

869 Electrical Signature Analysis v2.70

Application Note

Introduction

Electrical Signature Analysis (ESA) feature has been available in 869 relays since 2017 and has created much interest in the marketplace. Many new enhancements and features are incorporated in the v2.70 firmware release, based on the feedback received from users and commercial/sales teams, as well as advancements made in ESA technology. Support has been added for variable-frequency drive (VFD) motors and synchronous motors. There is a voltage-less ESA feature for performing signature analysis when a voltage signal is not

Overview of Key Enhancements in v2.70

The following are key enhancements in firmware v2.70.

- For bearing, mechanical and stator ESA functions, fast Fourier transforms (FFT) are performed on the squared current, I^2 signal, instead of just the I signal current waveform. This method extracts fault magnitudes better and emulates power-based, coherent demodulation. Figure 1 shows a power-based spectrum for the broken-rotor-bar (BRB) function
- With I^2 -FFT, coherent demodulation, the number of fault frequencies is reduced to half for each of the bearing, mechanical and stator functions as the fundamental (F_s) I signal is moved to DC, and the $2F_s$ signal is the new fundamental in the I^2 FFT spectrum. There are a total of nine fault frequencies for bearing, three fault frequencies for mechanical, and three fault frequencies for the stator function (from firmware v2.70 onwards)

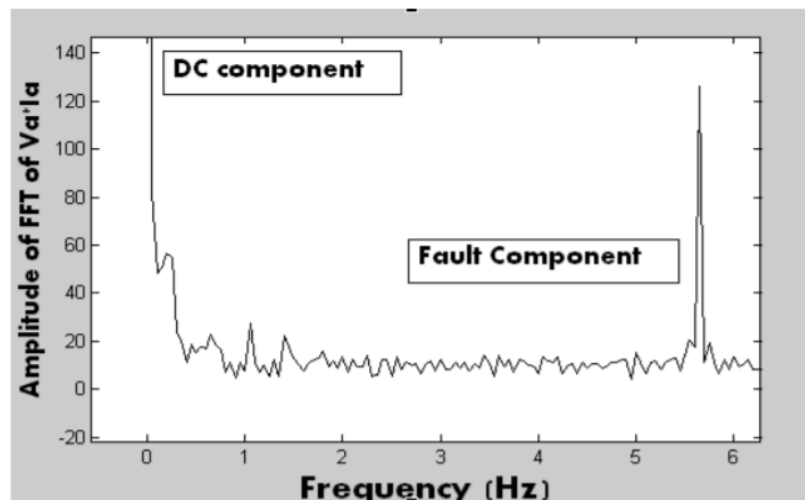


Figure 1. Power-based coherent demodulation

- c) The magnitude dB computation at a fault frequency is based on motor full load amperes (FLA) as reference instead of the fundamental current component. The reference for dB computation remains constant across all load bins and is independent of the motor operation power factor
- d) In firmware v2.70, the baseline period is configurable in minutes, instead of hours, to give more flexibility during installation, laboratory testing, and commissioning. However, it is suggested to have a minimum baseline period of 60 minutes for all cases with good motor conditions during the baseline period. The baseline period is increased in cases where baseline data are captured on an already aged or deteriorated motor
- e) To strengthen ESA performance, the relay checks fault frequencies for coincidence with harmonic frequencies to the 25th harmonic, including the fundamental. Earlier, it was to the 7th harmonic only
- f) Usually, ESA indicates a fault based on the change or increase in fault magnitude from the baseline condition. Hence, positive change in magnitude from baseline beyond threshold levels indicates an abnormal machine condition. In firmware v2.70, only positive change in fault magnitudes from baseline condition are reported in the device and software. In case of a negative change in fault magnitudes from baseline condition (from a spurious computation, noise, or supply/load fluctuations, etc.), previous computed values are retained in the actual values
- g) There are new settings for voltage and motor type added under ESA, to support different motor installations and configuration types
- h) Speed-estimation logic accommodates VFD, synchronous motor, and voltage-less ESA options
- i) The vicinity check is now dynamic, based on FFT resolution. The vicinity check is a frequency zone around the fault frequency that accounts for peak magnitude, to adjust for measurement/computation errors. Vicinity checks differ with and without relay VT input, to accommodate the speed-estimation error
- j) Voltage total harmonic distortion (THD) and voltage unbalance are included as part of the data-quality check, which increases ESA computation robustness
- k) During baseline mode, in addition to baseline data capture, the algorithm computes standard deviation on the baseline data. This supports setting an accurate threshold
- l) The ESA circle shows the last ten magnitude values (dBs) per load bin, to indicate movement of the fault trajectory
- m) ESA data-trend charts contain approximately 50 days of data, recorded at 15-minute intervals; view these charts as trends over time
- n) An ESA health report captures all functions-related data; this PDF report is useful for maintenance engineers
- o) Retrieve baseline data for all load bins as files in the Service Report

Major Enhancements in Firmware v2.70

The following are major enhancements in firmware v2.70.

VFD support

Firmware v.270 addresses the challenges when using a VFD to manage the input frequency and motor speed.

ESA for VFD with VT available on motor side

Motor speed is essential for computing ESA. When a VT input is available on the motor-terminal side (Figure 2), the ESA algorithm normalizes the VFD power input to the motor and tracks frequency to calculate the motor speed. This normalization accounts for the frequency variations when the machine is operating from a VFD (at a constant V/f ratio).

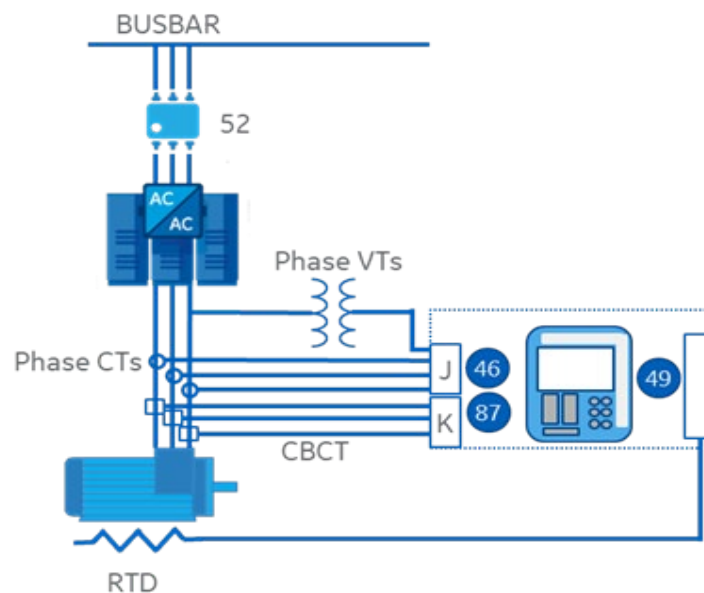


Figure 2. VFD configuration with VT on terminal side

ESA for VFD with no VT available, or VT on bus side

There are cases where a VT is not available, or the VT is on the bus side, as shown in Figure 3). Use the No VT option when VT data is not available or is not useful to compute power. The relay uses speed estimation based on load current and rated slip.

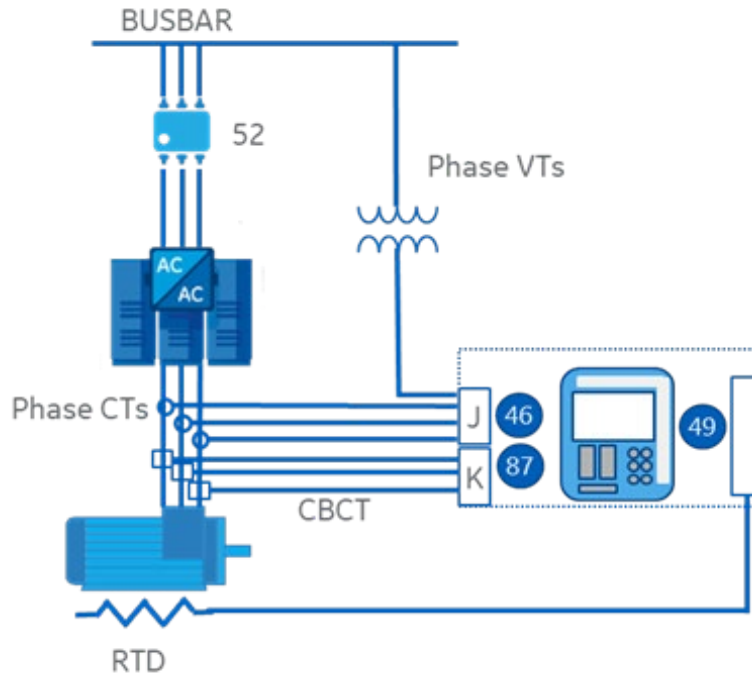


Figure 3. VFD configuration with VT on bus side (and No VT)

Application guidelines for ESA with VFD

You can use ESA with a VFD feeding the motor protected by an 869 motor relay. There are some configuration guidelines to follow:

- The CT is downstream of the VFD, on the motor side. The algorithm uses the VFD current signal to calculate the tracking frequency. The VT can be on the motor side, bus side, or not present. ESA speed estimation logic adapts to the presence and absence of a voltage signal. However, ESA accuracy is better with a VT present on the motor terminal side
- Select motor type as VFD-IND under ESA settings. Configure the Voltage Type as No-VT when the VT is on the bus side, or no VT is installed. Set as 3Ph-VT when the VT is on the motor-terminal side. Make all other 869 VFD settings per the manual to enable proper VFD functionality
- The 869 computes VFD ESA only when the motor load is between 0.4–1.0 times FLA, and the VFD frequency is less than the rated system frequency (50 Hz or 60 Hz). This is to ensure constant V/f operation
- When using the No Voltage option, the algorithm triggers pickup events based on the k=1 harmonic factor only. This is to prevent computing fault frequencies from speed-estimation errors at k=2,3, avoiding false positives.

Synchronous-motor Support

For synchronous motors, the ESA algorithm uses synchronous speed directly, computed from tracking frequency. It tracks frequency from the VT signal when voltage input is available, and from the CT signal when the voltage input is not available.

It is challenging to apply mechanical and stator ESA with synchronous motors when the number of poles is 2. For example, the synchronous motor speed is 3600 rpm when the number of poles is 2 and the system frequency is 60 Hz ($120^\circ \cdot 60 / 2$) = 3600 rpm. The mechanical fault frequency (F_r) is $3600/60 = 60$ Hz; this is exactly equal to the fundamental frequency; stator fault frequency = $CF \cdot F_r$ at higher-order harmonics. Hence, mechanical and stator ESA functions must be blocked for a synchronous motor when the number of poles is 2. The algorithm checks the computed bearing-fault frequencies if any of the fault frequencies matches the fundamental and harmonic frequencies.

Voltage-less ESA Support

In firmware v2.70, ESA does not need voltage to perform signature analysis. The following are some guidelines for use:

1-Ph VT option

When only one phase of measured voltage is available to the relay (configured at System > Voltage Sensing > Phase VT Connection), the algorithm computes the voltages of the other phases and power based upon a balanced, three-phase system. This 850-relay function is extended to 869 so that the one-phase power is the input to induction-motor, speed estimation. The remaining ESA procedure is same.

No VT option

The ESA setting Voltage Type has a No-VT option. When there is no VT input to the relay, the ESA algorithm estimates speed using the equation:

$$\text{Speed}_{\text{motor}} = \text{Speed}_{\text{Synchronous}} - \text{slip}_{\text{rated}}(\text{rpm}) \cdot \text{FLA}(\text{pu}) \quad (1)$$

Application guidelines for 1-Ph VT/No VT

You can use ESA with one or no VT feeding the relay in VFD operation. There are some configuration guidelines to follow:

- The Motor Voltage Type must be selected as 1-Ph VT or No VT under ESA settings, as appropriate
- Speed estimation accuracy is impacted. Although the algorithm increases vicinity checks around the fault frequency, it is recommended to increase pickup (PKP) setting levels 5–10 percent
- 1-Ph VT is **not** applicable for VFD fed M/c. You must disable Stator ESA and Stator turn-to-turn functions for all motor types for the 1- Ph VT and No VT options
- When using the 1-Ph VT and No Voltage settings, the algorithm triggers pickup events based on the $k=1$ harmonic factor only. This is to prevent computing fault frequencies from speed-estimation errors at $k=2,3$, avoiding false positives.

I² (current squared), FFT-based Demodulation

ESA fault detection uses a single frequency at a greater magnitude when employing a demodulated current signal. The algorithm uses FFTs of the squared stator current for eccentricity, bearing-fault detection after removing the mean DC component. Multiple laboratory tests show improved fault detection in the stator-current signal. Normalization of the fault index magnitudes (with respect to the rated line current) reduces voltage dependency and handles power-factor variation. Figure 4 depicts the demodulated, I² stator current, FFT spectrum; the eccentricity fault frequency is kf_r , and the bearing fault frequency is kf_{bearing} . For comparison, if the algorithm used the first order, I, stator current, the FFT-spectrum fault frequency for eccentricity is $f_s \pm kf_r$, and the bearing fault frequency is $f_s \pm kf_{\text{bearing}}$.

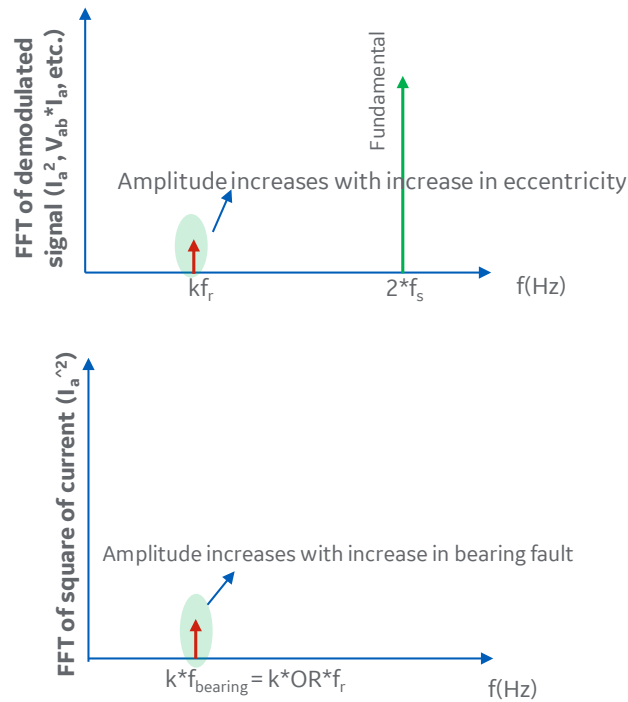


Figure 4. Eccentricity and bearing fault frequency from demodulated signal I_a^2

Baseline Data and Standard Deviation

Once the 869 relay is installed and commissioned successfully, it is in baseline mode for a default of one operational hour (baseline period) per load bin. In firmware v2.70, the baseline period is configurable in minutes. However, it is recommended to have a minimum of 60 minutes as the default baseline period for all machines in good condition when the algorithm is performing a baseline. For older machines and known-degraded machines, extend the baseline period.

During the baseline period, ESA averages all the dB magnitudes (mean), extracts standard deviation for each load bin, and stores this baseline data in files. You can retrieve these baseline data files for all load bins as part of the Service Report (the files are *ESA_baseline metering data.csv* and *ESA_detailed baseline data.csv*). The retrieved files can also be viewed offline in EnerVista software.

Fault Type	Load Bin	Item Name	Value	Value
Stator	1	Time of Baseline Computation	06/09/20 14:02:12	06/09/20 14:02:12
Stator	12	Avg. Norm Peak Mag @k=1(dB)	-150.0	-117.5
Stator	4	Avg. Norm Peak Mag @k=2(dB)	NA	-111.7
Stator	3	Avg. Norm Peak Mag @k=3(dB)	NA	-113.7
Mechanical	1	Avg. Energy at Peak Mag @k=1(dB)	-150.0	-119.6
Mechanical	12	Avg. Energy at Peak Mag @k=2(dB)	NA	-114.5
Mechanical	4	Avg. Energy at Peak Mag @k=3(dB)	NA	-116.7
Mechanical	3	Std. Dev Peak Mag @k=1(dB)	0.000	4.707
Bearing	1	Std. Dev Energy Mag @k=1(dB)	0.000	4.475
Bearing	12	Std. Dev Peak Mag @k=2(dB)	NA	0.009
Bearing	4	Std. Dev Energy Mag @k=2(dB)	NA	5.701
Bearing	3	Std. Dev Peak Mag @k=3(dB)	NA	3.736
Bearing	3	Std. Dev Energy Mag @k=3(dB)	NA	2.650

Fault Type	Fault Freq Number	Item Name	Value	Value
Stator	F15	Fault Freq(Hz)	0.000	0.000
Stator	F14	Load Bin	1	4
Stator	F13	Time of Baseline Computation	06/09/20 14:02:12	06/09/20 14:11:38
Stator	F15	Avg. Norm Mag(dB)	-150.0	-150.0
Stator	F14	Avg. Energy(dB)	-150.0	-150.0
Stator	F13	Std. Dev Peak Mag(dB)	0.000	0.000
Stator	F15	Std. Dev Energy Mag(dB)	0.000	0.000
Stator	F14			
Stator	F15			
Stator	F14			
Stator	F13			
Mechanical	F12			
Mechanical	F11			
Mechanical	F10			

Figure 5. Baseline data viewed offline in EnerVista (offline)

The *ESA_baseline metering data.csv* file has the normalized average peak and energy baseline dB magnitude data for each fault corresponding to k=1,2,3 (where applicable) for all load bins. In addition, it has the maximum standard deviation peak/energy dB values. These data as per operating load bin is also available as Modbus registers and shown as average values in the baseline metering screens for each fault type.

The *ESA_detailed baseline data.csv* file has average peak and energy magnitude dB data for each applicable FFT fault-frequency computation (F1 to F15) corresponding to k=1,2,3 (where applicable) for all load bins and fault types. In addition, it has the corresponding standard deviation peak/energy dB-magnitude values. These are internal, computed, average values that the ESA algorithm uses to extract normalized peak and energy baseline magnitudes and the maximum standard-deviation values that it updates in the metering average values. ESA captures each fault-frequency baseline value in this file in the same order of F1 to F15 fault frequencies as represented in FFT visualization screen. Recall that frequencies F1 to F9 correspond to bearing signatures, frequencies F10 to F12 are mechanical signatures, and frequencies F13 to F15 correspond to stator signatures.

The baseline-period standard deviation is one of the methods for modifying the fault-pickup thresholds. After computing the standard deviation for k=1,2,3 harmonic factors, the algorithm normalizes the data. Use the maximum, normalized standard deviation (SD) value to set PKP Threshold Level 1 at $2.5 \cdot SD$, and PKP Threshold Level 2 at $3 \cdot SD$.

EnerVista Software Enhancements

Firmware v2.70 adds enhancements to the EnerVista software in firmware v2.70.

ESA Health Report

The relay provides the ESA health report in .PDF format. It contains consolidated data on broken rotor bar, stator inter-turn, bearing, mechanical, and stator ESA functions. In addition, it contains the latest FFT waveforms and data. Maintenance teams use this report as digital records for asset management and condition-based maintenance scheduling.

ESA Historical Data trending

The 869 logs ESA historical data at 15-minute intervals, for approximately 4800 records (the last 50 days). This data are in logical groupings by sub-systems or models. The data trends over the time, as shown in Figure 6. In addition, there is a data-correlation window, where you can choose data parameters for trending and correlation.

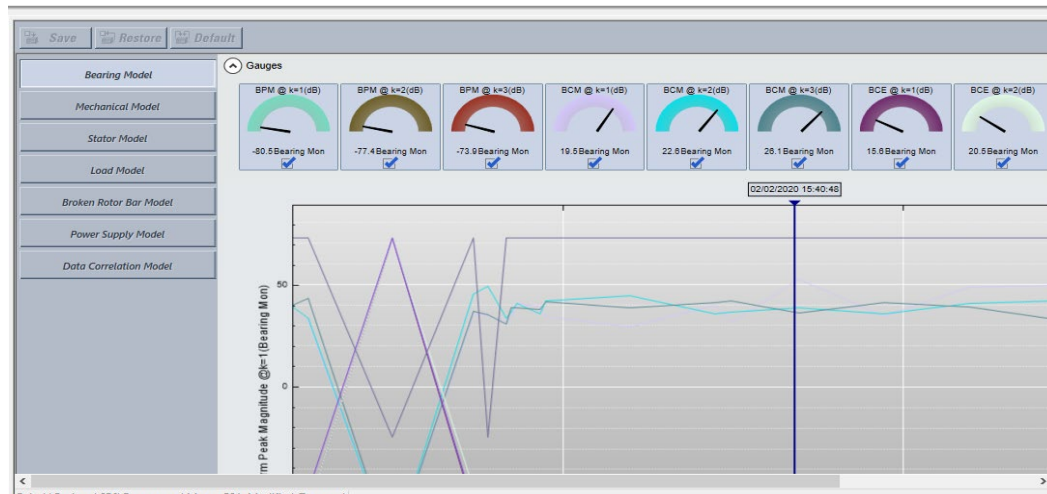


Figure 6. ESA data-models trend chart

ESA Circle Enhancement

The ESA circle depicts the fault condition (present operating point) for each operating load bin. In firmware v2.70, the circle displays the last ten operating points per load bin as a trend, as shown in Figure 7. This gives better representation of how fault trajectory is progressing from the normal to caution zones, and from the caution to alarm zones.

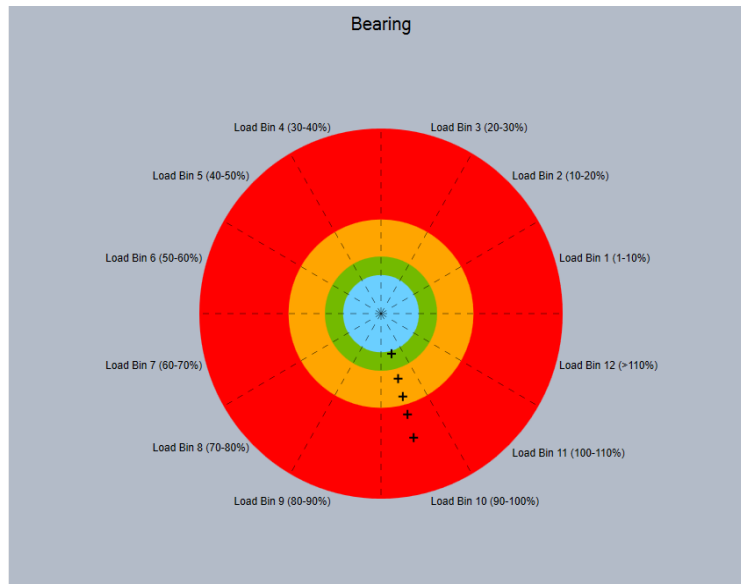


Figure 7. ESA circle with historical data

ESA Motor Types and Conditions

Table 1 defines ESA applications for motor types and voltage-input availability. Key points to note are the following:

- A synchronous motor does not have conductors in the rotor circuit; hence, broken-rotor-bar (BRB) protection is not applicable
- Stator ESA and stator inter-turn fault protections depend on availability of a three-phase voltage input for accurate fault diagnosis

Table 1. ESA applications

VT type / Motor Type	IND	SYNCH	VFD-IND
3-Ph VT	Yes	Yes (Except BRB)	Yes
1-Ph VT	Yes (Except Stator ESA)	Yes (Except Stator ESA, BRB)	No
No VT, or none	Yes (Except Stator ESA)	Yes (Except Stator ESA, BRB)	Yes (Except Stator ESA)

Table 2 shows the applicable ESA functions for different functions by motor type.

Table 2. ESA and motor type

Function Motor type	IND	SYNCH	VFD-IND
Bearing	Roller ball bearing only	Roller ball bearing only	Roller ball bearing only
Mechanical	Yes	Yes, number of poles > 2	Yes
Stator ESA	Fault freq. < 1600 Hz for 50-Hz system; Fault freq. < 1920 Hz for 60-Hz system. 3-Ph VT Input is available	Fault freq. < 1600 Hz for 50-Hz system; Fault freq. < 1920 Hz for 60-Hz system. 3-Ph VT Input is available Number of poles > 2	Fault freq. < 1600 Hz for 50-Hz system; Fault freq. < 1920 Hz for 60-Hz system. 3-Ph VT Input is available
Stator turn to turn	Yes, 3-Ph VT Input only	Yes, 3-Ph VT Input only	Yes, 3-Ph VT Input only
Broken rotor bar	Yes	No	Yes

Notes:

- a) Bearing ESA applies only for roller-ball-bearing type; it is not applicable to any other bearing design like journal, sleeve, spherical element, cylindrical element, etc.
- b) Synchronous-motor mechanical and stator ESA it is not possible when the number of poles is 2—the fault frequency matches the fundamental and higher-order harmonics
- c) Stator ESA is applied only to motors when the computed fault frequencies are less than 1600 Hz for a 50-Hz system, and 1920 Hz for a 60-Hz system. The maximum 869 sample rate is 64 samples/cycle, which, per the Nyquist criteria (divide by 2) limits the fault-detection frequency range. Stator inter-turn protection monitors the stator condition for larger frequencies. In addition, stator ESA is applied only when a 3-Ph VT input is available. It should be disabled when the 1-Ph VT or No-VT option is configured for voltage type
- d) Stator inter-turn protection works only when a 3-Ph VT input is available. It should be disabled when 1-Ph VT or No-VT option is configured for voltage type
- e) Broken rotor bar protection cannot be applied to synchronous motors, which do not use conductor bars in the rotor circuit

Additional Information for ESA in Firmware v2.70

- a) ESA computes normalized dB magnitudes at fault frequencies as the ratio of the magnitude at fault frequency and the rated magnitude
- b) Magnitude in dB = $20 \cdot \text{Log}_{10}(X1/Xr)$, where X1 is the peak magnitude within the fault-frequency f1 vicinity in I² FFT signal. The quantity Xr is the motor rated I². This is the motor full load amps (FLA), set under System > Motor > Setup.
- c) The algorithm computes the peak magnitude, in dB, as the largest magnitude observed at a specific fault-frequency, vicinity range. It computes Energy, in dB, as the ratio of the root-mean square of three points around the fault frequency, corresponding to the peak magnitude / rated magnitude ratio
- d) Energy in dB = $20 \cdot \text{Log}_{10}(E1/Er)$, where E1 is the root-mean square of three points around the peak magnitude at fault frequency f1; Er is the rated quantity or magnitude of the motor rated current, FLA
- e) The fault frequencies in the I² FFT signal are shifted toward the fundamental frequency in the spectrum
- f) Stator ESA is not applicable for the No voltage and the 1-Ph VT settings
- g) Configure the motor type properly as line-fed induction motor (IND), line-fed synchronous motor (SYNCH,) or VFD-fed induction motor (VFD-IND)
- h) Configure the voltage input to relay if available through VT as the following:
 - a. 3-Ph VT: If three-phase voltage input is available
 - b. 1-Ph VT: If only a single-phase voltage input is available
 - c. No VT: If voltage input is not available
- i) If voltage type is chosen as No VT (either VT is not available with VFD, or VT is on the bus side of the system), then VFD functioning is voltage-less. The 1-Ph VT setting is not applicable for VFD
- j) Voltage THD of Phase A and voltage unbalance functions are added to data quality check feature.
- k) To identify stator ESA applicability with 869, multiply the number of stator slots (SS) with the rated Fr in Hz (Fr = rated speed in rpm/60). This factor, SS • Fr, is known as the center frequency (CF); it should be less than approximately 1500 Hz for a 50-Hz system, and less than approximately 1820 Hz for a 60-Hz system
- l) The ESA function is blocked from picking up and the metering and logs retain the last computed values if, during any computation cycle, the monitoring-mode bearing, mechanical and stator functions peak or energy dB magnitude is less than the corresponding, captured baseline magnitude
- m) The fault frequency and corresponding magnitude is omitted from the dB computation and decision making if any of the fault frequencies (including its vicinity check zone is matching with a zero (DC) frequency, the fundamental or matching harmonic frequencies to the 25th harmonic (multiple of the supply frequency). ESA shows default values (-150 dB for peak/energy, and 0 dB for change in peak/energy magnitudes) when the fault frequency matches the fundamental and harmonics vicinity zone
- n) The vicinity check is fixed at 2 • FFT resolution when a 3-Ph voltage input is available to the relay. It is 3 • FFT resolution when a 1-Ph voltage input or no voltage input is available to the relay

- o) The relay computes ESA for a VFD-fed motor only when load is $0.40-1.00 \cdot \text{FLA}$ (the rated FLA is per the motor nameplate setting), and the frequency is less than the rated system frequency (50 or 60 Hz). This ensures constant v/f operation and avoids large errors in speed estimation. If this condition is not satisfied, then the relay blocks ESA computations and shows default values (-150 dB for peak/energy and 0 dB for change in peak/energy magnitudes)
- p) The relay HMI and EnerVista software show metering values for 1-PhVT and No-VT settings, for $k=1,2,3$. However, the algorithm pickup (PKP) decision is taken only from those fault frequency magnitudes corresponding to $k=1$. This avoids possible large errors in the computed fault frequencies at $k=2,3$, because speed-estimation errors increase
- q) The relay computes pseudo voltages, and thereby with the actual currents, three-phase power, when only a single-phase VT connection is available. Select the single-phase voltage setting (1-PH VT) in the Voltage Type at System >Voltage Sensing > Phase VT Connection
- r) The software plots an ESA circle with baseline data corresponding to the observed, fault-frequency, maximum change in dB. It does not use the normalized peak baseline data (shown in metering average values) because it might cause confusion. The software adds a note: "The latest point in ESA circle corresponds to baseline data of 'X' dB observed at specific YYYY fault frequency where change in dB from baseline is observed to be maximum," where X is dB value, YYYY is bearing, mechanical or stator, based on fault type
- s) In a future release, a machine-learning (ML) algorithm will be added, to make the existing ESA more sensitive towards fault pickup (PKP). It runs in parallel, with ESA output data as the inputs to the ML algorithm

Motor Degradation

If there is a zero or negative change in the baseline data, inspect the peak and energy magnitudes levels for possible motor degradation. Usual peak and energy magnitudes are the following for an abnormal condition:

- Mechanical ESA, less than -65 dB
- Broken rotor bar, less than -50 dB
- Stator and bearing, less than -55 dB

These are reference values based on literature and laboratory-test experience; these levels vary per motor and operating conditions.

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English