GE
Grid Solutions

Multilin 8 Series

Applying Electrical Signature Analysis in 859/869 for Motor M&D

Application Note

Overview

Motors play a key role in running industrial processes. The primary goal of motor component monitoring is to keep industrial processes running through predictive monitoring of critical motor components. Then, when a developing problem is detected, a diagnosis of the root cause can be reported without any interruption to the process, minimizing the problem and allowing immediate resolution of the issue (or plans for resolution in the next maintenance cycle). Event-driven reporting means that motors can inform the user when attention is required after each detected event. By utilizing a consistent monitoring and reporting solution for all motors, a standardized approach to managing information is provided by the asset management system. Predictive monitoring of asset health and proactive maintenance are the new industrial reliability strategies.

This application note discusses how to apply electrical signature analysis (ESA) functions using the 859/869 Motor Protection Relay for the following types of motor failure:

- Mechanical Faults (Foundation Looseness, Shaft Misalignment, and Eccentricity)
- Roller/Ball Bearing Faults
- Stator Inter-Turn Faults

Introduction

Electrical Signature Analysis

Electrical Signature Analysis (ESA), sometimes referred to as Motor Current Signature Analysis (MCSA) or Current Signature Analysis (CSA), is used to detect various failure modes in a rotating machine by analyzing stator voltage and current signals. The concepts surrounding ESA have been in commercial use for over three decades, however, ESA technology can be applied in new ways for easier detection of faults that challenge other technologies such as vibration analysis, and for enhancing maintenance and troubleshooting programs. ESA technology itself is not a replacement for technologies such as vibration analysis. Instead, it can enhance or provide a different dimension to an existing troubleshooting methodology, or it can provide a standalone cost-effective solution. For accurate analysis, ESA systems rely upon FFT (Fast Fourier Transformer) analysis, much like vibration analysis.

The 859/869 Motor Protection Relay offers a proven ESA-based method to detect various failure modes in a rotating machine and its assembly by analyzing the stator phase A current. This method provides detection of motor failures

such as stator inter-turn fault, broken rotor bar, roller/ball bearing fault, and mechanical faults like foundation looseness, load shaft misalignment, static and dynamic eccentricity. Unlike traditional methods, the 869 ESA method doesn't require additional measurements such as noise, vibration, or temperature.

859/869 ESA fault detection algorithm uses FFT computation of the current signal to detect fault conditions at vibration frequencies related to the corresponding fault condition. The relay also computes peak magnitudes, or energy in dB, at the stator current frequencies and calculates the change in dB magnitude with respect to the baseline peak magnitudes (healthy mode of the motor without misalignment), or energy at the corresponding stator current frequencies in dB with respect to each load operating zone.

Ball/Rolling Element Bearing Fault Detection

The faults occurring in a motor bearing are generally due to excessive load, rising temperatures inside the bearing, use of bad lubricant and so on. The bearing consists of the outer raceway and inner raceway, the balls, and the cage that assures equidistance between the balls. Different faults that may occur in a bearing can be indicated using a single parameter based on any affected component defect, such as the outer raceway, inner raceway, or rolling element.

Mechanical Faults Detection (Foundation Looseness, Misalignment, and Eccentricity)

Foundation Looseness, shaft Misalignment, and Eccentricity fault conditions result in nonuniformity of the air gap between the rotor and stator. Therefore, in the 859/869 relay, detection of these fault conditions is combined into one element referred to as the Mechanical Fault element.

Static/Dynamic Eccentricity

Air-gap eccentricity represents a condition where the air gap distance between the rotor and the stator is not uniform. Two types of abnormal air-gap eccentricities exist: static and dynamic. In case of static eccentricity, the position of the minimal radial air gap is fixed, while in the case of dynamic eccentricity, the position of the minimal air gap turns with the rotor.

Foundation Looseness/Shaft Misalignment Detection

Coupling misalignment is a condition where the shaft of the driver machine and the driven machine are not on the same centerline. Misalignment shows up in the frequency domain as a series of harmonics of the running speed, produced by the strain induced in the shaft. Foundation looseness represents the ground vibration affecting motor performance due to the improper basement.

Stator Inter-Turn Fault Detection

Stator inter-turn faults cause severely localized heating and may rapidly spread to a larger section of the winding, consequently resulting in a sequential phase-to-ground or phase-to-phase fault. If the fault is detected at its early stage, machine shutdown can be planned and accurate repair actions may be taken which includes re-winding. If preventative maintenance does not take place, once the fault propagates and the motor is forced out of service, a huge downtime is needed to replace the motor.

The 859/869 relay provides two advanced methods to detect stator inter-turn faults: (1) ESA-based; (2) Sequence Impedance-based. The latter is more sensitive and requires a negative sequence of the motor stator winding; it is recommended to use this method for protection by setting a small pickup time. The ESA-based method can help to detect an inter-turn fault before it evolves to insulation breakdown, minimizing unplanned system downtime. Both methods can be combined, using the 859/869 FlexLogic Builder in the EnerVista 8 Series Setup software to enhance the security and dependability of protection against stator inter-turn faults.

859/869 ESA Algorithm

859/869 ESA provides a complete autonomous analysis of mechanical and electrical failures.

Key differentiators and features of the 859/869 ESA algorithm

- Robust Data Quality Check
- Baseline Mode- Healthy Data (optional)
- Monitoring Mode – Fault Data
- Motor performance w.r.t baseline
- FFT waveform visualization
- Peak Magnitude & Energy dB for measurement error compensation

High-level architecture of the 859/869 ESA Algorithm

This section provides a step by step high-level procedure for the patented 859/869 ESA (Bearing and Mechanical faults) algorithm.

Step 1: Measure the current signal from the CT. Perform CT supervision.

Step 2: Consider the phase A current of the motor input power supply.

Step 3: Perform a data quality check to assess the input power supply condition and then sample for processing.

Step 4: Compute rotor speed, slip and supply frequency.

Step 5: Compute fault frequencies for all fault types.

Step 6: Compute normalized dB magnitudes at fault frequencies w.r.t measured supply fundamental frequency.

Step 7: Compute peak magnitude and energy in dB during baseline mode as an average of all dBs computed in the baseline period and stored as baseline data w.r.t each load bin interval (10%) of the motor operational load.

Figure 1: 859/869 ESA Architecture

Step 8: Compute peak magnitude and energy in dB during monitoring mode over each computational interval and compare with the baseline dB to determine the "Change in dB" with respect to each load bin interval.

Step 9: If the "Change in dB" value is greater than the configured pickup setting (1 or 2) and is sustained for the pickup delay time, generate an event and operate the element.
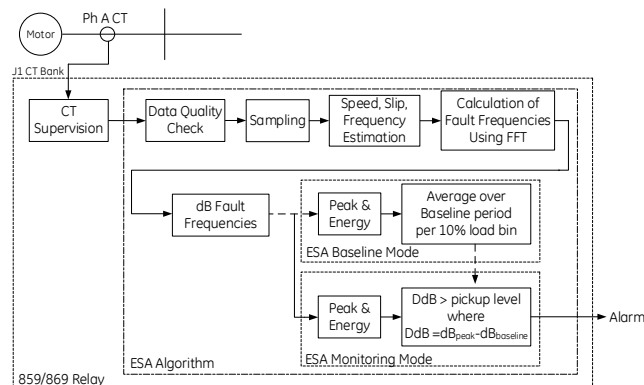
Setting Guidelines

This section explains ESA element setpoints and provides programming guidelines for the element using the Enervista 8 Series Setup software. Navigate **to Setpoints > Monitoring > ESA** to see the ESA settings menu.

The 859/869 ESA element setpoints menu comprises the settings of Bearing, Mechanical and Stator Inter-turn. These settings are applicable to both Baseline and Monitoring modes.

SETTING	PARAMETER
Motor Manufacturer	None
Function - Bearing	Enabled
Function - Mech	Enabled
Function - Stator	Enabled
Baseline Period	48 hrs
Baseline Mode	Enabled
No. of Rolling Elements	2
Cage Diameter	0.500 inches
Rolling Element Ball Diameter	0.100 inches
No. of Stator Slots	2
Bearing Flt PKP Stg 1	55 dB
Bearing Flt PKP Delay1	15 min
Bearing Flt PKP Stg 2	45 dB
Bearing Flt PKP Delay2	10 min
Mech Flt PKP Stg 1	55 dB
Mech Flt PKP Delay1	15 min
Mech Flt PKP Stg 2	45 dB
Mech Flt PKP Delay2	10 min
Stator Flt PKP Stg 1	55 dB
Stator Flt PKP Delay1	15 min
Stator Flt PKP Stg 2	45 dB
Stator Flt PKP Delay2	10 min
Block	Off
Output Relay	Relay : Disabled
Events	Enabled
Targets	Self-Reset

Annotations to table:
- Optional setpoint for record purpose only → Motor Manufacturer
- Setpoints "Baseline Mode" → Baseline Period / Baseline Mode
- Setpoints "Stator Fault Detection" → No. of Stator Slots
- Setpoints "Bearing Fault Detection" → Function - Bearing
- Setpoints "Mechanical Fault Detection" → Function - Mech

Before discussing the setpoints in more detail, it is important to first understand the concept of the Load Bins, Baseline Mode, Monitoring Mode, and Data Quality Check, which are extensively used in the 859/869 ESA Algorithm.
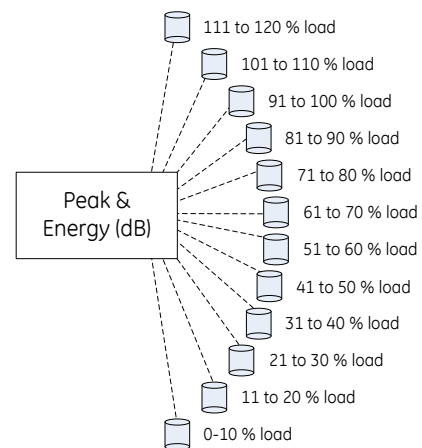
Load Bins

The magnitude of the fault frequency is impacted by the motor loading and therefore the magnitude (dB) changes as the motor load changes. 859/869 ESA handles the load changing condition by using the load bin concept. A load bin is defined as the load interval of 10% within the 0% to 120% range of motor load operation, with a total of 12 load bins.

During ESA baseline mode operation, peak and energy dBs are computed and averaged over the entire configured period (setpoint: Baseline Period) and then stored as averaged normalized dB with respect to each load bin of the motor.

Example

During Monitoring Mode, for instance, the motor is running at 95% load, and the ESA algorithm computes the ΔdB from the stored baseline dB of the appropriate load bin (91 to 100%) and the current dB level. The ESA element issues an alarm if ΔdB exceeds the set pickup threshold after the set pickup time delay.

Peak & Energy (dB)
- 111 to 120 % load
- 101 to 110 % load
- 91 to 100 % load
- 81 to 90 % load
- 71 to 80 % load
- 61 to 70 % load
- 51 to 60 % load
- 41 to 50 % load
- 31 to 40 % load
- 21 to 30 % load
- 11 to 20 % load
- 0-10 % load

Figure 2: Allocation of Peak & Energy dB values with respect to Load Bin during Baseline Mode

Baseline Mode

For an ideal motor having no bearing, mechanical or stator faults, the dB magnitude of any fault frequency corresponding to load bin is ideally -100dB, meaning that the magnitude of fault frequency is zero. However, in practice this may not be the case since a motor without any faults may still generate some or all fault frequencies at low dB levels.

The 859/869 ESA Baseline Mode establishes the baseline dB of the inherent fault frequencies for all the possible load bins during the programmed time duration of the Baseline Period, when enabled. It is recommended to run this mode once during the motor installation/commissioning phase for a default baseline period of 48 hours. Thereafter, by enabling Baseline Mode the device can be forced into this mode whenever there is a need to capture baseline data for a specific load bin if the baseline data was not captured during the initial 48 hours period (default) after installation.

Monitoring Mode

During Monitoring Mode, ESA algorithms for bearing, mechanical and stator faults are computed every 1 minute based on current (Ia) samples. FFT is run on these current (Ia) samples to capture the peak magnitude or energy for each possible harmonic factor (k = 1,2,3) related to the bearing, mechanical and stator faults, and stored in an internal file for each load bin. Computed ESA dB magnitudes at all fault frequencies after each interval are compared with baseline magnitudes to extract the maximum change in dB. Both data quality checks and ESA accuracy checks are performed prior to recording data. Users can clear operational data using the 'Clear ESA operational data' command.

Robust Data Quality Check

Before computing an FFT of the current signal, a quality check of the input supply data is performed by the ESA algorithm. If any of the following data checks fail, ESA does not perform the FFT or data recording.

- Fundamental frequency measured must be within +/- 5% limits of the nominal frequency.
- The voltage measured must be within +/- 10 % limits of the nominal voltage.
- THD (total harmonic distortion) of the phase current must be less than 5%.
- ROCOF (rate of change of frequency) computed must be less than 5%.
- Current unbalance in the system computed must be less than 10%.

Setpoints Related to Bearing Fault Detection

Setting guidelines for NO. OF ROLLING ELEMENTS, CAGE DIAMETER, and ROLLING ELEMENT BALL DIAMETER

In addition to setpoints Function – Bearing, Bearing FLT PKP and Bearing FLT PKP Delay, ESA bearing fault detection algorithm requires bearing setpoints that relate to the physical geometry of the ball/rolling bearing. These setpoints include No. of Rolling Elements, Cage Diameter, and Rolling Element Ball Diameter. Determination of these setpoints is discussed as follows:

These parameters can be obtained in one of the following ways:

1. **Bearing Specifications**

These parameters can be directly obtained by the bearing manufacturer. If detail specifications are not available then if necessary contact them directly. Note that manufacturers may provide these details on their website if they are not included in the product documentation. For example, SKF bearing part numbers can be entered in the SKF website to provide detailed specifications:

http://webtools3.skf.com/engcalc/CalcBearingFrequencies.do

The SKF tool can also provide bearing fault frequencies when the motor speed in rpm is specified. (This is for reference and cross-check purposes only.)

2. **Physical measurement using the measurement tools like Vernier Calipers**

Measure the bearing parameters using tools such as Vernier calipers. Note that any error in measurement, specifically of ball diameter can lead to errors in diagnosis results. Extreme caution is required.

Note that ball diameter is difficult to measure accurately in the field.

3. **Using software database** – see appendix for more details

Setpoints Related to Stator Inter-turn Fault Detection

This function requires settings: Function – Stator, Stator FLT PKP, Stator FLT PKP Delay, and No. of Stator Slots.

Setting of NO. OF STATOR SLOTS

No. of Stator Slots must be obtained from the motor manufacturer if not available in the motor design specifications. There are methods available to estimate the number of stator slots, however, obtaining the actual value is strongly recommended since a difference of 1 slot from the actual value can result in incorrect calculation of the fault frequencies associated with stator inter-turn faults.

Pickup and Time Delay Setpoints

Flt PKP Stg1, Flt PKP Delay 1 – Bearing, Mech, and Stator

For all the functions, this setting in dB corresponds to an alarm or alert condition of a fault in the motor. If the baseline data is available or Baseline Mode is used, then this setting should correspond to the change in dB (for example 10 dB). If the baseline data is not available, then this setting should correspond to the peak dB magnitude (for example 60-70 dB). This setting should be based on historical motor test/failure data, data captured when similar motor type/range is tested during a fault, interpretation from vibration analysis, or expert inputs. The delay setting specifies after how much time the element must trigger an alarm provided the condition is sustained (this is to avoid spurious alarms).

Flt PKP Stg 2 Flt PKP Delay 2 – Bearing, Mech, and Stator

The explanation for this setting is same as above, but the settings should correspond to the alarm condition. For example, a change in dB of 20dB and peak dB magnitude of 40 to 60 dB range. The values provided are for reference only.

869 ESA Algorithm Testing and Validation

In order to validate the performance of ESA algorithm, the ESA element has been tested on two motors with ratings 1000HP, 4kV, and 300HP, 600V. These tests have been performed in GMR Workshop facility in Saskatoon, Canada.

1000 HP Motor

Foundation Looseness

300 HP Motor

Misalignment
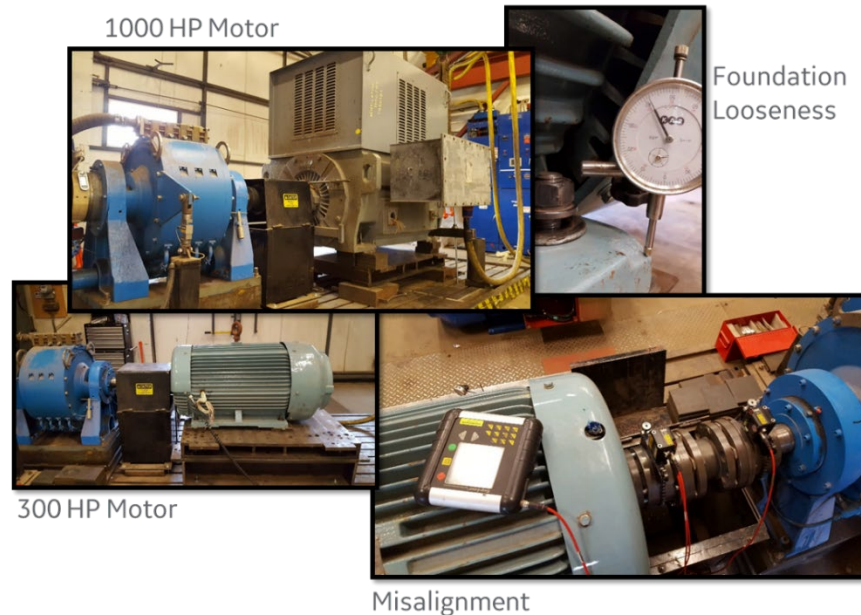
Applicability of ESA

For a motor application, the applicability of ESA can be verified based on the following:
- The motor must be line fed motor and squirrel cage type.
- The motor must have ball/rolling element bearings.
- Bearing specifications must be available.
- Nameplate data must be available.
- The ESA algorithm can be applied to cyclic load motor applications only when the cyclic load duty cycle is greater than 1 min.

Test Setup

The ESA algorithm was tested on these motors for Foundation Looseness and Shaft Misalignment failure modes. In addition to ESA testing, for validation purposes, the 869 ESA method was compared with test results of the commercially know M&D tool PdMA MCEMAX Gold.
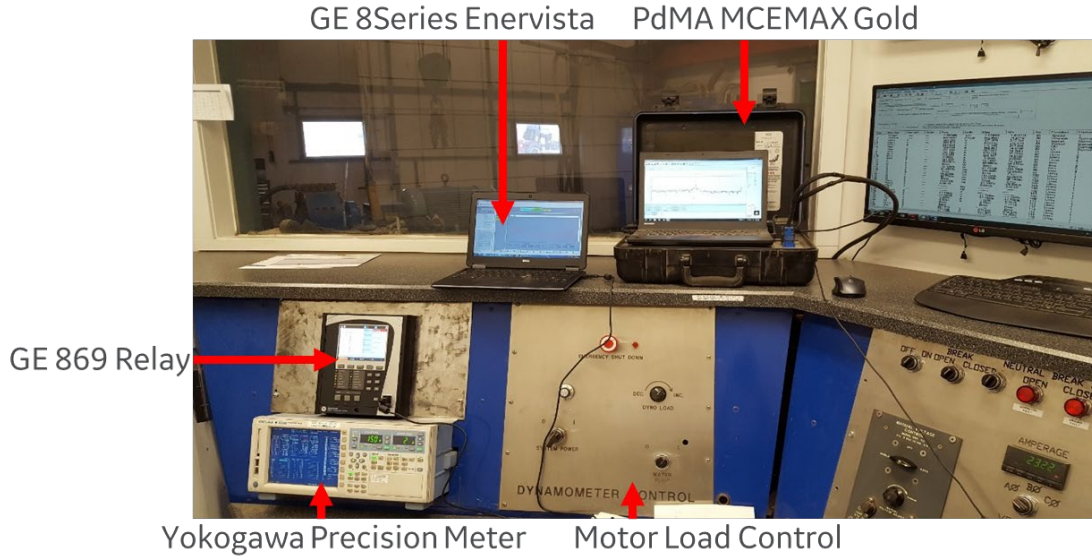

Figure 3: 869 Setup at GMR workshop

Test Results - Mechanical Fault: Foundation looseness

Fault Frequency determined by 869: 89.534 Hz
Fault Frequency determined by PdMA: 90 Hz

dB magnitude of the fault Frequency determined by 869: -48.598dB (ALARM)
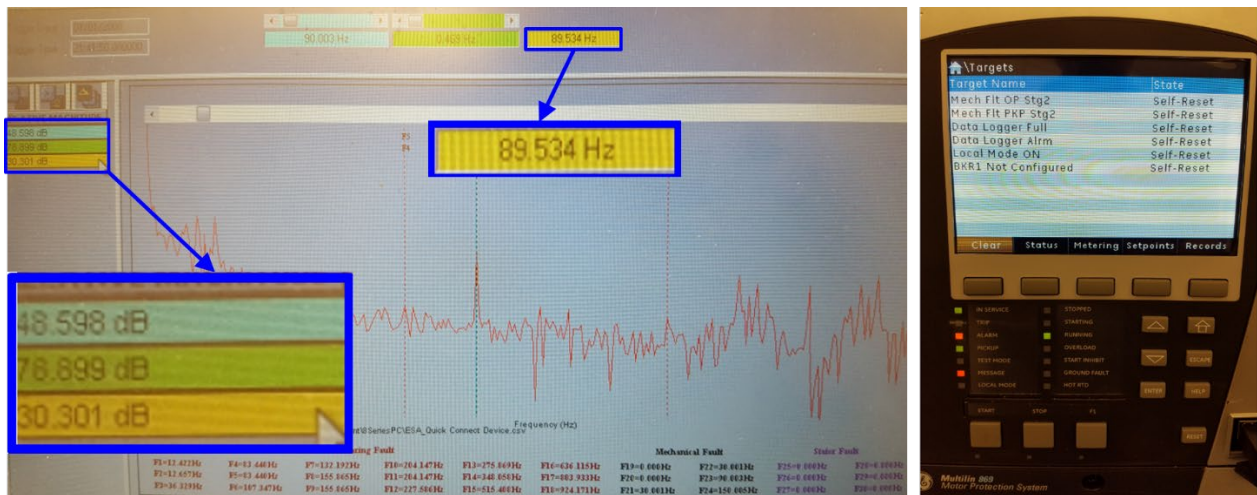dB magnitude of the fault Frequency determined by PdMA: -44.08dB (ALERT)

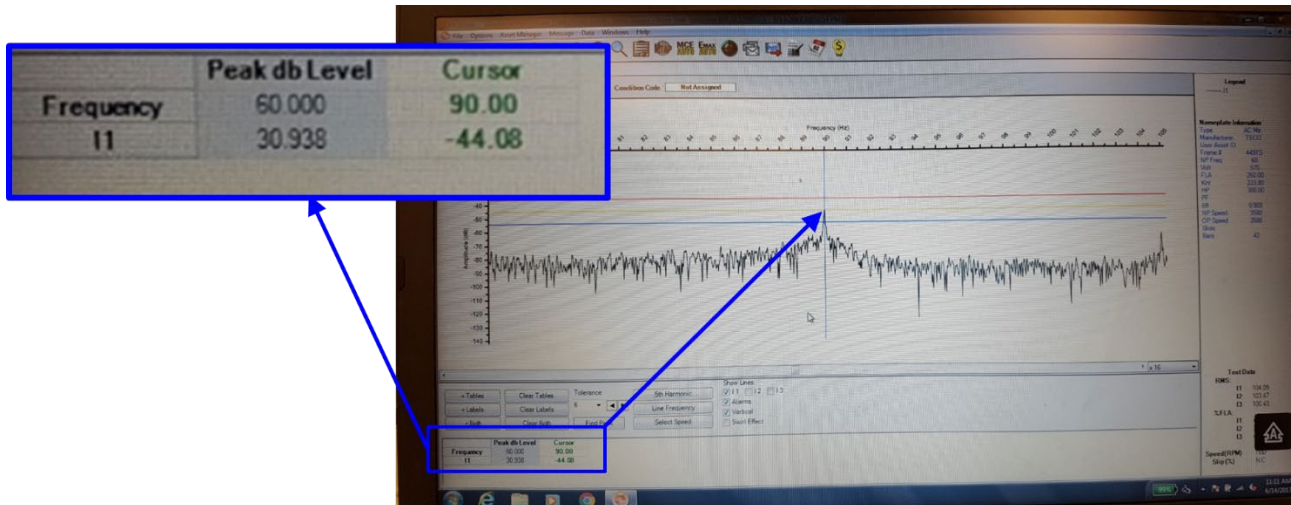**Figure 4: 869 ESA Result with foundation looseness fault in motor**

Figure 5: PdmA ESA Result with foundation looseness fault in the same motor

As shown in Figures 4 & 5, for foundation looseness fault, both 869 relay and PdmA devices detected a mechanical fault in motor with corresponding dB levels of -48.598 (alarm) and -44.08 (alert) respectively.

Key Advantages of the GE 859/869 Protection Relay Solution

In a nutshell, 859/869 offers reliable current sensing, accurate spectrum analysis, and all comprehensive instrumentation for monitoring motors and identifying different failure modes and fault mechanisms, and interpretation of current signatures of developing faults.

- Very low and very high-frequency faults can be detected (unlike vibration analysis).
- Compared to vibration analysis, faults appear earlier in the 859/869 ESA-based method.
- Power supply related problems are identified separately, and not attributed to the motor condition.
- Exact running speed and motor load at the time of data collection is used in calculations for increased accuracy in fault determination.
- Operators have access and control using standard protocol communications such as IEC 61850, IEC 104, Modbus, DNP.
- Advanced FlexLogic can be used to create custom logic in addition to ESA-computed data, power supply related data, and motor monitoring data such as temperature.
- State-of-the-art advanced protection and control functions can be used to correlate motor trip events with health-related data computed using ESA.
- The 859/869 Motor M&D solution is an add-on to the protection relay, resulting in fewer devices to manage and monitor.
- The 859/869 ESA interfaces with plant-level software such as power management, SCADA, and DCS systems.
- 859/869 ESA is a cost-effective solution specifically for MV motors when compared to vibration monitoring and offers continuous monitoring (24/7) when compared to hand-held monitors.

Conclusions

Rotating machines are a critical component of many industrial processes and are frequently integrated into commercially available equipment. The health of a rotating machine can be monitored effectively using a non-intrusive method called Electrical Signature Analysis (ESA). By treating the machine as an implicit transducer built into machine-driven equipment, the current behavior can be used to show various health conditions of the machine as well as the load it is driving. Analyzing motor health in a continuous manner using a protection relay platform embedded with ESA algorithms provides an appealing solution in terms of predictive monitoring with no additional wiring requirements. The 859/869 relay is a cost-effective solution, providing reliable data processing and spectrum analysis, autonomous procedures with built-in logic, and advanced protection & control functions.

Appendix

Determining Bearing Settings from the Software Database

Some motor diagnostics software from manufacturers (specifically vibration monitoring software) provides a database of bearing fault multipliers as shown below,

Bearing ID	# of Rolling Elements	FTF	BSF	BPFO	BPFI
9436	19	.434	3.648	8.247	10.753
9437	19	.434	3.648	8.247	10.753
9442	22	.443	4.191	9.740	12.260

Formula 1: $FTF = \frac{S}{2} * [1 - (\frac{Bd}{Pd} * \cos\Theta)]$

Formula 2: $BSF = \frac{Pd}{2Bd} * S * [1 - (\frac{Bd}{Pd} * \cos\Theta)^2]$

Formula 3: $BPFO = \frac{Nb}{2} * S * [1 - (\frac{Bd}{Pd} * \cos\Theta)]$

Formula 4: $BPFI = \frac{Nb}{2} * S * [1 + (\frac{Bd}{Pd} * \cos\Theta)]$

Where:

FTF = Fundamental Train Frequency (Hz)
BSF = Ball Spin Frequency (Hz)
BPFO = Ball Pass Frequency of Outer Race (Hz)
BPFI = Ball Pass Frequency of Inner Race (Hz)
Nb = number of rolling elements
S = speed (revolutions per second)
Bd = ball diameter (in or mm)
Pd = pitch diameter (in or mm)
Θ = contact angle (degrees)

By neglecting the contact angle and considering the specific speed of the motor, the parameters can be derived as follows:

No. of rolling elements = [BPFO + BPFI]/Nr, Where Nr or S = running speed = Motor speed in rpm/60

This can also be calculated simply as,

　　　= [BPFO/FTF] (This is the preferred method since it is not speed dependent.)

The ratio of 'Bd/Pd' can be computed as,

Ratio of Bd/Pd = [BPFI-BPFO]/[BPFI+BPFO].

This ratio can be used to approximate the values of Bd and Pd. Fault frequencies are only dependent on the ratio of 'Bd/Pd' rather than the individual values of Bd and Pd, thus they can be set accordingly. For example, assume Pd = X inches and set Bd = (X*Ratio) inches.

Computation of Fault Frequencies by the ESA Algorithm

This section explains how ESA automatically compute the fault frequencies associated with the fault type.

Bearing Fault

Fault or defect in the bearing generates frequencies in the current signal such that current frequencies related to bearing damage are computed using equation the following equation:

$$F_{bearing} = F_{supply} \pm k \times F_{vib} \tag{1}$$

where

k	any integer 1,2,3,...
F_{supply}	actual source supply frequency measured by the 859/869 relay
F_{Vib}	vibration frequencies obtained from the equation (2). Each part of bearing has its associate vibration frequency

Vibration Frequencies (F_{vib})

$$F_{vib} = \begin{cases} \dfrac{N_b}{2}\dfrac{\omega_r}{60}(1-\dfrac{D_b}{D_c}) & \text{(inner race)} \\[2mm] \dfrac{N_b}{2}\dfrac{\omega_r}{60}(1+\dfrac{D_b}{D_c}) & \text{(outer race)} \\[2mm] \dfrac{D_c}{D_b}\dfrac{\omega_r}{60}(1-\dfrac{D_b^2}{D_c^2}) & \text{(ball damage)} \end{cases} \tag{2}$$

where

Db or Bd	setpoint 'Rolling Element Ball Diameter'
Dc or Pd	setpoint 'Cage Diameter '
Nb	setpoint 'No. of Rolling Elements'
Wr	speed in rpm (relay internally determines the speed from motor parameters and current signal)

Note that ESA algorithm ignores negative fault frequencies.

Mechanical Faults (Foundation looseness, Eccentricity, and Mis-alignment)

Although Foundation looseness, Eccentricity and Mis-alignment (FEM) are different mechanical fault conditions in rotating machine, they can be identified at the same set of stator current frequencies related to eccentricity damage. This FEM fault element uses ESA computation on current signal to detect eccentricity failure of the machine.

The fault frequencies associated with FEM faults are computed by the ESA algorithms using equation (3) as follows:

$$F_{FEM}(k) = F_{supply} \times \left(1 \pm \frac{2 \times k \times (1-s)}{P}\right) \tag{3}$$

where

k	1, 2, 3,...
s	slip calculated by the 859/869 relay from nominal frequency(setpoint), motor speed and no of poles(setpoint)
P	setpoint 'Number of Poles'
F_{supply}	actual source supply frequency measured by the 859/869 relay

Stator Inter-turn Faults

The 859/869 relay detects stator faults using ESA based with fault frequencies computed as:

$$F_{Stator(Mech)} = CF \pm \text{Supply Frequency} \tag{4}$$
$$F_{Stator(electrical)} = CF \pm \text{Supply frequency} \pm RPS \tag{5}$$

where

Center Frequency, CF = RPS × Number of Stator Slots

Rotational frequency, RPS = Motor RPM/Supply Frequency

For further assistance

For product support, contact the information and call center as follows:

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