The AnomAlert Motor Anomaly Detector is a system of software and networked hardware that continuously identifies faults on electric motors and their driven equipment. AnomAlert utilizes an intelligent, model-based approach to provide anomaly detection by measuring the current and voltage signals from the electrical supply to the motor. It is permanently mounted, generally in the motor control center and is applicable to 3-phase AC, induction or synchronous, fixed or variable speed motors. AnomAlert models are also available for monitoring generators.
Alert under the hood
The AnomAlert diagnostic solution can be used together with a vibration monitoring system as a complementary tool for detecting electrical faults. Alternatively, it can be used where dedicated vibration monitoring is not practical, economical, or comprehensive enough. It can detect changes in the load the motor is experiencing due to anomalies in the driven equipment or process such as cavitation or plugged filters and screens. Since it doesn’t require any sensor installation on the motor itself or on the associated load, AnomAlert is especially attractive for inaccessible driven equipment and is applicable to most types of pumps, compressors, and similar loads. It is also well suited to the monitoring of submersible, borehole, downhole, and canned pumps.

The AnomAlert monitor uses a combination of voltage and current dynamic waveforms, together with learned models, to detect motor or driven equipment faults. Active learning is backed up by an additional fleet model in case the monitor has been installed on an already defective motor. The monitor detects differences between observed current characteristics and learned characteristics and relates these differences to faults.

Motor fault detection is based on a learned, physics-based motor model, where constants in the model are calculated from real-time data and compared to previously learned values.

Mechanical fault detection is based on power spectral density amplitudes in particular frequency bands, in relation to learned values. This information is combined automatically with expert diagnostic knowledge. Because of this spectral band approach, mechanical fault detection is not precise, but provides guidance toward a class of possible faults. The sensitivity to some faults (for example rolling-element bearing faults) will decrease with distance from the fault. On the other hand, faults that increase motor load are independent of the distance from the motor.

The spectrum-based mechanical fault detection in the AnomAlert monitor seems similar to Motor Current Signature Analysis (MCSA), but several important differences set it apart from typical MCSA:

- The AnomAlert monitor uses cause-effect (voltage-current) relationships, while MCSA uses the current only. Changes in input voltage will cause changes in the current that could lead to false alarms in MCSA. The cause-effect relationship in the AnomAlert processing helps protect against these false alarms.

- The AnomAlert monitor uses a stable reference data set that is obtained from ten days of motor operation, and it calculates alarm threshold levels specific to the equipment itself.

- Detected anomalies are subjected to a sophisticated change persistence algorithm to guard against false alarms, making the AnomAlert monitor less sensitive to random fluctuations in the signals.

Data Acquisition

Voltage and current signals from all three phases (6 total signals) are sent to the monitor where they are digitized for further signal processing. Voltages less than 480 V can be input directly, while higher voltages require a potential transformer. Depending on the application, current transformers or Hall-effect current sensors are used to sense and step down the motor currents.

AnomAlert processing operates on a 90 second iteration cycle. At the beginning of every 90 second iteration, the monitor samples voltage and current waveforms. The remainder of the period is used for post processing analysis and front panel update.
All six waveforms can be exported to a text file for further post processing. The text file has no headers and six columns, corresponding to paired voltage and current waveforms $V_1, I_1, V_2, I_2,$ and $V_3, I_3$.

**Modeling And Fault Detection**

The AnomAlert monitor uses four different approaches to fault detection. One is based on internal motor characteristics; another is based on frequency analysis of the residual current spectrum; a third analyzes actual line voltages and currents to check for certain types of line and current faults; finally, the fourth uses fleet data from similar motors to provide an independent diagnostic reference. We will discuss how all of these work in turn.

**The Internal Motor Model**

For an ideal motor, voltage and current waveforms are sinusoidal at line frequency. The changing line voltage creates magnetic forces that cause the rotor to turn, and the amplitude and phase of the motor currents are related to the input voltages through the internal mechanical and electrical workings of the motor. We can think of the line voltage waveforms as inputs to the motor, and the current waveforms as outputs. The motor electrical and mechanical internals can be thought of as a transfer function that converts the input voltage waveform into the output current waveform (Figure 1). This is the key to understanding the internal motor model in the AnomAlert monitor.

The monitor uses a linear model for the electrical and mechanical internals of the motor. This physics-based model is derived from a set of differential equations, and it can be expressed as a transfer function. During the learning process, the monitor determines the coefficients of this model. For a normal motor, the model transfer function is a close approximation to the real physical transfer function of the motor. We will discuss later the special case of what happens when the AnomAlert monitor models a motor that already has a defect.

While monitoring, the AnomAlert monitor takes the input voltage waveform and passes it through the model transfer function to obtain a theoretical current waveform. Meanwhile, the real motor transfer function converts the input voltage waveform into the observed (measured) current waveform. The theoretical current waveform is subtracted from the measured current waveform to produce a residual current waveform (Figure 2). The residual waveform contains the “errors” between theory and reality, and the monitor uses this residual waveform for mechanical fault analysis.

**FIGURE 1:** The motor as a transfer function. A voltage waveform is converted to a current waveform by the motor.

**FIGURE 2:** A source voltage waveform passes through the real motor transfer function, producing a current waveform with harmonic distortion, $I_{\text{Motor}}$. The same voltage waveform is passed through the learned model transfer function, producing a theoretical current waveform, $I_{\text{Model}}$. The two waveforms are subtracted, producing a residual current waveform. The residual waveform represents the error between theory and reality.
Motor Electrical Fault Detection
Changes in the internal characteristics of the motor (for example, a shorted winding) will cause the real motor transfer function to change. While monitoring, the AnomAlert unit takes the measured voltage and current waveforms and calculates a new set of observed coefficients for the internal motor model. The original model coefficients are subtracted from the observed coefficients to yield residuals. These residuals are used to detect internal electrical motor problems.

Mechanical Fault Detection
In an ideal motor, the rotor would be perfectly centered in the stator clearance, turn smoothly, and have no unbalance. In real motors, the rotor is never perfectly centered in the stator, bearings and driven equipment create disturbances, and the rotor always has some unbalance.

Mechanical faults disturb the rotor position and create disturbances and distortions in the current waveforms. As faults develop in the machine train, they will cause the output current to deviate further from the theoretical. For example, an unbalanced rotor will move in a 1X orbit that causes a rotating rotor/stator gap change. This change causes amplitude modulation of the current signals and causes sidebands to appear around the line frequency in the spectrum. In another example, a race fault in a rolling element bearing will cause a periodic disturbance in the rotor position; this disturbance in rotor position will create a corresponding disturbance in rotor/stator gap and amplitude modulation of the motor current. The modulation produces sidebands around the line frequency in the residual current spectrum, and the distance of the sidebands from the line frequency will correspond to the bearing defect frequency. Other kinds of faults can produce a wide variety of additional frequency content in the current waveforms. AnomAlert processing (and in general, MCSA) looks for this additional frequency content and uses it to diagnose different classes of mechanical problems.

AnomAlert analysis is different from MCSA. MCSA involves spectral analysis of the observed current waveform (sometimes demodulated), while AnomAlert processing produces a Power Spectral Density (PSD) plot from the residual current waveform (the difference between the theoretical current waveform and the measured current waveform). The AnomAlert residual current waveform is based on a learned model, so the PSD is a spectrum of the difference between theory and reality. Thus, AnomAlert methodology first detects change in the motor current, and then classifies the spectral characteristics of that change into fault classes. The monitor classifies PSD energy into 12 typical spectral frequency ranges that are associated with particular fault classes.

Line and Current Faults
During the learning period, the monitor learns typical behavior for that motor. Deviations of voltage or current from normal behavior can signal a problem. The monitor checks for significant changes in power factor, voltage, and current imbalance. Because an increase in driven load will cause an increase in motor current, AnomAlert methodology uses abnormal current as an indicator of a load problem. For example, decreasing flow through a fan or blower would cause a decrease in fan load and motor current, and this could signal an obstruction in flow.

The Fleet Model
What happens if the monitor is installed on a motor that has an existing fault? Will it learn the fault and fail to detect that something is wrong? No. This is where the fleet model comes in. The monitor has a database of residual waveform signal characteristics that are representative of a large fleet of similar motors. This is used as a backup to guard against missed alarms in case the AnomAlert monitor has learned a bad motor. When a measured value exceeds the High value in the database for that frequency range (Figure 3), the monitor will alarm – assuming that the alarm level has passed the persistence test. We will discuss this test later.
Learning

When first installed, the monitor learns the behavior of the motor it is hooked up to. It spends some time learning before starting to monitor the motor. Some motors drive equipment that operates at a constant speed and load. This is the simplest operating mode to learn and monitor because any change in operating characteristics is probably indicative of a fault. Many other machine trains operate at variable speed or variable load. In this case, what is normal for one load range may be abnormal for another. In this situation, the monitor learns and creates a separate internal motor model for each operating mode. Then, later, as conditions change, it will shift from one model to the next.

The AnomAlert learning period takes about 10 days (Figure 4), whether the motor is fixed or variable speed. During learning, the monitor iterates by collecting waveforms, performing analysis, then repeating the process. During each 90 second iteration, it simultaneously collects voltage and current waveforms for each phase, and then performs numerical analysis of the data. During the initial, 3 day Learn phase, the AnomAlert unit will not monitor. It is busy building a preliminary internal motor model and spectral statistics.

After the initial Learn phase is complete, the AnomAlert unit will begin to monitor the motor. While it does this, it will continue to improve the model for another 7 days (the Improve phase). For variable speed motors, these iterations are spread over as many operating modes as necessary. During the Learn and Improve phases, if motor operation shifts from one operating mode to another, the monitor will save the previous data and start learning the new operating mode. When the motor returns to a partially completed mode, the monitor will continue learning from the last point. Once the entire learning process has been completed, the monitor stops model refinement and continuously monitors the motor using the completed internal motor model and PSD spectral characteristics.

If, after model completion, the motor enters a new operating mode that hasn’t been seen before, the monitor may go into alarm if the current waveforms are significantly different from what has been modeled. At that time, the user can manually direct the AnomAlert unit to learn the new mode using the Update command. It will then learn the new operating mode. It will not monitor the new mode until the update learning process is completed.

During all learning, if either motor power or AnomAlert power is interrupted, the monitor will automatically recover and continue learning from the last point.

FIGURE 3: Residual current PSD plot showing the motor spectrum (blue) and the fleet High curve (red). If a motor frequency persistently exceeds a fleet High value, the monitor will alarm.

FIGURE 4: The AnomAlert learning period. After installation, AnomAlert spends about 10 days learning the motor behavior. It will start to monitor after the initial 3 day Learn period is complete.
Change Detection, Persistence, and Alarming

Because of noise and small changes in operating characteristics, there is always some variation between successively observed model and spectrum parameters. During the learning phase, the AnomAlert monitor builds statistics that describe the variation that occurs. When learning is complete, the monitor has a set of statistics for every model coefficient (electrical faults) and spectral band (mechanical faults).

The AnomAlert unit operates by detecting differences between observed and previously learned parameters; either internal model coefficients or spectral band amplitudes. These differences must pass a statistical test before being considered significantly different. These tests define minimum alarm thresholds. Check Line alarms are generated based on voltage imbalance variations and voltage fluctuations from the range encountered during the Learn phase. A similar alarm method is used for power factor, total harmonic distortion, voltage and current rms values, and voltage and current imbalance values.

Even large deviations could be expected to occur in a normal machine once in a while. To guard against false alarms, AnomAlert processing requires that the detected change be persistent over time. The monitor uses a sophisticated algorithm that compares the amount by which a parameter exceeds the threshold value and the number of times this has occurred in a window of time. This sliding window varies depending on the amount the measured parameter exceeds the statistical threshold. Large threshold exceedance will require only a short time window, while mild exceedance will require a long window. The monitor will alarm only when the persistence requirement has been satisfied.

Diagnostics

For the most part, the AnomAlert monitor does not provide precise diagnoses of particular faults. Instead, it reports categories of faults that act as indications and point to areas that should be further investigated. It uses four independent fault detection methods that cover two categories, electrical and mechanical.

Electrical faults are associated with either motor internal problems or external power supply issues. The AnomAlert unit monitors both using two independent methods. Internal motor faults are detected using the learned internal motor model as a reference. During each monitoring iteration, the monitor calculates a set of 8 internal motor model parameters based on the observed voltage and current. These observed parameters are compared against the parameters that were obtained during the learning phase, and significant and persistent changes are detected and reported as electrical faults. These faults include the following examples:

- Loose windings
- Stator problem
- Short circuit

External supply is directly checked for voltage or current imbalance, voltage range, maximum current, and low voltage or current.

Mechanical fault categories are detected and diagnosed using the PSD of the residual current waveform. The residual current represents the difference between the observed current and the theoretical current produced by the internal motor model using the same observed voltage. The PSD is divided into 12 frequency ranges that are typically associated with certain mechanical problems (listed below). Analysis of these frequency ranges produces fault classes for further investigation.

- Loose Foundation/Components
- Unbalance/Misalignment/Coupling/Bearing
- Belt/Transmission Element/Driven Equipment
- Bearing
- Rotor

Note that the Check Load alarm, caused by abnormally high or low current, is usually caused by a change in the driven machine’s load; machine load can change for two reasons, fault or process change. If the machine is running in a different condition which is not seen during the learn period, the user has to set
the AnomAlert unit to update mode to learn this new condition. If the load is changed due to a fault, the problem should be investigated, and the user needs to make sure the alarm is cleared in the monitor.

The Fleet Model provides an independent analysis in the event that the AnomAlert unit has learned a faulty system. The Fleet Model consists of Normal and High values for each of the 12 PSD ranges based on experience with a large number of similar motors. If a residual current PSD range value exceeds the fleet High value, then, after persistence checking, the monitor will warn that something is wrong.

Limitations
The AnomAlert Motor Anomaly Detector is a powerful motor monitoring system. However, there are some limitations on its use and interpretation.

- It cannot be used for DC or single-phase motors.
- For variable frequency drives, the inverter chopping frequency should be higher than 2 kHz.

Mechanical diagnostics are based on energy in 12 spectral frequency ranges. This is, by nature, an approximate analysis, and diagnostic indications usually only represent broad classes of problems. The customer will have to follow up using other methods to determine the actual fault. The PSD spectrum produced by the AnomAlert unit can be helpful, but may not be sufficient for problem identification.

The AnomAlert unit cannot be used on motors that have rapidly varying voltage or power. Voltage, frequency and current amplitude must not change by more than 15% in six seconds. This is not a serious restriction for most applications, but some applications, like crushers, will not fit this requirement. Note that if a sudden change of load occurs, the monitor will reject that sample; however, the same machine could run steadily at some load, and this would allow the unit to monitor the machine.

The AnomAlert unit will work very well on applications where the motor is located some distance from the current or potential transformers. However, the line at the current measurement point must be dedicated to a single motor; multiple motors downstream from a single CT cannot be monitored. On the other hand, one set of PTs can be used for all motors that are supplied from the same voltage source. The current measurement restriction is a consideration for subsea applications where power may be delivered to the sea floor only to branch off to multiple motors. In this case, an AnomAlert unit could not be used on the main delivery power line. However, it could be used if CTs could be installed on each branch (CT burden limits apply).