the peak-to-peak voltage.

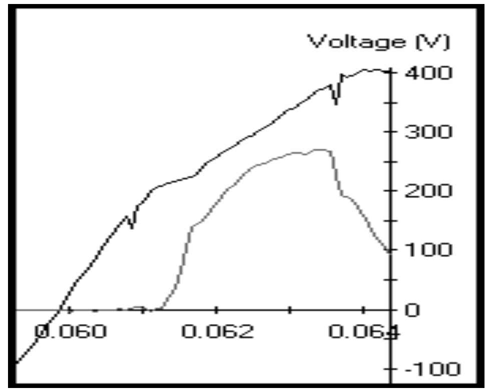

Figure 3. Notch Depth of Approximately 50 volts

Note: The depth of the notch in Figure 3 is approximately 50 volts.

Total Harmonic Distortion (Current)
To evaluate current Total Harmonic Distortion (Current) or more properly termed Total Demand Distortion (TDD), testing needs to be performed at the Point of Common Coupling (PCC). TDD limits are based on the short circuit current (I_{SC}) of the PCC divided by the maximum demand load current (I_L) for normal operation (conditions lasting more than one hour). These limits are listed in table 2 for systems less than 69 kVAC. These limits may be exceeded by 50% for situations lasting less than one hour.

Table 2
Maximum Harmonic Current Distortion in % of I_L

I_{SC}/I_L	H<11	11≤H<17	17≤H<23	23≤H<35	35≤H	TDD
<20*	4.0	2.0	1.5	0.6	0.3	5.0
20-50	7.0	3.5	2.5	1.0	0.5	8.0
50-100	10.0	4.5		1.5	0.7	12.0
100-1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

Notes: Even harmonics are limited to 25% of the odd harmonic limits
All power generation equipment are limited to these values

II. POWER CIRCUIT

The Power Circuit Fault Zone focuses on the conductors, connections, and components from the test point downstream to the motor. Power Circuit components include circuit breakers, fuses, contactors, overloads, disconnects, lug connections, and power factor correction capacitors. Voltage Imbalance and Resistive Imbalance measurements are used to analyze the power circuit fault zone.

Voltage Imbalance
Voltage Imbalance is a measure of the largest deviation in voltage between phases and is calculated as follows:

$$\% \ V_{imb} = \left|\frac{\Delta_{max}}{V_{avg}}\right| x100\%$$

Where:

$\% \ V_{imb}$	=	voltage imbalance in percent
Δ_{max}	=	maximum deviation of voltage from the average voltage
V_{avg}	=	average voltage

National Electrical Manufacturer's Association (NEMA) Motors and Generators Standards 1 (MG-1) provides a recommended derating factor based on percent voltage imbalance (Figure 4). When operating a motor with a phase-to-phase voltage imbalance, the rated horsepower of an induction motor should be multiplied by the derating factor. If the load on the motor exceeds this derated value, take steps to correct the imbalance.

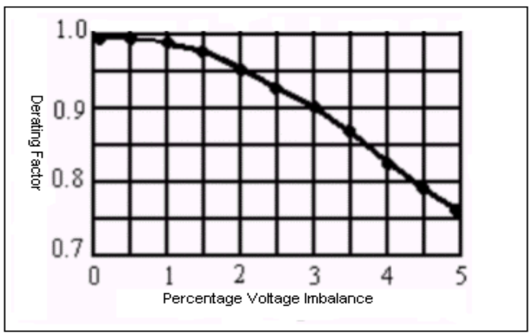

Figure 4. Derating Factor for Voltage Imbalance

Rules to apply when troubleshooting voltage imbalance for the power circuit fault zone are:

- A 1% voltage imbalance may result in a 6–7% current imbalance, according to the National Electrical Manufacturing Association (NEMA MG-1). NEMA MG-1 recommends a maximum voltage imbalance of 1% without derating the motor.
- A 3.5% voltage imbalance may increase winding temperatures by 25%, according to Electrical Power Research Institute (EPRI).
- For up to a maximum of a 5% voltage imbalance the motor may be derated to 75% of nameplate horesepower (HP). If the voltage imbalance exceeds 5%, it is recommended that the motor not be operated.
- A 10° Celsius increase in winding temperature (above insulation design class – commonly B or F) may result in a 50% reduction of motor life.

Resistive Imbalance

Percent Resistive Imbalance is measured using an offline test of the motor and is calculated by taking the largest deviation of resistance from the average resistance and then dividing it by the average resistance as follows:

$$\% \ R_{imb} = \left|\frac{\Delta_{max}}{R_{avg}}\right| x100\%$$

Where:

$\% \ R_{imb}$	=	resistive imbalance in percent
Δ_{max}	=	maximum deviation of resistance from the average resistance in Ohms
R_{avg}	=	average resistance in Ohms

Current Imbalance

Current Imbalance is a measure of the largest deviation in current between phases and is calculated as follows:

$$\% \ I_{imb} = \left|\frac{\Delta_{max}}{I_{avg}}\right| x100\%$$

Where:

$\% \ I_{imb}$	=	current imbalance in percent
Δ_{max}	=	maximum deviation of current from the average current in Amperes
I_{avg}	=	average current in Amperes

A current imbalance may be indicative of a high resistance connection. A voltage and current imbalance together is a more reliable indicator. Test location will determine whether both imbalances are present in the event of a high resistance connection as shown in Figure 5.

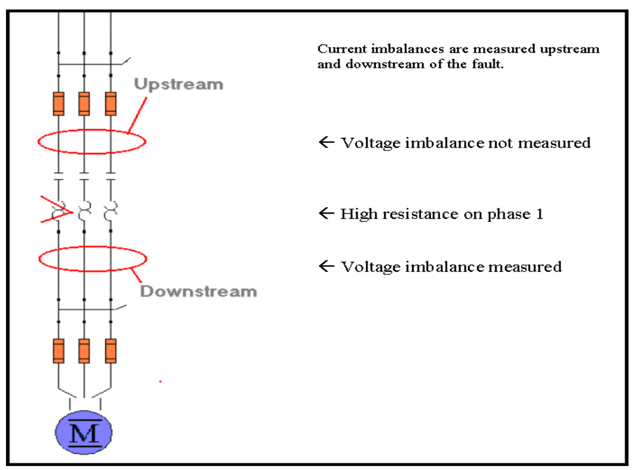

Figure 5. Power Circuit

If the test is performed upstream of an anomaly, there will only be a current imbalance. If the test is downstream of the anomaly, both a current and voltage imbalance will exist.

Parallel components such as power factor correction capacitors in the power may also cause a current imbalance. Testing needs to be performed with and without the parallel components in the system under test.

III. STATOR FAULT ZONE

The Stator Fault Zone refers to the turn-to-turn insulation and internal coil connections. Inductive and Impedance imbalances are used to analyze the stator fault zone.

Inductive Imbalance

Inductive Imbalance is a measure of the largest deviation in inductance between phases and is calculated as follows:

$$\% \; L_{imb} - \left| \frac{\Delta_{max}}{L_{avg}} \right| x100\%$$

Where:

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

Although no specific standards have been established, 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. Figure 6 shows an offline test with an inductive imbalance of 17.67% that resulted from a stator fault.

Frequency	1200
Mohm Ph 1 to Gnd	
Charge Time	60
Voltage	500
Motor Temp	28
Measured Mohm	0.0
Corrected Mohm	0.0
pF Ph 1 to Gnd	35750
ohm Ph 1 to 2	0.05250
ohm Ph 1 to 3	0.05950
ohm Ph 2 to 3	0.06150
mH Ph 1 to 2	1.980
mH Ph 1 to 3	2.165
mH Ph 2 to 3	2.675
Avg. Inductance	2.273
% Res. Imbalance	9.22
% Ind. Imbalance	17.67
$ Power Loss	260.23

Figure 6. Test Data Indicating a Possible Stator Fault

Some rotors have half of the cage shifted at the center of the rotor, which, from our experience, tends to create an inductive imbalance of approximately 8 to 15% between phases. When testing with the rotor removed, the inductive imbalance should be less than 1%.

Impedance Imbalance

Impedance Imbalance is a measure of the largest deviation in impedance between phases and is calculated as follows:

$$\% \; Z_{imb} - \left| \frac{\Delta_{max}}{Z_{avg}} \right| x100\%$$

Where:

$\% \; Z_{imb}$	=	impedance imbalance in percent
Δ_{max}	=	maximum deviation of impedance from the average impedance in Henries
Z_{avg}	=	average impedance in Henries

Average impedance and maximum deviation of impedance from the average are calculated using data obtained from a Rotor Influence Check (RIC) which will be discussed in the Rotor Fault Zone section of this paper.

Figure 7 shows online test results with a current imbalance and an impedance imbalance that resulted from a stator fault where the motor was able to continue running with the fault.

Current

Current 1	33.71	33.75	1.44	1.49
Current 2	28.40	28.43	1.44	1.19
Current 3	27.29	27.32	1.46	1.45
Average	29.80	29.83		
% Imbalance	13.12	13.12		
% FLA	68.51	68.58		

Impedance

	Real	Magnitude	Angle
Phase 1	40.36	74.91	57.39
Phase 2	36.05	87.97	65.81
Phase 3	58.03	92.65	51.22
% Imbalance	29.49		

Figure 7. Stator fault

Stator faults may also be diagnosed when there is any change in the real or reactive component of one phase that is not duplicated on another phase may indicate a change that needs to be investigated (Figure 8).

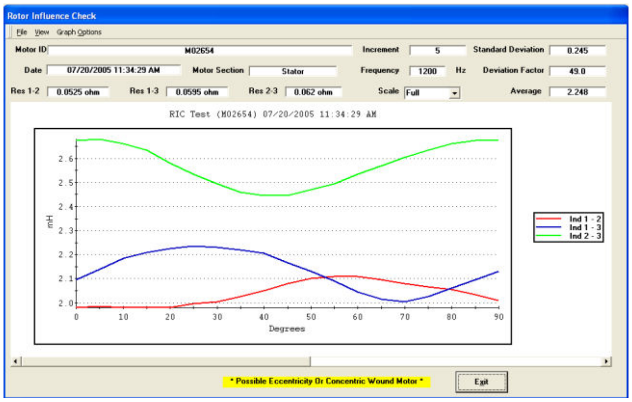

Figure 8. RIC confirming a Stator Fault

An *unloaded* motor may run with a current imbalance. This creates an impedance imbalance, which may mimic indications of a stator fault. Therefore, it is recommended to perform the tests when the motor is loaded to 70% or more. Tests performed at less than 70% load should be compared with other tests performed at the same load level for best results.

IV. INSULATION FAULT ZONE

The Insulation Fault Zone refers to the insulation between the windings and ground and is adversely affected by temperature, age, moisture, and contamination. Resistance-to-Ground (RTG), Capacitance-to-Ground (CTG), Polarization Index (PI), and Step Voltage are used to analyze this fault zone. Surge testing is not included as it is considered an acceptance or proof test.

Resistance-to-Ground

Resistance-to-Ground (RTG) or Insuation Resistance (IR) is obtained by applying a direct voltage to the entire winding for 1 minute. Once insulation resistance is measured, it should be correct to 40°C for historical data comparison. This temperature correction may be approximated by:

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

Where:

T = winding temperature at the time of the test

K_T = insulation resistance temperature coefficient at temperature T °C

RTG or IR can then be calculated using:

$$\text{RTG or IR} = K_T R_T$$

Where:

RTG or IR = insulation resistance (in Megohms) corrected to 40°C

K_T = insulation resistance temperature coefficient at temperature T °C

R_T = measured insulation resistance (in Megohms) at temperature T °C

Application of the DC test voltage should be in accordance with IEEE 43-2000 using the guidelines shown in Table 3.

Table 3
Guidelines for DC Voltages to be Applied During Insulation Resistance Test

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

Ref. IEEE Std. 43-2000

[A] Rated line-to-line voltage for 3 phase ac machines, line-to-ground voltage for 1-phase machines, and rated direct voltage for dc machines or field windings.

Temperature corrected insulation resistance values should be recorded and graphed for comparison over time. Decreasing trends in insulation resistance are typically indicative of contamination such as dirt or moisture. An increase in insulation resistance may indicate decomposition of the bonding materials or may be the result of a cleaning or repair of the motor windings. See Table 4 for recommended minimum insulation resistance after 1 minute of the test voltage application per IEEE 43-2000.

Table 4
Recommended Minimum Insulation Resistance after 1 minute of test voltage application corrected to 40°C
(All values in Mohm)

$IR_{1\ min} = kV_{rms} + 1$	For most windings made before about 1970, all field windings, and others not described below
$IR_{1\ min} = 100$	For most DC armatures and AC windings built after 1970 (form wound coils)
$IR_{1\ min} = 5$	For most machines with random wound stator coils and form wound coils rated below 1kV

Capacitance-to-Ground

Capacitance-to-Ground (CTG) measures the capacitance between windings and ground and reflects the cleanliness of the windings and cables. It is primarily a combination of resistance and geometric capacitance and is calculated as follows:

$$CTG - \sqrt{Z^2 - R^2}$$

Where:

CTG	=	geometric capacitance
Z	=	impedance of the insulation system
R	=	insulation resistance

For this measurement it is assumed that inductive reactance is negligible.

Geometric capacitance is primarily affected by changes to the dieletric properties of the insulation system such as voids and moisture content. Use of a high frequency AC source to measure geometric capacitance enables the detection of changes to the dielectric properties or structure of the insulation system due to its much higher sensitivitiy to these types of changes.

Polarization Index

$$PI = \frac{IR_{10\,\text{min}}}{IR_{1\,\text{min}}}$$

Polarization Index (PI) is the ratio of the insulation resistance at 10 minutes divided by the insulation resistance at 1 minute and is given by:

IEEE 43-2000 recommends a minimum PI value of 2.0 for most insulation systems. Lower readings may indicate insulation damage. Table 5 displays the minimum PI ratio values per IEEE 43-2000.

Table 5

Minimum PI values

Thermal Class	Minimum PI ratio
Class A	1.5
Class B, F and H	2.0

Presently, IEEE 43-2000 states, if the one-minute RTG reading is greater than 5000 Mohms, the calculated PI ratio may or may not be an indication of the insulation condition. This is due to the sensitivity of the test instruments. With the advent of higher resolution metering capabilities using digital electronics, accurate measurements at much higher values are possible.

Polarization Index Correction

When performing a PI test, it is not necessary to temperature correct. Typically, the machine temperature doesn't change appreciably between the one-minute and the ten-minute readings; thus, the effect of temperature on the PI index is usually small. However, if the motor was recently shut down the result may be a substantial increase in insulation resistance and a high PI value.

Polarization Index Profile

In addition to the Polarization Index ratio, a graphical representation of the insulation resistance, called the Polarization Index Profile (PIP) may provide additional information regarding the integrity of the insulation system. During the PI test, RTG readings are taken every second. Every five seconds the average of the previous five readings is plotted on the RTG (megohms) versus time (seconds) display (see Figure 9).

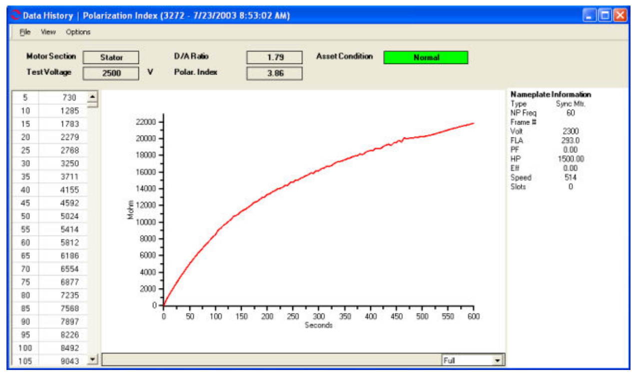

Figure 9. PIP of a Healthy Insulation System

When insulation systems become contaminated with debris such as dirt, carbon dust, etc., the PIP will have a significant amount of spiking in the profile throughout the test as shown in Figure 10. An important aspect in this situation is the minimum level the RTG values fall to. The IEEE minimum RTG value is 100 Megohms for form wound coils. For example, the RTG values dip below the suggested minimum in Figure 10. Figure 11 shows a grounded motor.

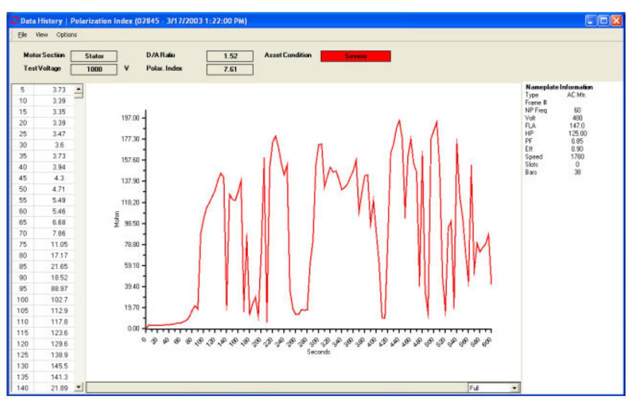

Figure 10. PIP of Contaminated Windings

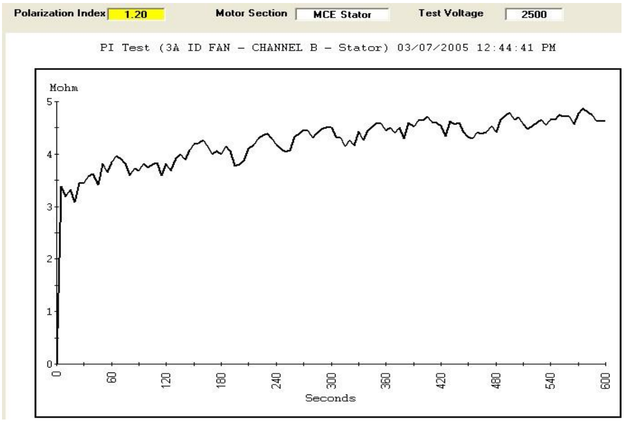

Figure 11. PIP of an Insulation System Containing a Significant Amount of Moisture

Although the PI ratio meets IEEE 43-2000 with a PI ratio >2.0, without the PIP shown in Figure 12, the embrittlement of the insulation system may have never been properly diagnosed.

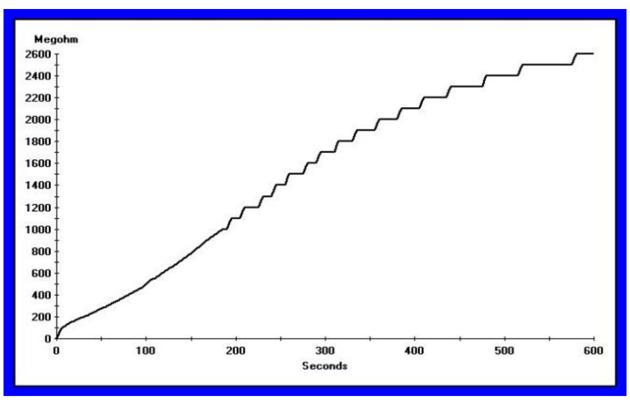

Figure 12. PIP Embrittled Insulation

Step Voltage Test

The Step Voltage test is a controlled overvoltage test in which the DC test voltage is increased in a series of uniform or graded steps at regular time intervals. The resulting leakage current, is recorded and graphed. These graphs are then analyzed for non-linear increases or other variations in leakage current versus applied voltage or time that are possible indications of insulation weakness.

Maximum voltage applied during the test is normally two times the motor's rated voltage. While moisture and dirt in the insulation are usually revealed at voltages far below those expected in service, the effects of aging or mechanical damage in fairly clean and dry insulation may not be revealed at such low voltage levels. When the voltage is increased in steps to exceed the level seen in service, local weak spots in the insulation may be revealed in the insulation resistance.

Controlled overvoltage tests may also afford the possibility of detecting impending insulation problems by recognizing abnormalities in the measured current response, thereby allowing the test to be discontinued prior to insulation failure.

Data Interpretation for Step Voltage Test

The curve of the plot of current versus voltage recorded should be nearly linear for a motor in good condition. The right panel reflects the leakage current at each time interval. Notice in Figure 13 how the current decay is consistent at each interval and how the current vs. voltage graph is linear. This is an acceptable reading.

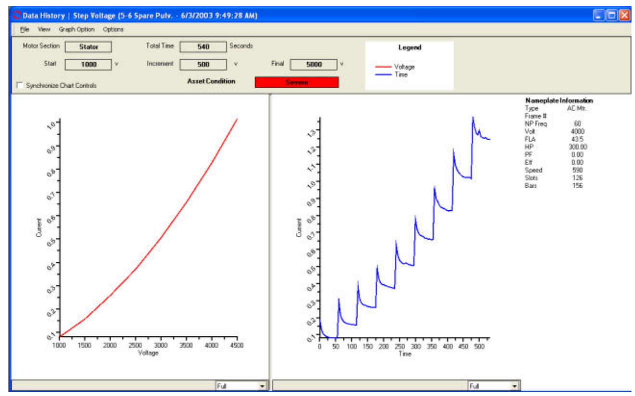
Figure 13. Step Voltage Test

Figure 14 shows an insulation system breaking down with excessive leakage current when the tester increases the voltage to 3500V.

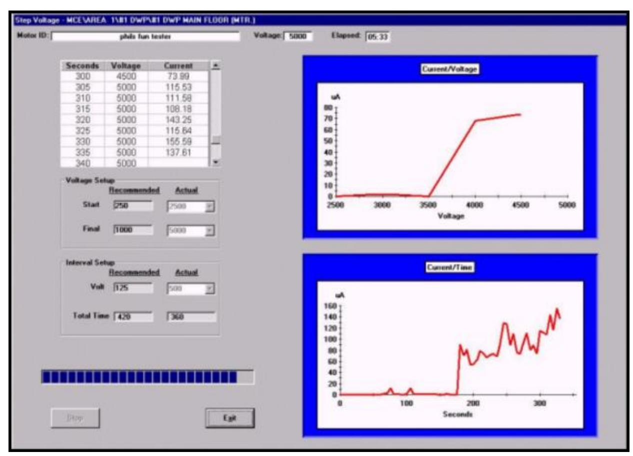

Figure 14. Failed Insulation System

V. ROTOR FAULT ZONE

The Rotor Fault Zone refers to the condition of the rotor bars, rotor laminations, and end rings. While contributing minimally to motor problems, rotor faults can influence other fault zones to fail. In-rush current, CSA, inductive imbalance, and a modified inductance measurement known as a Rotor Influence Check (RIC) test are used to analyze this fault zone.

In-Rush Current Profile

An in-rush current profile is obtained by taking a number of samples per cycle then calculating an RMS average of that cycle. Each average is then plotted to form in-rush current profiles as shown in Figure 15. The in-rush current profile may then used to analyze the health of the rotor.

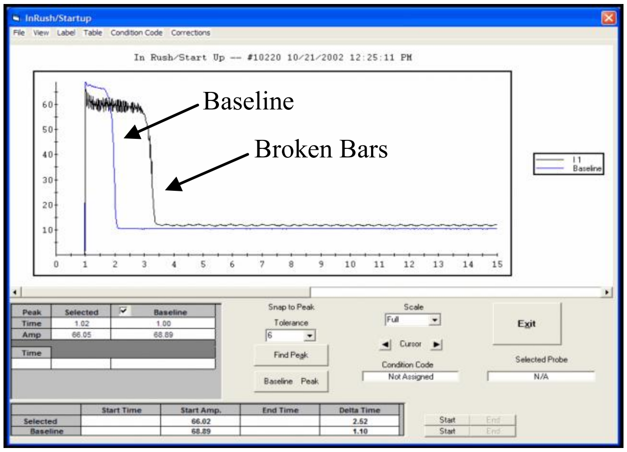

Figure 15. Current In-Rush Profiles – Normal vs. Broken Rotor Bars

A healthy motor exhibits the current profile shown by the baseline curve in Figure 15. As rotor bars break, the start-up current profile changes as less voltage is induced in the rotor cage due to the change in the effective turns ratio. This change in the ratio leaves a higher reflected impedance from the rotor to stator. Given a constant load and steady power during start-up, the higher reflected impedance lowers the amount of in-rush current (see Figure 15). Although the current is lower, the same total energy is needed to bring the motor up to speed. With less power from the rotor, the time required to put the same amount of energy (Joules) into the rotor has to increase.

Steady State Current Modulation

Healthy motors with no broken rotor bars draw steady current under constant load and power system conditions. Under constant load and power system conditions, cyclical changes (sinusoidal modulations) in current may indicate a broken rotor bar using an in-rush current profile (Figure 16). This profile may also be used to perform process analysis (such as varying loads or processes).

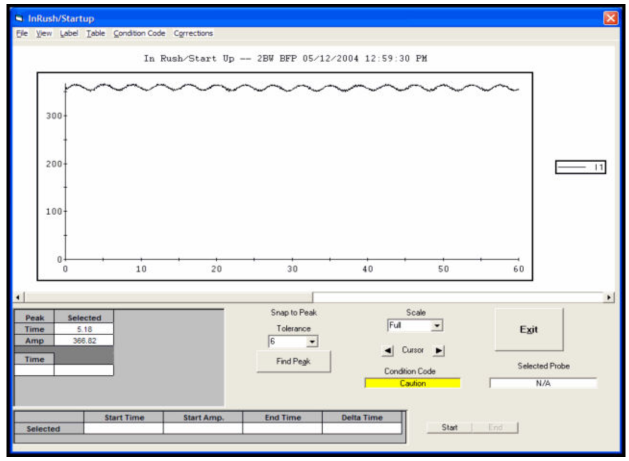

Figure 16. Current Cycling Due to Broken Rotor Bars

Current Signature Analysis

Pole-Pass Sidebands

A useful indicator of broken rotor bars is the pole-pass sidebands around line frequency. These side bands are located in the current spectrum at (Figure 17):

$$f_p = (1 + 2ks)f_{Line}$$

Where:

f_p	=	location of the peaks around line frequency
k	=	harmonic index 1,2,3...
s	=	slip
f_{Line}	=	line frequency

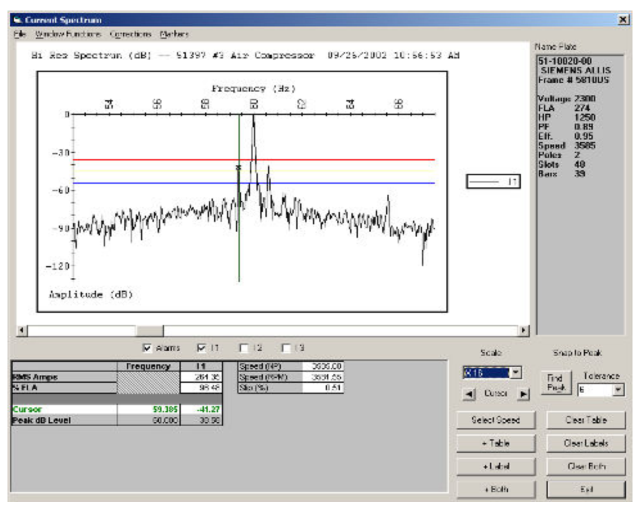

Figure 17. Pole-Pass Sidebands

Swirl Effect

Another useful spectral tool for detecting broken rotor bars is the swirl effect, which occurs at the 5th harmonic of line frequency (300 Hz on a 60 Hz line frequency) as shown in Figure 18. Swirl peaks are a confirming tool for the sidebands around line frequency and occur at:

$$f_{swirl} = [1 - (2/5)ks]5f_{Line}$$

Where:

f_{swirl}	=	location of the peaks around line frequency
k	=	harmonic index 1,2,3...
s	=	slip
f_{Line}	=	line frequency

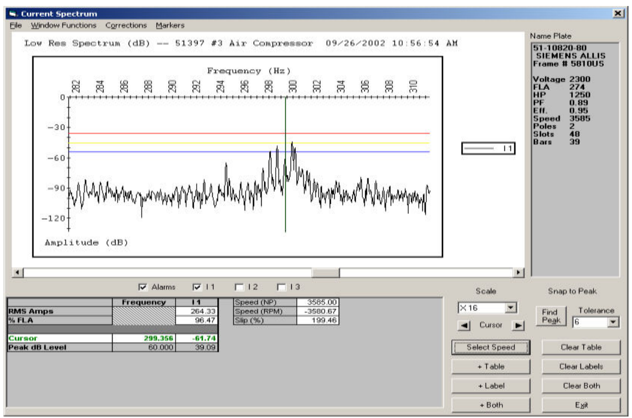

Figure 18. Swirl Effect

Rotor Influence Check

Plotting measured inductance with respect to rotor position (rotation) provides a valuable tool to determine the health of the motor. In this test, the rotor is rotated in discrete increments, and the inductance is measured at each point. The resulting graph of inductance will typically display sinusoidal waveforms that are then analyzed to determine the overall health of the rotor and stator.

When analyzing inductance waveforms, there are three main factors to consider, the amplitude of the inductance waveforms, repeated variations in the waveforms throughout all three phases, and the phasing of the waveforms. 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 (LIR) are typically higher quality, have copper bars, and have no defects (see Figure 19).

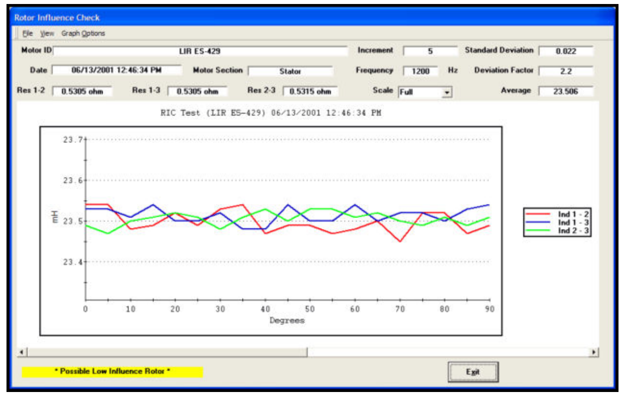

Figure 19. Inductance Test of a Rotor With "Low Influence"

An increase in the amplitude of the inductance waveforms often indicates a developing fault in the rotor, especially in rotors that initially have low influence. Rotors that are porous cast aluminum or that have adverse conditions such as broken or cracked rotor bars produce these effects. As the severity of the fault increases, the amplitudes of the waveforms increase and the waveforms will become sinusoidal in shape (see Figure 20). A baseline test should be performed prior to installation of the motor or as early as practical. Once a baseline test has been established, the motor should be monitored for trends of increasing amplitude and sinusoidal development of the inductance waveforms.

Figure 20. Inductance Test of a Rotor "With Influence"

Repeated variations throughout all three phases of inductance waveforms are a strong indicator of developing faults in the rotor as shown in Figure 21. Repeated variations are caused by the reflected impedance of the cage and the increase in residual flux on the rotor. Evaluate all three inductance waveforms for these repeated variations.

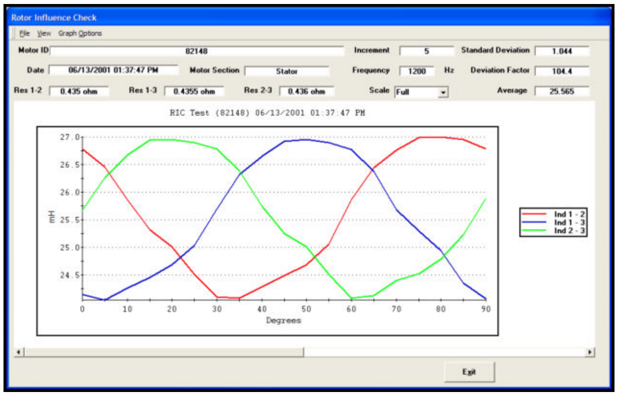

Figure 21. Repeated Variations Throughout All Three Phases of Inductance

Lastly, evaluate the waveforms for phasing differences. Phasing differences occur when the peak of one waveform will be shifted in phase.

VI. AIR GAP FAULT ZONE

The Air Gap Fault Zone refers to the air gap between the rotor and stator and includes two types of faults: static and dynamic eccentricity. These faults are analyzed using Current Signature Analysis (CSA) and the Rotor Influence Check (RIC) test.

- **Static eccentricity** occurs when the centerline of the shaft is at a constant offset from the centerline of the stator, such as a misaligned end bell.

- **Dynamic eccentricity** occurs when the centerline of the shaft is at a variable offset from the centerline of the stator, such as a wiped bearing.

Current Signature Analysis

Air gap eccentricity will show up as sideband activity around a location known as the Eccentricity Frequency (F_{ECC}). To calculate $F_{ECC,}$ multiply the number of rotor bars by the shaft frequency (RPM/F_{Line}) of the motor. The peaks in the spectrum will be odd multiple sidebands of line frequency (F_{Line}). In a 60 Hz system, the 1^{st} and 3^{rd} sidebands will appear as 4 peaks, 120 Hz apart, and non-synchronous to line frequency. These peaks are seen in Figure 22.

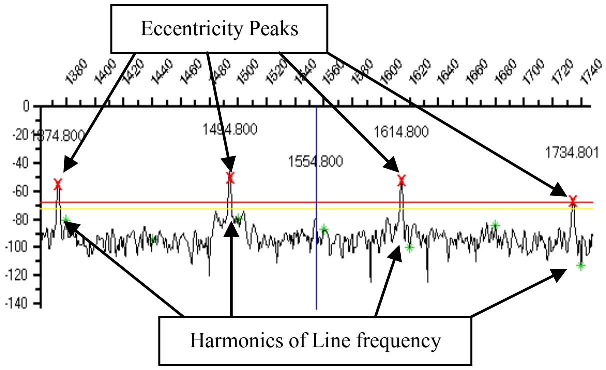

Figure 22. Side Band Peaks on the Spectrum

In Figure 22, the red X's indicate the eccentricity related peaks. The smaller green *'s indicate harmonics of line frequency. Eccentricity related peaks usually exist between 600 Hz and 2500 Hz on the current spectrum.

Rotor Influence Check

Alignment of the Inductance Waveform Peaks

An uneven alignment of the inductance waveform peaks is indicative of eccentricity. As eccentricity increases, the misalignment of the inductance waveform peaks will increase. See Figure 23.

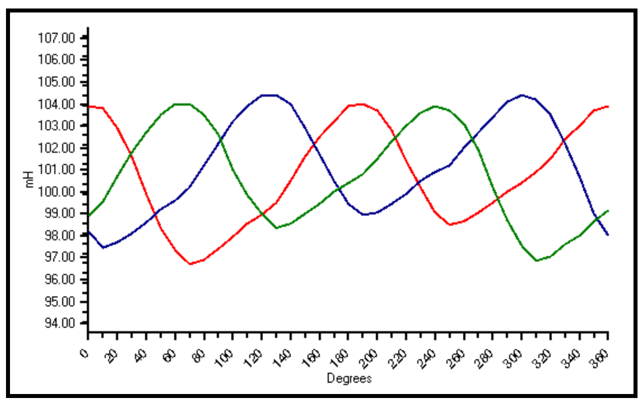

Figure 23. Eccentricity – Bowed Rotor

Peak-to-Peak Inductance

Peak-to-peak inductance for each individual phase will vary from one pole face to the next when there is eccentricity (See Figure 24). Each phase will have it's own minimum and maximum inductance values in a concentric wound motor.

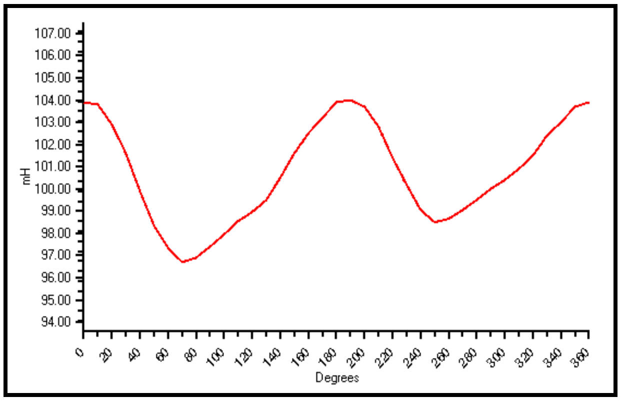

Figure 24. Peak-to-Peak Inductance Phase 1 to 2

Concentric vs. Lap Wound

An important consideration when evaluating RIC data for indication of eccentricity is whether the motor is concentric or lap wound. If a motor is concentric wound, it may be built with a pre-existing offset between the stator windings and the rotor. This results in a natural stair stepping indication of the phase-to-phase values seen in Figure 25.

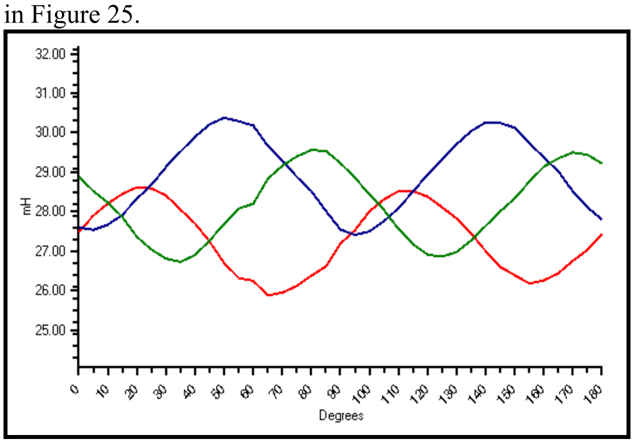

Figure 25. Concentric Wound Motor RIC Graph

Standard lap wound motor windings, typically have equal high/low inductance values.

Rules of thumb that should help identify whether a motor is concentric or lap wound. Please note that these are not absolute:

- If it is new and smaller than 50hp, it is very likely **concentric** wound.
- If it exhibits the pattern seen in Figure 25, it is very likely **concentric** wound.
- If it has been rewound at any size, it may be **lap** wound.

Figure 26 shows an example of dynamic eccentricity. Notice how the peak amplitudes of each phase vary from pole group to pole group as the rotor is rotated. Dynamic eccentricity is the more severe type of eccentricity due to the dynamic unbalance and the increased chance of a rotor/stator rub.

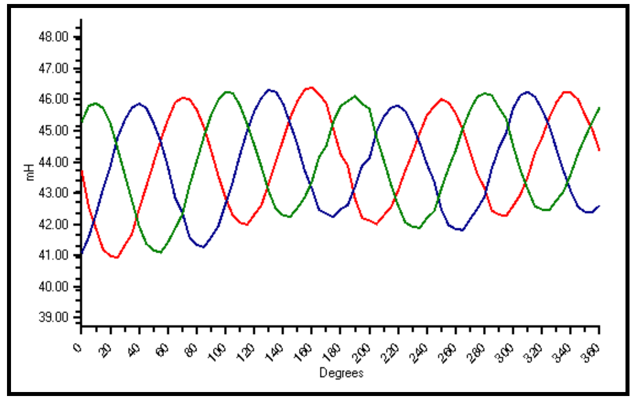

Figure 26. Dynamic Eccentricity

VII. SUMMARY

Using fault zone analysis approach provides a more complete analysis of motor health. This approach analyzes the Power Quality, Power Circuit, Stator, Air Gap, Insulation, and Rotor fault zones of your electric motor. All six fault zones should be analyzed to accurately assess the overall health of your motor.

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