

AnomAlert: Under the Hood

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What Is AnomAlert?

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.

AnomAlert is a diagnostic solution that 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 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.

AnomAlert 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 AnomAlert has been installed on an already defective motor. AnomAlert 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 AnomAlert seems similar to Motor Current Signature Analysis (MCSA), but several important differences set AnomAlert apart from typical MCSA:

- AnomAlert 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 AnomAlert helps protect against these false alarms.
- AnomAlert 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 AnomAlert less sensitive to random fluctuations in the signals.

We will now delve more deeply into the operating principles of AnomAlert. We will not discuss current and voltage transformer selection or installation, or operating modes and programming; these aspects are covered elsewhere¹.

Data Acquisition

Voltage and current signals from all three phases (6 total signals) are sent to AnomAlert 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 operates on a 90 second iteration cycle. At the beginning of every 90 second iteration, AnomAlert 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

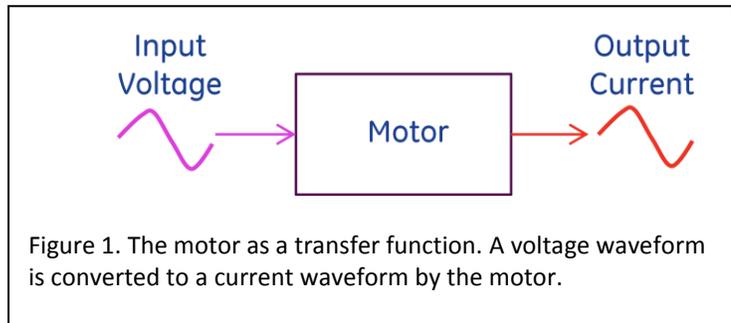
AnomAlert uses four different approaches to fault detection. One is based on internal motor characteristics; another is based on frequency analysis of the motor current spectrum; a third analyzes actual line voltages and currents to check for certain types of line and current faults; finally, the fourth 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

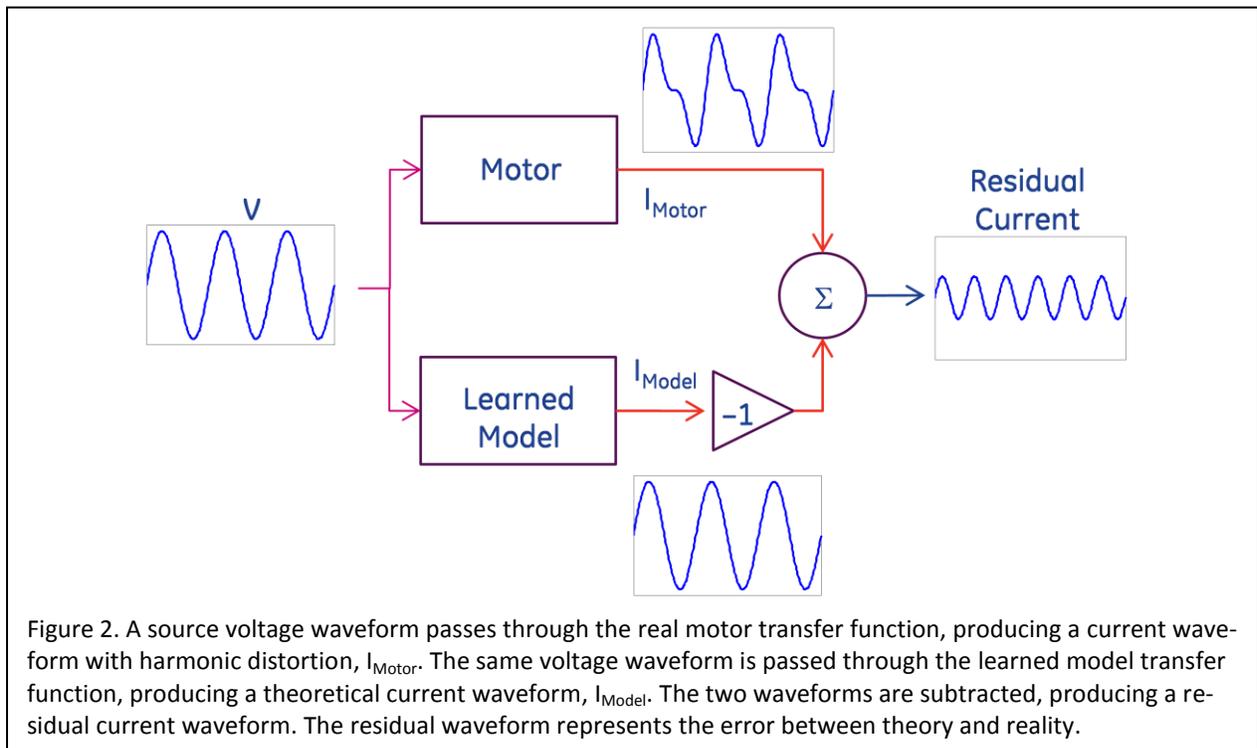
¹ For sensor selection and installation, see Bently Nevada Guide 286752, *Selection of CTs, CSs, and PTs for AnomAlert*. For general ordering information, see 286754-01, *Specifications and Ordering Information*.

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 AnomAlert.



AnomAlert 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 AnomAlert 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 motor².

While monitoring, AnomAlert 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 AnomAlert uses this residual waveform for mechanical fault analysis.



² We will discuss later the special case of what happens when AnomAlert models a motor with a defect.

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, AnomAlert 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 (and in general, MCSA) looks for this additional frequency content and uses it to diagnose different classes of mechanical problems.

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

Line And Current Faults

During the learning period, AnomAlert learns typical behavior for that motor. Deviations of voltage or current from normal behavior can signal a problem. AnomAlert 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 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 AnomAlert 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. AnomAlert 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 AnomAlert has learned a bad motor. When a measured value exceeds the High value in the database for that frequency range, AnomAlert will alarm³ (Figure 3).

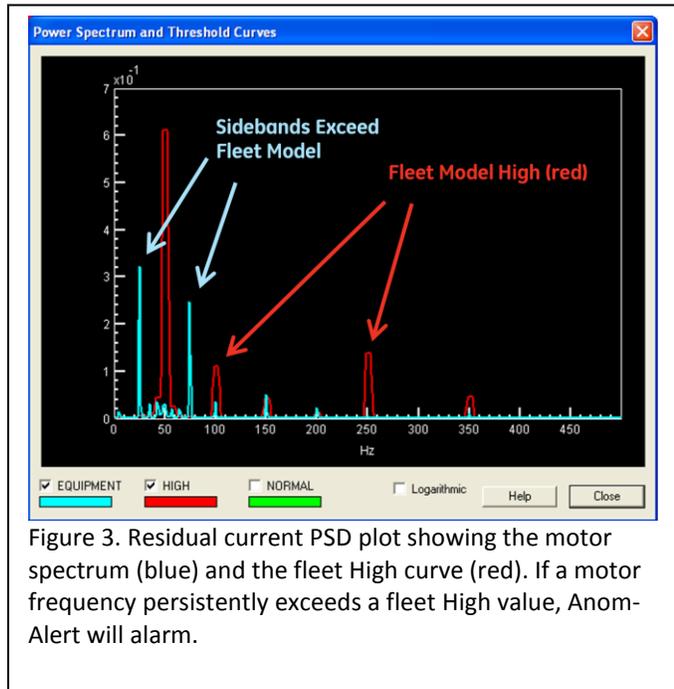


Figure 3. Residual current PSD plot showing the motor spectrum (blue) and the fleet High curve (red). If a motor frequency persistently exceeds a fleet High value, AnomAlert will alarm.

Learning

When first installed, AnomAlert 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, AnomAlert learns and creates a separate internal motor model for each operating mode. Then, later, as conditions change, AnomAlert 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, AnomAlert iterates by collecting waveforms, performing analysis, then repeating the process. During each 90 second iteration, AnomAlert simultaneously collects voltage and current waveforms for each phase, and then performs numerical analysis of the data. During the initial, 3 day Learn phase, AnomAlert will not monitor. It is busy building a preliminary internal motor model and spectral statistics.

After the initial Learn phase is complete,

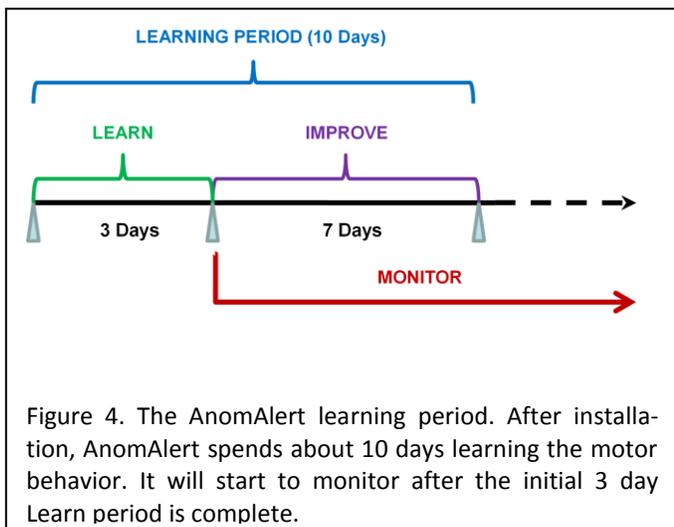


Figure 4. The AnomAlert learning period. After installation, AnomAlert spends about 10 days learning the motor behavior. It will start to monitor after the initial 3 day Learn period is complete.

³ This assumes that the alarm level has passed the persistence test. More on that later.

AnomAlert 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, AnomAlert will save the previous data and start learning the new operating mode. When the motor returns to a partially completed mode, AnomAlert will continue learning from the last point.

Once the entire learning process has been completed, AnomAlert 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, AnomAlert may go into alarm if the current waveforms are significantly different from what has been modeled. At that time, the user can manually force AnomAlert to learn the new mode using the Update command. AnomAlert will then learn the new operating mode. AnomAlert will not monitor the new mode until the update learning process is completed.

During all learning, if power is interrupted, AnomAlert will recover and continue learning from the last point.

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, AnomAlert builds statistics that describe the variation that occurs. When learning is complete, AnomAlert has a set of statistics for every model coefficient (electrical faults) and spectral band⁴ (mechanical faults).

AnomAlert 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.

Even large deviations could be expected to occur in a normal machine once in a while. To guard against false alarms, AnomAlert requires that the detected change be persistent over time. AnomAlert 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. AnomAlert will alarm only when the persistence requirement has been satisfied.

Check Line alarms are based on configured percent deviations from an objective norm. For example, a voltage or current imbalance alarm would be generated if the imbalance between phases exceeded a

⁴ Note that AnomAlert identifies the largest amplitude spectral line in a particular frequency range and uses that line's amplitude for the value in that range. AnomAlert does not add up all the spectral energy in a range.

maximum configured value in percent. A similar alarm method is used for voltage range, maximum current, and low voltage or current.

Diagnostics

For the most part, AnomAlert 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. AnomAlert 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. AnomAlert monitors both using two independent methods. Internal motor faults are detected using the learned internal motor model as a reference. During each monitoring iteration, AnomAlert 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:

- 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. These faults are reported as Check Line alarms.

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. 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 AnomAlert 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 AnomAlert.

The Fleet Model provides an independent analysis in the event that AnomAlert has learned a faulty system. The Fleet Model consists of Normal and High values for each of the 12 PSD ranges based on experi-

ence with a large number of similar motors. If a residual current PSD range value exceeds the fleet High value, then, after persistence checking, AnomAlert will warn that something is wrong.

Limitations

AnomAlert is a powerful motor monitoring system. However, there are some limitations on its use and interpretation.

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 AnomAlert can be helpful, but may not be sufficient for problem identification.

AnomAlert 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, AnomAlert will reject that sample; however, the same machine could run steadily at some load, and this would allow AnomAlert to monitor the machine.

AnomAlert 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 CTs are not allowed. 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, AnomAlert could not be used on the main delivery power line. It could be used if CTs could be installed on each branch (CT burden limits apply⁵).

AnomAlert cannot be used for DC or single-phase motors.

For variable frequency drives, the inverter chopping frequency should be higher than 2 kHz.

Summary

AnomAlert is a powerful motor monitoring system. AnomAlert's power comes from both sophisticated signal processing and analysis algorithms and from built-in redundancy. Its ability to learn makes it sensitive and flexible, and a fleet reference database protects against missed alarms caused by learning an already defective motor. Alarming is clever and uses statistical analysis combined with an adaptive persistence test. These features produce a product that is a significant improvement over conventional Motor Current Signature Analysis, and AnomAlert has a proven track record documented by many case histories.

⁵ The burden of a current transformer is the maximum resistance that the secondary of the CT (the part hooked up to AnomAlert) can drive and meet specification. Long wires from the CT will have more resistance that will limit the allowable distance from the CT to AnomAlert. See Bently Nevada Guide 286752, *Selection of CTs, CSs, and PTs for AnomAlert*.