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- Switching Sequence Management
- Interchange Transaction Management

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- Economic Dispatch
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Motor Protection Principles

1. Introduction

Three phase motors can be classified into two types: induction and synchronous. An induction motor consists of two parts: the stator and the rotor. The stator core is built of sheet-steel laminations that are supported in a frame.

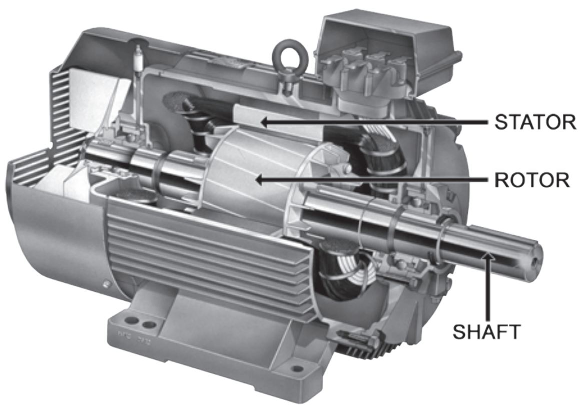


Figure 1.
3 phase AC Motor

The windings are placed in the stator slots 120 electrical degrees apart. Windings may be connected in "star" (or wye) or delta configuration.

The rotor of the induction motor is made of a laminated core with conductors placed parallel to the shaft. The rotor conductors are embedded in the surface of the core and are not insulated from the core, because rotor currents follow the "least resistance" path. The rotor conductors are shorted by end rings at both ends.

Any motor failure will have the following cost contributors: repair or replacement, removal, installation and loss of production. Most of the motor failure contributors and failed motor components are related to motor overheating. Thermal stress can potentially cause the failure of all the major motor parts: Stator, Rotor, Bearings, Shaft and Frame.

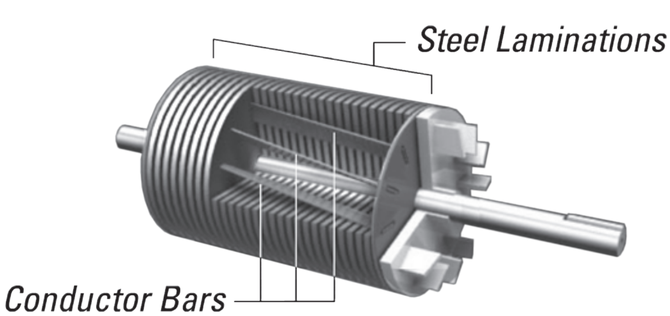


Figure 3.
Squirrel Cage Motor

2. Motor Protection Overview

There are two main risks for an overheated motor: Stator windings insulation degradation and rotor conductors deforming or melting. Insulation lifetime decreases by half if the motor operating temperature exceeds its thermal limit by 10°C. There are a number of conditions that can result in damage to three-phase motors. These damages are a result of operating conditions or internal or external faults. External faults and operating conditions include: undervoltage, asymmetrical loading, phase and ground faults on the motor feeder and overloading during starting and running operation. Internal faults include: ground faults, faults between windings and inter-turn faults.

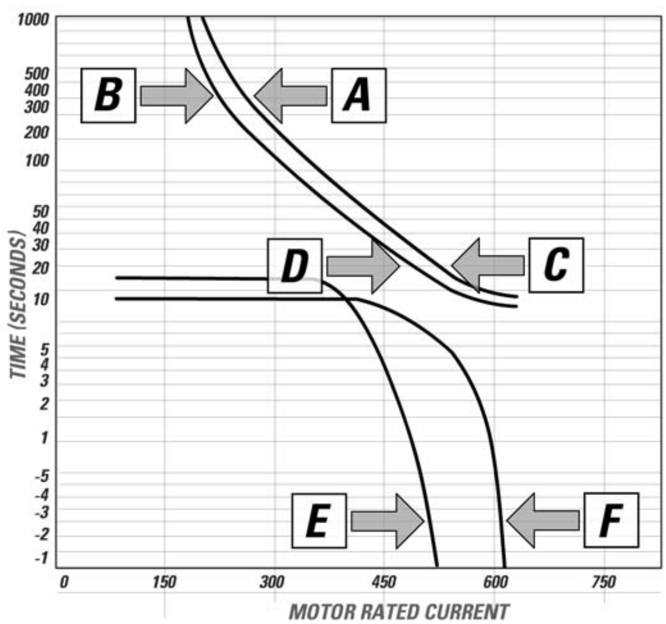
Fault Type	Protection Philosophy
Internal Fault	
Stator ground faults	Ground/Neutral IOC/TOC (50/51G/N), Neutral Directional TOC (67N)
Stator phase faults	Phase differential protection (87), Phase IOC/TOC (50/51P), Phase short circuit (50 P)
External Fault	
Overheating	Overload - Thermal model with Programmable Curves and biased with RTD and/or Unbalance (49/51) Voltage Dependant Curve for Large Inertia Loads Overtemperature via thermistors and/or RTDs (38,49) Locked rotor / mechanical jam, Stall Protection (39, 51R) Jogging, Starts/hour, time between starts, restart time delay (66), Acceleration Time Logic Reduced voltage start (19) Incomplete sequence (48) Overload lock-out (86)
Phase unbalance	Overload - Thermal model with Programmable
Phase reversal	Negative Sequence Overvoltage (47)
Abnormal voltage	Overvoltage (57), Undervoltage (27)
Abnormal frequency	Overfrequency (81O), Underfrequency (81U), Speed switch (14)
Loss of load	Undercurrent/minimum load (37), Underpower, Sensitive Directional Power (32)
Back-Spin	Back-Spin Detection
Breaker failure	Breaker failure (50BF)
Power factor	Power factor (55)
Feeder Ground Fault	Ground/Neutral IOC/TOC (50/51G/N) Neutral Directional TOC (67N)
Feeder Phase Fault	Phase differential protection (87), Phase IOC/TOC (50/51P), Phase short circuit (50 P)

Table 1.
Motor Faults

3. Overload Protection

Three-phase motors are designed in such a way that overloads must be kept below the machine thermal damage limit. The motor thermal limits curves consist of three distinct segments, which are based on the three running conditions of the motor: the locked rotor or stall condition, motor acceleration and motor running overload. Ideally, curves should be provided for both hot and cold motor conditions. For most motors, the motor thermal limits are formed into one smooth homogeneous curve.

The acceleration curves are an indication of the amount of current and associated time for the motor to accelerate from a stop condition to a normal running condition. Usually, for large motors, there are two acceleration curves: the first is the acceleration curve at rated stator voltage while the second is the acceleration at 80% of rated stator voltage (soft starters are commonly used to reduce the amount of inrush current during starting). Starting the motor on a weak system can result in voltage depression, providing the same effect as a soft-start.



A. Cold Running Overload
B. Hot Running Overload
C. Cold Locked Rotor Curve
D. Hot Locked Rotor Curve
E. Acceleration curve @ 80% rated voltage
F. Acceleration curve @ 100% voltage

Figure 4.
Motor Thermal Limits Curves

The primary protective element of the motor protection relay is the thermal overload element and this is accomplished through motor thermal image modeling. This model must account for all thermal processes in the motor while the motor is starting, running at normal load, running overloaded and if the motor is stopped. The algorithm of the thermal model integrates both stator and rotor heating into a single model. If the motor starting current begins to infringe on the thermal damage curves or if the motor is called upon to drive a high inertia load such that the acceleration time exceeds the safe stall time, custom or voltage dependent overload curves may be required. Negative sequence currents (or unbalanced phase currents) will cause additional rotor heating that will not be accounted for by electromechanical relays and may not be accounted for in some electronic protective relays. The main causes of current unbalance are: blown fuses, loose connections, stator turn-to-turn faults, system voltage distortion and unbalance, as well as external faults.

Thermal models can have following enhancements and additions: motor start inhibit; standard, custom and voltage dependant overload curves;

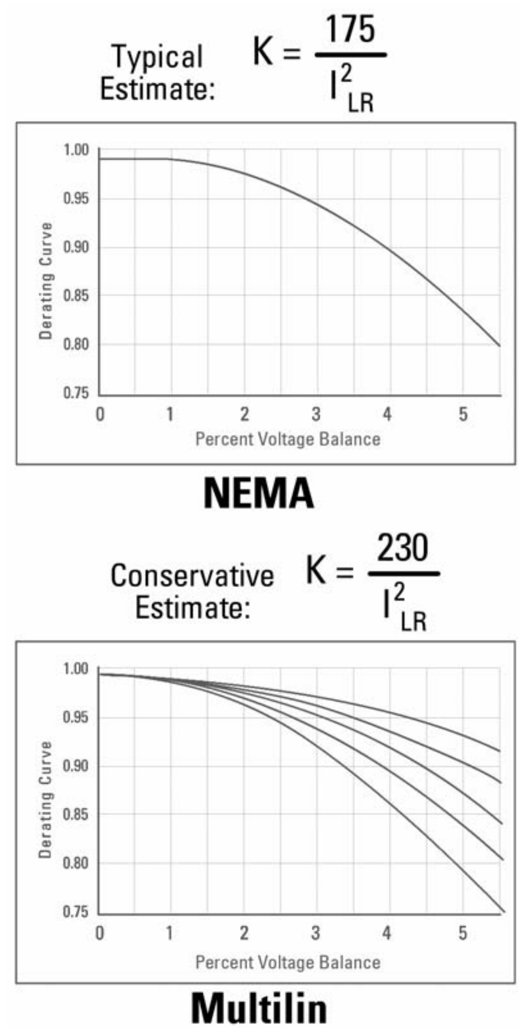


Figure 5.
Motor Derating Curves

thermal model biasing by measured current unbalance and RTD's; separate thermal time constants for running and stopped motor conditions; independent current unbalance detector; acceleration limit timer; mechanical jam detector; start and restart supervision.

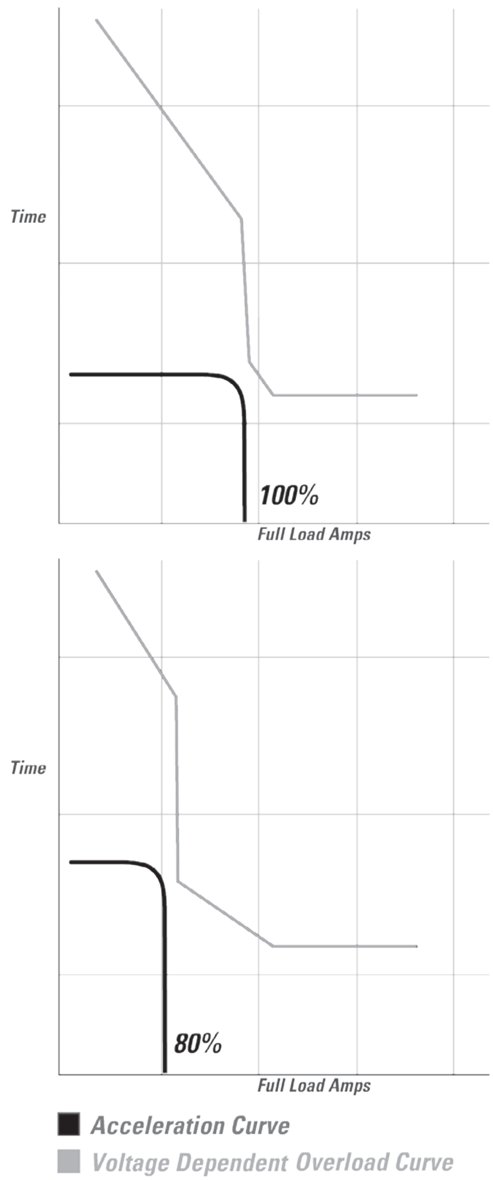


Figure 6.
Voltage Dependent Overload Curves

4. Differential Protection

This protection function is mostly used to protect induction and synchronous motors against phase-to-phase faults. This function requires two sets of CT's, one at the beginning of the motor feeder, and the other at the start point. Differential protection may be considered the first line of protection for internal phase to phase or phase to ground faults. In the event of such faults, the quick response of the differential element may limit the damage that may have otherwise occurred to the motor.

Figure 7.
RTD connection for Thermal Protection and Biasing.

The differential protection function can only be used if both sides of each stator phase are brought out of the motor for external connection such that the phase current going into and out of each phase can be measured. The differential element subtracts the current coming out of each phase from the current going into each phase and compares the result or difference with the differential pickup level. If this difference is equal to or greater then the pickup level a trip will occur. GE Multilin motor protective relays support both three and six CT configurations. For three CT configuration both sides of each of the motors stator phases are being passed through a single CT. This is known as the core balance method and is the most desirable owing to it's sensitivity and noise immunity.

If six CTs are used in a summing configuration, during motor starting, the values from the two CTs on each phase may not be equal as the CTs are not perfectly identical and asymmetrical currents may cause the CTs on each phase to have different outputs. To prevent nuisance tripping in this configuration, the differential level may have to be set less sensitive, or the differential time delay may have to be extended to ride through the problem period during motor starting. The running differential delay can then be fine tuned to an application such that it responds very fast and is sensitive to low differential current levels.

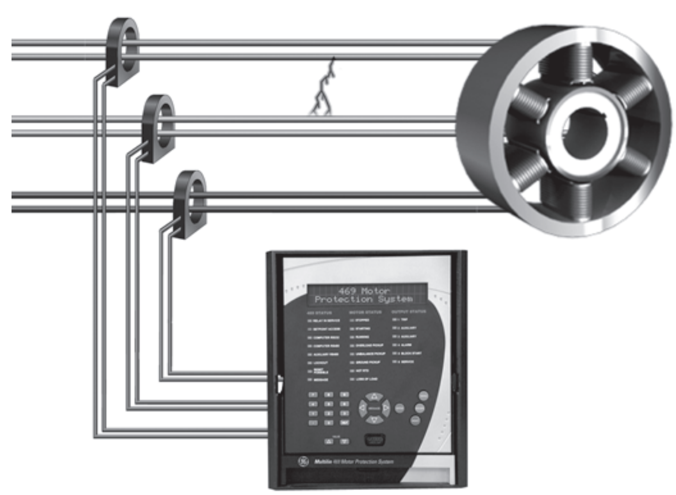


Figure 8.
Phase to Phase Fault

The Biased Differential protection method allows for different ratios for system/line and neutral CT's. This method has a dual slope characteristic to prevent a maloperation caused by unbalances between CTs during external faults. CT unbalances arise as a result of CT accuracy errors or CT saturation.

5. Ground Fault Protection

Damage to a phase conductor's insulation and internal shorts due to moisture within the motor are common causes of ground faults. A strategy that is typically used to limit the level of the ground fault current is to connect an impedance between the neutral point of the motor and ground. This impedance can be in the form of a resistor or grounding transformer sized to ensure that the maximum ground fault current is limited to a level that will reduce the chances of damage to the motor.

There are several ways by which a ground fault can be detected. The most desirable method is to use the zero sequence CT approach, which is considered the best method of ground fault detection methods due to its sensitivity and inherent noise immunity. All phase conductors are passed through the window of a single CT referred to as a zero sequence CT. Under normal circumstances, the three phase currents will sum to zero resulting in an output of zero from the zero sequence CT's secondary. If one of the motor's phases were shorted to ground, the sum of the phase currents would no longer equal zero causing a current to flow in the secondary of the zero sequence CT. This current would be detected by the motor relay as a ground fault.

If the cables are too large to fit through the zero sequence CT's window or the trench is too narrow to fit the zero sequence CT, the residual ground fault configuration can be used. This configuration is inherently less sensitive than that of the zero sequence configuration, owing to the fact that the CTs are not perfectly matched. During the motor start, the motor's phase

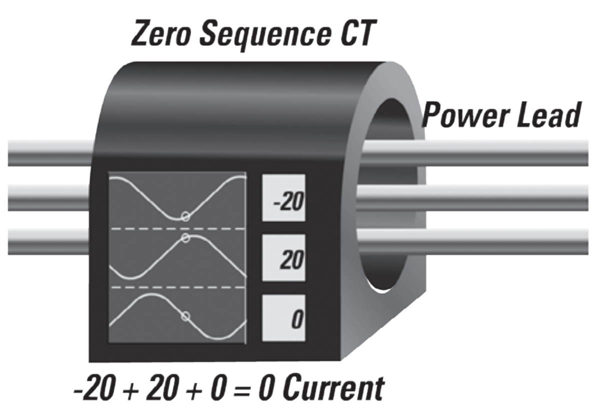


Figure 9.
Ground Fault CT Configuration

currents typically rise to magnitudes greater than 6 times the motors full load current. The slight mismatch of the CTs combined with the relatively large phase current magnitudes produce a false residual current, which will be seen by the relay. This current can be misinterpreted by the motor relay as a ground fault unless the ground fault element's pickup is set high enough to disregard this error.

6. Unbalance Protection

Unbalanced load in the case of AC motors is mainly the result of an unbalance of the power supply voltages. The negative-sequence reactance of the three-phase motor is 5 to 7 times smaller than positive-sequence reactance, and even a small unbalance in the power supply will cause high negative sequence currents. For example for an induction motor with a starting current six times the full load current, a negative sequence voltage component of 1% corresponds to a negative sequence current component of 6%. The negative-sequence current induces a field in the rotor, which rotates in the opposite direction to the mechanical direction and causes additional temperature rise. Main causes of current unbalance are: system voltage distortion and unbalance, stator turn-to-turn faults, blown fuses, loose connections, and other internal motor faults.

7. Short Circuit

The short circuit element provides protection for excessively high overcurrent faults. When a motor starts, the starting current (which is typically 6 times the Full Load Current) has asymmetrical components. These asymmetrical currents may cause one phase to see as much as 1.7 times the RMS starting current. As a result the pickup of the short circuit element must be set higher than the maximum asymmetrical starting currents seen by the phase CTs to avoid nuisance tripping. The breaker or contactor that the relay is to control under such conditions must have an interrupting capacity equal to or greater then the maximum available fault current.

8. Undervoltage

If an induction motor operating at full load is subjected to an under voltage condition, full load speed and efficiency will decrease and the power factor, full load current and

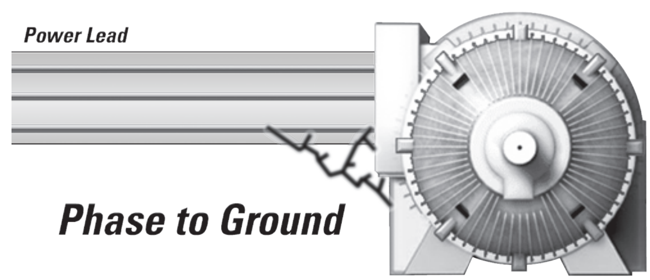


Figure 10.
Phase to Ground Fault

temperature will increase. The undervoltage element can be considered as backup protection for the thermal overload element. If the voltage decreases, the current will increase, causing an overload trip. In some cases, if an undervoltage condition exists it may be desirable to trip the motor faster than the overload element.

The overall result of an undervoltage condition is an increase in current and motor heating and a reduction in overall motor performance.

9. Overvoltage

When the motor is running in an overvoltage condition, slip will decrease as it is inversely proportional to the square of the voltage and efficiency will increase slightly. The power factor will decrease because the current being drawn by the motor will decrease and temperature rise will decrease because the current has decreased (based on I^2t). As most new motors are designed close to the saturation point, increasing the V/HZ ratio could cause saturation of air gap flux causing heating.

In this case the overall result of an overvoltage condition is an increase in current and motor heating and a reduction in overall motor performance.

10. Mechanical Jam

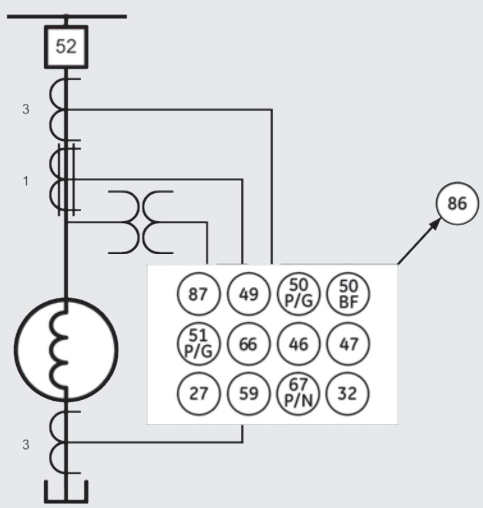
The mechanical jam element is designed to operate for running load jams due to worn motor bearings, load mechanical breakage and driven load process failure. This element is used to disconnect the motor on abnormal overload conditions before the motor stalls. In terms of relay operation, the Mechanical Jam element prevents the motor from reaching 100% of its thermal capacity while a mechanical jam is detected. It helps to avoid mechanical breakage of the driven load and reduce start inhibit waiting time.

11. Load Loss Detection

Undercurrent protection is useful for indicating the loss of suction in a pump application or a broken belt in a conveyor application. The second method of load loss detection is the use of the underpower protection element.

12. Typical Motor Protection Applications

Large motor - Two sets of CT's for differential protection

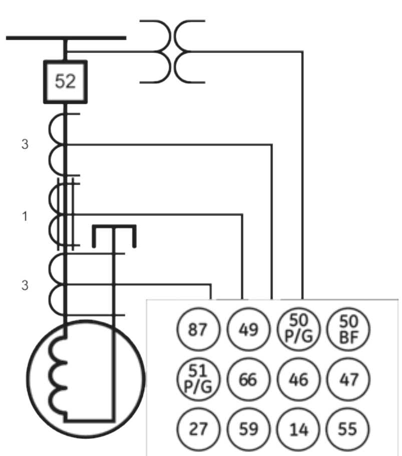


Typical Functions

87S	Stator Differential	66	Starts per hour
49	Thermal Overload	46	Current Unbalance
49RTD	RTD Biased Thermal Overload	47	Phase Reversal
49S	Stator RTD	27P	Undervoltage
38	Bearing RTD	59P/N	Overvoltage
51R	Mechanical Jam	67P/N	Directional Overcurrent
50P/G	Instantaneous Overcurrent	32	Directional Power
51P/G	Time Overcurrent	81U	Underfrequency
50BF	Breaker Failure	81O	Overfrequency

Functions		Typical Product Order Code
Typical Functions		M60-E00-HCH-F8L-H6P-M8N-P5C-UXX-WXX
Ethernet Communications	Copper	M60-N00-HCH-F8L-H6P-M8N-P5C-UXX-WXX
	Fiber	M60-G00-HCH-F8L-H6P-M8N-P5C-UXX-WXX
Lockout	Standalone	HEA61-A-RU-220-X2
	Integrated	M60-E00-HPH-F8L-H6P-M8N-P5C-U4L-WXX

Large motor - One set of CT's for differential protection

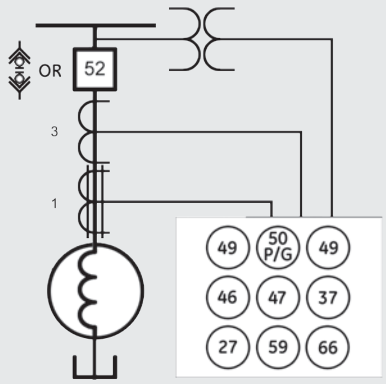


Typical Functions

87S	Stator Differential	66	Starts per hour
49	Thermal Overload	46	Current Unbalance
49RTD	RTD Biased Thermal Overload	47	Phase Reversal
49S	Stator RTD	27P	Undervoltage
38	Bearing RTD	59P/N	Overvoltage
51R	Mechanical Jam	14	Speed Switch
50P/G	Instantaneous Overcurrent	55	Power Factor
51P/G	Time Overcurrent		
50BF	Breaker Failure		

Functions		Typical Product Order Code
Typical Functions		469-P5-HI-A20-E
Communications	Ethernet	469-P5-HI-A20-T
	DeviceNet	469-P5-HI-A20-D
Lockout	Standalone	HEA61-A-RU-220-X2
	Integrated	M60-E00-HPH-F8L-H6P-M8N-P5C-U4L-WXX

Large or medium size motor

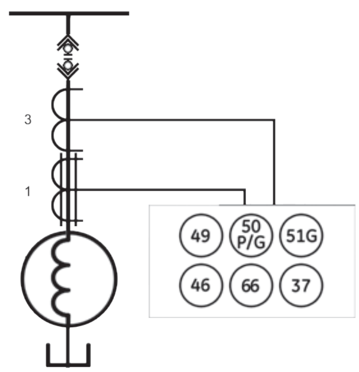


Typical Functions

49	Thermal Overload
49RTD	RTD Biased Thermal Overload
49S	Stator RTD
38	Bearing RTD
51R	Mechanical Jam
50P/G	Instantaneous Overcurrent
51G	Time Overcurrent
66	Starts per hour
46	Current Unbalance
47	Phase Reversal
27P	Undervoltage
59P/N	Overvoltage
37	Undercurrent

Functions		Typical Product Order Code
Typical Functions		M60-E00-HCH-F8L-H6P-M5C-U5D-WXX 469-P5-HI-A20-E 369-HI-R-M-0-0-0
Communications	Ethernet	M60-N00-HCH-F8L-H6P-M5C-U5D-WXX 469-P5-HI-A20-T 369-HI-R-M-0-E-0
	DeviceNet	469-P5-HI-A20-D 369-HI-R-M-0-D-0
	Profibus	369-HI-R-M-0-P-0
Lockout	Standalone	HEA61-A-RU-220-X2
	Integrated	M60-E00-HPH-F8L-H6P-M8N-P5C-U4L-WXX
Harsh Environment		469-P5-HI-A20-E-H 369-HI-R-M-0-0-H

Medium size motor

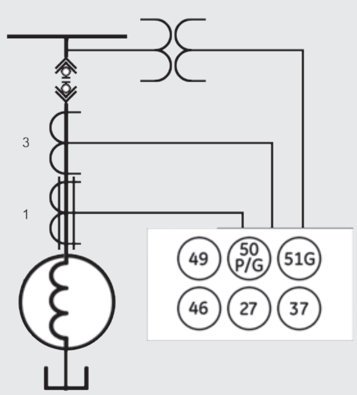


Typical Functions

49	Thermal Overload
49RTD	RTD Biased Thermal Overload
49S	Stator RTD
38	Bearing RTD
51R	Mechanical Jam
50P/G	Instantaneous Overcurrent
51G	Time Overcurrent
46	Current Unbalance
66	Starts per hour
37	Undercurrent

Functions		Typical Product Order Code
Typical Functions		369-HI-R-M-0-0-0 269Plus-SV-1-1-100P-HI 239-RTD-AN
Communications	**Ethernet**	369-HI-R-M-0-E-0
	DeviceNet	369-HI-R-M-0-D-0
	Profibus	369-HI-R-M-0-P-0
Lockout	**Standalone**	HEA61-A-RU-220-X2
Harsh Environment		369-HI-R-M-0-0-H 239-RTD-AN-H

Small size, low voltage motor



Typical Functions

49	Thermal Overload
49RTD	RTD Biased Thermal Overload
49S	Stator RTD
38	Bearing RTD
51R	Mechanical Jam
50P/G	Instantaneous Overcurrent
46	Current Unbalance
27P	Phase Undervoltage
37	Undercurrent

Functions		Typical Product Order Code
Typical Functions		MM300-B-E-H-S-S-C-A-G 239-RTD-AN MM2-PD-2-120
Lockout	**Standalone**	HEA61-A-RU-220-X2
Harsh Environment		239-RTD-AN-H