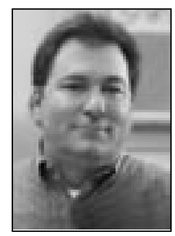
Advanced Spectral Analysis



by Pete Bechard
PdMA Corpration

Current-Signature Analysis

As industries continue to look for new methods of identifying and predicting equipment failures, manufacturers of predictive maintenance equipment are developing new tools to add to their arsenal of available technologies. Newly developed methods of extracting information from the line current supplied to a motor have uncovered information on both the electrical and mechanical health of the equipment. Not just the power supply and motor, but now tracking and trending of information deep into the load and shaft line components can be done through the line current as well. This article discusses the fundamentals of these new current-demodulation methods and shows how they are being used to identify both electrical and mechanical anomalies existing in plants today. It also discusses how using this new feature helps bridge the communication barrier between the mechanical and electrical departments relating to vibration and electrical power analysis.

Since 1985, current-signature analysis (CSA) has been growing as a preferred predictive maintenance tool to identify damaged rotors and air-gap eccentricity in induction motors. CSA is based on the observation that variances in the stator-rotor air gap are reflected back into the motor's current signature through the air-gap flux affecting the counter electromotive force (CEMF). These changes in CEMF then modulate the running current turning an induction motor into an efficient transducer. By performing a fast Fourier transform (FFT) on motor current, the power cables can act as permanently installed test leads for predictive maintenance applications.

An FFT is a mathematical operation that extracts the frequency information from a time-domain signal and transforms it to the frequency domain. The frequency domain is a graph of the amplitude of a signal at a given frequency. In the frequency domain, the height of the peak represents the amplitude of the signal. Figure 1 shows the relationship between the time domain (t), the frequency domain (f), and amplitude (A).

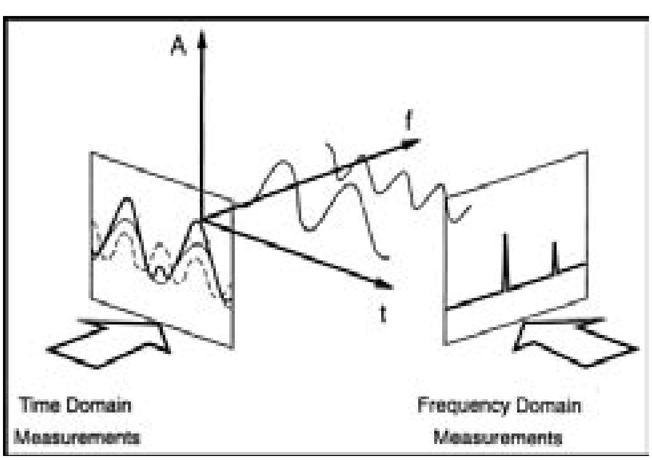


Figure 1 – Relationship between Time, Frequency, and Amplitude

Rotor-Bar Damage

In CSA, the pole-pass frequency (F_P) appears as sidebands surrounding the line frequency (F_L) after performing an FFT on a captured signal. The synchronous magnetic pattern of the stator rotates faster than the rotor cage. This implies that any given rotor bar is passed by all of the magnetic poles in one rotation of the slip frequency. The rate at which this occurs is termed the F_P. Often in vibration analysis the term for this is called the motor pole-passing frequency (PP_F). (PP_F = motor slip x number of poles.) The difference in amplitude between the F_L and the F_P is an indication of rotor health. Empirical research has shown that a difference of over 54 decibels indicates a healthy rotor while less than 45 decibels indicates a degraded (i.e., high-resistance joints, cracked or broken bars) condition exists in the rotor. An example of CSA showing a damaged rotor is shown in Figure 2.

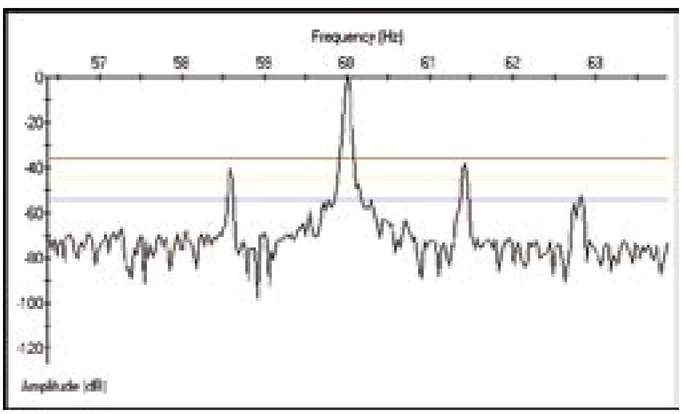


Figure 2 – Spectrum of a Motor with Damaged Rotor

Stator-Rotor Air-Gap Eccentricity

Air-gap eccentricity describes the measurable distance between the stator and rotor within the motor. Manufacturers take great care to ensure that air-gap eccentricity is kept to a minimum. Typical maximum levels for large induction motors are between five and 10 percent. There are two types of eccentricity: static and dynamic. **Static eccentricity** is when the minimum air gap is fixed in space, such as when the rotor is misaligned along the stator bore. **Dynamic eccentricity** describes the condition when the minimum air gap revolves with the rotor. A bowed rotor results in a dynamic eccentricity. If the distance between the length of the stator bore and rotor is not equal throughout the entire circumference, varying magnetic flux within the air gap creates imbalances in the current flow, which can be identified in the current spectrum. The effect of this condition is seen as multiple sidebands of odd harmonics of the line frequency powering the motor. These sidebands will develop around the eccentricity frequency (F_{ECC}).

F_{ECC} = (# of rotor bars) x (RPM/60)

Figure 3 shows CSA results from a motor operating with an excessive air-gap eccentricity. The more severe the eccentricity becomes, the more the amplitude of the peaks will increase.

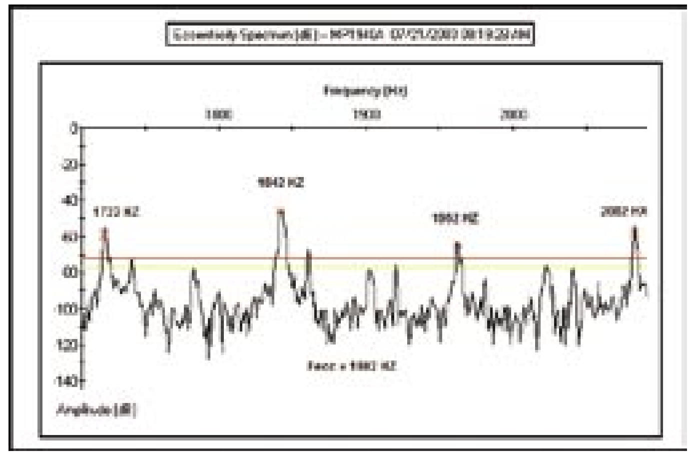


Figure 3 – Current Spectrum of a Motor with Air-Gap Eccentricity

Mechanical Components

Developing the ability to condition and filter the current signal passing through a motor's windings expands CSA to detect load variations related to mechanical processes. The term used for this process is **demodulation**. Demodulation is the process by which a signal is recovered from a modulated carrier. **Modulation** is the process by which some characteristic of a carrier (the 60 hertz applied to the motor) is varied (the rotor flux creating CEMF) in accordance with a modulating wave. Simply put, the load variations that repeat at a constant frequency are reflected into the stator currents through the motor's CEMF. Remove the 60-hertz signal and these frequencies become apparent. Removal of the 60-hertz portion of the signal (demodulation of the carrier frequency) reveals repetitive load variations for analysis.

PdMA is currently using amplitude demodulation of the current signal to greatly expand the capabilities of the EMAX tester. Using a software-driven mode of demodulation to remove the 60-hertz signal, the ability to detect motor speed, pole pass, mechanical pass-through, and reflected frequencies is greatly enhanced. These mechanical and reflected frequencies are related to load variances from items such as belts, gears, pumps, fans, and other mechanical components. To evaluate the magnitude of these frequencies, an FFT is performed on the demodulated signal resulting in a spectrum for analysis. Without the demodulation, many of these load-related frequencies are buried in the signal-to-noise ratio of the captured data.

The following examples of using motor-current demodulation to evaluate equipment condition are from a large public aquarium. The data was gathered using PdMA Corporation's MCEmax motor tester with Advanced Spectral Analysis. When using demodulated-current analysis to monitor mechanical components, it is important to establish a baseline when the equipment is known to be in satisfactory condition. After identifying frequencies related to specific components and conditions, any significant increase in amplitude should be investigated.

Rotor Unbalance/Misalignment: The number of poles, the power system frequency and, to a lesser extent, the motor load determine the speed of an ac induction motor. A two-pole ac induction motor being powered by a 60-hertz line frequency runs at a speed slightly lower than 3,600 revolutions per minute (RPM) or 60 cycles per second (hertz). A four-pole motor runs at a speed less than 1,800 RPM or 30 hertz, and so on. By utilizing current demodulation, the speed of the motor can be identified by a peak in the spectrum and monitored for changes in amplitude. A properly balanced and aligned motor has a frequency peak related to its speed that is barely visible. When the motor is out of balance, or misaligned, this peak's amplitude will increase. As the condition increases in severity, multiples of the speed frequency develop in the demodulated-current spectrum. Figures 4 and 5 demonstrate the change in amplitude of the running speed and 2X running speed during a precision alignment of a pump and motor.

Belts: When transmitting power to the load via a belt attached to the motor, changes in alignment can be evaluated using the demodulated-current spectrum. Evaluation of the current spectrum is similar to alignment in that increases in the amplitude of the belt frequency and the development of multiples of the belt frequency indicate a problem. To calculate belt frequency requires the operator to know the diameter of the pulley mounted on the motor and the length of the belt.

Belt Frequency = 3.142 (D/L) x (RPM/60),

where
D is diameter of the motor-mounted pulley
L is the length of the belt
RPM is the motor speed

In the following example, the dramatic change in the demodulated-current spectrum can be seen after proper tensioning and alignment was performed on a drive belt. In Figure 6, the belt frequency is 8.188 hertz, and there are elevated peaks at multiples of the belt frequency. Notice in Figure 7 how the multiples of the belt frequency have disappeared and how much lower the amplitude of the belt frequency is after the work has been completed. These frequencies can now be easily monitored detecting possible problems developing in the belt drive of this system.

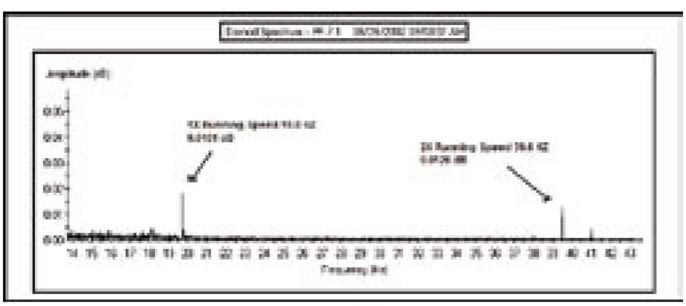


Figure 4 – Demodulated-Current Spectrum Prior to Alignment

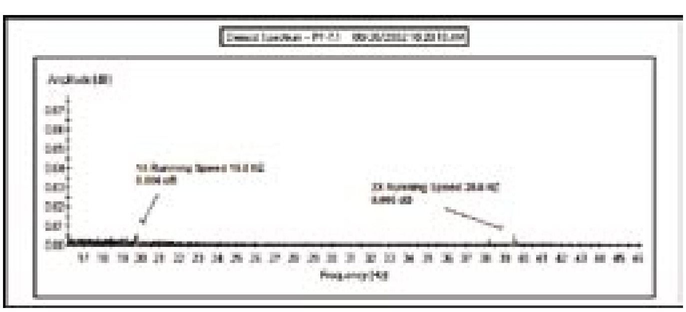


Figure 5 – Current-Demodulation Spectrum after Alignment

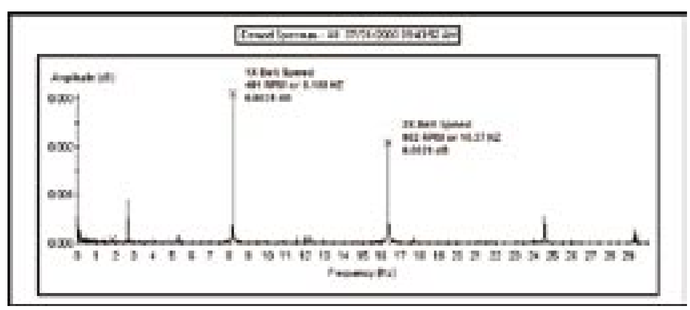


Figure 6 – Demodulated-Current Spectrum Prior to Belt Alignment

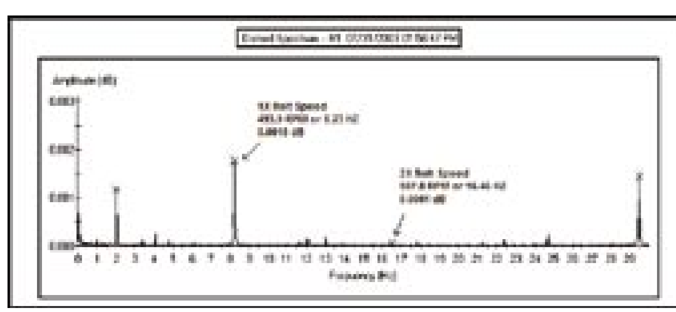


Figure 7 – Current-Demodulation Spectrum after Belt Alignment

Fans/Centrifugal Pumps: Fan blades and centrifugal-pump vane frequencies can be monitored in a demodulated-current spectrum at a frequency equal to the number of blades (or vanes) times the F_P. Increasing amplitude at this frequency as well as a possible increase at the motor-speed frequency peak is an indication of possible blade or pump-vane damage. After initial installation or verification that the pump or fan is in satisfactory condition, identify the vane frequency and record the amplitude of the peak. With baseline amplitude for the equipment established, the demodulated-current spectrum is used as a simple and efficient method to monitor the equipment.

Figures 8 and 9 are a comparison between two identical horizontal pumps. Figure 8 is typical for this application with the pump-vane frequency amplitude of 0.027 decibel. In Figure 9, pump PF-8.6A pump-vane frequency amplitude is 0.046 decibel – nearly double that of all the other identical equipment platforms. Additional testing was performed on pump PF-8.6A, and it is currently scheduled for inspection of the impeller.

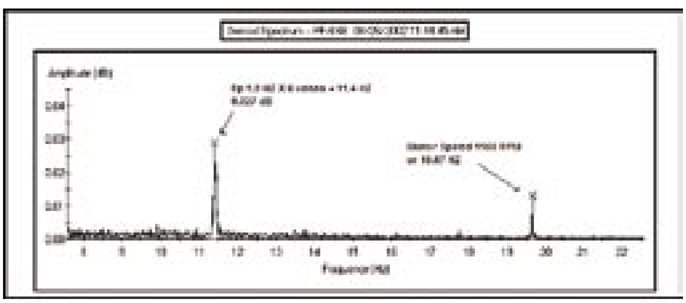


Figure 8 - Typical Current-Demodulation Spectrum for Several Identical Pumps

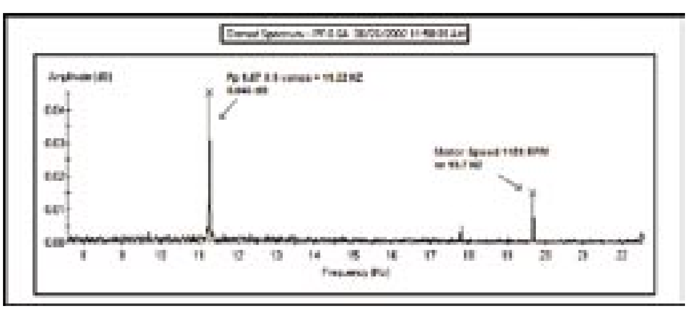


Figure 9 – Current-Demodulation Spectrum of Pump with Suspected Impeller Damage

Loose Motor Foundation: Loose foundation bolts, soft foot, or a distorted bedplate can lead to air-gap eccentricity in a motor. Over time an improperly mounted motor can develop a distorted frame due to thermal expansion and contraction as the motor heats up and cools down. Additionally, a loose motor foundation will make it all but impossible to maintain correct alignment with the powered load. Loose motor foundation can be detected in a demodulated-current spectrum by an elevated peak at half of the motor's running frequency. If the amplitude of this peak is increasing over time, the condition of the motor's foundation, mounting bolts, and shims should be investigated.

Figure 10 is a demodulated-current spectrum from an induction motor powering a pump with possible loose mounting bolts. When the motor is properly mounted to its foundation, this peak is usually not even visible. Having identified this peak in a demodulated-current spectrum indicates that a thorough inspection of the motor's foundation is warranted. If the condition worsens the amplitude of the frequency peak will increase.

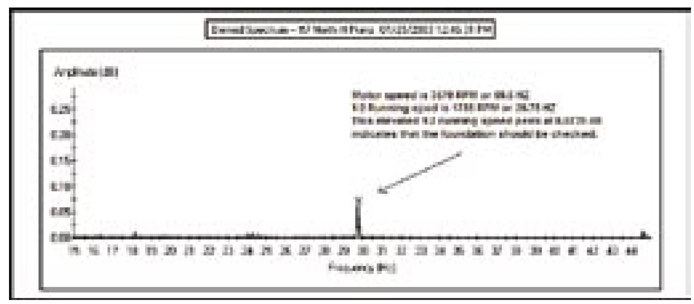


Figure 10 – Current-Demodulation Spectrum of Motor/Pump with Loose Foundation

Motor Bearings: A roller bearing will have a set of unique defect frequencies, and current demodulation utilizes these frequencies to evaluate a bearing. Frequencies are based on the size and design of the bearing. These frequencies are monitored for possible defects in the inner race, outer race, ball (roller), and cage of the bearing. Calculating the inner race, outer race, and ball frequencies uses the formulas listed in Table 1.

The formulas for calculating frequencies are a little imprecise because axial loading and slippage affects them in an unpredictable manner. In order to ensure that the dimensions and contact angle are correct, the technical documents from the bearing manufacturer need to be reviewed or, if no documents are available, the manufacturer needs to be contacted. Bearing manufacturers can provide these frequencies for each bearing they manufacture.

However, good approximations of bearing frequencies for most common ball bearing are as follows:

Outer race fault = (# rollers) x (RPM/60) x (0.4)
Inner race fault = (# rollers) x (RPM/60) x (0.6)
Fundamental train frequency = (0.4) x (RPM/60)

Table 1

BPFI = Ball Pass Frequency, Inner Race	BPFO = Ball Pass Frequency, Outer Race
$BPFI = \frac{n}{2}\left(1 + \frac{Bd}{Pd}\cos\theta\right) RPM$	$BPFO = \frac{n}{2}\left(1 - \frac{Bd}{Pd}\cos\theta\right) RPM$
FTF = Fundamental Train Frequency	BSF = Ball Spin Frequency
$FTF = \frac{1}{2}\left(1 + \frac{Bd}{Pd}\cos\theta\right) RPM$	$BSF = \frac{Pd}{2Bd}\left[1 - \left(\frac{Bd}{Pd}\right)^2 (\cos\theta)^2\right] RPM$

Bd = Ball diameter
n = Number of rolling elements
Pd = Pitch diameter of the bearing
θ = Contact Angle

Slippage and contact angle variances still need to be accounted for. Because of these variances, actual bearing frequency could be slightly higher or lower. When setting up to monitor these frequencies using a demodulated-current spectrum, ensure the envelope or band is plus and minus 10 percent the estimated bearing frequency. It is important to understand that, although one can monitor these bearing frequencies utilizing a demodulated-current spectrum and that an increase in amplitude is cause for investigation, detailed analysis to determine actual bearing condition should be performed with a vibration analyzer.

Conclusion

Analyzing a motor's current can effectively improve the efficiency and effectiveness of any maintenance organization. As more empirical data from the field is gathered, it is becoming clearer that mechanical components can be monitored through the use of a motor's power leads. Using current analysis in conjunction with other predictive maintenance equipment can lead to significant savings in cost by reducing the man-hours spent on collecting data. Current analysis can be used to monitor belts, gears, alignment, and other mechanical components. Use these new features in current analysis to bridge the communication barrier between the mechanical and electrical departments relating to vibration and electrical analysis.

References

1. White, G. D., *Introduction to Machine Vibration*, DLI Engineering Corporation, 1997.
2. Schoen, R. R., Kamram, F., Habetler, T. G., and Habetler, R. G., "Motor Bearing Damage Detection Using Stator Current Monitoring," *IEEE Transactions on Industry Applications, Vol. 31, No. 6,* November/December 1995.
3. Azovtsev, A., and Barkov, A., *Rolling Element and Fluid Film Bearing Diagnostics Using Enveloping Methods*, VibroAcoustical Systems and Technologies, Inc.
4. Jones, R. M., "A Guide to the Interpretation of Frequency and Time Domain Spectrums," *SKF Condition Monitoring, Revision 1*, February 19, 2009.
5. Thomson, W. T., "A Review of On-Line Condition Monitoring Techniques for Three-Phase Squirrel-Cage Induction Motors Past present and Future," The Robert Gordon University, Schoolhill, Aberdeen, Scotland.

Pete Bechard, a native of California, has been living in Tampa, Florida, since retiring from the United States Navy six years ago. He graduated from Columbia College with a degree in Business Administration. During eleven years of his Naval career, Pete was the lead supervisor for several electrical workshops and departments responsible for the maintenance, repair, and operation of both ac and dc rotating equipment. He also spent three years working as a quality assurance officer for nuclear submarine repairs conducted at the Pearl Harbor Submarine Base. During his time with PdMA Pete has completed formal qualification requirements as an instructor/facilitator through Langevin Learning Services. He has also completed formal training in Servo motor operation and repair and harmonic current/power quality in industrial distribution systems. His travels with PdMA have sent him as far as Singapore for motor reliability workshops and as close as The Florida Aquarium in Tampa where PdMA provides MCEmax services as part of their predictive maintenance program.