ALL-TEST *Pro*, LLC.

ALL-TEST *PRO*® On-Line Series
Desk Guide and
Pattern Recognition Manual

2nd Edition

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Disclaimer

This Guidebook was designed to assist the user of the ALL-TEST *PRO*® OL series in the art of troubleshooting equipment using Electrical Signature Analysis. The recommendations are based upon available data at the time of this guidebook's development and have been found to be accurate with a high degree of confidence. Use of this guidebook or the information contained does not imply or infer warranty or guarantees in any form. Users of ALL-TEST*PRO* instruments are expected to observe the standards of safety for their company and/or country.

This Guidebook is designed to be a living document. Users are encouraged to provide test results and findings to:

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Introduction

The ALL-TEST *PRO*® On-Line series (ATPOL) online testing system is commonly referred to, within industry, as a Motor Current Signature Analysis (MCSA) device. This is, in fact, a misnomer. The ATPOL system is actually an Electrical Signature Analysis (ESA) device as it reviews all aspects of the electrical system.

The purpose of ESA is to view a number of critical elements within an electric motor system, as well as generator outputs, transformers, driven equipment, the distribution system, system efficiency, power quality and much more. The challenge has always been viewed as understanding the complex results of ESA and interpretation. When, in reality, neither are very complex.

The ALL-TEST *PRO*® On-Line series provides information and performs basic analysis functions automatically, relying on the user to spend a minimal amount of time analyzing data. Of course, the more experience and knowledge you have with electric motor systems and analysis, the more accurate you will be.

Much of ESA current signature (and voltage signature) data can be handled much like vibration data. Most of the faults are actually calculated in much the same way. On the electrical side of the spectrum, ESA provides quick, fairly early, detection of most faults while detecting faults in their later stages on the mechanical side. The opposite is true for vibration analysis.

This manual will be broken up into several sections:

1. Induction Motor Troubleshooting Procedure
2. Induction Motor Troubleshooting Analysis and Pattern Recognition
3. Induction Motor Trending Procedure
4. Induction Motor Comparative Analysis
5. DC Motor Testing Procedure
6. DC Motor Analysis and Pattern Recognition
7. Synchronous Generator Testing Procedure
8. Synchronous Motor Analysis and Pattern Recognition
9. Special Applications
10. Hints and Tips for a Faster Analysis

What are MCSA and ESA?

Motor Current Signature Analysis (MCSA) is a commonly mis-used term within industry. MCSA refers to the evaluation of current-waveforms only, including the demodulation of the current waveform and FFT analysis. Electrical Signature Analysis, on the other hand, is the term used for the evaluation of the voltage and current waveforms. This provides an increased advantage to diagnostics as power-related, motor-related and load-related signals can be quickly filtered. It also provides several unique abilities when related to power quality, DC motor analysis, generator analysis and other advantages. These will become obvious in this manual. However, we will use the terms interchangeably.

ESA is a system used for analyzing or trending dynamic, energized systems. Proper analysis of ESA results will assist the technician in identifying:

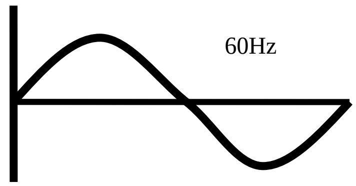
1. Incoming winding health
2. Stator winding health
3. Rotor Health
4. Air gap static and dynamic eccentricity
5. Coupling health, including direct, belted and geared systems
6. Load issues
7. System load and efficiency
8. Bearing health
9. Much more

(Note that all ESA systems are not the same and may be limited in performing the analysis cited here)

ESA uses the electric motor as a transducer, allowing the user to evaluate the electrical and mechanical condition from the Motor Control Center (MCC) or disconnect. For accurate analysis, ESA systems rely upon FFT analysis, much the same as vibration analysis. Most ESA systems also rely upon analysis of demodulated voltage and/or current, which involves the removal of the fundamental frequency (Line Frequency or LF).

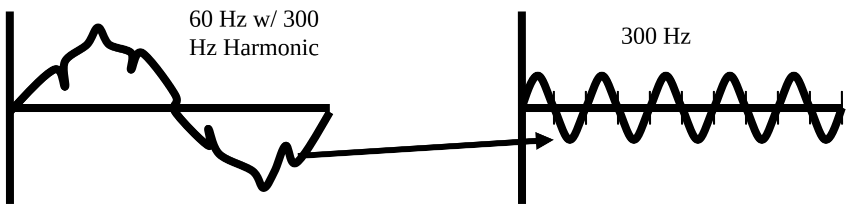
The frequencies found within the LF are used to identify faults. These frequencies are found as 'ripples' within the LF caused by incoming power or load-related (including motor condition-related) effects.

Figure 1: Line Frequency



If we take the frequency shown in figure 1 as the LF of the system, this would be a good or 'perfect' frequency. Now if we add a 'sub-harmonic' or a second frequency to the sine-wave, it will appear as shown in figure 2.

Figure 2: Line Frequency with Harmonic Content



If these frequencies are calculated by using FFT, the result will look like figure 3.

Figure 3: FFT Analysis

What could be causing these frequencies? How can they be determined? These answers are to be provided.

Alternating Current Induction Motors

Induction Motor Troubleshooting Procedure

In general, there are basic steps that can be used for accurate analysis using ATPOL. The steps are as follow:

1. Map out an overview of the system being analyzed.
2. Determine the complaints related to the system in question. For instance, is the reason for analysis due to improper operation of the equipment, etc. and is there other data that can be used in an analysis.
3. Take data (see procedure below).
4. Review and Analyze:
   a. Review the 10-second snapshot of current to view the operation over that time period.
   b. Review low frequency demodulated current to view the condition of the rotor and identify any load-related issues.
   c. Review high frequency demodulated current and voltage in order to determine other faults including electrical and mechanical health.

Testing Procedure:

Note: You are working with energized circuits when performing ESA. Ensure that you are following required industry and company-related safety programs and following safety-related information pertinent to the use of the associated test equipment.

1. Set up ATPOL data collector. Ensure Measure Mode is indicating Phase to Phase measurements.
2. Obtain information on the motor. At a minimum, include nameplate RPM, Voltage, Current and Horsepower/kW. When possible, the bearing information, number of stator slots and rotor slots will allow for a more accurate analysis.
3. Connect Voltage and Current Probes (following safety practices for your plant). If it is difficult to connect, the minimum required for motor analysis is A-Phase current. However, all data is required for ESA.
   a. Ensure current probes are set with the direction arrows in the same direction.
   b. If testing systems above 600 Volts, connect to CT's and PT's. Ensure that you obtain the CT and PT ratios.
4. Using the 'SETUP' button, ensure that Voltage and Current are properly connected. The values should show ~120 degrees. Use Voltage and Current buttons to view values.
5. Follow data collection procedure (See Attachment A)

6. Repeat for additional data or motors.
7. Upload Data for Analysis
    a. Upload using the Power System Manager module of EMCAT.
    b. Place data into an appropriately named folder
    c. Open data with the ATPOL software for troubleshooting.
    d. Use automated analysis (make sure to re-check using ‘eye’ icon)

Induction Motor Troubleshooting Analysis Overview

Most faults can be determined at a glance, with many rules being similar for both MCSA and vibration analysis. The basic rules for pattern recognition and troubleshooting are:

1. Pole Pass Frequency (PPF) sidebands around line frequency indicate rotor bar faults. The higher the peaks, the greater the severity of the fault.
2. Harmonic sidebands of PPF often relate to casting voids or loose rotor bars.
3. Non-PPF sidebands that cause a ‘raised noise floor’ around the line frequency peak normally relate to driven load looseness or other driven problems.
4. ‘Raised noise floor’ signatures relate to such things as looseness or cavitations.
5. Peaks that show in current and voltage relate to electrical issues, such as incoming power. Peaks that show in current only relate to winding and mechanical faults.
6. Peak pairs that do not relate to running speed or line frequency are most often bearing related problems.

Power Quality and Electrical Analysis

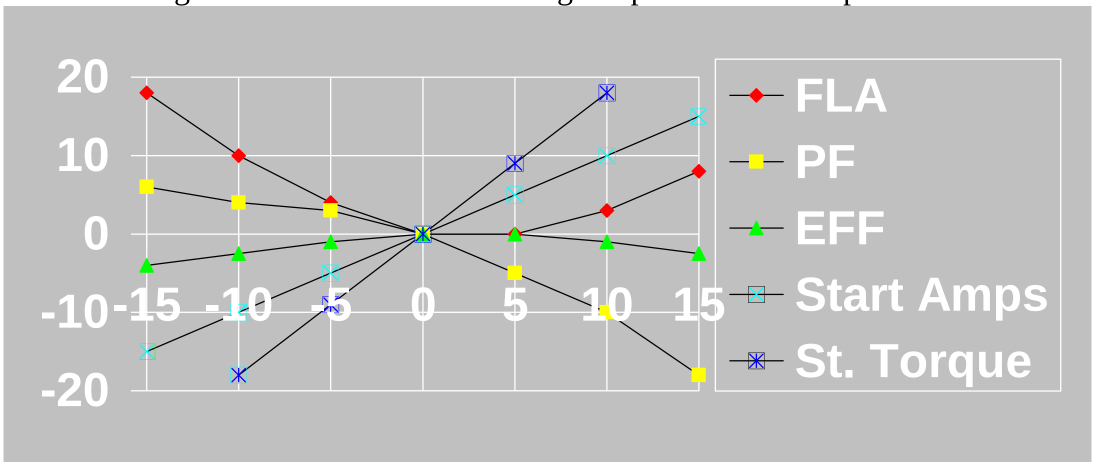
Power quality involves the condition of power supplied to the motor system. In a perfect world, the supply power will have a perfectly balanced voltage and current sine-wave. However, rarely, if ever, will you find a 'perfect' system. Power quality, alone, will be covered more in-depth in a following guide. We shall cover the more common issues that meet the requirements of this guide here.

The most common power quality issues and limits are:

1. Voltage quality: In an electric motor system there are two primary issues with voltage:

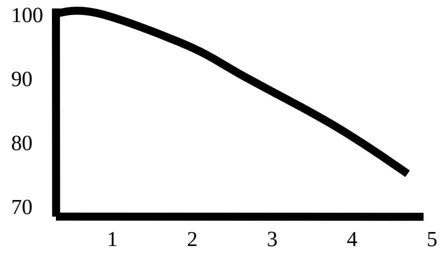
Over or under voltage or voltage deviation from nameplate. The limits on supply voltage re +/- 10% of nameplate voltage with+/- 5% being optimal. Deviation from nameplate will result in changes to the motor operating characteristics as identified in figure 4.

Figure 4: Over and Under Voltage Impact on Motor Operation



Voltage unbalance, which causes unbalanced current in the motor resulting in overheating of the winding. The relationship of voltage and current unbalance can be a few to over 20 times, depending on the motor size and winding design. As a result, identifying voltage unbalance has more of an impact than identifying current unbalance, alone. The limit is 5% with 2% being optimal. The increased heating of the motor windings requires de-rating of the motor load as shown in figure 5.

Figure 5: Voltage Unbalance (Derating Factor)



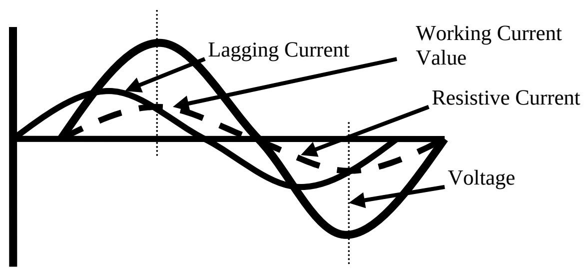
2. Harmonic distortion is another area of concern and is normally caused by electronic switching systems which cause standing, negative and positive rotating fields within the motor. Single phase systems, such as computers and electronic lghting ballasts, cause neutral, or third, harmonics that result in neutral currents and transformer heating. Fifth and seventh harmonics are

caused by three phase systems, such as variable frequency drives, and cause motor stator and rotor heating. There are two major players in system power harmonics:

2.1. Voltage harmonics are of concern with a recommended limit of 5% THD (Total Harmonic Distortion) per IEEE Std. 519.
2.2. Current harmonics are considered far more serious with a recommended limit of 3% THD per IEEE Std. 519.

3. Power factor is represented, in an inductive circuit, as how the peak current lags behind the peak voltage. The result is additional current requirements for the same load as current lags further behind voltage (ref figure 6). The optimal is a factor of '1,' however, in most systems a power factor of 0.85 is considered OK.

Figure 6: Power Factor

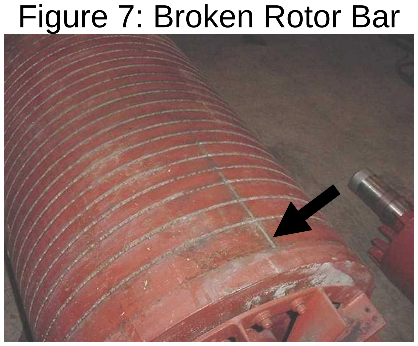


Rotor Analysis

One of the primary strengths of MCSA is rotor analysis. Broken rotor bars, static eccentricity and dynamic eccentricity are three basic types of rotor issues that MCSA can evaluate.

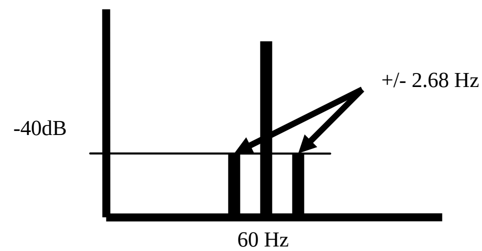
Broken rotor bars are generally found as slip frequency sidebands around the fundamental frequency. The standard rule of thumb is that faults are detected when these sidebands meet or exceed -35db (often referred to as '35 dB down').

Figure 7: Broken Rotor Bar



For example, a motor running 1760 RPM in a 60 Hz system would have a running frequency of 1760 RPM/60 sec/min = 29.33 Hz. The slip frequency would be ((2*LF)/poles = (2*60 Hz)/4 poles = 30Hz (synchronous speed) then 30Hz - 29.33 Hz (running speed) = (0.67 Hz * 4 poles) = 2.68 Hz. If 2.68 Hz sidebands occur around the 60 Hz FFT peak and they were to have a value of -40 dB, then broken rotor bars exist.

Figure 8: Example of Broken Rotor Bar Sidebands

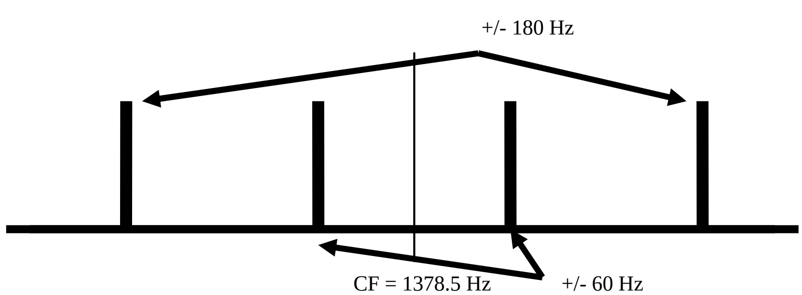


Static eccentricity can be found in the high frequency spectrum. Static eccentricity occurs where the Center Frequency (CF - Definition: The rotor bars times running speed and stator slots times running speed are often referred to as CF. CF's are not peaks in the spectrum but are made up as (frequency + frequency)/2) CF = Running Frequency (RF) * the number of rotor bars (RB) with line frequency times N sidebands, where N is an odd integer.

Formula 1: Static Eccentricity = (RB * RF) +/- (N * LF), where N = odd integer

For example, if the 1760 RPM motor, cited earlier, was known to have 47 RB, the base frequency would be: 29.33 Hz * 47 RB = 1,378.5 Hz CF with 60 Hz, 180 Hz, etc. Sidebands (reference figure 8).

Figure 8: Static eccentricity



Dynamic eccentricity differs from static eccentricity only in that there will also be running speed sidebands around the static eccentricity sidebands of the base frequency as shown in figure 9.

Figure 9: dynamic eccentricity

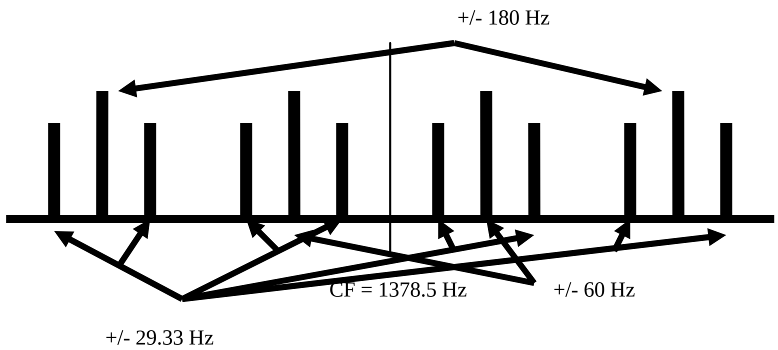


Table 1: Rotor Analysis[1]*

Condition	dB Value	Rotor Condition	Action
1	>60	Excellent	None
2	54-60	Good	None
3	48-54	Moderate	Trend
4	42-48	Rotor Fracture or High Resistance Joint	Increase Test Intervals and Trend
5	36-42	Two or more bars cracked or broken	Confirm with motor circuit analysis
6	30-36	Multiple cracked or broken bars and end ring problems	Overhaul
7	<30	Multiple broken rotor bars and other severe rotor problems	Overhaul or Replace

*Note: Values measured through CT's may show dampened results. Results might be more severe in these cases.

Table 1 indicates severity of rotor condition based upon the dB value difference of the peak current (0 dB) and the PPF sidebands. The dB value is counted down from the top, resulting in the common phrase 'dB down' which relates to the values of the height of the sideband peaks to the peak current.

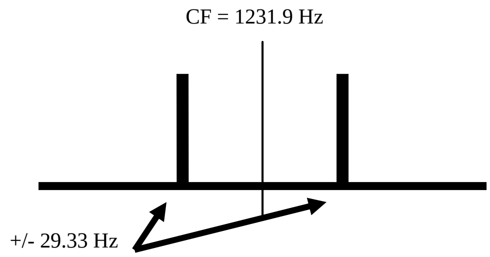
[1] Don Ferree, Framatome

AC Motor and Stator Analysis

Stator winding problems are found by first identifying stator slot passing frequencies (SP). CF is found by multiplying the number of stator slots by the running speed. Problems are found when sidebands appear around the SP CF.

For example, the running speed of 29.33 Hz * 42 Slots = 1,231.9 CF. If the CF has sidebands of running speed, then stator mechanical or electrical degradation has occurred.

Figure 10: stator passing frequencies



Mechanical imbalance is found by determining the RB * RS center frequency, as in static and dynamic eccentricity, 47 RB * 29.33 Hz RS = 1,378.5 Hz. There will be LF sidebands around the CF, then a space of four times LF, then two 2*LF peaks. You may also see a heightened running frequency peak.

The pattern to view is twice line frequency, four times line frequency, twice line frequency. In a 60 Hz system, this will appear as 120 Hz, 240 Hz, 120 Hz.

Figure 11: Mechanical Imbalance

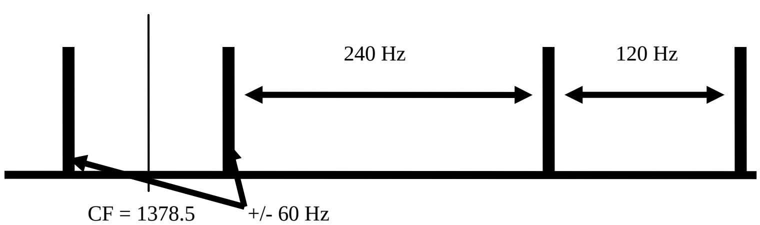
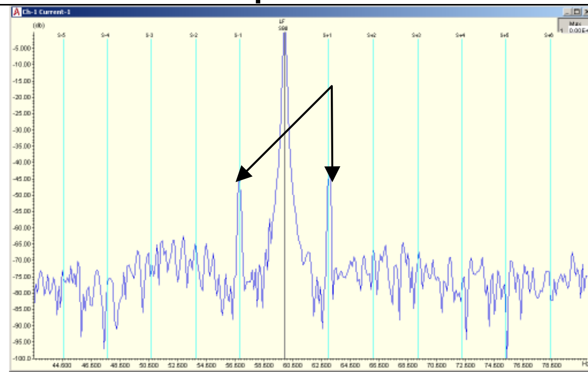
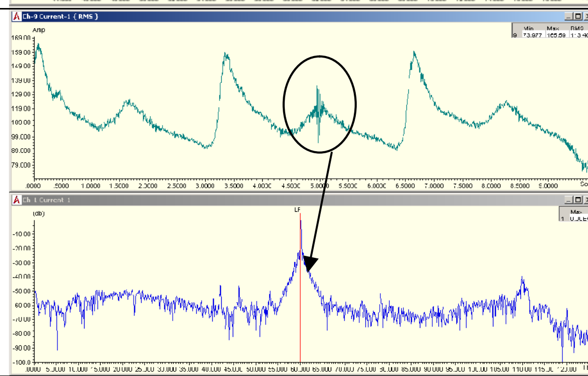
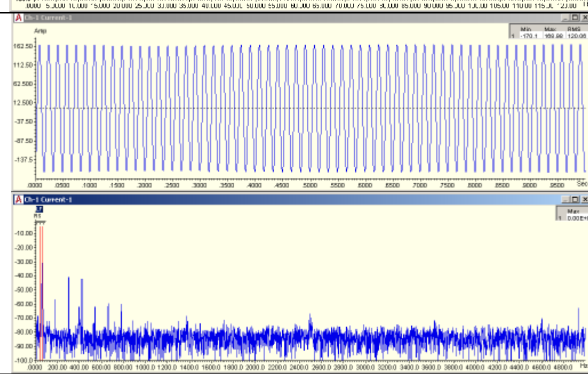
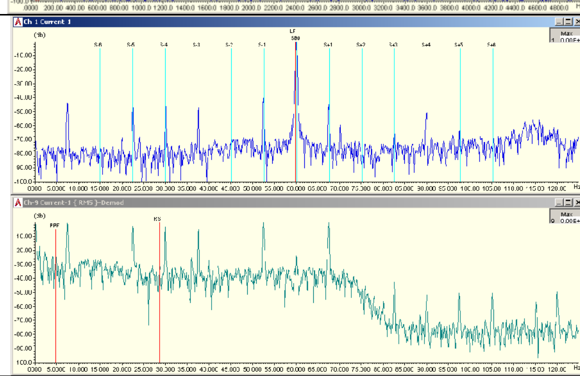


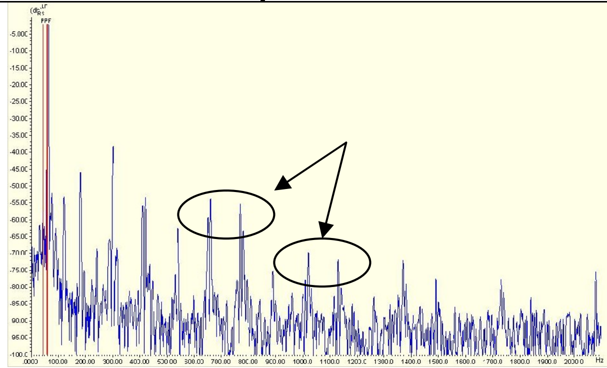
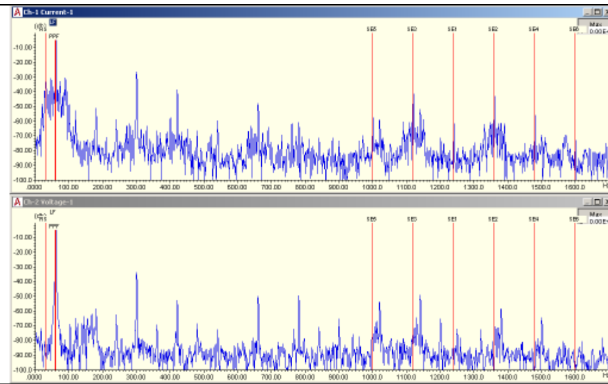
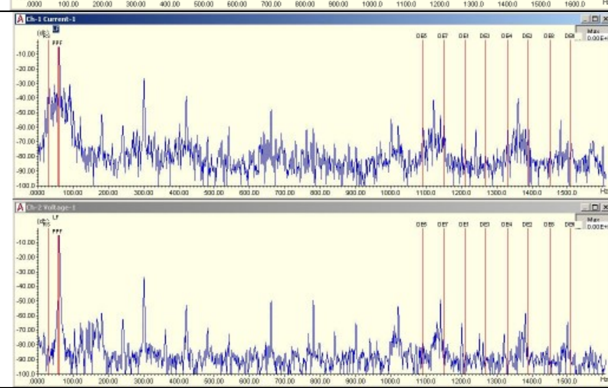
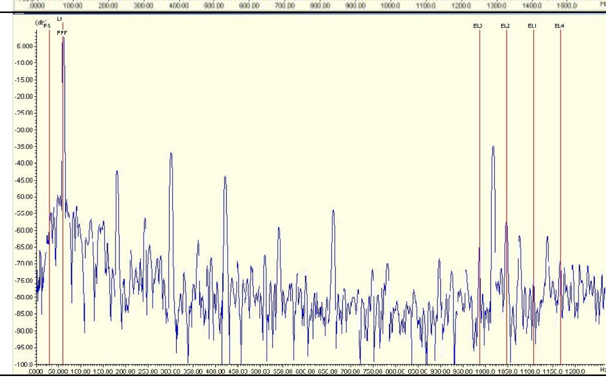
Table 2: Motor Fault Signatures

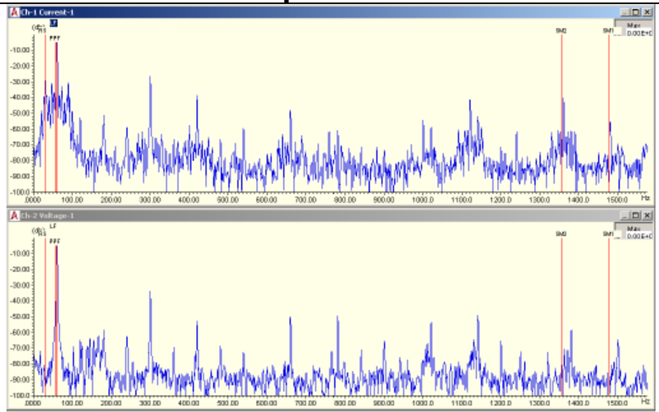
Type of Fault	Pattern (CF = Center Frequency)
Stator Mechanical (ie: loose coils, stator core movement, etc.)	CF = RS x Stator Slots Line Frequency Sidebands
Stator Shorts (shorted windings)	CF = RS x Stator Slots Line Frequency sidebands with Running Speed sidebands
Rotor Indicator	CF = RS x Rotor Bars Line Frequency sidebands
Static Eccentricity	CF = RS x Rotor Bars Line Frequency and twice Line Frequency sidebands.
Dynamic Eccentricity	CF = RS x Rotor Bars Line Frequency and twice Line Frequency with Running Speed sidebands
Mechanical Unbalance (and Misalignment)	CF = RS x Rotor Bars Line Frequency Sidebands, Space of four times Line Frequency then two Line Frequency peaks

AC Motor Patterns

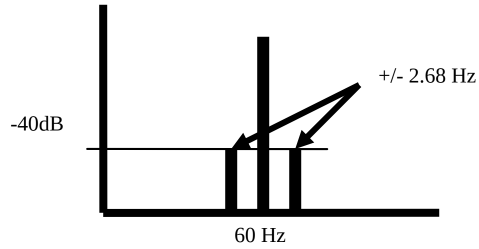
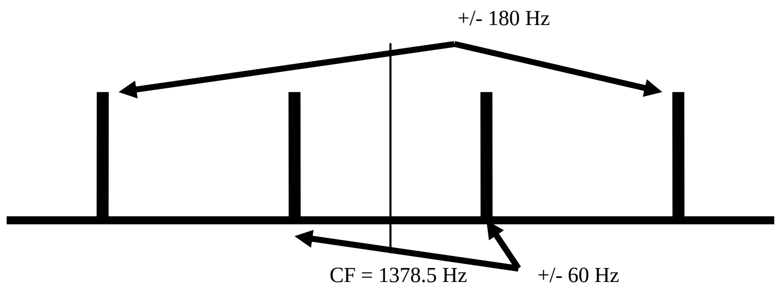
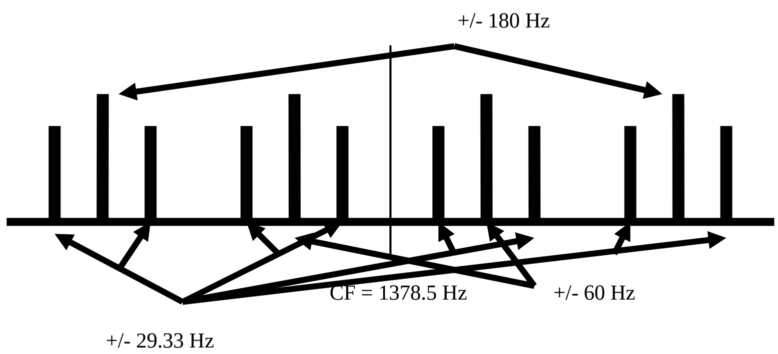
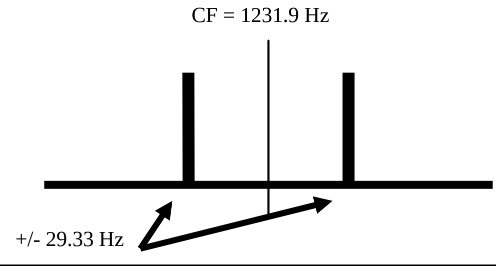
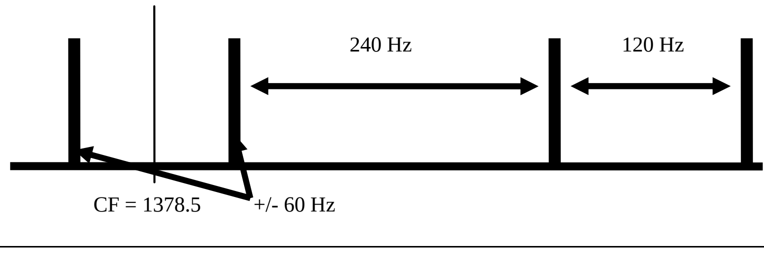
Table 3: AC Motor Patterns

Fault	Description	Sample Pattern
Rotor Bars	PPF peaks around Line Frequency in Current Confirm with MCA	
External Looseness such as bad gear teeth	Raised Noise Floor around line frequency	
Good Results	Few Peaks in High Frequency and Low Frequency spectra	
Rotor Rub	PPF Sidebands in Low Frequency current and high running speed peak with PPF sidebands with harmonics. Confirm eccentricity with MCA	

Fault	Description	Sample Pattern
Mechanical Unbalance	Running speed times rotor bars with line frequency sidebands, a spacing of 4 times line frequency, then two times line frequency. Usually also accompanied by a high running speed peak in low frequency.	
Static Eccentricity	Running speed times rotor bars with line frequency and twice line frequency sidebands. Confirm with MCA	
Dynamic Eccentricity	Running speed times rotor bars with line frequency and twice line frequency sidebands.	
Stator Electrical	Running speed times stator slots with line frequency sidebands which then have running speed sidebands. Confirm with MCA	

Fault	Description	Sample Pattern
Stator Mechanical	Running speed times stator slots with line frequency sidebands. Raised noise floor also indicates later stage of looseness. Test with MCA to measure possible insulation damage.	

AC Induction Fault Pattern Charts part 2

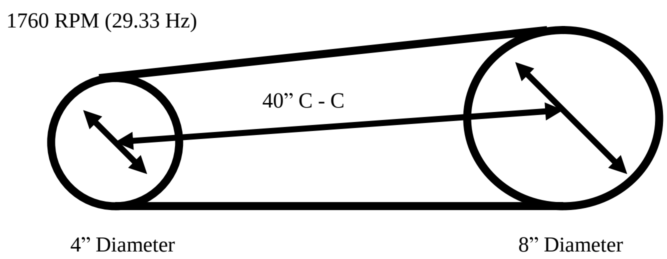
Fault	Pattern
Broken Rotor Bars	
Static Eccentricity	
Dynamic Eccentricity	
Stator Electrical	
Mechanical Imbalance	

Driven Equipment Evaluation

Driven equipment frequencies can also be detected. We will cover belted, geared, direct drive and fans and impellors in this section.

Belts

Figure 12: Belts and Sheaves



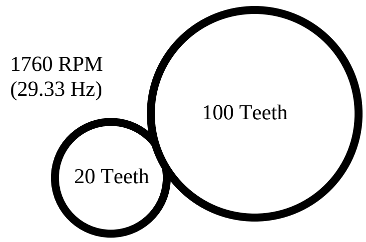
In order to determine the frequencies associated with the system identified in figure 13, there are several steps. In this example we shall identify the motor speed as 1760 RPM (29.33 Hz), one 4 inch (driver) and one 8 inch (driven) diameter sheave with a 40 inch center to center sheave distance.

Step 1: Determine the driven shaft speed by determining the sheave ratios. In this case, it will be RS * (driver dia/driven dia) = 1760 RPM * (4 inch/8inch) = 880 RPM which is 14.67 Hz.

Step 2: Determine the belt speed by determining the belt length which is equal to: (center to center distance (C-C) * 2) + ½((driver” * π) + (driven” * π)) = (40” *2) + ½((4” * π) + (8” * π)) = 97.28”. Next, the surface (conveyor) speed can be determined by calculating the conveyor speed for either sheave. In this case, we can use the motor sheave and calculate (radius * 2π * RPM) = 2” * 2π * 1,760 RPM = 22,117 inches per minute (IPM) or 368.6 inches per second (IPS). The belt speed can then be determined by taking the conveyor speed and dividing it by the belt length. In this case, 368.6 IPS / 97.28 inches = 3.79 Hz.

Gear Mesh

Figure 13: Gear Mesh



The driven shaft speed in a geared system is fairly straight forward to determine, as well as the gear mesh frequencies.

The driven shaft speed can be determined by multiplying the driver speed times the ratio of the driver gear to the driven gear number of teeth: Driven = 29.33 Hz * (20 Teeth/100 Teeth) = 5.87 Hz.

The gear mesh frequencies are determined by taking the running speed times the number of teeth. The value is the same for either geer: Gear Mesh = 29.33 Hz * 20 Teeth = 587 Hz. Sidebands around this CF would indicate gear mesh problems.

Driven Equipment – Blade Pass Frequencies

As with calculating the driven speed in a geared system and gear mesh, calculating blade pass frequencies for either fans or impellors is straight forward: The number of blades multiplied by the shaft speed.

In the direct drive system used in the previous examples, the operating speed is 29.33 Hz. A pump with six blades would have a blade pass frequency of 29.33 Hz * 6 Blades = 175.98 Hz.

If it was a fan with 12 blades using the pulley system in the belts section of the previous example, the blade pass frequency would be 14.67 Hz * 12 Blades = 176.04 Hz.

Faulty impellors or blades would be indicated at these frequencies and may include sidebands. The frequencies and harmonics remain the same regardless of how many blades have faults.

Induction Motor System Trending Procedure

Induction motor ESA is a trendable analysis system. The key to trending is to compare older data to newer data.

1. Set up folder(s) for the motors to be uploaded.
2. Place nameplate information in each folder and set up as a default (See attachment for Creating a Database).
3. Collect data and upload
4. Compare earlier test data to new test data by using the FILE, COMPARE feature. Changes to the signature over time will show up as increases to existing frequency peaks or new frequency peaks.

Quick Procedure for Collecting Large Amounts of Data

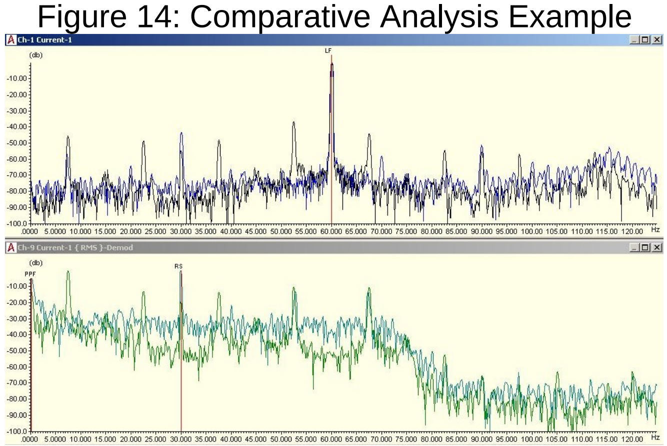
When collecting a large amount of data, for instance from a motor control center, you can operate the ATPOL unit directly from the Power System Manager via your laptop and mouse. Data can be uploaded following each set of data collected, directly into the appropriate folder(s).

1. Open Power System Manager software
2. Connect ATPOL unit to laptop – total distance from test point 14-15 feet
3. Using the instrument icon, operate the ATPOL from the laptop. All buttons are duplicated on the unit and the unit display shows on the screen.
4. Move data directly to the appropriate folder.

Comparative Analysis

The ATPOL system allows for directly comparing any two sets of data. This can be used to compare a known ‘good’ motor to an unknown motor.

Figure 14: Comparative Analysis Example



DC Electric Motors

Direct Current electric motor analysis utilizes a simple concept – form factor analysis (AC ripple). The output of a rectified DC drive leaves an AC ripple at the top of the DC voltage and related current. The armature is actually also an AC circuit in that, as the armature turns, current flows through conductors in one direction, then in the other. As a result, for the purposes of DC Electrical Signature Analysis, we will analyze the demodulated AC ripple and resulting voltage and current FFT's. In addition, because there is no 'slip,' there is no CF and the calculated frequencies are what will appear in the signature.

DC Motor Testing Procedure

Following is the procedure for testing DC motors. To view the actual current value, the DC Hall-Effect CT is required. The 0.1 to 100 Amp AC CT's may be used for accurate analysis, as well. However, the AC ripple will be the only component of current evaluated.

1. Obtain field and armature nameplate voltage, horsepower, RPM and current values
2. Change the Setup frequency on the ATPOL unit to '60 Hz and DC' (or '50 Hz and DC').
3. Clip the Va voltage probe to the positive armature lead and the Vb lead to the negative armature lead.
4. Place the Ia CT with the CT arrow facing towards the DC drive.
5. Note voltage and current using the appropriate selections on the ATPOL.
6. Take data following the standard operating procedure for the ATPOL.
7. Upload data using upload procedures. Ensure to select the DC motor selection in the header screen of the ATPOL software.

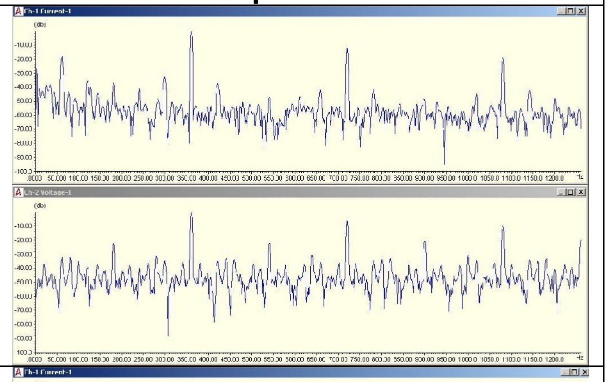
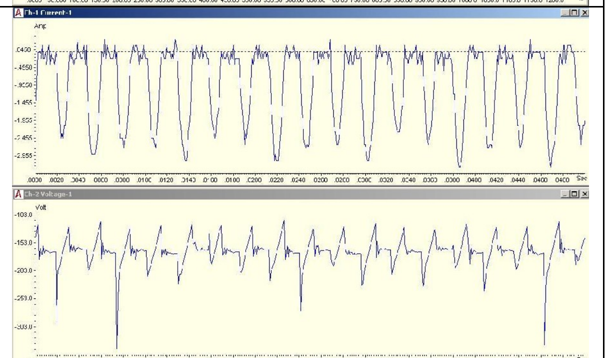
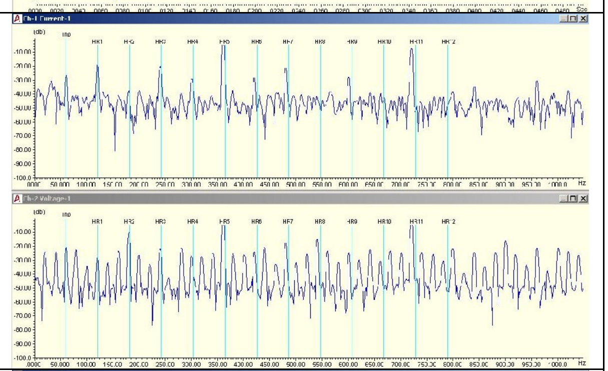
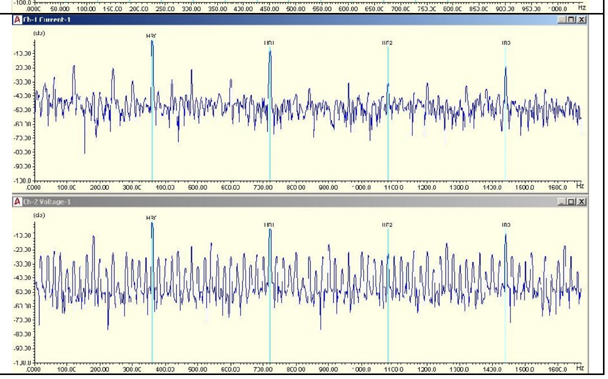
DC Motor Analysis and Pattern Recognition

Pattern recognition is similar to the signatures evaluated using vibration analysis.

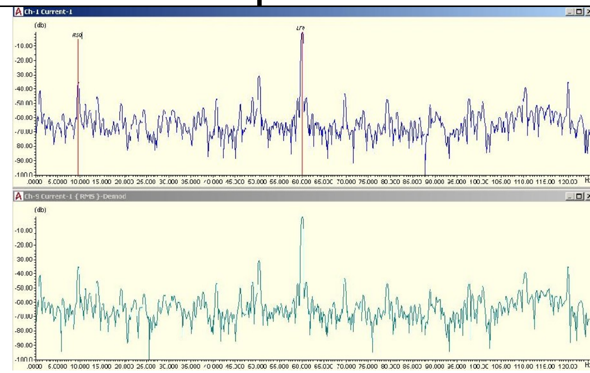
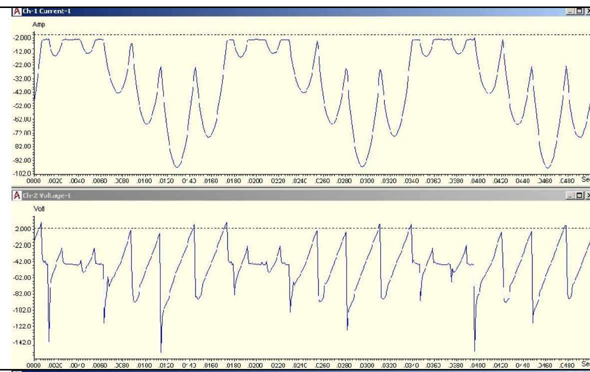
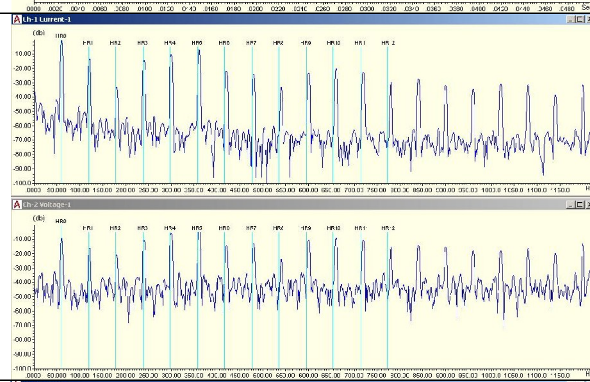
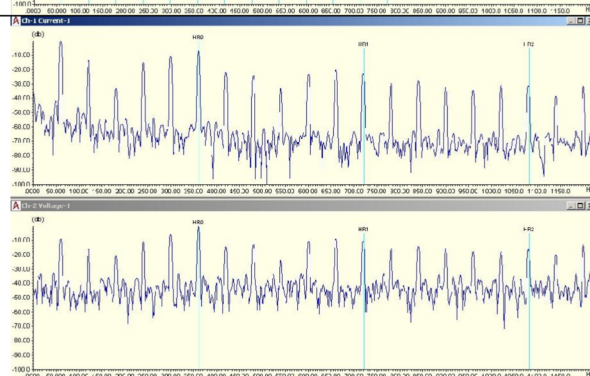
1. Determine DC motor speed through calculating (voltage/nameplate voltage) times nameplate RPM.
2. View the low frequency data. Note the demodulated current and current values.
    a. Place an RS cursor at the estimated running speed. There may be a peak at the actual value.
    b. Print the spectra.

3. View the high frequency data.
    a. Note the voltage and current waveforms and view for a repeating pattern.
    b. Non-repeating or odd patterns will denote problems with the DC drive.
4. View the voltage and current FFT's.
    a. Zoom in to 1200 Hz
    b. Place cursor on line frequency peak (ie: 60 Hz) and create harmonic cursors.
    c. Print waveforms
    d. Place cursor on (number of SCR's times line frequency) drive frequency and create harmonic cursors.
    e. Print waveforms.
5. Analyze printed waveforms.

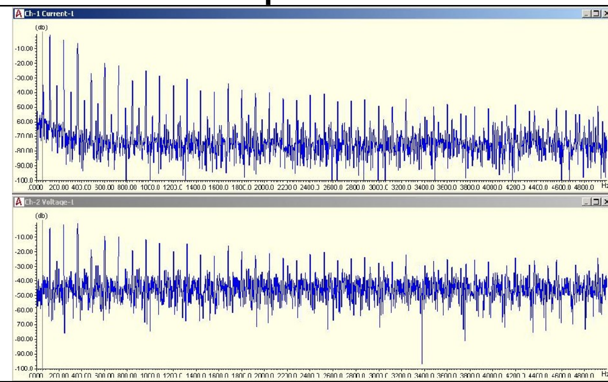
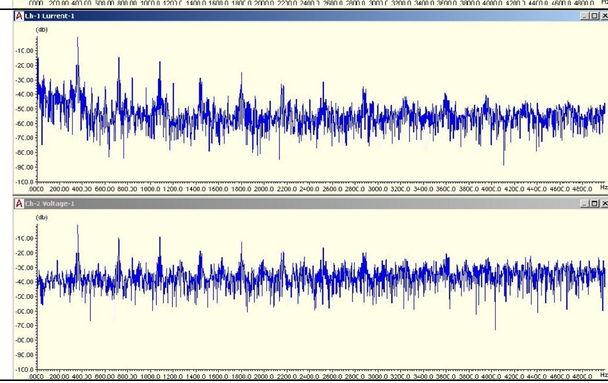
DC Troubleshooting Patterns

Fault	Description	Sample Pattern
Good DC Pattern	RPM, line frequency and SCR frequency. When harmonics of line frequency or SCR frequency exist, Trend. High running speed peaks indicate misalignment or mechanical imbalance (<50 dB)	
DC Drive Problem 1 Loose connections or firing card.	Consistent pattern with ragged peaks in voltage and current indicated loose connection or firing card problem.	
	Also, large number of voltage harmonics of line frequency	
	And SCR Frequency. Check for loose connections. If a comparable motor or previous MCA reading exists, evaluate circuit with MCA to confirm or eliminate connection as problem.	

DC Signatures Continued

Fault	Description	Sample Pattern
DC Drive Problem 2 Faulty SCR's – Severe "AC Blow-By"	SCR's not properly gating and excessive AC voltage is introduced to the armature. A high Line Frequency peak will show in low frequency data and high running speed peak will show due to resulting vibration. Line frequency will also show running speed sidebands in severe conditions. This fault results in early armature winding failure and excessive brush wear.	
	Note voltage and current patterns are inconsistent.	
	Extremely high line frequency peaks in high frequency data and multiple harmonics. Meets similar dB level as SCR frequency.	
	And significant SCR frequency harmonics. Troubleshoot SCR's and firing circuit.	

DC Signatures Continued

Fault	Description	Sample Pattern
Bad Armature Circuit: Commutator, Brushes and/or Faulty Armature	This pattern shows as alternating high and low line frequency and SCR frequency harmonics throughout the Current FFT. Brush or commutator wear will also show raised noise floors around line frequency peaks.	
Worn Brushes and Commutator or looseness in load	This pattern shows a raised noise floor around SCR frequencies with sidebands of running speed. Check for brush or commutator wear, if OK, then problem is in load.	

Synchronous Generators

The evaluation of AC generators is not as difficult as many think. It just requires the analyst to view things in reverse and requires voltage FFT analysis capabilities, as those found in the ATPOL unit. Electrical Signature Analysis is the only online technology capable of evaluating generators, accurately, for complete circuit and mechanical faults. Instead of looking to current, you must perform the same analysis that you would perform with current using voltage.

Synchronous Generator Testing Procedure

The standard procedure is the same as testing AC induction motors (see AC induction motor procedure). However, you will need to note the following:

- The number of rotor field coils, which should match the number of poles of the generator.
- Point at which you are testing and controls in the circuit. For instance, capacitors and other control components towards the generator will show as voltage frequencies, components away from the generator and test point will show as current.
- Machine type driving the generator as diesel engine, turbines and other drivers will have frequencies within voltage.

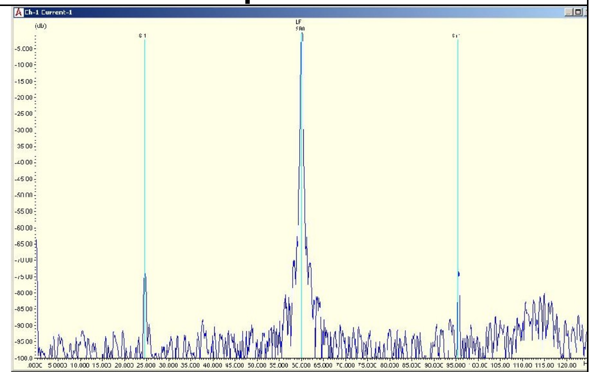
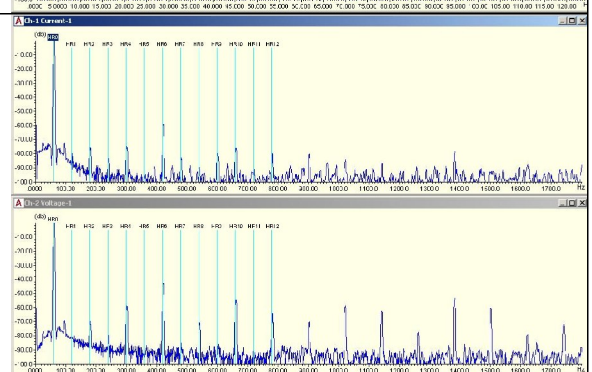
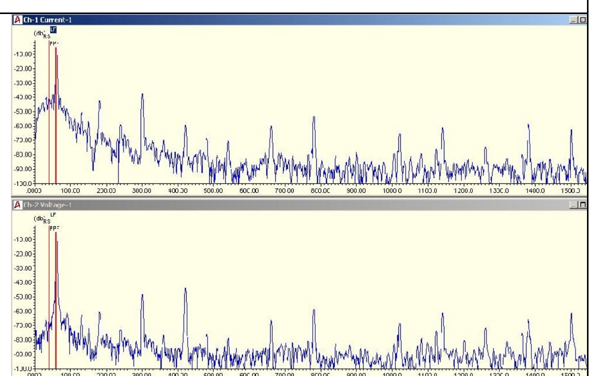
Synchronous Generator Analysis

Readings detected in current that relate to the generator are actually the reflection of voltage signatures due to the circuit impedance. This makes accurate analysis of generators with current signatures extremely difficult. The most accurate method is to use voltage FFT and use current only to assist in determining the severity of the faults detected. Stator faults are detected the same as AC motors, however in voltage vs current. The rotating fields, on the other hand, require some special attention:

Rotating Field Analysis

Rotating field faults will show as the number of poles times line frequency with line frequency sidebands in voltage. Severe faults may also show sidebands around the line frequency (in low frequency) of the number of poles times the number of field coils. These problems will indicate magnetic-field related issues such as eccentricity, shorted fields or uneven field poles. MCA can be used to confirm the condition of the fields.

Synchronous Generator Signatures

Fault	Description	Sample Pattern
Rotating Field Faults	Reflected sidebands of the number of field poles times the number of poles of the generator indicate severe rotor issues as amplitudes exceed -55dB. This sample pattern shows 6-pole times 6-field coil sidebands around 60 Hz.	
	Line frequency sidebands, in the high frequency voltage FFT, of the number of field coils times the line frequency indicate rotating field problems. May be due to eccentricity, field coil faults, etc. Eccentricity will also show a running speed peak in voltage FFT. Use MCA or voltage drop test to determine cause.	
Load Related Faults	These will show as a raised noise floor around line frequency for looseness and other current frequencies for related faults. Note the raised noise floor in current versus voltage – any problem is related to the load.	

Special Applications

Special applications include variable frequency drives, machine tool motors, synchronous motors, etc. As the applications are numerous and varied, this chapter will be updated frequently.

Variable Frequency Drives

Variable frequency drives (VFD's), also referred to as 'Adjustable Speed Drives,' 'Inverters,' etc., provide a unique set of rules for analysis. In particular, Pulse Width Modulated (PWM), which will be covered here, generates a greater amount of 'noise' into the system making analysis a little more interesting.

The ATPOL system will allow you to view and determine the condition of the motor AND some basic drive troubleshooting capabilities. Issues that can be evaluated:

- ✓ Mis-firing IGBT's
- ✓ Poor grounding system
- ✓ Some causes of shaft currents
- ✓ Excessive harmonics

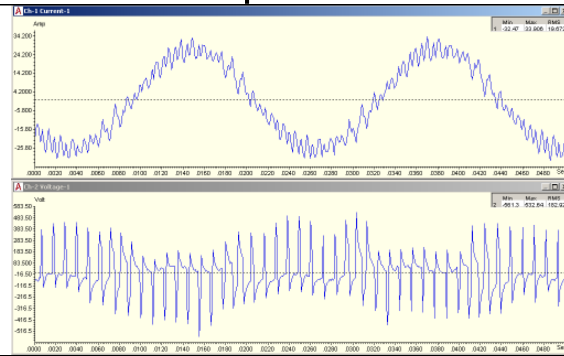
The procedure for testing is the same as AC induction motors. However, you want to make sure to test from the output of the VFD. If a problem exists, and bypass is available, you can isolate the problem from the drive and motor by switching to bypass to see if the signature goes away. If it does, the problem is a result of the drive, if not, it is a problem with the motor.

Analyzing VFD Signatures

The analysis of faults within the VFD system is similar to that of the analysis of AC induction motors, all of the same rules apply. However, there are a few additional items to consider:

- ✓ High frequency voltage in the high frequency data screens should be steady and not vary. If the pattern looks sinusoidal and opposite that of current, then a poor or noisy ground exists.
- ✓ Sidebands and multipliers will change based upon the output frequency of the drive. For instance, if the motor is running at half speed in a 60Hz system, the current fundamental frequency will be about 30 Hz.
- ✓ Non-symmetrical voltage pulses will indicate issues within the VFD itself.

VFD Signature Analysis

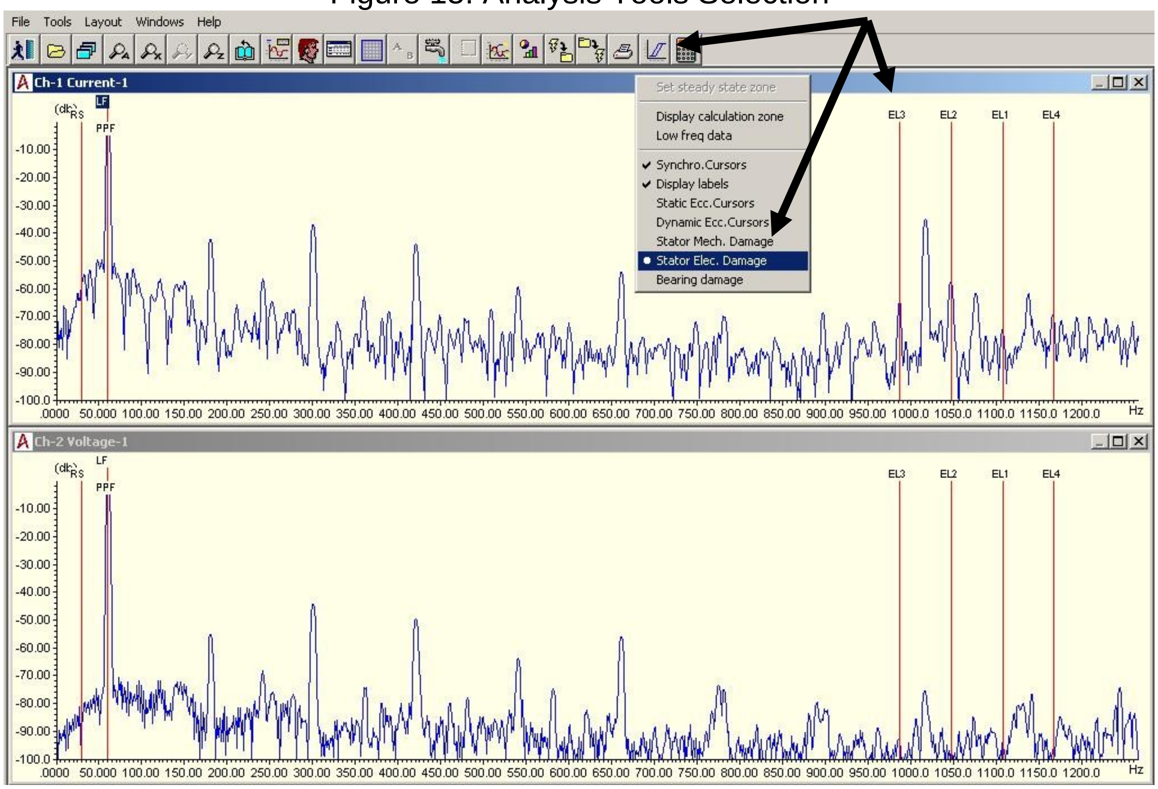
Fault	Description	Sample Pattern
Poor or Noisy Ground	Voltage and Current Oppose Each Other. Voltage should be constant. Corrected by correcting ground circuit.	

Hints and Tips for Faster Analysis

There are a number of simple steps to improve your analysis.

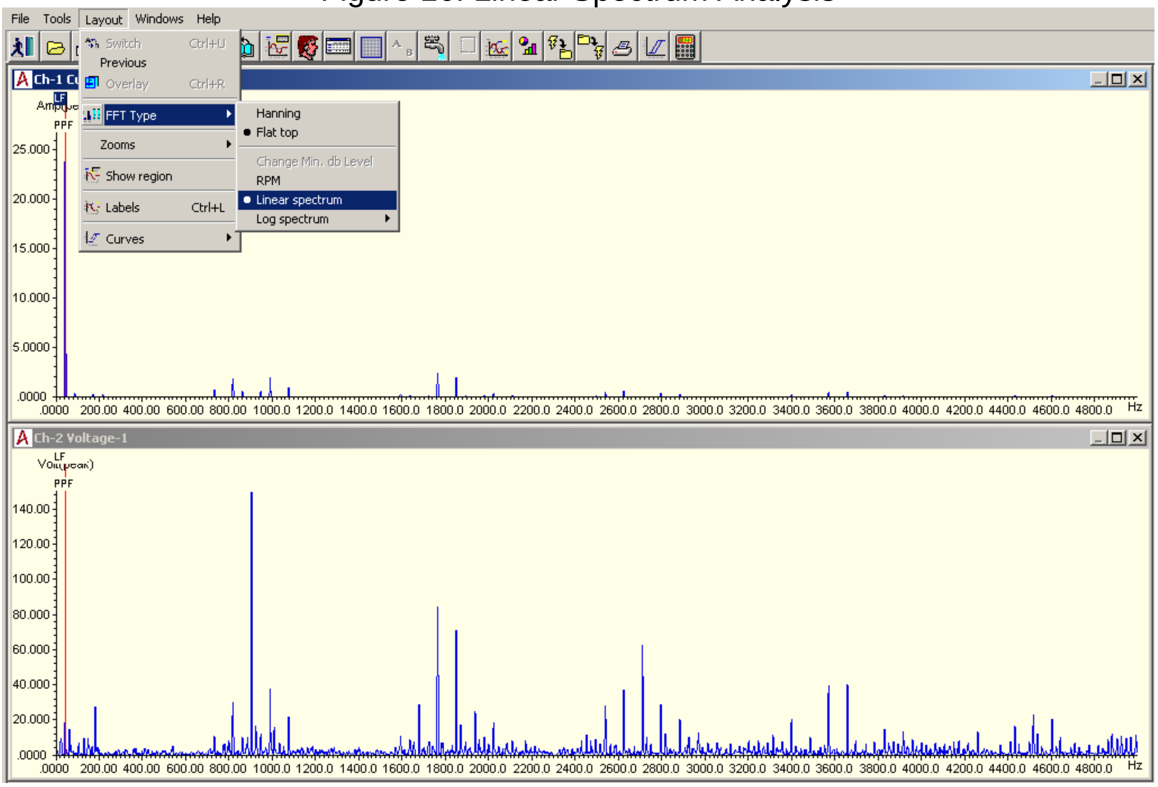
✓ With AC Induction Motors, upload the data, enter information and then print out the trouble report. Check the trouble report against the signatures by using this manual and the 'ANALYSIS TOOLS' button in the high frequency data. This will provide a drop-down list of potential problems and will place red cursors in the spectra where the software feels that a signature exists. If more than two lines fall on the peaks of the fault frequencies, then a fault exists. See Figure 15.

Figure 15: Analysis Tools Selection



✓ The 'LAYOUT' – 'FFT TYPE' – 'LINEAR SPECTRUM' selection allows you to view if the dominant frequencies are present in voltage or frequency (incoming power related frequencies or motor/load related frequencies). This can eliminate a fair amount of analysis time. For instance, Figure 16 shows the Linear Spectrum for a variable frequency drive that was being considered whether a problem was related to the drive or motor. In this case, the dominant frequencies from the fundamental are in voltage and, therefore, the problem is most likely coming from the VFD.

Figure 16: Linear Spectrum Analysis



The Multi-Technology Approach to Motor Diagnostics

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Introduction

Over the years, some manufacturers of Conditioned Based Monitoring (CBM) equipment have suggested that their equipment can be used to evaluate the health of an entire electric motor system. In reality, no single instrument will provide the user with every piece of information they need. The 'Holy Grail' of CBM and reliability does not exist. However, through an understanding of the electric motor system and the capabilities of multiple CBM technologies, you can achieve a complete view of your system and its health. Moreover, the user can have confidence in estimating time to failure when making recommendations to management.

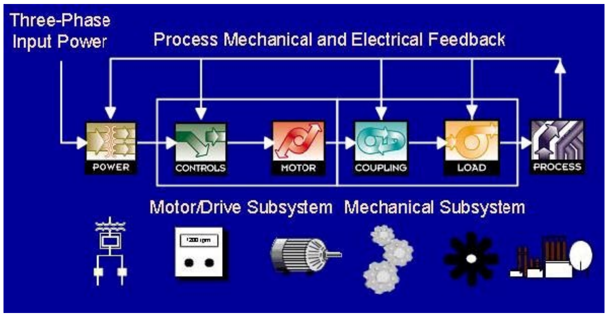
The purpose of this paper is to: 1) Outline the components of an electric motor system; 2) Discuss the modes of failure of each major component; 3) Discuss how each of the major technologies address each component; 4) Discuss how the technologies can be integrated for a complete view of the system; 5) Discuss the bottom-line impact of the Multi-Technology approach. The types of CBM equipment to be reviewed are standard off-the-shelf Technologies.

The Electric Motor System

The electric motor system involves far more than just the electric motor. In fact, it is made up of six distinct sections, all with their different failure modes. The sections are (Figure 1):

- The facility power distribution system which includes wiring and transformers.
- The motor control, which may include starters, soft starts, variable frequency drives and other starting systems.
- The electric motor – A three phase induction motor for the purpose of this paper.
- The mechanical coupling, which may be direct, gearbox, belts or another coupling method. This paper will focus on direct coupling and belts.
- The load refers to the driven equipment such as a fan, pump, compressor or other driven equipment.
- The process, such as waste-water pumping, mixing, aeration, etc.

Figure 1: The Motor System



Most will view individual components of the system when troubleshooting, trending, commissioning or performing some other reliability-based function related to the system. What components are focused on depends upon several factors, which include:

- What is the experience and background of the personnel and managers involved? For instance, you will most often see a strong vibration program when the maintenance staff is primarily mechanical or an infrared program when the staff is primarily electrical.
- Perceived areas of failure. This can be a serious issue depending upon how the motor system is perceived and will deserve more attention to follow.
- Understanding of the various CBM technologies.
- Training. But since when is training ever not an issue?

The perceived areas of failure provide an especially serious problem when viewing the history of your motor system. Often, when records are produced, the only summary might state something like, “fan failure, repaired,” or “pump failure, repaired.” The end result is that the perceived failure has to do with the pump or fan component of the motor system. This especially becomes more of an issue when relying upon memory to provide the answers to the most serious problems to be addressed in a plant, based upon history. For instance, when looking to determine what part of a plant has been causing the most problems, the answer might be, “Waste water pump 1.” The immediate perception is that the pump has a consistent problem and, as a pump is a mechanical system, a mechanical monitoring solution might be selected for trending the pump’s health. If a root-cause had been recorded on each failure, it might have been determined to be the motor winding, bearings, cable, controls, process or a combination of issues.

In a recent meeting, while discussing the selection of CBM equipment, the attendees were asked for modes of failure from their locations. The answers were fans, compressors and pumps. When discussed further, the fans were found to have bearing and motor winding faults being most common, pump seals and motor bearings for pumps, and, seals and motor windings for compressors. When viewed even closer, the winding faults had to do with control and cable problems, improper repairs and power quality. Bearing issues had to do with improper lubrication practices.

When determining the best way to implement CBM on your electric motor system, you need to take a system, not a component, view. The result is simple: Improved reliability; fewer headaches; and, an improved bottom line.

Condition Based Monitoring Test Instruments

Following are some of the more common CBM technologies in use, more detail on the technologies can be found in "Motor Circuit Analysis"[2] Details as to the components of the system tested and capabilities can be found in Tables 1-4 at the end of this paper:

De-Energized Testing:

- DC High Potential Testing – By applying a voltage of twice the motor rated voltage plus 1,000 volts for AC and an additional 1.7 times that value for DC high potential (usually with a multiplier to reduce the stress on the insulation system), the insulation system between the motor windings and ground (ground-wall insulation) is evaluated. The test is widely considered potentially destructive.[3]
- Surge comparison testing: Using pulses of voltage at values calculated the same as high potential testing, the impedance of each phase of a motor are compared graphically. The purpose of the test is to detect shorted turns within the first few turns of each phase. The test is normally performed in manufacturing and rewinding applications as it is best performed without a rotor in the stator. This test is widely considered potentially destructive, and is primarily used as a go/no-go test with no true ability to trend.
- Insulation tester: This test places a DC voltage between the windings and ground. Low current leakage is measured and converted to a measurement of meg, gig or tera-Ohms.
- Polarization Index testing: Using an insulation tester, the 10 minute to 1 minute values are viewed and a ratio produced. According to the IEEE 43-2000, insulation values over 5,000 Meg-Ohms need not be evaluated using PI. The test is used to detect severe winding contamination or overheated insulation systems.
- Ohm, Milli-Ohm testing: Using an Ohm or Milli-Ohm meter, values are measured and compared between windings of an electric motor. These measurements are normally taken to detect loose connections, broken connections and very late stage winding faults.

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[2] Motor Circuit Analysis: Theory, Application and Energy Analysis, Howard W. Penrose, Ph.D., SBD Publishing, ISBN: 0-9712450-0-2, 2002.

[3] Potentially Destructive: Any instrument that can potentially change the operating condition of the equipment through misapplication or finish off weakened insulation conditions shall be considered potentially destructive.

- Motor Circuit Analysis (MCA) testing: Instruments using values of resistance, impedance, inductance, phase angle, current/frequency response, and insulation testing can be used to troubleshoot commission and evaluate control, connection, cable, stator, rotor, air gap and insulation to ground health. Using a low voltage output, readings are read through a series of bridges and evaluated. Nondestructive and trendable readings often months in advance of electrical failure.

Energized Testing:

- Vibration Analysis: Mechanical vibration is measured through a transducer providing overall vibration values and FFT analysis. These values provide indicators of mechanical faults and degree of faults, can be trended and will provide information on some electrical and rotor problems that vary based upon the loading of the motor. Minimum load requirements for electric motors to detect faults in the rotor. Requires a working knowledge of the system being tested.
- Infrared analysis provides information on the temperature difference between objects. Faults are detected and trended based upon degree of fault. Excellent for detecting loose connections and other electrical faults with some ability to detect mechanical faults. Readings will vary with load. Requires a working knowledge of the system being tested.
- Ultrasonic instruments measure low and high frequency noise. Will detect a variety of electrical and mechanical issues towards the late stages of fault. Readings will vary with load. Requires a working knowledge of the system being tested.
- Voltage and current measurements will provide limited information on the condition of the motor system. Readings will vary with load.
- Motor Current Signature Analysis (MCSA) and Electrical Signature Analysis (ESA) use the electric motor as a transducer to detect electrical and mechanical faults from incoming power to the driven load. ESA is a newer test method, as it works with both the voltage and current waveforms, so analysis can be done not only on motors, but generators and alternators also. ESA will detect rotor and air gaps faults, mechanical issues such as misalignment and gear box faults, and can detect later stage bearing faults. ESA does have trending capabilities, but will normally only detect winding faults and mechanical problems in their late stages. Sensitive to load variations and readings will vary based upon the load. Requires nameplate information and some systems require the number of rotor bars, stator slots and manual input of operating speed.

Major Components and Failure Modes

Some of the major issues from the various components of the motor system shall be reviewed in order to provide an understanding of the types of faults found and the technologies used to detect them. As an overview, this may not encompass all of the modes of failure that you may experience.

Incoming Power

Starting from the incoming power to the load, the first area that would have to be addressed is the incoming power and distribution system. The first area of issue is power quality then transformers.

Power quality issues associated with electric motor systems include:

- Voltage and current harmonics: With voltage limited to 5% THD (Total Harmonic Distortion) and current limited to 3% THD. Current harmonics carry the greatest potential for harm to the electric motor system.
- Over and under voltage conditions: Electric motors are designed to operate no more than +/10% of the nameplate voltage.
- Voltage unbalance: Is the difference between phases. The relationship between voltage and current unbalance varies from a few time to many times current unbalance as related to voltage unbalance based upon motor design (Can be as high as 20 times).
- Power factor: The lower the power factor from unity, the more current the system must use to perform work. Signs of poor power factor also include dimming of lights when heavy equipment starts.
- Overloaded system: Based upon the capabilities of the transformer, cabling and motor. Detected with current measurements, normally, as well as heat.

The primary tools used to detect problems with incoming power are power quality meters, ESA and voltage and current meters. Knowing the condition of your power quality can help identify a great many ‘phantom’ problems.

Transformers are one of the first critical components of the motor system. In general, transformers have fewer issues than other components in the system. However, each transformer usually takes care of multiple systems both in the electric motor as well as other systems.

Common transformer problems include (oil filled or dry-type transformers):

- Insulation to ground faults.
- Shorted windings.
- Loose connections
- Electrical vibration/mechanical looseness

Test equipment used for monitoring the health of transformers (within the selection of instruments within this paper) include:

- MCA for grounds, loose/broken connections and shorts
- ESA for power quality and late stage faults
- Infrared analysis for loose connections
- Ultrasonic for looseness and severe faults
- Insulation testers for insulation to ground faults.

MCC's, Controls and Disconnects

The motor control or disconnect provides some of the primary issues with electric motor systems. The most common for both low and medium voltage systems are:

- Loose connections
- Bad contacts including pitted, damaged, burned or worn
- Bad starter coils on the contactor
- Bad power factor correction capacitors which normally results in a significant current unbalance

The test methods for evaluating the controls include infrared, ultrasonic, volt/amp meters, ohm meters and visual inspections. MCA, ESA and infrared provide the most accurate systems for fault detection and trending.

Cables – Before and After the Controls

Cabling problems are rarely considered and, as a result, provide some of the biggest headaches. Common cable problems include:

- Thermal breakdown due to overloads or age
- Contamination which can be even more serious in cables that pass underground through conduit
- Phase shorts can occur as well as grounds. These can be caused by 'treeing' or physical damage. Opens due to physical damage or other causes.
- Physical damage is often a problem in combination with other cable problems Test and trending is performed with MCA, infrared, insulation testing and ESA.

Motor Supply Side Summary

On the supply side to the motor, the problems can be broken down as follows:

- Poor power factor – 39%
- Poor connections – 36%
- Undersized conductors – 10%
- Voltage unbalance – 7%
- Under or over voltage conditions – 8%

The most common equipment that covers these areas include MCA, infrared and ESA.

Electric Motors

Electric motors include mechanical and electrical components. In fact, an electric motor is a converter of electrical energy to mechanical torque.

Primary mechanical problems:

- Bearings – general wear, misapplication, loading or contamination.
- Bad or worn shaft or bearing housings
- General mechanical unbalance and resonance

Vibration analysis is the primary method for detection of mechanical problems in electric motors. ESA will detect late stage mechanical problems as will infrared and ultrasonic.

Primary electrical problems:

- Winding shorts between conductors or coils
- Winding contamination
- Insulation to ground faults
- Air gap faults, including eccentric rotors
- Rotor faults including casting voids and broken rotor bars

MCA will detect all of the faults early in development. ESA will detect late stage stator faults and early rotor faults. Vibration will detect late stage faults, insulation to ground will only detect ground faults which make up less than 1% of motor system faults, surge testing will only detect shallow winding shorts and all other testing will only detect late stage faults.

Coupling (Direct and Belted)

The coupling between the motor and load provides opportunities for problems due to wear and the application.

- Belt or direct drive misalignment
- Belt or insert wear
- Belt tension issues are more common than most think and usually result in bearing failure
- Sheave wear

The most accurate system for coupling fault detection is vibration analysis. ESA and infrared analysis will normally detect severe or late stage faults.

Load (Fans, pumps, compressors, gearboxes, etc.)

The load can have numerous types of faults depending on the type of load. The most common are worn parts, broken components and bearings.

Test instruments capable of detecting load problems include ESA, vibration, infrared analysis and ultrasonic.

Common Approaches to Multi-Technology

There are several common approaches within industry as well as several new ones (See Table 3). The best use a combination of energized and de-energized testing. It is important to note that energized testing is usually best under constant load conditions and trended in the same operating conditions each time.

One of the most common approaches has been the use of insulation resistance and/or polarization index. These will only identify insulation to ground faults in both the motor and cable, which represents less than 1% of the overall motor system faults (~5% of motor faults).

Infrared and vibration are normally used in conjunction with each other with great success. However, they miss a few common problems or will only detect them in the late stages of failure.

Surge testing and high potential testing will only detect some winding faults and insulation to ground faults, with the potential to take the motor out of action should any insulation contamination or weakness exist.

MCA and ESA support each other and detect virtually all of the problems in the motor system. This accuracy requires MCA systems that use resistance, impedance, phase angle, I/F and insulation to ground and ESA systems that include voltage and current demodulation.

The newest, and most effective, approach has been vibration, infrared and MCA and/or ESA. The strength of this approach is that there is a combination of electrical and mechanical disciplines involved in evaluation and troubleshooting. As found in the Motor Diagnostic and Motor Health Study[4], 38% of motor system testing involving only vibration and/or infrared sees a significant return on Investment. This number jumped to 100% in systems that used a combination of MCA/MCSA along with vibration and/or infrared.

In one case, a combined application of infrared and vibration saw an ROI of $30k. When the company added MCA to their tool box, the ROI increased to $307,000, ten times the original by using a combination of instruments.

Application Opportunities

There are three common opportunities for electric motor system testing. These include:

- Commissioning components or the complete system as it is newly installed or repaired. This can provide a very immediate payback for the technologies involved and will help you avoid infant mortality disasters.
- Troubleshooting the system through the application of multiple technologies will assist you in identifying problems much more rapidly and with greater confidence.
- Trending of test results for system reliability, again using the proper application of multiple technologies. Using tests such as MCA, vibration and infrared, potential faults can be trended over the long term, detecting many faults months in advance

[4] Motor Diagnostic and Motor Health Study, Penrose and O’Hanlon, SBD Publishing, 2003

Conclusion

This paper provided a brief overview of how multiple technologies work together to provide a good view of the electric motor system. With an understanding and application of this approach you will realize fantastic returns on your maintenance program.

Table 1: Motor System Diagnostic Technology Comparison

	PQ	Cntrl	Conn	Cable	Stator	Rotor	Air Gap	Brgs	Ins	Vibe	Align	Load	VFD
Off-Line Testing													
High Potential Testing	-	-	-	-	-	-	-	-	X	-	-	-	-
Surge Test	-	-	-	-	X	-	-	-	-	-	-	-	-
Insulation Tester	-	-	-	-	-	-	-	-	X	-	-	-	-
Ohm Meter	-	-	L	-	L	-	-	-	-	-	-	-	-
PI Testing	-	-	-	-	-	-	-	-	X	-	-	-	-
MCA Test	-	X	X	X	X	X	X	-	X	-	-	-	-
On-Line Testing													
Vibration Analysis	-	-	-	-	L	L	L	X	-	X	X	X	-
Infrared	X	X	X	L	L	-	-	L	-	-	L	L	-
Ultrasonic	-	L	-	-	L	-	-	X	-	-	-	L	-
Volt/Amp	L	L	L	-	L	L	-	-	-	-	-	-	-
ESA	X	X	L	-	L	X	X	L	-	X	X	X	L

Table 2: Management Considerations Table 3: Common Approaches

Test Method	Estimated Pricing	Non-Destructive	Requires Experience	Dedicated Personnel	Included Software	Other Applications
Off-Line Test						
High Potential	$10,000 +	Potentially Destructive	High	Recommend	No	No
Surge Test	$25,000 +	Potentially Destructive	High	Recommend	Some	No
Insulation Tester	$1,000 +	(NDT) Non-Destructive	Some	No	No	Yes
Ohm Meter	$500 +	(NDT)	Some	No	No	Yes
PI Tester	$2,500 +	(NDT)	Medium	No	Some	No
MCA	$1,500/ $10,000 +	(NDT)	Some	No	Yes	Yes
On-Line Test						
Vibration	$10,000 +	(NDT)	High	Recommend	Yes	Yes
Infrared	$10,000 +	(NDT)	High	Recommend	Yes	Yes
Ultrasonic	$10,000 +	(NDT)	High	Recommend	Some	Yes
Volt/Amp	$500 +	(NDT)	Some	No	No	Yes
ESA	$16,000 +	(NDT)	High	Recommend	Yes	Yes

	PQ	Cntrl	Conn	Cable	Stator	Rotor	Air Gap	Brgs	Ins	Vibe	Align	Load	VFD
Insulation Resistance and PI	-	-	-	L	-	-	-	-	X	-	-	-	-
Infrared and Vibration	L	X	X	L	L	L	L	X	-	X	X	X	-
Surge and Hi-Pot	-	-	-	-	X	-	-	-	X	-	-	-	-
MCA and ESA	X	X	X	X	X	X	X	X	X	X	X	X	X
MCA and Infrared / Vibe	L	X	X	X	X	X	X	X	X	X	X	X	L

Table 4: Additional Considerations

Test Method	Where Can You Test
High Potential Testing	At Motor – Requires disconnect
Surge Test	At Motor – Requires disconnect
Insulation Tester	From MCC
Ohm Meter	At Motor – Requires disconnect
PI Testing	At Motor – Disconnect Recommended
MCA Test	From MCC
Vibration Analysis	At each location tested
Infrared	At each location tested
Ultrasonic	At each location tested
Volt/Amp	From MCC
ESA	From MCC