Advanced Motor Protection for Variable Speed Operation

Background

Today industrial equipment is designed to last 20 years or longer. Over time, site operating and environmental conditions may change affecting the life of the equipment. Medium voltage motors are exposed to environmental and mechanical stresses that can lead to motor degradation and malfunction. The monitoring and protection of such medium voltage motors are an essential elements in the overall industrial process protection. These schemes are needed to avoid financial losses caused by unexpected process downtime.

Medium Voltage motors are operated either directly on line (DOL) or through variable frequency drives (VFD). According to a 3rd party report, 75% of motors shipped globally operate directly on line, as such, they require protection from the following conditions:

- Input line events like harmonics, out of frequency conditions, loss of phase or phases, voltage imbalance, overvoltage and undervoltage, phase reversal and out-of-step condition resulting from system disturbance
- Protection from high temperatures, insulation and bearing failures
- Conditions created by change in a load, for example overload or underload, imbalance, and jamming

Application of VFDs has increased recently due to the ability to improve process efficiency through variable speed operation. In addition, compared to DOL operation, VFDs have the advantage of soft-starting, soft-stopping, and offer speed and torque control of the motors. Starting motors with a VFD not only saves energy but also reduces maintenance costs.

Today, owners/operators of motors running directly on line use motor protection relays to ensure reliable and safe operation. While medium voltage drives typically include some standard motor protection as a part of the drive control system. Despite the built-in motor protection functionalities of VFDs, some customers request traditional motor protection relays installed on the drive output for additional motor protection. This approach requires additional consideration while operating with the VFD.

Digitalization has many layers, some of them are improving end user efficiency, reducing complexity and streamlining process operation. As part of the digitalization effort, Siemens introduces a new integrated motor and process protection and monitoring solution. This functionality uses drive integral sensors to offer reliable protection at variable speed operation by simplifying protection schemes, while saving customers space and engineering efforts. This paper provides detailed discussion on the new feature’s performance and capability.
Drive Standard Motor Protection Functions

Medium voltage drives typically include some standard motor protection as a part of the drive control system. The inherent nature of the drive limits the contribution of the VFD to short circuits in the motor. Typical short circuit contributions are less than 1.5 times motor full load current on a steady state basis. As a result, additional short circuit over-current protection (ANSI 50) is generally not applicable to the VFD driven motor. The VFDs include protection from power quality events such as undervoltage (ANSI 27), over frequency and under frequency.

Drives with an input transformer provide galvanic isolation that mitigates the effects of ground faults. The transformer also protects drive power electronics and the motor from potential voltage transients in the grid (i.e. overvoltage (ANSI 59)) and input harmonic distortion including waveform notching. These functions are fundamentally inherent properties of the VFD itself and since the motor is run by the drive, it isolates the motor from the same issues.

VFD fed motors have the benefit of a balanced source since the drive supplies each of the three motor phases, it eliminates the voltage imbalances and phase reversal that the motor is subjected to when fed from a utility supply. This is why phase reversal and imbalanced voltage protections (ANSI 47) on the load side is unnecessary.

Motor Protection Relay use with VFD

Traditional microprocessor based motor protection relays are designed to protect motors that operate directly on line at fixed 60Hz or 50Hz frequency. They usually include a relay box with customer inputs and outputs and a communication port. They may or may not include RTD inputs. They always require current transformers (CT) to measure motor current and in some case potential transformers (PT) for voltage feedback. Current based thermal protection in most of today's multifunctional motor protection relays determines motor heating and cooling by monitoring motor input current.

Most customers are familiar with the benefits of motor protection relays (MPR). These customers often request that a motor protection relay is installed into a VFD. Only when the customer selects the synchronous transfer option does Siemens recommend installation of an MPR. Once the motor is transferred directly on line, it is no longer protected by the VFD.

MPR Considerations when Installed with VFD Operated Motors

When a customer would like to have an MPR on a VFD dedicated motor, careful selection of the relay and associated components is required to assure proper operation. The voltage on the load side of the VFD is unrelated to the voltage on the source side of the VFD so in addition to CTs, PTs on the load side must be provided. This requires additional engineering. Drives create other challenges for motor protection relays that are not present in line-connected motors. Direct on line motors see perfect voltage and current waveforms, while the output waveforms produced by the VFD are non-sinusoidal (or almost sinusoidal), pulse width modulated voltage that has some DC voltage content.

VFD operated motors have a fundamental frequency that changes rapidly in response to speed. Since the load side of the VFD operates at variable frequency, it is critical that the relay selected has robust frequency tracking with a frequency range at least as large as the VFD operating range. A typical specification for frequency tracking is 20 – 65 Hz or in some cases even higher. The algorithm used in a traditional MPR to determine RMS values provides non stable magnitude at lower frequencies so further finetuning is needed for proper operation at lower speeds.

The operation at lower frequencies affects performance of the protection relays. Most instrument CTs are designed to perform between 40 and 400 Hz and are typically optimized for 50 or 60 Hz operation [1]. The published saturation curves for the CTs’ core are usually based on 60 Hz or 50 Hz excitation voltage. The CTs operate accurately near a nominal frequency [2]. However, operation at lower frequencies and below minimum design frequency (>40 Hz) may lead to saturation and heating of the magnetic core [1].

The low frequency also impacts phasor measurements, metering, and monitoring elements [3]. The reliability of PTs is affected during the motor start up, so PTs may saturate and blow the fuses. Due to their design and performance limitations, both CTs and PTs potentially provide misleading information to the relay and hindering its protective response time.

Motor thermal protection based on a thermal model is another challenge for traditional MPRs operating with the VFD. These models rely on motor thermal damage curves limits which are typically provided by motor manufacturers at nominal frequency of 60 or 50 Hz. Even if the motor thermal limits are known over the operating frequency range of the drive, it may be difficult to utilize them in many traditional motor protective relays over the range of frequencies.

Some MPR manufacturers resolve these issues by specifying more expensive CTs and PTs and by altering their algorithms to compensate for variable frequency operation. It is left up to the customer to properly set up and tune these algorithms for proper operation. This requires the customer to provide additional engineering and expertise to properly program and set-up these protection functions. When this expertise is not available, some functions in MPR sold with VFDs are disabled to avoid nuisance trips [4].
Advanced Motor Protection – a true variable speed performance

It was mentioned in this paper that most VFDs have built-in standard motor protection functions. Even though these functions are enough to protect motor from most events some customer may want additional functionalities and the flexibility of creating their own protection limits based on their process. That is why Siemens introduces the Advanced Motor Protection (AMP) option with an extended list of motor protection features including built-in 12 channel RTD monitoring capability.

SINAMICS Perfect Harmony GH180 is the only medium voltage drive that offers a patented solution for motor protection at variable speed operations. The drive protection does not rely on feedback from external CTs and PTs, it uses integral closed-loop hall effect current sensors and output attenuators to obtain accurate motor data. There is no core flux in these sensors that is why they are not susceptible to saturation issues at lower frequencies like traditional current transformers.

This option offers additional features and allows customers to set pick up and trip levels at various points across the speed curve. Most functions offered within the AMP option can be enabled to start monitoring and protecting the motor along the speed curve: the operator can set protection at any point that is critical for their application and process including time delays.

No other solution available today on the market offers this flexibility and capability. The standard motor protection available with most VFDs only allows fixed default settings.

The graph below serves as an example and shows another level of flexibility to set up process defined curves for the undercurrent and overload protection schemes. The gray color is normal operating conditions, the yellow color represents the alarm setting area and the orange color represents the fault setting area. Many of the protection curves have a latched minimum speed enable at which point protection settings do not apply. The thermal protection function offer either an alarm or trip setting. All other functions provide an alarm or fault setting.

These protections are applicable to constant torque applications as well. The tolerances would vary for these applications, but the AMP option has the flexibility to set alarm or trip levels based on the process curve and not just the speed curve. It is customizable with time delays and minimum speed enable capabilities.

Another big difference between standard protection and an advanced one is enhanced thermal motor protection (ANSI 49T). The algorithm is designed to meet the requirements of IEC 60255-149 standard. This is the only function that offers both an alarm setting and the trip setting to give customers advanced warning before the process and the motor are taken off line. The Advanced Motor Protection Option has a patented thermal model to provide locked rotor and running overload protection. It includes the following elements:

- Motor thermal capacity
- Biasing based on both measured stator and ambient temperatures (optional)
- Measure of negative sequence current
- Average RMS phase currents
- Motor Run and Stop status

RTD biasing is used as a backup protection to account for such things as loss of cooling or unusually high ambient temperature. This measured temperature is used to modify the thermal capacity value. Thermal overload pickup is set to the maximum allowed by the service factor of the motor. It is typically about 10% above motor service factor. If RTD biasing is enabled, it can be higher since it provides a more accurate temperature feedback.

The graph 3 shows setpoints for traditional RTD bias [5]. In this instance, the motor has F class insulation which is rated at 155°C, the stator temperature rise is 85°C with SF@1.0 and ambient temperature of 40°C. The maximum point is set based on motor insulation temperature at 155°C. The center point is set at the motor running temperature that equals to temperature rise of stator + hot spot allowance (typically 10%) + ambient temperature. The temperature rise of the stator is 85°C + 10°C for hot spot allowance, so mid-point is set at 85+10+40=135°C. The minimum point is typically the ambient temperature 40°C.
The motor overload curves or hot-to-cold starts ration are used to determine motor thermal capacity for the mid-point.

Some customer only use temperature measuring devices like transducers, thermistors, thermocouples and RTDs to measure stator temperature to provide a thermal protection for the motor. The RTDs are the most common ones. They provide a final absolute trip, but it is still not enough to fully protect the motor. While they give accurate temperature readings, they are very slow [6]. Due to this slow response time, RTDs should not be used as a primary protection. By the time the RTD reaches the trip temperature the winding insulation has exceeded the limits [7].

**Ground Fault Detection and Protection**

It is typical to use ground fault CTS on the output of the VFD to detect motor ground fault. In a typical three-phase 3-wire system the sum of all three phase currents is zero. This logic is used to determine a ground fault condition when non-zero current flow is detected through the ground fault CT. The sensitivity of such detection is limited by the high frequency voltage variations developed by the drive output which causes currents to flow through the parasitic capacitance of the system to ground that includes cable capacitance, motor winding capacitance and drive-to-ground capacitance.

In most VFDs, where the input transformer isolates the drive and the motor, some ground faults can be difficult to detect with CTs. Single point ground fault is one of them. This type of ground fault does not create sufficient current flow to be measured by CTs and as such can go undetected and lead to motor failure.

A ground fault condition always occurs due to a change in the impedance between one or more phases to ground, that causes an imbalance in the phase-to-ground voltages. This results in a change of the motor neutral voltage to ground.

In the SINAMICS Perfect Harmony GH180, the output phase-to-ground voltages are used to reconstruct the motor neutral to ground voltage and determine the existence of a ground fault. This method provides very sensitive detection and does not depend or rely on the current flowing through the fault.

To establish the level of ground fault detection and its effectiveness Siemens performed several tests. During the tests the VFD residual voltage ground fault protection showed high sensitivity to ground faults detection. The results demonstrated the detection of a 5mA ground fault current through a fault impedance of 460 kΩ and a 2.6% voltage imbalance drive parameter setting.

This level of sensitivity is considered to be high for most applications. The setting of 5% voltage imbalance is used as default in SINAMICS Perfect Harmony GH180 resulting in 10mA ground fault detection in 9 cell system and less than 10mA for 15 and 24 cells configurations. The big advantage of this sensitivity is that ground fault detection is possible before any currents can create a hazardous situation.

**Differential Motor Protection**

When a motor operates directly on-line, the traditional differential relay protection detects low-magnitude fault currents during normal loads and does not trip during high-magnitude external faults or during starting periods. It is also affective in protecting from winding-to-winding faults. Though differential relay does not detect turn-to-turn faults in the same winding unless it is applied in a split phase winding [8].
The differential relay protection is based on comparing two currents, the first one entering a winding with the second one leaving the motor winding. During normal operating conditions the two currents are equal. If there is a difference between the two currents, a fault is detected. In standard differential motor protection scheme there are six CTs to measure each phase input and output current. As we have already mentioned in this paper, the sensitivity and accuracy of protection in the VFD driven motors affected by the CTs performance at a lower frequency.

In direct on line configuration the motor traditionally a part of the grounded system. In such system differential protection provides the most reliable and sensitive motor protection. In ungrounded or isolated system created by the VFDs with the input transformer some ground faults might go completely undetected as we described in the section on the ground fault detection and protection.

SINAMICS Perfect Harmony GH180 advanced motor protection option offers one of the most sensitive solution available today with the VFD operation. The combination of such protections as 59G (zero sequence overvoltage) and 46_2 (current imbalance, negative sequence) provides the equivalent protection to standard direct online differential protection for the motors. Not only it can detect very low levels of the motor ground faults (see page 4 for more details) but also protects from both the winding-to-winding, turn-to-ground and turn-to-turn faults in the same winding faults without additional motor modifications.

Features That Go Beyond Motor Protection

Some functions are not only designed to protect motors but can also be used to diagnose abnormal load or process conditions. Below is the description of some of these functions.

Mechanical Jam

Some traditional functions like ANSI 50P Mechanical Jam cannot be applied directly in VFD driven machines. Function 50P mechanical jam is similar to thermal overload in which the motor draws current above normal operating conditions. The main differences are that thermal overload follows the thermal curves and trip behavior, the mechanical jam is user configurable to create different tripping behavior, and it is designed to take the motor offline quickly.

Drives limit the motor current so traditional MPRs would have difficulty using pure overcurrent as a jam detection method, this is why underspeed function (ANSI 14) is a better indicator of the mechanical jam conditions in VFD applications in cyclical loads and frequency rate of change (ANSI 81) in non-cyclical loads. If there is an instance when something is blocking a load at the start of the motor, the AMP function incomplete sequence (ANSI 48) will detect this condition and prevent motor damage during start up.

There are several events that would trigger this protection:

- Mechanical stall,
- Interference,
- Jam or seizure of the motor or motor load.

For example, a rock crusher application in which a rock that is too hard or too large jams the crusher or debris stuck in the pump. If it is not addressed quickly, jam conditions will damage both the motor and the driven equipment.

Function frequency rate of change (ANSI 81) provides additional benefits for applications in master-follower configurations where coordination scheme is based on speed command. In the case where the drive in the follower configuration loses load due to a broken belt, the rate of change function would pick up this event before the master drive would be able to see it. Function ANSI 81 can sense rate of change in both directions - acceleration and deceleration of the motor. This provides the operator with more visibility into the process and minimizes the impact on the equipment. This type of configurations is very common in a conveyor application.

Undercurrent and Underpower functions

Functions 37 undercurrent and 37P underpower are designed to protect the mechanical load that is connected to the motor. These faults usually happen when a portion of the user’s load disappears. The following conditions can trigger this protection:

- A broken fan belt,
- Pump is running dry,
- Pump intake is partially or totally restricted,
- Closed valve,
- Conveyor broken belt,
- Broken coupling or shaft.

The reduced flows or sudden reduction in load can be detected by a drop in current to the motor and trigger the undercurrent
protection. The mechanical characteristics of a centrifugal pump cause a low power condition when dead-headed. In this case, underpower is a more reliable means of protection.

Underpower more accurately reflects a lack of load torque at a given speed than undercurrent. The motor will draw 50% current at low loads while the power will be around 10%; a change in mechanical load is a change in power. The benefit of the AMP is the flexibility of either setting a fix value regardless of the speed or set the individual points along the process curve with the minimum speed enabled to minimize false alarms.

With the proper protection, one can avoid running in this situation, and in case of pumps avoid failure of expensive seals. With the flexibility of AMP option customer can select multiple points relevant for their site to ensure that the equipment is properly protected.

Current imbalance, negative sequence

Loss of power to one phase of a three-phase motor is typically described as "single-phasing." There are multiple causes for this fault:
- Loose wire,
- Improper wiring,
- Grounded phase,
- Motor insulation deterioration, etc.

Motor current increases substantially in the remaining two phases causing excessive heating in the motor. In addition to excessive heat, single-phasing causes large unwanted motor vibrations that will impact not only the motor but also a driven load as well.

This event can be detected by protection function 46_2 (current imbalance, negative sequence) which saves the customer money by avoiding not only expensive motor repairs, but also damage to the driven equipment and product. If this event occurs, it will result in controlled shutdown minimizing impact on your process and output.

Mechanical condition monitoring

A function that is only available with SINAMICS Perfect Harmony GH180 is ANSI 39 (mechanical condition monitoring). This function is designed to protect against excessive torque pulsation with limited minimum speed. The drive will measure the RMS value of the torque ripple. The customer will be able to set allowable torque pulsation limits based on their process and application.

Certain mechanical faults, such as gearbox faults, shaft misalignment, load imbalance or bearing faults, may produce periodic variations in the load torque. The function can be used as an early indicator for identifying abnormal operating conditions prior to any damage and to schedule preventive maintenance.

There are several successful cases where torque monitoring has been used effectively to identify mechanical failure. Instantaneous torque has been used to identify a multitude of field relevant failure modes. Looseness, cavitation and pumping of sand were successfully identified using the time-domain torque signal. Mechanical imbalance and bearing faults were recognized with the torque vs. frequency representation [9].
Advanced Motor Protection Option Set Up

The Advanced Motor Protection option simplifies commissioning - easy communication set up, as there is no need to configure a separate communication channel, and the status is sent through the drive serial network to a customer DCS or Plant HMI. All faults or alarms are stored and can be viewed through the drive event log for a complete picture. In addition, this option simplifies protection configuration since most of the motor data is already included in the interface as a part of the drive set up. When a customer buys the Advanced Motor Protection option, they double the protection, the drive will include both standard and advance protection functions. The standard functions will serve as a backup to ensure maximum availability.

Motor Protection Feature Comparison

The table below provides side by side comparison of the available functions of SINAMICS Perfect Harmony GH180 drive and leading microprocessor-based motor protection relays vendors.

<table>
<thead>
<tr>
<th>ANSI</th>
<th>Protection</th>
<th>Standard Motor Protection</th>
<th>Advanced Motor Protection</th>
<th>Traditional MPR vendor 1</th>
<th>Traditional MPR vendor 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>Directional Power</td>
<td>Not applicable with VFD</td>
<td>Not applicable with VFD</td>
<td>x</td>
<td>x</td>
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<tr>
<td>67</td>
<td>Directional Overcurrent</td>
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<td>Not applicable with VFD</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>50P</td>
<td>Mechanical Jam</td>
<td>Not applicable with VFD</td>
<td>Not applicable with VFD</td>
<td>x</td>
<td>x</td>
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<tr>
<td>27</td>
<td>Undervoltage</td>
<td>inherent</td>
<td>inherent</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>59</td>
<td>Overvoltage</td>
<td>inherent</td>
<td>inherent</td>
<td>x</td>
<td>x</td>
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<tr>
<td>47</td>
<td>Phase-Sequence or Phase Balance Voltage</td>
<td>inherent</td>
<td>inherent</td>
<td>x</td>
<td>x</td>
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<td>50LR</td>
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<td>inherent</td>
<td>x</td>
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<td>86</td>
<td>Lock-out</td>
<td>inherent</td>
<td>inherent</td>
<td>--</td>
<td>x</td>
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<tr>
<td>66</td>
<td>Starts per hour</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td>12</td>
<td>Overspeed</td>
<td>+</td>
<td>+</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>49T</td>
<td>Machine Thermal Model</td>
<td>+</td>
<td>+</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>59G*</td>
<td>Zero sequence overvoltage</td>
<td>+</td>
<td>+</td>
<td>--</td>
<td>--</td>
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<tr>
<td>51G*</td>
<td>Motor Ground Fault</td>
<td>+</td>
<td>+</td>
<td>x</td>
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<td>50</td>
<td>Motor Short Circuit</td>
<td>+</td>
<td>+</td>
<td>x</td>
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<td>51</td>
<td>Inverse Time Overcurrent</td>
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<td>+</td>
<td>x</td>
<td>x</td>
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<tr>
<td>37</td>
<td>Undercurrent</td>
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<td>+</td>
<td>x</td>
<td>x</td>
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<tr>
<td>14</td>
<td>Underspeed</td>
<td>--</td>
<td>+</td>
<td>x</td>
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<td>37P</td>
<td>Underpower</td>
<td>--</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<td>38</td>
<td>Bearing Temperature RTD</td>
<td>--</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<td>39</td>
<td>Mechanical Condition Monitoring</td>
<td>--</td>
<td>+</td>
<td>--</td>
<td>--</td>
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<td>46_2</td>
<td>Current Unbalance, Negative Sequence</td>
<td>--</td>
<td>+</td>
<td>x</td>
<td>--</td>
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<tr>
<td>48</td>
<td>Incomplete Sequence – maximum start time/ maximum stop time</td>
<td>--</td>
<td>+</td>
<td>--</td>
<td>--</td>
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<td>49 RTD</td>
<td>Machine Thermal Overload RTD</td>
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<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td>55</td>
<td>Power Factor</td>
<td>--</td>
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<td>x</td>
<td>x</td>
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<tr>
<td>81</td>
<td>Over/Under Frequency</td>
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<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>81</td>
<td>High Frequency Rate of Change</td>
<td>--</td>
<td>++</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>87M**</td>
<td>Differential protection</td>
<td>--</td>
<td>++</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

Legend: + function performed better than MPR for variable speed; ++ additional capability; x same as MPR
*Ground Fault detection in SINAMICS Perfect Harmony GH180 is based on detection of zero sequence voltage scheme
** Differential protection 87M=46_2+59G
-- Not available
References


Abbreviations

AMP Advanced Motor Protection
CT Current Transformer
DCS Distributed Control System
DOL Direct On Line
HMI Human-Machine Interface
Hz Hertz
MPR Motor Protection Relay
PT Potential Transformer
RMS Root Mean Square
RTD Resistance Temperature Detectors
VFD Variable Frequency Drive
Security information

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