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ELECTRICAL SIGNATURE ANALYSIS (ESA) DEVELOPMENTS AT THE OAK RIDGE DIAGNOSTICS APPLIED RESEARCH CENTER

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ABSTRACT

Since 1985, researchers at the Oak Ridge National Laboratory (ORNL) have developed and patented several novel signal conditioning and signature analysis methods that have exploited the intrinsic abilities of conventional electric motors and generators to act as transducers. By using simple nonintrusive sensors such as clamp-on current and voltage probes, these new diagnostic techniques provide an improved means of detecting small time-dependent load and speed variations generated anywhere within an electro-mechanical system and converting them into revealing "signatures" that can be used to detect equipment degradation and incipient failures.

These developments have been grouped under the general name of electrical signature analysis (ESA) and together provide a breakthrough in the ability to detect, analyze, and correct unwanted changes in process conditions or the presence of abnormalities in electrical and electro-mechanical equipment.

ESA techniques were developed initially as a means of remotely monitoring the performance and condition of motor-operated valves used in nuclear power plant safety-related systems. Since then, they have been successfully demonstrated on a large variety of consumer and industrial equipment such as air compressors and water pumps, residential air conditioning units and heat pumps, large chillers, fans of various types and designs, automobile alternators and helicopter generators, home appliances and tools, and other devices.

Typical diagnostic information provided by ESA is comparable to that provided by conventional vibration analysis in that both time waveform and frequency spectrum signatures may be produced. The primary benefit of ESA is that an extensive range of diagnostic information can be obtained from a single transducer that may be installed several hundred feet or more from the monitored device on its electrical lines supplying input power (e.g., to a motor) or carrying output power (e.g., from a generator); thus, ESA is truly remote and nonintrusive.

ESA is one of several nonintrusive diagnostic technologies developed at the ORNL Diagnostics Applied Research Center (DARC) in Oak Ridge, Tennessee. These and other technologies have been transferred to industry through several nonexclusive patent licenses with Martin Marietta Energy Systems, Inc. (MMES) who manages ORNL for the U. S. Department of Energy.

1. BACKGROUND

In 1985, the Oak Ridge National Laboratory (ORNL) began a comprehensive aging assessment of motor-operated valves (MOVs) at the request of the U. S. Nuclear Regulatory Commission. A major objective of this study was to identify methods of monitoring the aging and service wear of MOVs so that maintenance could be performed prior to their failure. In addition to evaluating the diagnostic information provided by several MOV-mounted sensors, considerable efforts were made to extract useful information from the motor's running current since it could be acquired remotely (e.g., at the motor control center) and nonintrusively (using a clamp-on current sensor) [1].

MOV motor current research led to the development of several signal conditioning and signature analysis methods which exploit the intrinsic ability of an electric motor to act as a transducer. These methods were observed to provide an improved means of detecting small time-dependent load and speed variations generated anywhere within the MOV and converting them into revealing "signatures" that can

be used to detect degradation and incipient failures [2]. These motor current signature analysis (MCSA) techniques [3] were found to be applicable to a wide variety of motor driven equipment and have provided the foundation on which additional signal conditioning and analysis tools have been developed by ORNL in the area of electrical current, voltage and power monitoring. These developments are applicable to both motors and generators, and have now been grouped under the name electrical signature analysis (ESA).

In addition to MCSA, ESA encompasses a much broader range of electrical signal monitoring such as analyses of line voltage noise, electric current signals from sources other than motors, and power signatures derived from voltage and current measurements (see Figure 1). ESA technologies have been successfully demonstrated by ORNL on a large variety of consumer and industrial equipment such as air compressors, water pumps [4], residential air conditioning units and heat pumps [5], large chillers, fans of various types and designs, automobile alternators and helicopter generators, home appliances and tools, and other devices.

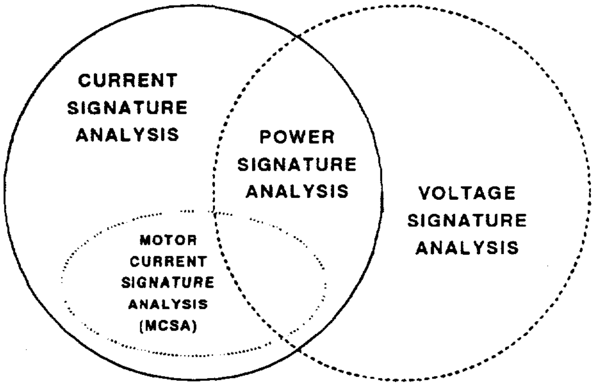

Figure 1 Variety of monitoring techniques included under the name Electrical Signature Analysis (ESA).

Examples of ESA techniques are provided below, beginning with illustrations of MCSA techniques on motor operated valves and other equipment, and followed by additional ESA developments having different and complementary benefits.

2. MCSA

As shown in Figure 2, motor current signals can be obtained at a remote location, such as at a motor control center, which may be several hundred feet away from the equipment being monitored. By utilizing a clamp-on current probe to acquire raw motor current signals, no electrical connections need to be made or broken, thus, equipment operation is not interrupted and shock hazard is minimal.

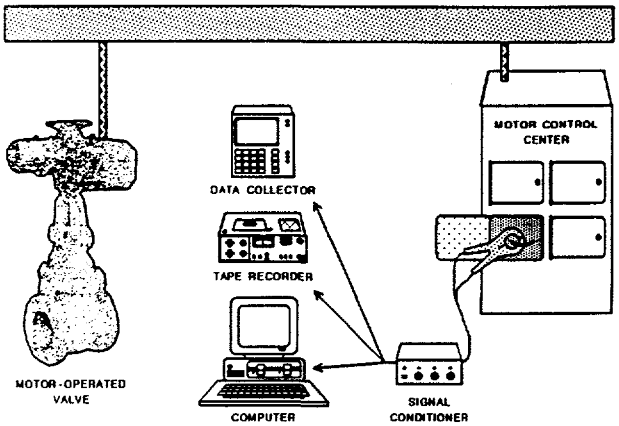

Figure 2 Motor current data may be acquired, processed and analyzed at a remote location. In this example, the monitored device is a motor-operated valve.

Signal conditioning electronics are used to amplify, filter, and demodulate the raw current signal prior to recording and/or analyzing. Amplitude demodulation provides an efficient method of extracting the electrical "noise" information (modulations) from the current signal by treating the dominant power line frequency component as a carrier for the machine-induced modulations. These modulations can often be hard to detect in the raw signal due to their small size; however, once demodulated and amplified, the conditioned motor current signal can be easily recorded and analyzed by a variety of standard off-the-shelf data recorders and signal analyzers.

Figure 3 is included in this paper to show the difference between raw and amplitude demodulated signals for the same motor-driven device; in this case, a small squirrel-cage fan. In this example, the magnitude of the 60-Hz raw current waveform is essentially constant. Only very small amplitude modulations induced by the motor are present. These modulations produce three pairs of sidebands in the raw signal spectrum, all of which provide direct motor speed indication: one pair reflecting the true motor shaft speed and two pairs associated with the motor's slip frequency. These modulations are more clearly seen as single frequency peaks in the spectrum of the demodulated signal.

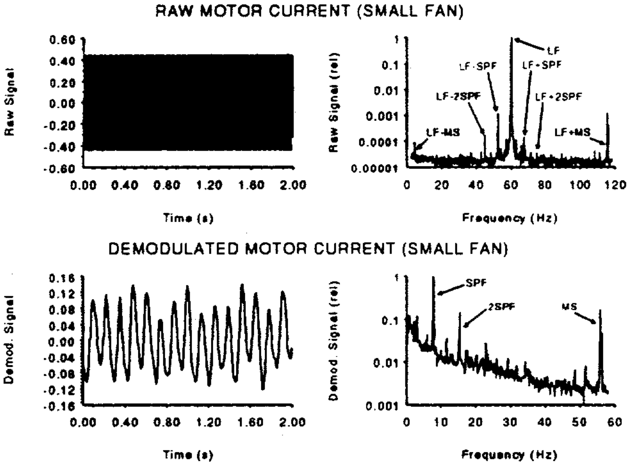

Figure 3 Comparison between "raw" and amplitude demodulated motor current signals from a small squirrel-cage fan.

The observed "slip-poles" frequency is related to the motor shaft speed by the equation:

$$SPF = NP(SS - MS) \qquad (1a)$$

where SPF = the slip-poles frequency, SS = the synchronous speed for the motor, and MS = the actual motor speed, all in Hz, and NP = the number of motor poles. Since the motor's synchronous speed is equal to 2 times the power line frequency divided by the number of motor poles, equation (1a) may be rewritten as follows:

$$SPF = 2(LF) - NP(MS) \qquad (1b)$$

where LF = power line frequency (e.g., 60 Hz or 50 Hz).

Since the variation in slip-poles frequency is several times that observed in motor speed, the slip-poles frequency provides a more sensitive indicator of subtle changes in motor speed that occur as a result of changing mechanical loads. In this example, the fan's 2-pole motor turns at a speed of 3372 rpm (56.2 Hz), producing a slip-poles frequency of 7.6 Hz.

In the following example, MCSA is used as a condition monitoring method for a MOV. In order to provide the reader adequate information to understand the MOV MCSA signatures, a brief MOV description is included.

Motor-operated valves (MOVs) are used in large numbers to control the flow of fluids (e.g., water, steam, etc.) within many industrial facilities including nuclear and fossil power plants, chemical plants, food processing facilities, and others. A typical motor-operated gate valve (see Figure 4) includes a motor operator capable of providing sufficient torque that, when applied to the stem threads of a rising stem valve, produces enough stem thrust to open and close the valve. Forces opposing stem travel can include stem packing friction, stem ejection force due to internal fluid pressure, and gate-to-guide friction induced by high fluid flow.

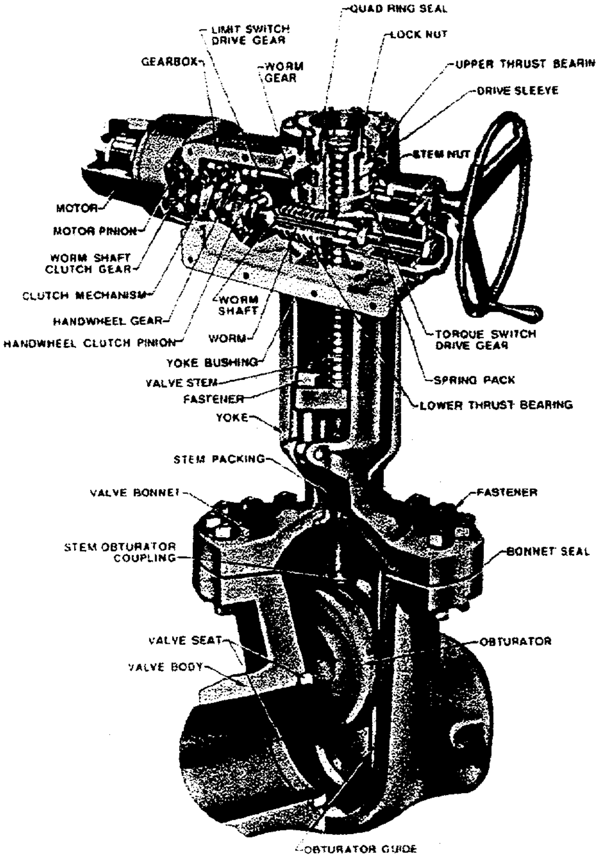

Figure 4 Cutaway view of a typical motor-operated valve (MOV).

In a typical motor operator, the drive sleeve (containing the stem nut that mates with the valve stem) is driven by the worm gear through lug-to-lug contact. In this way, the motor can start in a relatively unloaded condition and can reach full speed before the worm gear and the drive sleeve engage. The transient running load that occurs at this engagement is referred to as the "hammerblow" and can usually be detected in a simple time waveform obtained by rms-to-dc conversion of the raw motor current signal. Figure 5 shows a motor current time waveform acquired during the beginning of an opening stroke for an 18-in gate valve. In addition to the hammerblow, an increase in running current is observed as a result of friction between the valve stem and the stem packing rings when the stem begins to move.

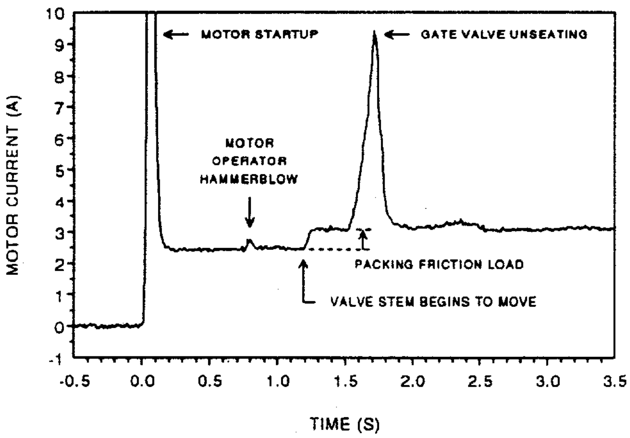

Figure 5 The initial 3.5 seconds of a MOV motor current time waveform showing the detection of several transient loads occurring in the motor operator and valve.

Both the amplitudes and the times of occurrences of these features provide useful condition indicators that may be trended over time. For example, the time differential between the hammerblow and initial stem movement generally reflects the clearance between the stem nut and stem thread surfaces. Likewise, the time between initial stem movement and gate unseating largely reflects the clearance between the gate and stem coupling surfaces. A precise measure of these times can provide an early indication of wear in these regions.

Figure 6 illustrates a typical frequency spectrum for an amplitude demodulated MOV motor current signal. In addition to the slip-poles peak (explained earlier), another prominent component in this MOV motor current spectrum is the worm gear tooth meshing (WGTM) frequency. The existence of a spectral component at this frequency indicates that a significant motor load is associated with the meshing of the worm and worm gear. In addition to the fundamental WGTM frequency, its second harmonic (2 x WGTM) is observed and worm gear rotational sidebands are seen around the WGTM peak, providing further MOV condition indication related to the worm gear drive.

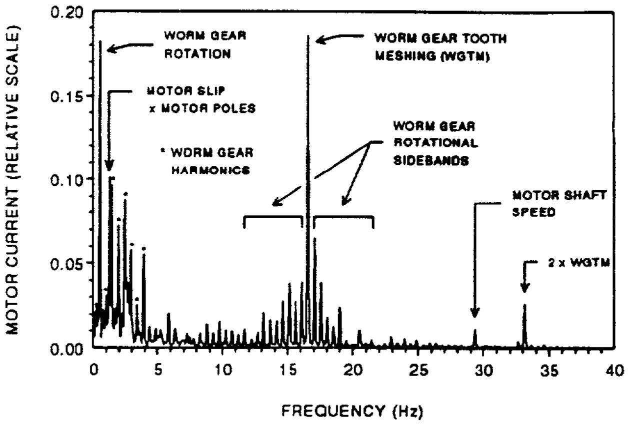

Figure 6 Demodulated MOV motor current spectrum.

If familiar with vibration spectrum analysis, the reader should appreciate the direct correlation between the periodic mechanical loads present in the motor operator (e.g., gear meshings and shaft rotations) and the frequency components present in the demodulated electric current signal. While the author does not recommend the generic replacement of vibration analysis with MCSA, it is suggested that vibration monitoring can be complemented by periodic MCSA testing at the appropriate motor control center(s). In certain specific monitoring situations, vibration analysis may be replaced with MCSA after a clear correlation between "electrical noise" and "mechanical noise" has been established.

In order to further illustrate the variety of MCSA techniques, an additional method is now described that has been named the selective waveform inspection method (SWIM). By selectively filtering the demodulated motor current noise signal, a unique time waveform is obtained which reveals the amplitude modulations of a specific periodic load component. Thus, if the WGTM frequency component is "singled out" using the SWIM technique, a unique signature is produced, as shown in Figure 7. In this example, the signature exhibits a repetitive modulating pattern consisting of 34 shorter period events. Since, in this example, the number of teeth on the MOV's worm gear also equals 34, the observed pattern appears to represent individual tooth meshings between the worm and worm gear. Studies of MOVs on test stands have confirmed that this worm gear tooth meshing profile is nearly constant (very little amplitude modulations) for a new MOV, but varies widely for MOVs that have seen service wear.

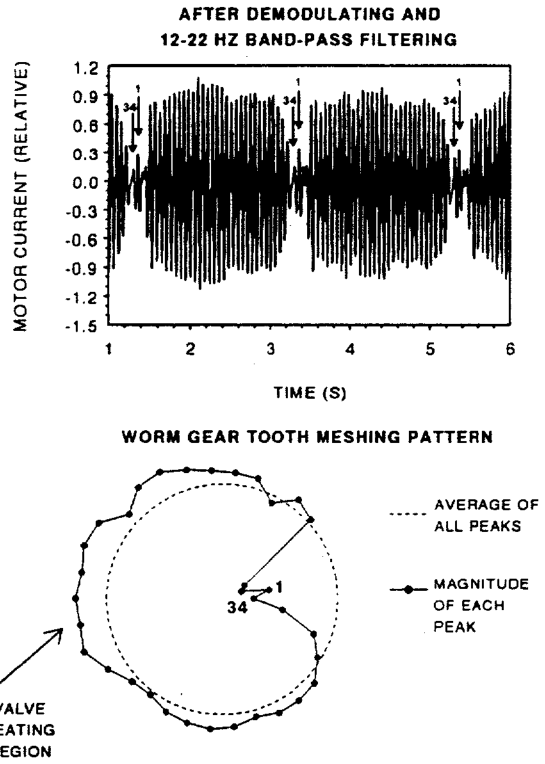

Figure 7 Application of SWIM (Selective Waveform Inspection Method) to the demodulated motor current signal from a MOV whose worm gear has 34 teeth.

The MCSA techniques described above can provide means of detecting many MOV abnormalities such as degraded valve stem and gearcase lubrication, abnormal line voltage, obstructions in the valve seat area, worm gear tooth wear, disengagement of the motor pinion gear, stem nut thread wear, stem packing degradation or tightness changes, valve stem taper, and incorrect torque and limit switch settings. The interested reader is referred to [1] for a more comprehensive description of MOV degradation monitoring using MCSA.

Continued MCSA research and development by ORNL has resulted in the identification of an additional technique that provides enhanced sensitivity to detecting motor degradation, especially the existence of broken rotor bars. As an introduction to this technique, a brief description of an alternating current (ac) induction motor is provided.

There are a variety of electric motor designs; however, all induction motors function as an electric transformer whose primary and secondary windings are separated by an air gap. The primary windings are stationary and are referred to as the stator, while the secondary windings are carried in a cylindrical rotor that is free to rotate within the stator. Alternating current supplied to the stator windings from an electric power system produces a magnetic field that is carried from multiple stator slots to multiple rotor bars which in turn induces an electric current in the rotor windings when the latter is short circuited or closed through an external impedance. The induced currents in the rotor produce a magnetic field which opposes the field produced in the stator, and thus provides the motive force within the motor.

A new technique was developed by ORNL that is based on the recognition that as each rotor bar passes a stator slot, the momentary change in impedance seen by the stator results in a small perturbation in the current flowing to the stator from the power supply. For one complete rotation of the motor shaft, the stator current is modulated a number of times equal to the number of stator slots. Thus, the motor current carrier (line frequency) is modulated at the "slot-pass frequency" (SLF) which is equal to the motor's speed times the number of stator slots.

As an example, motor current and vibration data were acquired on a reciprocating piston vacuum pump that is V-belt driven by a 1-hp ac induction motor having 36 stator slots and 48 rotor bars. A vibration spectrum (Figure 8) contains frequency components reflecting the mechanical loads associated with the motor speed (29.47 Hz), belt rotation (5.0 Hz), and pump pulley rotation (6.5 Hz).

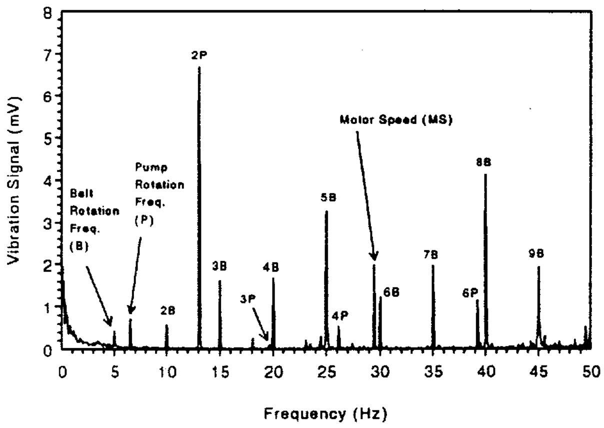

Figure 8 Vibration spectrum for a reciprocating vacuum pump.

In addition to these fundamental frequencies, a strong second harmonic (13.0 Hz) of the pump pulley speed is present and reflects the two direction (and load) reversals that the piston undergoes as a result of the reciprocating action. The V-belt was found to be loose and contained a "lump" which produced numerous belt-rotation harmonics. The demodulated motor current spectrum (Figure 9) compared favorably with the vibration spectrum in that it contained diagnostic information at all key mechanical event frequencies. It should be noted that the motor current spectrum was unaffected by current probe location, whereas the vibration spectrum was dramatically influenced by the proximity of the accelerometer to mechanical loads.

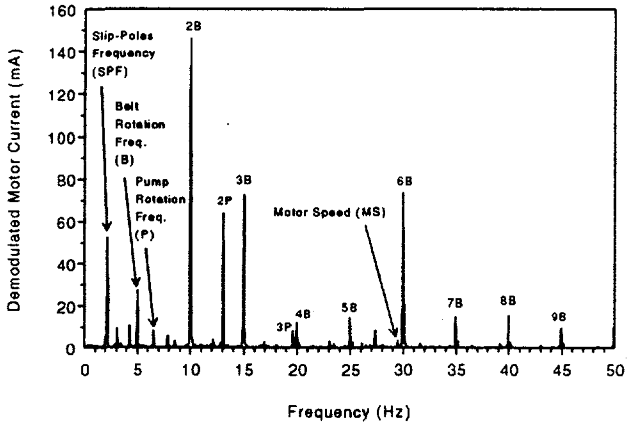

Figure 9 Demodulated motor current spectrum for the reciprocating vacuum pump.

For this vacuum pump, the SLF is equal to 29.47 Hz x 36 stator slots = 1061 Hz., which is greater than the line frequency (60 Hz), thus producing peaks in the raw current spectrum at SLF + LF and SLF - LF as shown in Figure 10. In addition, peaks at SLF + 3LF and SLF - 3LF are also present due to the harmonic structure of the power line voltage. The SLF-related peaks are also intermixed with several odd-harmonics of the power line (15LF, 17LF, and 19LF). The 800-to-1300 Hz region of the raw motor current signal, which is dominated by SLF components, was then band-pass filtered and demodulated. The resultant frequency spectrum of the conditioned signal (see Figure 11) is also dominated by motor-related events such as motor speed and slip-poles harmonics (in contrast to Figure 9 which was derived from the full-bandwidth motor current signal). The band-pass filtered MCSA technique may be used alone or in conjunction with the standard MCSA (full-bandwidth) technique to assist in the separation of motor-related and mechanical load-related information.

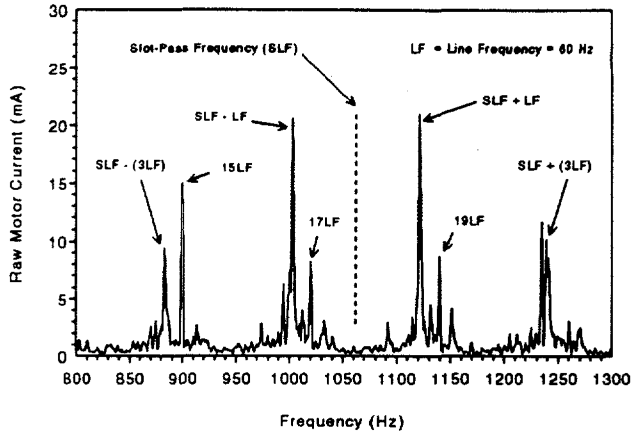

Figure 10 Stator slot-pass frequency components present in the raw motor current signal from the reciprocating vacuum pump.

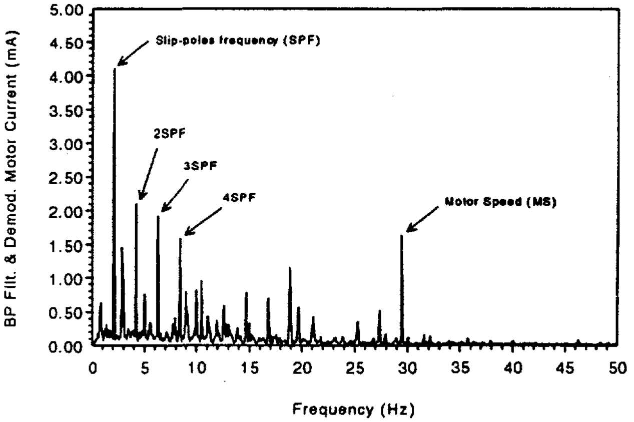

Figure 11 Band-pass filtered (800-1300 Hz) and demodulated motor current spectrum for the vacuum pump.

3. SIGNATURE ANALYSIS OF ALTERNATOR AND GENERATOR VOLTAGE SIGNALS

This paper has focussed on describing how an ac induction motor can be effectively used as a transducer for monitoring the condition of itself as well as the mechanical equipment it drives. It is equally important to realize that alternators and generators also produce voltage signals containing equipment diagnostic information. Figure 12 illustrates an "ESA demonstration device" built by ORNL to show the similarity between mechanical vibration, motor current, and generator voltage signatures on a common device; in this case, a small commercially-available air compressor. The compressor is belt driven by a ½-hp ac induction motor. Also belt driven by the motor is a standard automotive alternator. Compressor belt tension can be adjusted during operation to engage or disengage the compressor while the motor and alternator are still running.

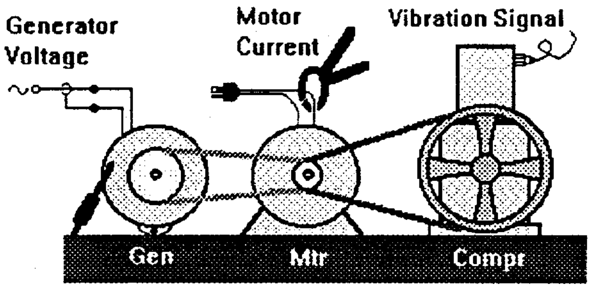

Figure 12 ESA demonstration device having an air compressor, an ac induction motor, and a dc voltage generator.

Figure 13 (top plot) shows a frequency spectrum of the vibration signal acquired from an accelerometer located on the compressor during its operation. Vibration frequencies associated with motor, compressor, and generator shaft speeds were detected, and from both belt rotations as well. Demodulated motor current signals shown in Figure 13 (middle plot) also contain similar frequency components, with the addition of the motor slip-poles frequency.

The alternator output signal (which has already been rectified by a diode-trio) was ac coupled to filter out the primary dc voltage component, and low-pass filtered to attenuate the pole-pass frequency and higher frequency components. The frequency spectrum of the conditioned signal is shown in Figure 13 (bottom plot) and includes all major electrical and mechanical event frequencies, thus demonstrating the alternator's usefulness as a transducer for equipment condition monitoring.

Voltage signature analysis, like MCSA, can be a useful diagnostic approach for a wide range of equipment. For example, preliminary research by ORNL has shown a correlation between helicopter generator voltage signature features and imbalance of the helicopter's main rotor.

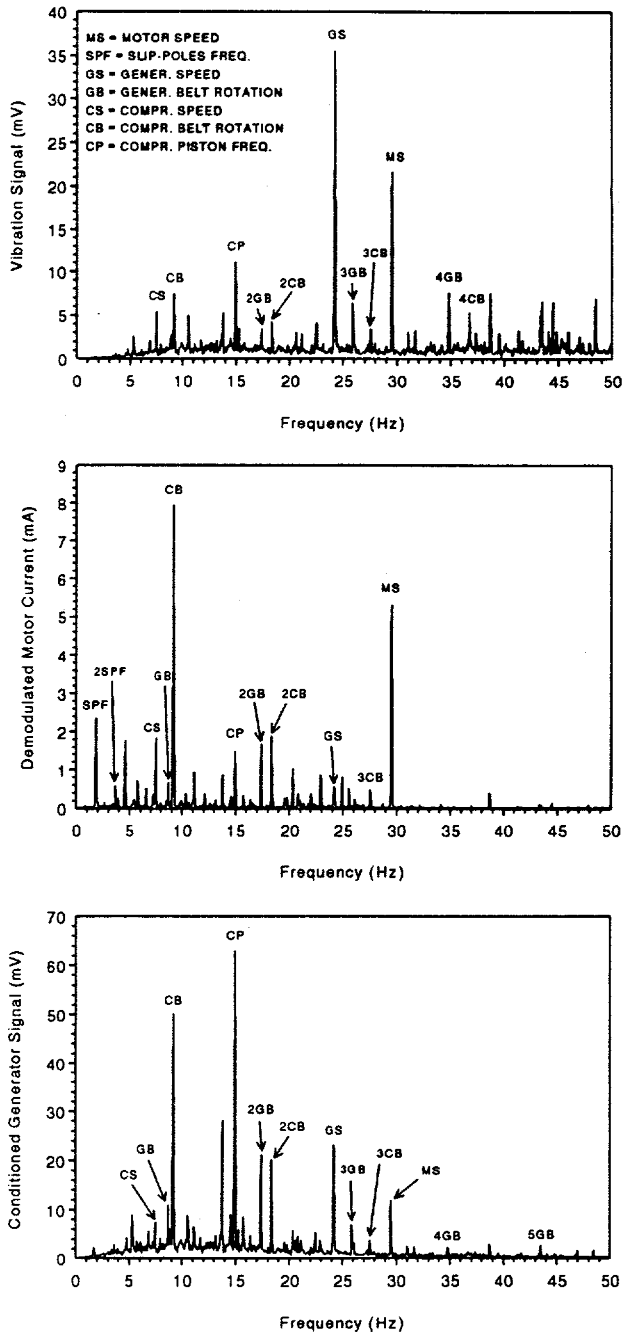

Figure 13 Electrical signatures obtained from the ESA demonstration device while the compressor is engaged.

4. ADDITIONAL ESA DEVELOPMENTS

Additional ESA techniques have been developed by MMES researchers at Oak Ridge, but were not described in this paper, due to space limitations. These developments (all patents applied for) include:

1. The generation and "injection" onto the power line of a new "carrier" whose frequency is selected

to be high enough as to be far removed from the normal power line frequency components. An electrical device connected to the modified power line will modulate not only the normal power line frequencies but the new high frequency carrier as well. The normal power line frequency components can then be removed by filtering, leaving the modulated high frequency carrier for analysis. Since the injected carrier frequency is now considerably higher than any power line harmonic, equipment-induced modulations may be easier to analyze over a much wider frequency band than when the fundamental line frequency carrier is used.

2. The use of other data acquisition and demodulation techniques such as synchronous sampling [6] and phase demodulation [7]. These methods provide additional motor current signal conditioning options that can be used by themselves or in conjunction with those techniques described in this paper.

5. TECHNOLOGY TRANSFER

Since 1988, ESA technologies developed by ORNL have been transferred to 8 private companies under non-exclusive patent licenses with MMES. Those companies currently having an active license to use and/or market ESA technologies include:

- B&W Nuclear Service Company
- Intelligent Sensors, Inc.
- ITI Movats
- Performance Technologies, Inc.
- Predictive Maintenance Inspection, Inc.
- Public Service Electric and Gas of NJ

For more information on licensing options, contact Larry Dickens, Licensing Executive, Office of Technology Transfer, Martin Marietta Energy Systems, Inc., P. O. Box 2009, Oak Ridge, Tennessee, 37831-8242.

6. CONCLUSIONS

The purpose of this paper has been to briefly describe the benefits that are achievable through the use of electrical signature analysis (ESA) techniques that have been developed by ORNL. These new techniques provide a means of remotely detecting load and speed variations generated anywhere within an electro-mechanical system and converting them into revealing "signatures" containing useful equipment diagnostic information.

The interested reader is encouraged to contact the author for additional information on ESA and for descriptions of other diagnostic techniques developed at ORNL.

7. REFERENCES

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