Penrose Lecture Series™: Estimating Time to Failure

Electrical Signature Analysis

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This paper contains the referenced papers at the end of the series. The lecture series represents a continuing educational lecture on Motor Diagnostics started in 2003.
In this lecture series, we will be discussing Electrical Signature Analysis (ESA), which is a method for evaluating electrical machinery while energized. The topic will be quite broad and is to include an analysis of supply power through the driven load.

While we will rely upon some of our previous discussions to provide information and definitions for some of our new information, we will start this series by providing some definitions unique to ESA:

- **Voltage**: Electrical pressure, is also termed as electromotive force. Voltage is generated.
- **Current**: Defined in classical physics as electron flow. Current is demanded in order to produce work and is a result of the load.
- **Upstream/Downstream**: Upstream refers to the electrical system in the direction of generation or distribution from the point of test. Downstream is towards the motor and load from the point of test.
- **FFT**: Fast Fourier Transform (FFT) is a mathematical method of separating the frequencies of a `sine wave` and presenting them as frequencies and amplitude.
- **Spectra**: Is the graph of frequencies and amplitudes resulting from an FFT.
- **Voltage and Current FFT**: Spectra of voltage and current.
- **Motor Current Signature Analysis (MCSA)**: A method of viewing demodulated current and current FFT’s to evaluate the condition of machinery downstream of the point being tested.
- **Voltage Signature Analysis (VSA)**: A method of viewing voltage FFT’s to evaluate the condition of machinery upstream of the point being tested.
- **Torsional Analysis (TA)**: A method of viewing the current resulting from the load and its torsional effect (pulsating loads, etc.).
- **Inrush Analysis**: A method of viewing the inrush effects on voltage and current when electrical machinery is started.
- **Power Quality**: The industry has defined this as reviewing voltage and current. Voltage unbalance, over/under voltage, voltage and current harmonics and current unbalance.
- **Power Analysis**: This is defined as viewing power quality as well as surges, swells, transients, interruption, etc. and requires datalogging capabilities.
- **Electrical Signature Analysis (ESA)**: A method of evaluating the motor system, which includes supply, control, motor, coupling, load and process, utilizing MCSA, VSA, TA, Inrush Analysis and Power Analysis.

The purpose of ESA is to obtain enough information, concerning the circuit being tested, to evaluate the health of the electrical system from supply through load.
ESA has been successfully applied in these applications:

- AC induction motors
- Variable Frequency Drives (VFD’s)
- Wound Rotor Motors
- Synchronous Machines
- DC Motors
- Alternators and Generators
- Machine Tool Motors and Servos, including robotics
- Driven equipment including Belted, Direct Drive and Geared
- Transformers
- Traction Equipment
- And numerous other applications

What it comes down to is the ability to evaluate the information provided by ESA. That is the purpose of this lecture series.
As we start into ESA theories and application, we will have to spend a little time on electric motor theory. As we will start out with a basic system, AC motors are the simplest in terms of operation and components, we will start out with AC induction motors. Using this base knowledge, we can later expand it to cover wound rotor motors, synchronous motors, machine tool motors, servos, traction machines, generators, DC motors, transformers, etc.

In fact, in order to open this topic, we will have to briefly discuss some transformer theory. Keep in mind, an AC induction motor is just a transformer with a rotating secondary. As a transformer transforms one level of voltage and current to a second level of voltage and current, an AC induction motor converts electrical energy to mechanical torque.

Trivia: One of the purposes of using high voltages for transmission is to reduce losses in the transmission wires. Voltage does not produce losses, only resistance and current as electrical losses through a conductor are Watts = I^2R. Therefore, if you were moving 480 Volts and 1,000 Amps across a conductor with a total resistance of 10 Ohms, you would have 10 million Watts or 10,000 kW (10MW) of losses. However, if you increase the voltage to 13,200 Volts, the current will be 36.4 Amps which would produce losses of only 13,250 Watts or 13kW, a reduction of 99.9%! Therefore, the purpose of a transformer is to increase T&D (Transmission and Distribution) voltages then to reduce them to a usable level. This reduces the overall T&D system losses. Transformers also work to isolate systems from each other.

The primary purpose of a transformer is to increase or reduce voltage and to have the inverse effect on current. This concept took the brilliance of a Croatian immigrant electrical engineer by the name of Nikola Tesla (we will discuss Tesla in more depth in a following part of this lecture series, including the technology battle between Tesla and Thomas Edison, which I briefly covered in an earlier Blog). The concept is simple and has to do with using alternating current, magnetic fields and the use of a transformer ratio. For the purpose of this first part, we will be working with the concepts with an ‘ideal transformer’ (ie: no losses, no connections, theoretical). We will represent transformer ratio as N_a and will use a subscript 1 for the primary (high voltage, low current side) and a subscript 2 for the secondary (low voltage, high current side).

The transformer ratio can be determined by comparing the number of conductors (turns – T) on the primary side to the secondary side such that N_a = T_1/T_2. The effect is due to the mutual inductance between the primary and secondary circuits as described in the “Motor Diagnostics and Quantum Mechanics Part 7” lecture. Therefore, if a transformer has 100
turns in the primary \( (T_1 = 100) \) and 10 turns in the secondary \( (T_2 = 10) \), then the transformer ratio would be described as a ratio 10:1.

Now, if you have 480 Volts and 100 Amps required at the secondary, and 13,200 Volts available at the primary, you would use the formula: \( V_1I_1 = V_2I_2 \) in order to calculate the current at the primary. Therefore: \( I_1 = (480V \times 100A)/13,200V = 3.6 \) Amps on the primary. The transformer ratio can be determined as \( 13,200V/480V = 27.5 \). For example: The transformer may have 275 turns in the primary and 10 turns in the secondary.

Now, the question is, how does this impact our understanding of a three phase induction motor? Simple: The stator windings are the primary and the rotor bars in the motor are the secondary of a transformer.

How is the voltage and current induced into the transformer?

This is where we fall back onto a basic understanding of physics. If I pass a magnet over a conductor, it causes electrons (classical physics) to move in the inductor, creating a current (electron flow). Now, if I pass a current through a conductor, I will generate a magnetic field. If I create a coil, the magnetic fields add, and the magnetic field increases. If I then place a medium (such as a piece of iron) within the coil, I begin to direct the magnetic field such that the medium has a North and South pole. This is the action in a DC field.

Now, in an AC field, as the voltage and resulting current increase in a coil (ie: the primary), a magnetic field increases. If you have a coil in close proximity, the increasing field will effectively ‘cut through’ the conductors in the second coil, generating a voltage and current in the second coil. Because you will also have a magnetic field in the second coil (secondary), you will generate a torque between the fields. This torque is referred to as Electro-Motive Force (EMF). The currents in both coils will depend upon, not only the impedance of the transformer, but the impedance of any loads attached to the secondary of the circuit. The frequency will also be maintained in both the primary and secondary.

Now, starting tomorrow, we can begin describing the operation of an AC induction motor, using the basic principles of this Blog. However, as we will discover, there are a few complex principles required as we move forward (such as the interaction of fields in a three phase system).
Today, we will begin to explore the operation of a three phase induction motor. The motor consists of the following components:

1. **Stator Frame**: Encases the motor. Acts to protect the winding, contains the stator core and is used to hold the end shields centered on either end of the stator.

2. **Stator Core**: Is made up of many layers of either laminated annealed steel or silicone steel. The layers average 0.019 to 0.049 inches thick to reduce eddy currents and are arranged (manufactured) in such a way that the grains allow for less resistance to the change of magnetic flux (hysteresis losses). The stator core both houses the stator coils (primary) and uses the ‘back iron’ (area between the stator housing and coil slots) to direct the magnetic fields into the airgap between the stator core and rotor.

3. **Stator windings**: Connected to create a north and south pole (pole pairs) separated by 120 electrical degrees. Each pole will normally be made up of a coil grouping, or number of coils, that can be calculated as follows: If a stator has 36 slots, and the motor is designed to be 4-pole, and you have 2 coil sides per slot (36 coils total), you will have: 36 coils/3 phases = 12 coils per phase; 12 coils per phase/4-poles = 3 coils per phase per pole. Therefore, you would have 12 groups of three coils in this motor.

4. **Rotor**: The rotor is held centered in the stator by the end shields of the motor and bearings mounted on a shaft. It is suspended in such a way that there is even clearance on all sides of the rotor in relation to the stator core. The clearance is defined as the air gap of the motor.

5. **Rotor Core**: The rotor is also made up of many layers of steel, as outlined in the stator core description. It houses the rotor bars.

6. **Rotor Bars**: Are made of either an aluminum alloy (caste rotors, normally in motors under 600 Volts) or a copper alloy (normally in motors above 600 V). The rotor bars are shorted on either end by end rings, which are part of the casting for aluminum or welded, for copper. The rotor bars can also be referred to as the secondary, as in the secondary of a transformer.

**Author’s Note**: The fun part of the exercise of writing a Blog is that you have to illustrate everything in writing. In order to make this readable to the average person, I will withhold formulae for the operation of a motor until it is either necessary to describe the operation or to calculate for fault analysis.

For the purposes of this initial description, we are going to treat the motor as an ideal motor. This means that it is theoretically perfect, with no defects and perfect tolerance. Also, that the power supply is also perfect. As we start into the different sections of analysis, we will begin to describe the imperfections in the motor, how to analyze them and how to determine pass/fail and trending.
Visualization:

Three phases of voltage are supplied to the motor separated by 120 electrical degrees. We will assume that Phase A (we will refer to the phases as A, B and C) is at 0 Volts. The peak voltage in a 480 Volt motor will be \((480 \text{ Vrms}/0.707 = )\ 679\ \text{V peak (V}_p)\). As Phase A increases towards 679 V\(_p\), the four coils will become more magnetically North, South, North, South. Once the voltage reaches its peak and starts to decrease, the coils will become less magnetically N, S, N, S until the voltage reaches 0 V, again. It then starts towards negative 679 V\(_p\) and the four coils become more S, N, S, N. When viewing all three phases, if you could see the magnetic fields, looking through the stator from the end, you would see a vortex (it would look like a whirlpool) that is very strong close to the core and weaker towards the center. The speed of the vortex is called the synchronous speed and can be calculated as \(N_s = (120 \times f)/p\), where 120 is a constant, \(f\) is the operating frequency (60 Hz in the USA) and \(p\) is the number of poles of the motor. In this case, we are dealing with a 4-pole, 60 Hz motor which would then have a synchronous speed of 1800 RPM.

The rotor bars in the induction motor, sometimes referred to as a ‘squirrel cage’ rotor, have the magnetic fields cutting through the bars at \(N_s\). This generates a voltage and current, with a resulting magnetic field, within the rotor. The initial rotor frequency \(f_r\) will be the same as the stator frequency \(f_s\), resulting in a very high rotor current and resulting strong magnetic field. The fields induced into the rotor will be the opposite of the fields within the stator (S below a N) and will be both attracted and repulsed (opposites attract, likes repulse) placing a magnetic torque on the squirrel cage. As a result, the rotor begins to turn.

In an ideal motor, where there is no load, the rotor can come close to the \(N_s\), but can never reach it as there must always be a magnetic field crossing through the rotor bars in order to produce voltage and current. The difference between the speeds is referred to as the Slip \((N_{\text{slip}})\), which is normally referred to as a percentage. Therefore: \(N_{\text{slip}} = ((N_s - N_{\text{actual}})/N_s) \times 100\). So, if our ideal motor runs at 1785 RPM and has an \(N_s\) of 1800 RPM, the \(N_{\text{slip}}\) would be 0.8%. At 1785 RPM, the rotor frequency would be: \(f_r = 60 \text{ Hz} \times 0.8\%\/, \) or 0.5 Hz, which can also be referred to as the slip frequency \((f_{\text{slip}})\).

*Note: As a reference, when we discuss PPF (Pole Pass Frequency), we will be referring to the number of poles of the motor times the slip frequency. In this case, it would be: 0.5 Hz \times 4\text{ poles} = 2 \text{ Hz. This is an extremely important point to remember.}*

Now, during all of this, work and heat are being generated in terms of losses and torque. We will discuss these in tomorrow’s lecture.
There are a number of stresses and losses that occur in an induction motor that directly affect its life, electrically and mechanically. For today’s lecture, we are, again, going to assume a perfect motor and will deal only with the stresses and losses that occur in this type of system. As we move forward to discuss each type of fault detected with ESA, we will go into the real-life variations from the ideal.

While we are discussing this section, there are a few quick definitions that will have to be covered:

1. Torque ($T$): Is the rotational (twisting) energy produced by the motor. In English units, it can be represented as Torque (lb-ft) = (horsepower x 5250)/RPM; in Metric: Torque (N.m – Newton.meter) = (kW x 9550)/RPM.
2. Inertia ($W^2$): The resistance to change in speed. In the case of an electric motor, we will use $W^2 = \text{Inertia of rotor} + ((\text{Inertia of load} \times \text{load RPM}^2)/\text{Motor RPM}^2)$.
3. Locked Rotor Torque (LRT): The torque a motor will develop while the rotor is stationary and full voltage and frequency are applied.
4. Pull-Up Torque (PUT): The torque a motor will develop as it is accelerating to its breakdown torque.
5. Breakdown Torque (BDT): The maximum torque a motor can develop before it stalls, from a full load.
6. Full Load Torque (FLT): The torque the motor produces at rated speed at rated voltage and frequency under full load.

**Rotor Losses**

An electric motor comes up to speed at a rate depending on it’s inertia:

Seconds = ($W^2 \times \text{Speed Change})/(308 \times \text{Avg Accelerating Torque (lb-ft)})$

The Average Accelerating Torque (AAT) can be calculated as:

$AAT = (((\text{FLT} + \text{BDT})/2) + \text{BDT} + \text{LRT})/3$

The actual rotor losses in kW-seconds are:

$kW\text{-sec} = (0.00136 \times W^2 \times N_s^2 \times (\text{initial slip}^2 – \text{final slip}^2))/5910$
The slip is represented as the per unit slip, which is \( \% \text{slip}/100 \). So, 100% slip (stationary) = 1.

Therefore, on startup, as the motor goes from a standstill (100% slip) to full speed, heat is developed. The heat causes the rotor bars and end rings of the rotor to expand. This heat must then be dissipated, otherwise the motor would overheat. The heat dissipation is directly related to the mass of the motor materials. In smaller motors, the amount of material per horsepower is much greater than for larger motors, so smaller motors can be started more often than larger motors, under full voltage, full frequency.

You will also note that the heating of the rotor is directly related to the time it takes to accelerate from one speed to another. This acceleration time is directly related to the size of the motor and the load it is driving. As a result, some loads will reduce the number of starts that a motor is allowed. However, high inertia loads also take a long time to come to a stop, unless an outside source is provided, such as a brake. The good news is that, in very high inertia loads, different designs of motors are available that produce different values of LRT, PUT, BDT and FLT.

Inrash Losses

At the point in time where a motor starts, the rotor sees full line frequency and high current \( (I = E/Z \text{ – Ohms law}) \) as the frequency both reduces the cross section of the rotor bar used (skin effect), increasing its basic resistance, saturates the core and changes the impedance of the circuit. This value of rotor current is seen on the motor leads, due to the transformer effect, as 4 to 8 times the nameplate current.

The result of the high current causes two additional losses:

\[
\text{kW}_{\text{rotor}} = I_{\text{rotor}}^2 R_{\text{rotor}} \\
\text{kW}_{\text{stator}} = I_{\text{stator}}^2 R_{\text{stator}}
\]

In addition, there is coil movement at this point, as the large magnetic fields, due to the high current, cause the turns within the coils to move inwards towards the rotor (the conductors actually move due to the high current – this effect can be seen in a short circuit condition if you have a cable and induce a sudden, direct short circuit, you can see the cable move). This flexion causes mechanical stresses on the end turns of the coils, but particularly on the insulation system as the coils leave the stator slots.

Other Losses:

Other losses include the hysterisis loss, which is higher at startup due to the increased magnetic fields. The cause is related to our previous lecture series and has to do with forcing dipolar spin.
Eddy current losses are due to currents in shorted laminations, which are higher during startup.

Leakage losses also increase. Leakage has to do with the capacitance of the circuit. Details can be obtained from the MCA Blog Lecture Series.

In effect, a high rate of losses occur on startup. The stresses also make this one of the most dangerous times for the motor, as weakness’, mechanically or electrically, can be forced and the machine fail. This causes many to consider inrush analysis as a good method for analyzing a machine. However, the high current and chaos that is occurring during this stage in the motor operation, will often mask many important issues within the motor, itself. We will discuss that as we move forward.

Tomorrow, we will discuss the operation, losses and stresses in a motor during steady-state operation. From that point we can begin our true discussion on ESA, including discussions on how to evaluate systems that are not operating steady-state. (Test methods applying steady-state operating conditions are great in laboratories. However, most real systems, even when considered steady-state, are very dynamic, and the potential for error increases).
In today’s topic, we are briefly going to describe two items that will be of importance as we move forward: Steady state losses and torque in a motor; and, How sidebands are formed.

Steady State Losses

Although eluded to in a number of cases, throughout the past and present lectures, following are the losses that are common within an electric motor during operation (All losses are represented as Power or Watts):

- Stator $I^2R$ losses: The heat energy produced, in Watts, as current flows through the conductors of the windings. Calculated as current squared times the DC resistance of the stator circuit.
- Rotor $I^2R$ losses: The heat energy produced, in Watts, as current flows through the rotor bars of the rotor. Calculated as current squared times the DC resistance of the rotor circuit.
- Friction and Windage losses: The drag caused by air passing over the surface of the rotor and fans as well as the friction of the bearing surfaces.
- Core Losses: There are two types of core losses that occur both in the rotor and in the stator:
  - Eddy Currents: Result from a magnetic field interacting with metal. This can also be referred to as ‘induction heating.’ In a stator, this can be found as localized heating when you have shorted laminations. The maximum allowable ‘hot spot’ in the stator is 10 degrees C. This heating will accelerate the degradation of electrical insulation at the point of fault. In a rotor, the effect of shorted laminations and eddy current heating is a ‘bowing’ rotor. This means that the side with the defect expands, while the side without the defect does not and the rotor ‘bends’ in operation.
  - Hysteresis Losses: This is the heat generated due to the resistance in change to the magnetic field by the stator lamination material. This was covered more in-depth in the “Motor Diagnostics and Quantum Mechanics” series in July and early August, 2004.
- Leakage Losses: The final set of losses actually encompass all other losses in the motor including magnetic, fringing and capacitance losses.

The efficiency of an electric motor is defined as: $\frac{(kW\;input - \;Losses)}{kW\;input} \times 100$. 
Sidebands – How They Occur

One of the more interesting aspects of what we will be dealing with, while performing analysis using ESA, is sidebands.

In ESA we will be dealing with sinusoidal waves in the following manner:

- **Fundamental Frequency:** This is the primary frequency of the voltage or current. In the USA, this fundamental frequency (when dealing with an ideal power source) will be 60 Hz. When dealing with variable frequency drives, the fundamental frequency can be changed to some other frequency.

- **Harmonic Frequency:** Is a frequency that resides in the fundamental frequency. For instance, a fifth harmonic in a 60 Hz system would have a 60 Hz sinewave with a 300 Hz sinewave within it.

For now, we will relate this to sound: The carrier (modulated fundamental - \(W_c\)) frequency is induced. An event occurs in which a sound is introduced (harmonic \(W_m\)). The induced sound is considered a cosine function where (law of cosines):

\[
S = (\cos W_c x t) + (1/2\cos(W_c + W_m)t) + (1/2\cos(W_c - W_m)t) \text{ [where } t = \text{ time]} 
\]

The strength of the harmonic is represented by \(b\). When \(b\) is introduced into the modulated frequency, the intensity is proportional to the strength of the event, \(b^2\), at frequency \(W_c + W_m\) and \(W_c - W_m\).

OK, now lets relate this to a series where we are looking at an FFT (Fast Fourier Transform) of a signal, such as current:

Suppose we have a modulated signal of 60 Hz, an event occurs that is related to the pole pass frequency of the motor (we will use 2 Hz from our previous example). We will then have a 60 Hz signal with sidebands of +/- 2 Hz.

Now, suppose we have a new harmonic, that relates to the line frequency of the machine being analyzed, of the line frequency times running speed frequency (example: 60 Hz x 30 Hz (1800 RPM) = 1800 Hz). An event occurs that creates a forcing function at this frequency. The harmonic is the fundamental frequency and the line frequency is the forcing function \((b^2)!!\) Due to the amplitude of the fundamental, the forcing function becomes very dominant and you will, most likely, not be able to see the fundamental (1800 Hz) but only the resulting sidebands of +/- 60 Hz. Therefore, the FFT will only show 1740 Hz and 1860 Hz.

This will become more important as we explore some of the discoveries that our engineers have uncovered while analyzing a large number of systems. These concepts will assist us in determining the severity of a fault in terms of decibels (db) due to fundamental and sideband signatures as they relate to the line frequency of the system.
When a rotor bar breaks or fractures, a portion of the rotor winding circuit is open. This requires higher current to flow in the bars immediately surrounding the break in the circuit. This high current generates a higher than normal (unbalanced) magnetic circuit at the point of fault causing a wave of magnetic force to proceed with the fault. The result is a pulsating beat pattern in the operation of the motor that is directly related to the slip frequency and the number of poles: $\text{ppf} = f_{\text{slip}} \times \text{poles}$. 

In the past, you could use an analog amp meter to observe the beat by the deflection of the needle during operation. This can even be observed on analog CT meters in motor control centers. Now, modern Electrical Signature Analysis methods can immediately identify the fault and magnitude of the fault, when presented as dB. As a fault peak becomes greater in magnitude, the peaks rise towards the peak magnitude of line frequency current. dB measurements, in the case of ESA, are measured from the peak of the line frequency current magnitude to the base of the line frequency current (the same will be for voltage when we approach that discussion).

As discussed in yesterday’s lecture, a beat frequency results in sidebands. As a broken rotor bar causes a significant change to the magnetic field, within the airgap of the motor, and is directly related to the line frequency of the supply voltage, ppf and resulting current, the sidebands MUST be ppf frequencies around the line frequency current. The magnitude, as determined by experiment (in a separate paper, to be presented in the next few months, we will be mathematically (theoretically) representing the values), appears to be -35 dB (dB down from the current peak) as a pass/fail value for sidebands related to the rotor bars.

Contrary to traditional thinking, Broken Rotor Bars Are a Progressive Fault.

What are the effects of broken rotor bars?

There are three specific faults related to broken rotor bars: Efficiency; Winding; and, Torsional. Each type of fault results in damage to the motor or driven equipment.
The efficiency of the motor depends directly on the amount of torque the motor can provide. The amount of torque depends directly on the amount of current that can be provided to develop a magnetic field, evenly, within the airgap of the motor. Broken rotor bars have two impacts on efficiency:

1. They interrupt the rotor winding circuit causing changes to the magnetic fields in the airgap (uneven transformer effect), generating increased magnetic field losses in the motor and reducing the ability of the rotor to generate torque.
2. The ppf current beat is the result of torsional pulsation caused by the variance in the magnetic field. The torsional pulsation represents stalling and starting of the rotational energy making the delivered torsional energy less than it would be in an even field.

The winding effect comes directly from the ppf current, as well. The result of the broken rotor bar is a magnetic force wave that rotates with the broken bar. As this force wave passes over each stator magnetic pole, the force wave puts physical movement stresses on both the windings and rotor. Picture a large football (either American or European) stadium. Now, picture the crowd performing the ‘wave,’ where they progressively stand up and raise their hands, then sit down again. This is, basically, what is happening to the windings within the motor, with the fault point drawing the conductors up into the wave, then letting the conductors fall. This movement puts wear and tear on the conductors and insulation system, eventually leading to a winding failure, usually at the point where the coils leave the stator slots. In another, worst-case scenario, a broken rotor bar may come loose and impact the windings directly.

The final(?) effect is the torsional effect on the load. The ppf beat directly effects the output torque of the motor and, in effect, impacts the driven load directly. For example, let us consider a motor driving a gearbox. When the motor is operating properly, and smoothly, the gears, even if worn, mesh together and an even amount of power is introduced into each gear tooth. Now, if we have broken rotor bars, we are introducing a pulsating power against the teeth at the ppf of the motor. The result is much like turning the gear with a hammer, with the eventual result of cracked or broken gear teeth. In the case of a belt, additional wear on the sheave and belt, itself. In a coupling, wear of the insert or damage to the coupling bolts, keys, etc. In addition, in belted applications, the angular torsional beats will generate increased wear and tear on the motor and load bearings.

Are we finished? No, there is actually one more problem that comes with the broken rotor bar issue: The supply side impact. Broken rotor bars, once they have progressed, will cause current pulsations back into the power supply, and, due to the reduced efficiency, will require more power to operate the motor and load. This puts additional stress on the conductors, connections, starters, contacts and transformers, based upon the size of the motor, severity of the fault and loading of the circuit.

How Common Are Broken Rotor Bars?
The good news is that broken rotor bars are a rare occurrence in small motors (< 600 Volts) and occasional in large motors (> 600 V). One plant that has all less than 600 V motor systems put it this way (they have maintained records for over 10 years): In 10 years, with an average rate of motor repair on their 30,000+ motors of 750 per year, they have only seen 3 cases of broken rotor bars, only during the repair process.

However, in power plants, chemical, petroleum and similar heavy industries that use a large number of >600 V motors, the rate is much, much higher. The primary cause being too many starts. As noted in Part 2 of this lecture series, each start generates a significant amount of heating within the rotor, which does not rapidly dissipate. Many large machines have a limit of one or two starts per day (some less). However, they may be started and stopped many times per day.

Rotor Bar Case Study: Pre-ESA:

In the early 1990’s, I was called out, on a Sunday, to a petro-chemical site to look at two 1500 hp, 3450 RPM, 4160 Vac motors on high pressure pumps (coke cutters) to perform vibration analysis as both motors were not producing enough power through the pumps to effectively perform their function. Upon arriving, I noticed the analog meters associated with each pump and saw the current fluctuating, on the worst one, from 180 Amps to 210 Amps in a regular beat. Vibration was performed and it was noted that twice line frequency peaks appeared with ppf sidebands (in vibration, electrical issues show as twice line frequency, which is different than the one time line frequency seen with ESA) and harmonics. Also, high peaks in acceleration that related to what might be rotor bar pass frequencies (# of rotor bars times RPM) with harmonics.

The motors were pulled and taken to the repair shop. There, once the motors were disassembled, it was noted that on the worst motor, over half of the rotor bars had failed! The other one had about 1/3rd of the bars broken. During the root-cause investigation, it was discovered that the motors, rated for one cold and two hot-starts per day, were being started a minimum of 12 times per day and a maximum of 24 times per day, seven days per week.

Total time to perform the investigation, once on site, was about 2 hours, not including shop time or root-cause-analysis.

Rotor Bar Case Study: Post-ESA

In a recent case, a 500 hp, 3600 RPM motor on a compressor was showing signs of wear, as was the compressor. Routine vibration analysis identified RBPF and 2LF signatures, indicating probable broken rotor bars. The motor was sent to a repair shop who replaced the bearings, painted the motor and returned it stating that there were no other problems. The reliability program was brought into question because of the impact that the
compressor has on production and the time it was out of the facility. The vibration group continued to monitor the fault, which appeared to progress.

ESA was performed on the motor as part of an onsite training course. Classic pff sidebands at -38 dB were immediately detected (we could not have hoped for a better example). Using both the ESA and vibration data, the reliability manager had the motor pulled and sent into the repair shop. The repair shop again stated that there were no problems with the motor.

At this point, the method to evaluate the rotor bars by the repair shop was brought into question. There are several ways of testing for broken rotor bars through the repair process:

2. ‘Growler’ test: Where the rotor is placed on a half-transformer fixture and current is induced. A medium such as iron filings or magnetic paper can be used to trace each good bar. Because of the energy used to cross the fault point, this (and the next method) method can go through the oxidized surfaces of a fracture and the fault missed. The best approach is to heat the rotor in an oven to about 210 degrees F prior to performing the test (expansion will separate the fracture).
3. Single Phase Test: Where 10% of the motor rated voltage is provided to two phases of the motor, in effect single-phasing the load. The rotor is hand-turned slowly with a clamp-on amp meter attached to one phase. Variations of more than 3% indicate a fault. There should be an increase and decrease of current once for each pole of the motor (always in pairs).
4. MCA Rotor Test: Using inductance, as outlined in last month’s series on Motor Diagnostics and Quantum Mechanics.
5. Dye Test: Similar to a visual test, however the dye is used to readily find the broken or cracked bar.

Trivia: The term ‘growler’ comes from when the system was used to detect shorts in DC armatures. The power would be induced and a hacksaw blade would be brought over the surface of each armature slot. The charging and discharging point (arching) of the short would cause the blade to vibrate and make a growling noise.

As it turned out, the repair shop had used a visual check. The site used MCA to verify the fault, again (now three methods) and sent the motor to another repair shop. The new repair shop utilized a proper growler test method and identified two severely broken rotor bars.

In the continuation of this lecture series, next week, we will start investigating other faults that can be analyzed by ESA.
Time to Failure Series Continued

Electrical Signature Analysis – Part 8 Static Eccentricity

Howard W Penrose, Ph.D.
ALL-TEST Pro, A Division of BJM Corp

Homework:

On the website [http://www.motordiagnostics.com/motor_diagnostics_papers.htm](http://www.motordiagnostics.com/motor_diagnostics_papers.htm) download: “Applications for Motor Current Signature Analysis,” and, “Motor Current Signature Analysis and Interpretation.” These papers will help with the following Blogs.

Rotor eccentricity can be caused by a number of issues, such as eccentric machining of the rotor, end shield rabbet fits, machining of the rotor or shaft, foot flatness problems, twisted base and severe bearing problems. This causes the rotor to sit to one side of the stator bore during operation.

Each rotor bar passes each pole pair at running speed. This causes a base frequency of the running speed times the number of rotor bars plus and minus the line frequency of the motor ((RS x RB) +/- (N * LF)) as the forcing frequency is related to the Line Frequency of the motor, which generates sidebands (The rotor pushes and pulls within the airgap at 2LF). N is an odd integer starting with 1.

Several problems arise from static eccentricity, including:

- Magnetic pulse waves that put electrical and mechanical stress on the winding;
- Danger of the rotor touching or rubbing the stator laminations; and,
- Additional stresses on the motor bearings, reducing bearing life.

Normally, eccentric rotor problems are found along with other electric motor problems, such as misalignment, bearing faults and mechanical unbalance.
Time to Failure Series Continued

Electrical Signature Analysis – Part 9 Dynamic Eccentricity, Misalignment and Unbalance

Howard W Penrose, Ph.D.
ALL-TEST Pro, A Division of BJM Corp

Homework:

Contact me and request the ‘MCSA Pattern Recognition Guide Excerpt’ for general reading on this topic.

It has been a long week on the road, so I have fallen behind. Therefore, I am going to cover the remaining topics for this week in this lecture.

Dynamic Eccentricity

Dynamic Eccentricity is similar to Static Eccentricity in that the rotor is operating off-center. The difference, however, is that there is a driving force causing the rotor to flex out of alignment versus the rotor being mounted eccentrically. One example of a cause for dynamic eccentricity is smeared rotor laminations. In this case, the motor will start with a relatively even air gap (it could also start with static eccentricity, multiple problems can exist in a motor), then, as eddy currents in the damaged laminations generate heating, the laminations will expand in that area, reducing the air gap on that side.

You will now have two forcing functions: Line Frequency and Running Speed.

The result is (RS * RB) +/- (N * LF) with RS sidebands, of lower magnitude, around the LF sidebands. N is an odd integer starting with 1.

Misalignment and Mechanical Unbalance

This one is potentially misleading as the basic signature for both is the same. However, there is a rule of thumb for evaluating which condition exists.

In high frequency FFT, you will have a pattern that appears as line frequency sidebands, 4*LF then 2*LF with the original sidebands existing around the point RS * RB. You can determine if the defect is misalignment or unbalance by looking at the demodulated current spectrum. If a peak exists at running speed AND you have the misalignment or mechanical unbalance signature described above, then the defect is most likely significant mechanical unbalance. Less likely, but possible, is severe misalignment.
The reason for the 1x peak is that the rotor is forced off center in one location.

Conclusions on Rotor Related Faults

As you may have noticed, all rotor related faults appear as rotor eccentricity. This re-enforces the previous lecture statement that these faults are detected due to rotor movement, radially, within the air gap. This results in an eccentric magnetic field, which causes ripples in the motor current.

Next week, we are going to work on AC induction motor stator faults such as loose coils, stator core movement and winding shorts, including how to determine the severity of these problems.
Time to Failure Series Continued

Electrical Signature Analysis – Part 10 Winding Shorts and Stator Mechanical Faults

Howard W Penrose, Ph.D.
ALL-TEST Pro, A Division of BJM Corp

Homework:

Contact me and request the ‘MCSA Pattern Recognition Guide Excerpt’ for general reading on this topic.

Stator Winding Shorts

Electrical winding shorts cause variations in the magnetic field at the point of fault as the resulting arcing will cause high current at this point. As the fault is occurring in the stator, the faults related to winding shorts will have a forcing function relating to the running speed of the rotor times the number of stator slots. The winding fault is electrical in nature which results in line frequency sidebands of the stator slot passing forcing function.

(Running Speed x Stator Slots) +/- Line Frequency = Stator Electrical.

The fault then has a second, lesser, forcing function around the electrical forcing function of the running speed. Therefore:

Stator Electrical +/- Running Speed sidebands = Winding Shorts.

The detection of stator winding shorts with ESA requires frequent monitoring as detection online will indicate a later stage winding fault.

Stator Mechanical Faults

Stator mechanical faults are defined as loose coils, loose wedges or loose stator. The movement occurs with a forcing function of the line frequency. However, there will be no running speed sidebands (Stator Electrical only).

Small sidebands, or a raised noise floor around the Stator Electrical peaks, indicate a worsening condition which should be addressed.

Stator mechanical faults will normally be detected above 25% load and the fault should be at least -60dB to be considered serious.
Homework:

Contact me and request the ‘MCSA Pattern Recognition Guide Excerpt’ for general reading on this topic.

**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**

In order to determine the frequencies associated with a belted system, 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 Running Speed (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, inches * π) + (driven, inches * 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, inches * 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**

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 gear: 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.
Time to Failure Series Continued

Electrical Signature Analysis – Part 12: DC Motor Analysis

Howard W Penrose, Ph.D.
ALL-TEST Pro, A Division of BJM Corp

DC motor analysis can be a challenge with ESA, if you do not know what you are looking for. In today’s lecture, we will review a few key points in ESA analysis of a DC motor and drive.

In order to fully analyze a DC electric motor, you still require the ability to test AC voltage and current. When DC is rectified, a small amount of AC remains at the peak of the DC voltage and current, known as ‘form factor’ or ‘AC ripple.’ In an ESA FFT, there will be a dominant voltage line frequency and SCR frequency (# of SCR’s times the line frequency) with harmonics that will taper off. The line frequency harmonics should end by the first SCR frequency. Demodulated voltage and current should show a ripple-type waveform. A hall-effect transformer can be used to show absolute current values. Finally, all test results should be taken from the armature leads only, as the armature contains an AC current during operation, which will allow some load analysis capabilities.

One key difference between AC analysis and DC analysis is that the sidebands evaluated in AC do not exist. Instead, the results will be similar to those found in vibration, requiring FFT capabilities out to 5kHz to detect most faults outside of the motor.

A few DC Drive Faults

One problem that can occur in DC drives is a condition which I will refer to as ‘blow-by.’ In this condition, at least one SCR is shorted so that AC voltage is present on the DC side of the drive. This will result in a strong line frequency peak in current and demodulated current. Also, the line frequency peak will be close to the same value (in dB), or the same for extreme SCR faults, with harmonics across the complete FFT.

Loose connections will show strong line frequency harmonics at a value of approximately -60 dB, or less.

A few DC Motor Faults

A few common problems with DC motors include sparking due to raised mica between commutator bars and worn brushes. In both cases, the resulting sparks cause a raised noise floor around the SCR frequency peaks.
Unbalance will cause a low frequency running speed peak, just the same as found in an AC motor. It is important to note that this will also occur in cases of misalignment.

In our next lecture, we will discuss the analysis of Servo equipment.
Practical Motor Current Signature Analysis
Taking the Mystery Out of MCSA

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Introduction

The purpose of this paper is to provide the MCSA user with practical instruction in identifying key frequencies detected using MCSA. Several items will be assumed based upon previous white papers and articles produced by the author: Definitions such as 'slip speed,' 'synchronous speed,' 'running speed,' 'harmonics,' etc. Will not be defined. Also, the difference between RPM and RPS (Hz), etc. Will be the RPM/line frequency (ie: 60 Hz in the USA).

It must be noted that most of the frequencies and faults identified within this ALL-TEST Pro white paper are automatically identified when using the ALL-TEST PRO OL (ATPOL) motor current signature analyzer and associated software. In many cases, the only information that you will need is the motor nameplate information. The number of rotor bars and stator slots, if unknown, is estimated directly by the ATPOL system.

In this paper, however, we will identify the need to review a complete motor system as identified in the ‘Multi-Technology Approach to Motor Diagnostics.’ This will assume that all information is obtained, including:

1. Number of rotor bars
2. Number of stator slots
3. Driven equipment diameters, etc.
4. Bearing sizes and manufacturers.

Our next white paper will focus on the identification of MCSA results when little, or none, of this information is known.

What is MCSA?

Motor Current Signature Analysis (MCSA) is a system used for analyzing or trending dynamic, energized systems. Proper analysis of MCSA 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 MCSA systems are not the same and may be limited in performing the analysis cited here - The ATPOL system can perform well beyond the analysis identified within this paper)
MCSA 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, MCSA systems rely upon FFT analysis, much the same as vibration analysis. Most MCSA 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

![Figure 1: Line Frequency](image1)

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

![Figure 2: Line Frequency with Harmonic Content](image2)

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

Figure 3: FFT Analysis

![Figure 3: FFT Analysis](image3)

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

Power Quality

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 paper. We shall cover the more common issues that meet the requirements of this paper 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:
   1.1. 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

   1.2. 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 lighting 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](image)

### 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](image)

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.
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 \((\text{frequency} + \text{frequency})/2\) CF = Running Frequency (RF) \(*\) the number of rotor bars (RB) with line frequency times \(N\) sidebands, where \(N\) is an odd integer.

\[
\text{Formula 1: Static Eccentricity} = (\text{RB} \times \text{RF}) \pm (\text{N} \times \text{LF}), \text{where N = odd integer}
\]

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

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.
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

CF = 1231.9 Hz

Mechanical Analysis

Bearings

In order for bearing problems to appear in MCSA, the condition will be severe. Bearing problems found through this method should be considered urgent and addressed as soon as possible.

To determine bearing issues, you must first obtain the appropriate bearing manufacturer and size, then obtain the bearing multipliers, which can be obtained from the manufacturer's catalog or directly through ATPOL's MCSA software. These multipliers include:

1. Ball Pass Outer Race (BPOR)
2. Ball Pass Inner Race (BPIR)
3. 2x Ball Spin Frequency (2xBSF)
4. Cage Frequency (FTF)

The bearing frequencies are found as each multiplier times running frequency with line frequency sidebands (ie: (BPOR * RF)+/-LF). Harmonics of the bearing frequencies can be found by multiplying each bearing frequency by integers (N) with line frequency (LF) sidebands around each.

Formula 2: Bearing frequencies = (BPOR * RF * N) +/- LF

For example, the bearing frequencies for a 6305 NTN bearing in a motor with 29.33 Hz running speed would be found as: BPIR = 4.394; BPOR = 2.606; FTF = 0.372; and, 2xBSF = 1.830.

When calculated, the results are found in table 1.

Table 1: NTN 6305 bearing frequencies

<table>
<thead>
<tr>
<th></th>
<th>1x</th>
<th>2x</th>
<th>3x</th>
<th>4x</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPIR</td>
<td>128.9</td>
<td>257.8</td>
<td>386.7</td>
<td>515.6</td>
</tr>
<tr>
<td>BPOR</td>
<td>76.43</td>
<td>152.9</td>
<td>229.3</td>
<td>305.7</td>
</tr>
<tr>
<td>FTF</td>
<td>10.91</td>
<td>21.82</td>
<td>32.73</td>
<td>43.64</td>
</tr>
<tr>
<td>2xBSF</td>
<td>53.67</td>
<td>107.3</td>
<td>161.0</td>
<td>214.7</td>
</tr>
</tbody>
</table>
Mechanical Imbalance

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.

Driven Equipment

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

Belts

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 * 2 * π * RPM) = 2" * 2 * π * 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 14: Gear Mesh](image)

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 this paper, 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.
**Bringing It All Together**

Now, to tie it all together, we shall review the system as found in Figure 15. As noted in the beginning of the paper, we shall assume that all necessary data is available.

![Figure 15: Fan System for Evaluation](image)

**Motor Information**

- 1750 RPM
- 50 HP
- 58 A
- 460 V
- 40 Rotor Bars
- 48 Stator Slots
- 2× NTN 6310 Brgs

**Operating Information**

- 1755 RPM
- 57, 59, 56 Amps
- 464, 470, 466 Volts

In this section, we will calculate all of the critical frequencies that would help us identify problems in this system. The system consists of a 50 horsepower motor with the identified Motor Information, fan information and bearing information.

**Basic Power Quality**

The running information shows a 57, 59 and 56 Amp draw with voltage values of 464, 470 and 466. There is no perceptible harmonic distortion and the power factor of the system is above 0.85.

**Example 1: Voltage Unbalance**

\[
\frac{(464Va + 470Vb + 466Vc)/3 = 467 Vave}{(467Vave - 464Va)/467Vave * 100% = 0.6%}
\]

0.6% Voltage unbalance is acceptable.

**Example 2: Voltage Deviation**

\[
\frac{(467 Vave - 460 Vnp)/467 Vave * 100% = 1.5%}
\]

**Determine Rotor Bar Sideband Frequencies and Eccentricity CF**

The running frequency is determined by calculating the operating speed divided by the LF. In this case, 1755 RPM/60 Seconds/min = 29.25 Hz. The sidebands are determined by subtracting the running frequency by the actual speed: 30Hz – 29.25Hz = 0.75Hz * 4 Poles = 3 Hz.

In this exercise, we shall consider two frequencies around the 60Hz line frequency peak of 59.25
Hz and 60.75 Hz (+/- 3 Hz) with a value of -20 dB. This is less than the -35 dB that would indicate a severe problem, but sidebands do exist, indicating that the condition of the equipment should be watched. If multiple sidebands of slip frequency occur, there may be high resistant connections (in copper rotor bar machines) or casting voids. Either condition can be confirmed using a de-energized motor circuit analysis rotor test.

The center frequency for static or dynamic eccentricity is: 29.25 Hz * 40 Rotor Bars = 1170 Hz. The stator center frequency would be: 29.25 Hz * 48 Stator Slots = 1404 Hz.

Belt Speed Frequencies and Driven Speed

Next, the belt speed and driven frequencies are calculated:

\[
\text{Driven Shaft} = 29.25 \text{ Hz} \times (6"/18") = 9.75 \text{ Hz}
\]

\[
\text{Belt Length} = (36" \times 2) + (0.5(6\pi + 18\pi)) = 147.4"
\]

\[
\text{Conveyor Speed} = 6\pi \times 29.25 \text{ Hz} = 551.3"/\text{sec (IPS)}
\]

\[
\text{Belt Frequency} = 551.3 \text{ IPS}/147.4" = 3.74 \text{ Hz}
\]

Bearing Frequencies Driver and Driven

Table 2: Bearing Base Frequency Multipliers

<table>
<thead>
<tr>
<th></th>
<th>6310 NTN Brgs</th>
<th>6315 NTN Brgs</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPIR</td>
<td>4.929</td>
<td>4.919</td>
</tr>
<tr>
<td>BPOR</td>
<td>3.071</td>
<td>3.081</td>
</tr>
<tr>
<td>FTF</td>
<td>0.384</td>
<td>0.385</td>
</tr>
<tr>
<td>2xBSF</td>
<td>2.036</td>
<td>2.062</td>
</tr>
</tbody>
</table>

The multipliers are multiplied by the running frequency and integers in order to determine bearing CF and harmonics of CF. Following would be the base (1X) harmonic CF’s for these bearings with the motor frequency at 29.25 hz and a fan shaft frequency of 9.75 Hz.

Table 3: Bearing Base Harmonic CF’s

<table>
<thead>
<tr>
<th></th>
<th>6310 NTN Brgs</th>
<th>6315 NTN Brgs</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPIR</td>
<td>144</td>
<td>47.96</td>
</tr>
<tr>
<td>BPOR</td>
<td>89.8</td>
<td>30</td>
</tr>
<tr>
<td>FTF</td>
<td>11.23</td>
<td>3.75</td>
</tr>
<tr>
<td>2xBSF</td>
<td>59.55</td>
<td>20.1</td>
</tr>
</tbody>
</table>

Blade Pass Frequencies and Mechanical Unbalance Frequencies

The blade pass frequency would be figured using the fan shaft speed:

\[
\text{Blade Pass} = 9.75 \text{ Hz} \times 12 \text{ Blades} = 117 \text{ Hz}
\]

The mechanical imbalance CF would be calculated as:

\[
\text{Mechanical Imbalance} = 29.75 \text{ Hz} \times 40 \text{ Rotor Bars} = 1190 \text{ Hz}
\]
Through a review of the higher frequency peaks of the FFT spectrum, the closest values to center frequencies are the rotor and stator center frequencies. In order to determine which values fit, take the two surrounding frequencies, add them together and divide by two:

For Rotor Eccentricity and Imbalance = \( \frac{1110 \text{ Hz} + 1230 \text{ Hz}}{2} = 1170 \text{ Hz} \)
This meets the Rotor CF of 1170 Hz

For Stator Faults = \( \frac{1350 \text{ Hz} + 1470 \text{ Hz}}{2} = 1470 \text{ Hz} \)
This does not meet the Stator CF of 1404 Hz

Once the CF has been determined, the data can be analyzed. In this case, the rotor CF has 1x and 3x line frequency sidebands which indicate static eccentricity. The additional peaks show the 120 Hz, 240 Hz and 120 Hz pattern that indicates mechanical imbalance.

**Considerations in Modern MCSA Instrument Technology**

At the end of 2003, ALL-TEST Pro, A Division of BJM Corp, introduced the ALL-TEST PRO OL Motor Current Signature Analysis (MCSA) system. The abilities of the system include:

- Automated analysis with limited information
- Automated detection of rotor bars and stator slots
- Complete Power Quality Datalogging capability
- Hand-Held

A typical approach using the ALL-TEST PRO™ OL system for MCSA includes:
1. Follow all applicable safety requirements for your plant.
2. Collect data using the data collector – 30 to 60 seconds following connections using voltage clips and current clamps.
3. Upload data and put in nameplate information in the header – 2-3 minutes.
4. Auto-Analysis – 1-2 minutes, including printing report.

For additional evaluation, the EMCAT Motor Diagnostics software system can calculate most primary frequencies (See Figure 18).

Application Example

Routine test on a repaired submersible 1 horsepower pump, single phase, 1800 RPM system. Data was taken using one current probe only:

✓ Collect Data – 2 minutes, including setup
✓ Data Upload and Data Entered – 5 minutes, including entering header data
✓ Automated Report – 1 minute, including printing report (See Attachment)
✓ Findings – Mechanical Imbalance in the impellor under load detected in less than 10 minutes without knowing rotor bars or stator slots. Time invested was the same as technicians performing standard voltage, current and other testing.
The pump impellor was replaced and the system retested and shipped.

Savings: Future warranty repair on bearings and seal as well as reduced test times with greater accuracy.

**Conclusion**

Motor Current Signature Analysis techniques can be fairly simple, or complicated, depending on the system available for data collection and evaluation. In this paper, we described methods for evaluating a system when complete information is available, as well as how information can be automatically evaluated using the ALL-TEST IV PRO OL system.

MCSA technology can be used in conjunction with other technologies, such as motor circuit analysis, in order to provide a complete overview of the motor circuit. The areas under review include power quality, transformers, AC/DC motors, controls, electrical and mechanical condition of the motor, air gap and rotor circuit condition, and mechanical condition of the load. The result of using MCSA as part of your motor diagnostics program is a complete view of your motor system health.

**About the Author**

Dr. Howard W. Penrose, Ph.D. is the General Manager of the ALL-TEST Pro Division of BJM Corp. He can be contacted at hpenrose@bjmcorp.com.

BJM Corp is a manufacturer of submersible pumps and MCA/MCSA motor diagnostic equipment. For more information go to www.bjmcorp.com or [www.alltestpro.com](http://www.alltestpro.com).
EMCAT Analysis Results

PERFORMANCE SUMMARY

**Bottom Line**
- This motor is operating normally, no action is required.
- X This motor exhibits suspicious operation, trending of the motor is warranted.
- This motor exhibits abnormal indications, action is warranted, NOW.

**Power Factor Commentary**
- Power factor exceeds 0.85.
- Power factor is below 0.85, see detailed report.

**Current Commentary**
- X Current variation is within normal limits.
- Current variation is beyond normal limits, see detailed report.

**Voltage Commentary**
- Voltage variation is within normal limits.
- Voltage variation is beyond normal limits, see detailed report.
- RMS voltage differs from nameplate by more than 5%.

**Load Commentary**
- X Load on the motor is consistent with nameplate values.
- Load on the motor exceeds nameplate values, see detailed report.
- Load on the motor is less than 25%.

**Phase Connection Commentary**
- Connections are normal.
- Voltage ground reference is NOT neutral.
- Loose connection.

**Rotor Commentary**
- X Rotor bar health is normal.
- Rotor bar health is questionable, see detailed report.
- Load is insufficient to determine rotor bar health, at this time.

**Stator Commentary**
- X Stator health is normal.
- Stator electrical health is questionable.
- Stator mechanical health is questionable.
- Turn to turn short.

**Rotor/Stator Air-gap Characteristics**
- Dynamic or static eccentricity indications do not exist.
- Indications of static eccentricity exist.
- Indications of dynamic eccentricity exist.

**Harmonic Distortion Commentary**
- X There is no evidence of harmonic distortion.
- There is evidence of harmonic distortion, see detailed report.

**Misalignment Indications**
- There are no indications of mechanical problems like misalignment or unbalance.
- X There are indications of mechanical problems like misalignment or unbalance; Perform vibration survey to identify and correct the cause.

**Bearing Commentary**
- X There is no evidence of bearing problem.
- Indications of potential bearing problems, perform vibration survey to verify.
# EMCAT INPUT SUMMARY

## NAMEPLATE INFORMATION

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>*****</th>
</tr>
</thead>
<tbody>
<tr>
<td>Serial Number</td>
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<tr>
<td>Model Number</td>
<td>*****</td>
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<tr>
<td>Motor type</td>
<td>Induction</td>
</tr>
<tr>
<td>Power</td>
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<tr>
<td>RPM</td>
<td>1800.0 Rpm</td>
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<td>AC/DC</td>
<td>AC</td>
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<td>Poles</td>
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<td>Phases:</td>
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<tr>
<td>Voltage</td>
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<tr>
<td>Full Load Current</td>
<td>12.00 Amp</td>
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<tr>
<td>Number Stator Slots</td>
<td>-1</td>
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<td>Rotor Bars</td>
<td>28</td>
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<tr>
<td>Torque (ft-lbs):</td>
<td>2.9 In.Lb</td>
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<tr>
<td>CT Ratio</td>
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<tr>
<td>PT Ratio</td>
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<td>Insulation Type</td>
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<tr>
<td>Ambient Temperature</td>
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## Detailed Calculations

### LEGENDS:

- **Impedance** = Complex Impedance = $v_i/c_i$
- **CF** = Crest Factor = (waveform peak)/(waveform rms)
- **CFC** = Carrier Frequency Content = $10^{x/20}/frms$, %
- **THDF** = Transformer Harmonic De-rating Factor = $\sqrt{2}/CF$, %
- **VDF** = Voltage De-rating Factor = 100 - (voltage unbalance, %)$^2$, %
- **Se, fund** = Location of EMCAT slip fundamental, Hz  (EMCAT slip is the same as pole passing frequency)
- **Se, harm** = Number of EMCAT slip harmonics
- **Level** = Sum of spectral amplitudes of EMCAT slip fundamentals and harmonics
- **Slip %** = SRSS sum of slip and harmonic "levels" divided by RMS level of RMS DEMOD spectra between 0 and 65 Hz.
- **Upper sb** = dB level of upper slip sideband of power line peak
- **Lower sb** = dB level of lower slip sideband of power line peak
- **Rotor bar health** = Estimate of the percent of broken or cracked rotor bars
- **Thd** = Total harmonic distortion
- **+Ve** = Positive sequence harmonic
- **-Ve** = Negative sequence harmonic
- **Zero** = Zero sequence harmonic
Running Speed = 29.175 Hz / 1750 Rpm
Pole pass frequency = 3.174 Hz
Load = 104.4 %

THDF = 32.5

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<tr>
<th>Time</th>
<th>RMS</th>
<th>Peak</th>
<th>CF</th>
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<tr>
<td>Current</td>
<td>12.400</td>
<td>18.012</td>
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Harmonic Distortion Results:
Voltage input, from 59.937 Hz harmonics

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<tr>
<th>THD Odd %</th>
<th>THD Even %</th>
<th>+ve %</th>
<th>-ve %</th>
<th>Zero %</th>
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<td>6.073</td>
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Figure- 1: Current Harmonic distortion graph

Figure- 2: Voltage Harmonic distortion graph

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<th>Hz</th>
<th>Cur1</th>
<th>Vlt1</th>
<th>Cur2</th>
<th>Vlt2</th>
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Description:
Mechanical Imbalance of impeller using single phase current only