Motor Principles

Introduction

A motor is an electric machine that converts electrical energy to Mechanical energy with typical 98% efficiency. An electric motor is powered from an external electric AC or DC power source.

The energy generated by the motor, also known as mechanical energy, can be used to drive several different types of equipment such as, pumps, compressors, fans, etc.

The power a motor generates determines how it is rated, and is measured in either kilowatts (kW) or horsepower (Hp). Horsepower and kilowatts the standard unit of measure for electric motors. One horsepower is equivalent to 746 watts.

Hp = kW / 0.746
kW = HP x 0.746

Ratings of AC and DC motors can range from as little as a micro horsepower up to and over 100,000 horsepower. The motor's application will determine the necessary size.
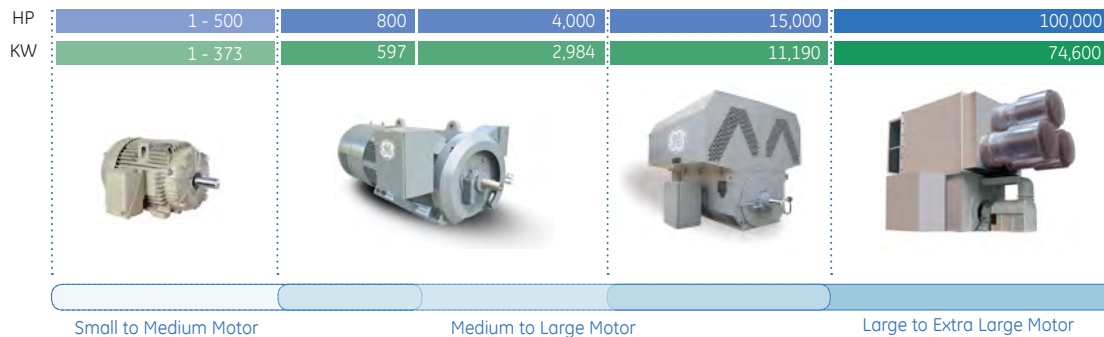
HP	1 - 500	800	4,000	15,000	100,000
KW	1 - 373	597	2,984	11,190	74,600

Small to Medium Motor   Medium to Large Motor   Large to Extra Large Motor

Figure 1.
Motor power range

Induction Motors

Three-phase induction motor are the motors that are most commonly used in the industry. They are inherently, simple, rugged, cost effective and easy to maintain. Induction motors range in horsepower from fraction horsepower to several thousand horsepower.

A three-phase induction motor consists of two main parts: the stationary stator and the rotating rotor. The rotor is separated from the stator by a small air gap which ranges from 0.4 mm to 4 mm depending on the size of the motor.

The stator consists of a steel frame which supports a hollow, cylindrical core made up of stacked laminations. A number of evenly spaced slots, punched out of the internal circumference of the laminations, provide the space for the stator windings.

The rotor is also composed of punched laminations. These are stacked to create a series of rotor slots to provide space for the rotor winding.

Power is applied from the stator to the rotor by means of electromagnetic induction, which causes the rotor to rotate when power is applied to the stator.
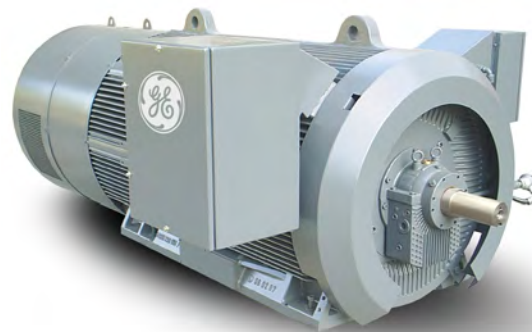
Figure 2.
Induction motor

Synchronous Motors

The major difference between a synchronous and an induction motor is in their respective rotors. Unlike an induction rotor, which consists of laminations and rotor bars, the synchronous rotor has field windings wrapped around protruding poles that create a DC field.

A synchronous motor will start similar to an induction motor. When a pre-determined amount of slip is reached a DC field will be applied to the rotor. Once the DC field is applied, the rotor will lock in with the stator creating synchronous operation.

Synchronous motor are used mainly when an application requires the motor speed to be consistent without load fluctuations, and also to assist in regulating power quality and power factor.
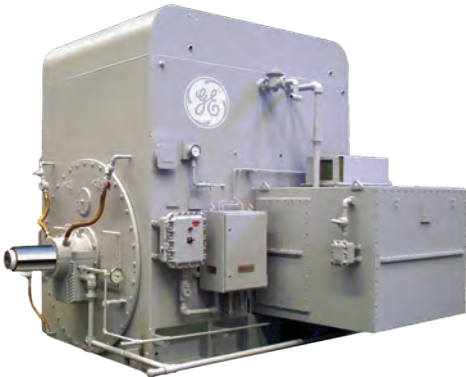

Figure 3.
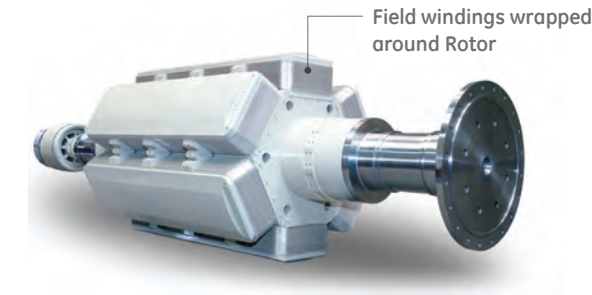Medium voltage synchronous motor

Field windings wrapped around Rotor
Figure 4.
Rotor of a synchronous motor

Figure 5.
Medium voltage motor core

Motor Application Considerations

Induction

- Pumps
- Fans
- Compressors
- Conveyors
- Crushers
- Mixers
- Shredders
- Extruders

Synchronous

- Compressors (High & Low Speed)
- Fans (High & Low Speed)
- Extruders
- Refiners
- Vacuum Pumps
- Chippers
- Special Apps. with Large AFDs
- Mining Mills

Figure 6.
Typical applications for Induction and synchronous motors

Motors in a Typical Mining Application

Electric motors are the workhorse and backbone of industrial process applications. Motors ranging from medium voltage large motors to low voltage small motors can be found in applications such as oil & gas, water treatment, and as shown below, the mining industry.

Medium voltage motors can be used in applications such as, crushers, grinding, and large pumps and fans where high horsepower ratings are required to process or move material.

Low voltage motors are typically used in secondary process applications in the mid to final stages of the process of the material. These motors are vital to ensure the process remains running in order to finalize the process of the material.

With motors found in many different processes in each application, it is vital to ensure each motor is adequately protected so that process uptime is not interrupted. Before motor protection can be implemented, vital information, known as motor performance data, is required to ensure correct configuration.
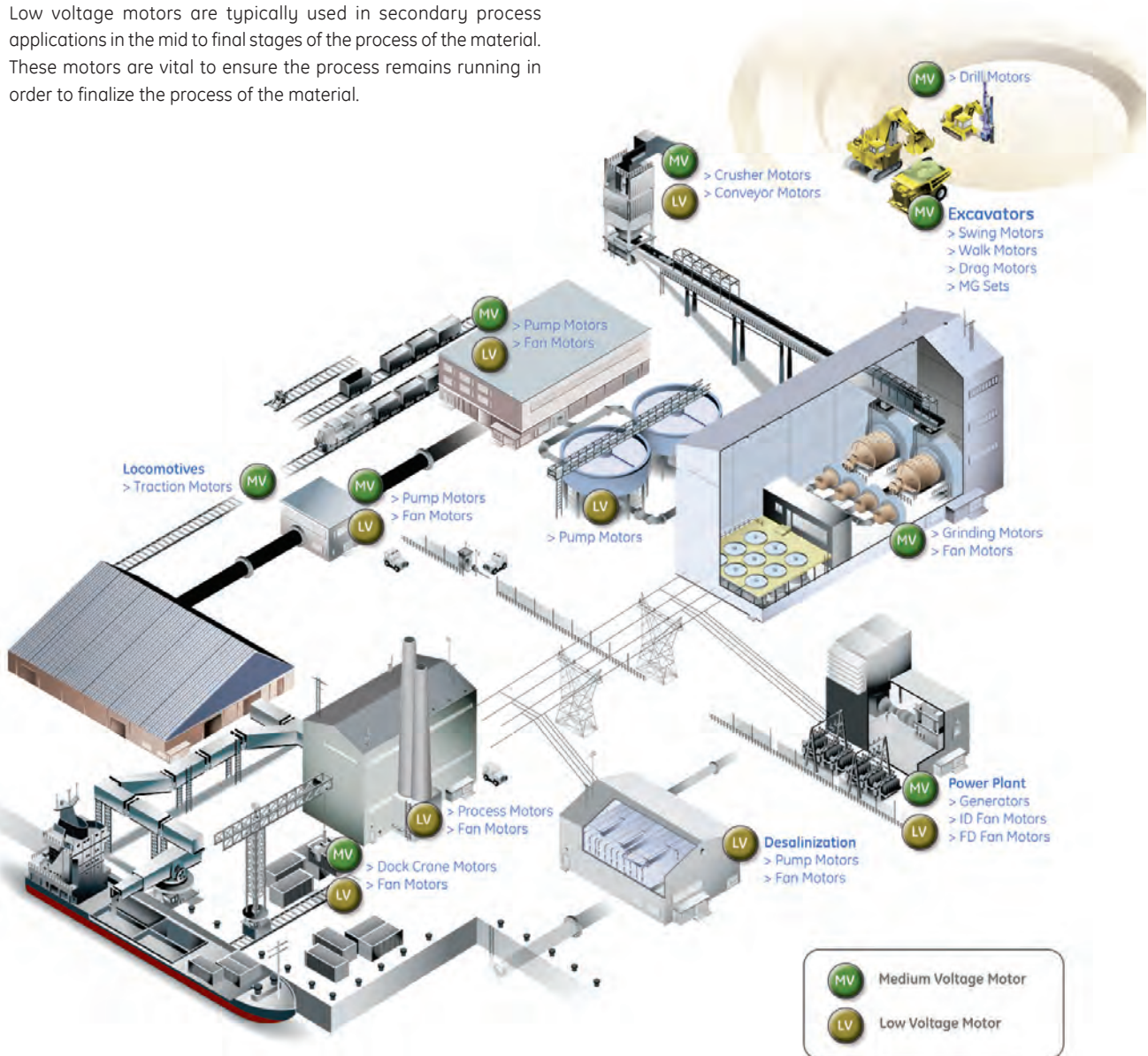

Figure 8.
Motor applications in the mining process

Motor Performance Data

Correct motor protection setup and configuration is essential to ensuring proper operation, performance, and efficiency of a motor.

Key elements to ensuring correct protection setup of the motor relies on the Motor Performance Data, or Motor Nameplate Data, which is supplied by the motor manufacturer.

This information can be used to configure the Motor Protection Device to ensure overall performance of the motor is maximized.

The Motor Performance Data as shown in Figure 7, identifies key information required to set up the Motor Protection Device.

1. Thermal overload Pickup

   a. The thermal overload pickup is set to the maximum allowed by the service factor of the motor. In this case it would be set to 1.10 × FLC for the motor service factor of 1.00. If the service factor is unknown we must assume 1.00.

2. Voltage Sensing

   a. The connection type (wye or delta) is required for the relay to perform proper calculations. In this example a 4160/120 PT will be required with a ratio of 35:1.

3. Motor FLA and Phase CT's

   a. Motor FLA is applied to the motor protection device, and in this case is 413 amps. FLA also dictates the CT's required size.
   b. FLA should be 50% - 100% of chosen CT primary. This logic will provide accurate protection pick-up and metering.

4. Starting Time

   a. The starting time is the maximum amount of time the motor takes to achieve full load speed. The motor nameplate data will typically list the starting times at 100% and 80% rated voltage, in this case 3.4 seconds for 100% and 6.1 seconds for 80%. Should the starting time at the respective voltage level exceed the designated start time the relay will trip the motor offline.

5. Number of consecutive starts

   a. Relates to the thermal heating effects experienced by the motor during starting conditions. Since the motor will experience a high inrush of current during starting, which increases the Thermal Capacity used, the motor can only safely start a certain number of times within an hour.
   b. In this example the motor can safely be started 3 times when the motor is cold or at ambient temperature, or 2 times hot.

Figure 7.
Typical motor performance data sheet

Additional Essential Data

Ground CT

For high resistance grounded systems, sensitive ground detection is possible with the 50:0.025 CT. On solidly grounded or low resistance grounded systems where the fault current is much higher, a 1A or 5A secondary CT should be used. If residual ground fault connection is to be used, the ground fault CT ratio must equal the phase CT ratio. If residual connection is used, pickup levels and timers must be set with respect to the acceleration time. The zero sequence CT chosen needs to be able to handle all potential fault levels without saturating.

Overload Curve

The overload curve should be chosen so that the curve falls in between the Cold Thermal Limit Curve and the Hot Thermal Limit Curve. The correct overload curve will provide the most accurate protection of the motor and allow for maximum process uptime.

Motor Protection

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 10ºC. 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 K factor setting
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

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, Figure 9, 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 protective relay integrates stator and rotor heating into a single model, by measuring the terminal currents. The Thermal capacity Used (TCU) value is maintained in a register and when the motor is on overload, the motor temperature and the TCU will rise. When the TCU reaches 100% a trip occurs. When the motor is stopped and is cooling to ambient, the TCU decays to zero.

The acceleration curves, Figure 9, 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: Curve F is the acceleration curve at rated stator voltage while curve E is the acceleration at 80% of rated stator voltage (soft starters are

Motor Rated Current
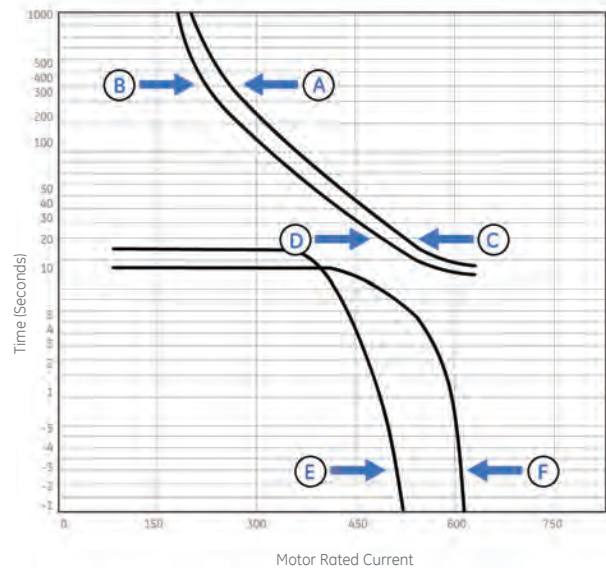
A. Cold Running Overload

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 9.
Motor thermal limits curves

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.

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

Typical Estimate: $K = \dfrac{175}{I^2_{LR}}$

NEMA

Conservative Estimate: $K = \dfrac{230}{I^2_{LR}}$

Multilin

Figure 10.
Motor derating curves

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 the following enhancements and additions:

- Motor start inhibit
- Standard, custom and voltage dependant overload 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
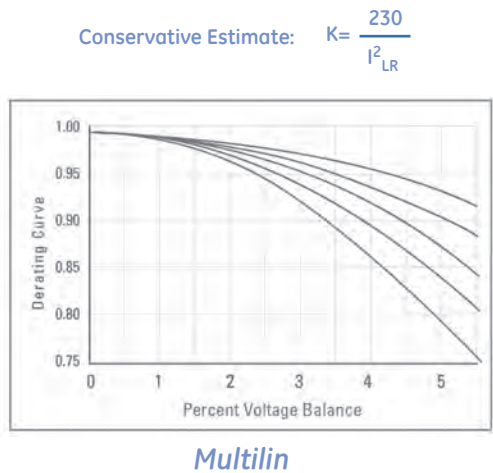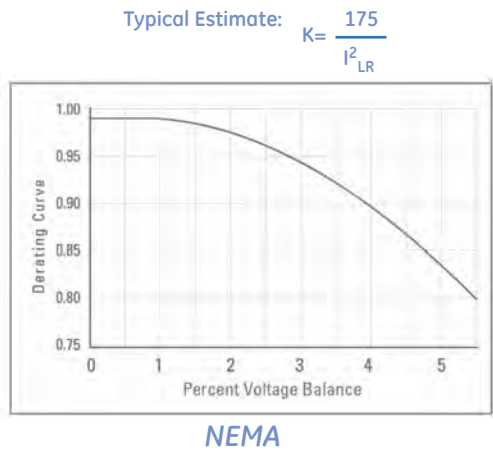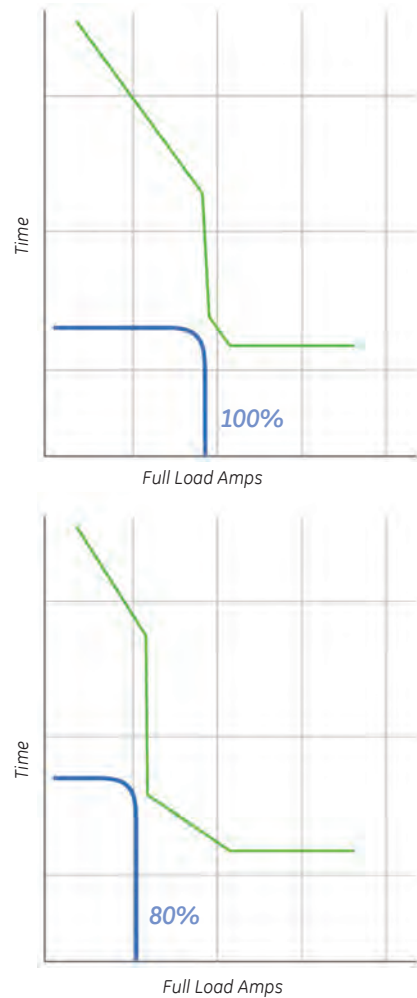- Start and restart supervision

Full Load Amps

Full Load Amps

■ Acceleration Curve
■ Voltage Dependant Overload Curve

Figure 11.
Voltage dependant overload curves

The current unbalance cause rotor heating in addition to the normal heating caused by positive sequence currents. The curves on Figure 10 shows recommended NEMA derating as a function of voltage unbalance. Multilin motor protection relays allows the biasing of the Thermal model to comply with the NEMA standards.

The Thermal Model is also biased by the RTD's temperature feedback, as shown in Figure 10. This feature allows the relay to protect the motor against unusual high ambient temperatures or abnormal heating due to overvoltage or damaged bearings. The RTD biasing feature can correct for this temperature rising by forcing the TCU register up to the value appropriate to the temperature of the hottest stator RTD.

Differential Protection

This protection function is mostly used to protect induction and synchronous motors against phase-to-phase faults

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.

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 (Figure 12) 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 its sensitivity and noise immunity.

If six CT's are used in a summing configuration, during motor starting, the values from the two CT's on each phase may not be equal as the CT's are not perfectly identical and asymmetrical currents may cause the CT's 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.

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 CT's during external faults. CT unbalances arise as a result of CT accuracy errors or CT saturation.
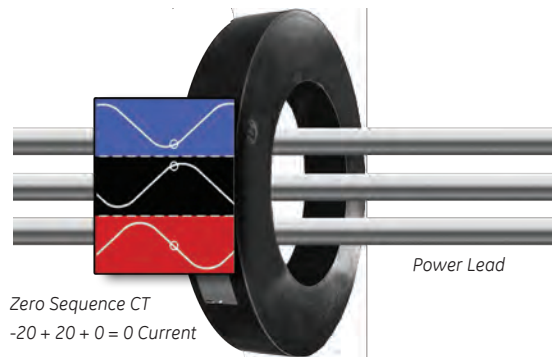
Ground Fault Protection

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.

Power Lead

Zero Sequence CT
-20 + 20 + 0 = 0 Current

Figure 13.
Ground fault CT configuration

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 CT's are not perfectly matched. During

Figure 12.
Differential protection of phase to phase faults

the motor start, the motor's phase currents typically rise to magnitudes greater than 6 times the motors full load current. The slight mismatch of the CT's 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.

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.

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.
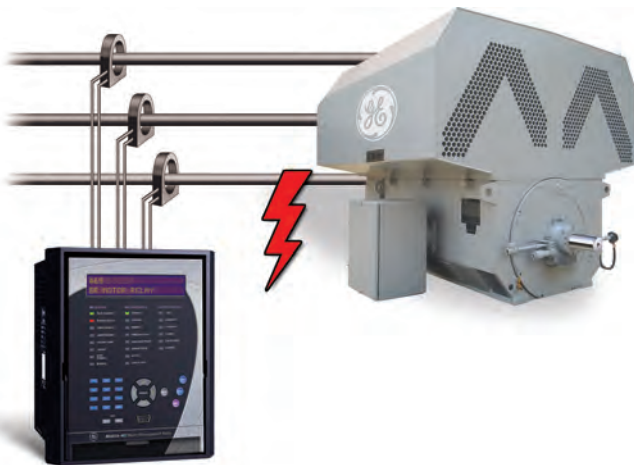

Figure 14.
Phase to ground fault

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 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.

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. Overvoltage causes an increase in magnetization current due to an increase in iron losses, and could cause the motor to overheat, but at a given shaft load, the overvoltage also causes a decrease in load current and the resulting total current will be less than the motor current at rated voltage. Therefore, higher stator winding temperatures at higher voltages are unlikely. However, if the magnetization current increases due to overvoltage while the load current were to remain constant, the motor operating temperature would increase.

The only way to protect a motor against overvoltage conditions is by utilizing a device that senses winding temperature, Multilin relays include options to sense motor's temperature with RTD's and also includes overvoltage alarm and trip features to allow alarming or tripping of the motor under extended overvoltage conditions.

Mechanical Jam

An induction motor stalls when the load torque exceeds the breakdown torque and causes its speed to decrease to zero, or to a point below rated speed.

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. After a motor start, once the magnitude of any one of either phase A, B, or C exceeds the Trip/Alarm pickup level × FLA for a period of time specified by the delay, a trip/alarm will occur. It helps to avoid mechanical breakage of the driven load and reduce start inhibit waiting time by taking the motor off-line quicker than the thermal model or overload curve.

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. A loss of load condition will not always cause a significant loss of power. Power is a more accurate representation of loading and may be used for more sensitive detection of load or pump cavitations.