AC MOTOR PROTECTION

Because motors provide a vital service to industrial and commercial installations, any failure of motors to perform to their specifications must be detected, and appropriate action initiated. Techniques for protecting are well-developed, but which to apply and how to set protection limits may differ in response to the failure cause, motor importance, or system design philosophy.

The above statement can be further clarified by separating the protection function into three categories:

1. The motor itself may be failing or has failed.
2. The driven equipment (fan, pump, etc.) may have failed, unable to be rotated by the rated motor horsepower.
3. The utility power supply may have failed or been corrupted in such a way that its power quality is inadequate.

In the case of impending motor failure, certain signs may be detected. One such sign is that the motor fails to start (rotate) when commanded, or the motor trips off the line because of excessive motor current. Other signs include a high motor temperature during normal performance. Some of the natural causes of motor failure are failed windings due to an insulation system that is inadequate for the environment and/or a ventilation/cooling system failure. There can also be bearing problems due to lubrication system failures or poor maintenance. Vibrations can shorten the life of a motor. Certain installations may apply a monitoring system which will continuously scan many sensors for a group of motors.

When the driven equipment fails, the motor current increases, causing a higher temperature; and at a certain stage, the motor may not be able to rotate. When slowed down due to the motor's inability to rotate, the motor acts like a transformer with its secondary winding short-circuited, producing high currents in both the stator and rotor.

All of the above failure symptoms could be the result of poor quality of the supplied power. Poor power quality may include loss of a phase, incorrect phase rotation, high harmonics content, voltage sags, or voltage loss. For instance, a phase could open in the utility source due to a blown fuse or circuit-breaker contact failure. An extreme case of poor power quality is when the utility source has the wrong phase rotation—that is, c-b-a instead of a-b-c rotation. This could cause reverse rotation of motors. While such instances do not occur frequently, a downed power line may be improperly reconnected during an emergency repair. A sustained undervoltage condition will lead to lower efficiencies and higher operating temperatures, while a momentary sag can possibly drop out magnetically held motor contactors.

MAJOR STUDIES

In the design of a facility, many electrical studies are performed (1). One basic study is to size the loads and then group them so that they are supplied from common switchgear. Load sizes generally determine the distribution and motor voltage. Other studies include short circuit and load flow. A protection study will follow the fault and voltage studies, and it will be based upon plant operating philosophy.

Short Circuits

A short circuit (or fault) is defined as an abnormal connection of low impedance between two points in an electrical system. The connection can occur in a machine winding, transmission line, or distribution equipment. Faults rarely begin as a bolted fault, a term used when the impedance of the connection is close to zero. A short-circuit study is one of the many needed to (1) determine the capability of the system to start and run motors, (2) select system components adequate for conducting the normal current continuously, and (3) be able to interrupt fault current. For protective devices to operate properly within their ratings, it is necessary to determine the amount of currents they have to interrupt when the worse-case fault occurs. Assuming that this study were done, the interrupting time of the protective device must be coordinated with the thermal capability of the conductors between the motor and its source circuit breaker or motor controller. The type of system neutral grounding will influence the nature of short circuits.

Faults may begin with a defect in the equipment (motor or transformer) winding during manufacturing or installation. Small nicks can lead into minute values of current, often of an arcing nature. Arcing limits the amount of fault current initially and, depending on certain factors, can simply burn itself out, leaving a high-impedance condition with carbonized insulation around the failure location. This is particularly true in ungrounded delta or high-resistance, low-voltage grounded systems where the protection may not sense low values of current, and thus would not trip. At a later time, a voltage surge on another phase or ground can lead to a fault between the two phases or between the first faulted phase and ground. This latter short circuit may result in a high level of current equal to a bolted fault.

On systems with solidly grounded neutrals or low-resistance grounded neutrals, an incipient fault can develop into the bolted fault without ever being extinguished. This is why some system designers prefer the lower-impedance grounded neutral system because faults are easy to detect and cause the protective device to clear the fault.

Short Circuits on the System. When a fault develops on a distribution system, the immediate effect is to funnel most of the electrical energy into the fault location. This includes power from the source transformer or generator plus the contribution from motors connected at the time. Power is supplied to most low-voltage motors by combination controllers that consist of a contactor, a circuit protective device, and an overcurrent device that protects the motor. Many of the contactors are held in place magnetically, and a voltage sag may initiate the contactor to disconnect from the source.

Short Circuits in the Motor Circuit. A fault on a motor circuit will draw fault current from the source as well as from other motors connected to the system. If the fault is on the circuit between the motor and the controller, the motor will also feed into the fault. Bolted faults can be sensed with instantaneous overcurrent trip elements, and the circuit can be opened within fractions of a second. When applying a magnetically held contactor, a voltage drop could force its contacts open before the protective device operates, whether fuse or circuit breaker. For this reason, the contactor should be rated for the short-circuit interruption, or its operation should be delayed from dropping out. Separate, reliable alternating-current (ac) or direct-current (dc) sources can be applied to the control circuits for this contingency.

Voltage Drop Study

One of the most important studies is to determine how the voltage is maintained on the distribution system during starting or running conditions. The study must be coordinated with the short-circuit study, and a principal starting point is to determine the characteristics of the source voltage. Utilities can furnish the available fault MVA with a range of a nominal voltage as having plus and minus percentages. Generally, this is a small deviation of ±5%. There have been cases whee the utility fault MVA has been too low to maintain system integrity, a condition to consider when setting overcurrent relays which may not have sufficient current to operate relays.

For a conservative design, a short-circuit study will begin by using the plus value, the worst condition where the fault current will be higher. Likewise, the load study begins by using the minus value, a case where low-voltage motors may have insufficient voltage to start with certain designs. Motor controllers have capabilities to start from less than nominal voltage, and they accelerate the motor to rated speed. Similarly, these controllers and their motors can predictably ride through voltage sags. The study is complex, because of decisions made on conductor sizes, transformer impedances, tap changing ability, plant location, cogeneration, and other factors. While motors may be applied to a particular system, it is important to recognize that the motor voltage will be lower than the distribution system voltage. Some typical values are shown in Table 1.

Table 1. Typical Voltages (2)

Nominal System Voltage	Motor Utilization Voltage
480	460
2,400	2,300
4,160	4,000
6,900	6,600
13,800	13,200

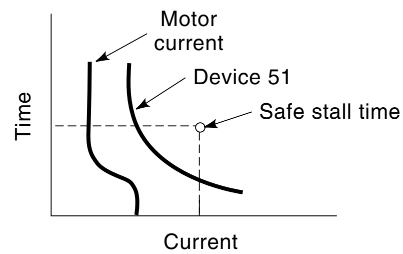


Figure 1. Time-thermal limit of motor protection safe stall time.

Protection Techniques (3). Each load (motor, transformer, etc.) will be protected, and its protection will be coordinated with system protection. The simplest approach is to provide backup overcurrent protection that permits individual load circuit protection to operate first. If the primary protection fails to clear the overcurrent condition, the backup protection will operate following a delay. However, this backup protection removes all circuits connected to the bus, and not just the motor circuit on which the primary protection failed.

Another major consideration is ground fault protection (GFP), the philosophy of which may differ from one plant to another. Some schemes alarm first, and then the circuit is tripped by operator action following whatever adjustments had to be made to the process control. Other GFP schemes may first alarm and then trip automatically when a second phase has been grounded to form a phase-to-phase-to-ground fault, much higher in magnitude than ground fault current in most cases. These are advantages to all schemes, but the philosophy must be understood before selection of the neutral grounding transformer connection scheme and the GFP devices.

In a typical installation (4), utility power is transformed down to a plant distribution voltage system. The most common protection practice is to measure motor current and compare it against some protective device set above the rated nameplate current. When the current exceeds the device setting, the condition must cause an alarm or trip action. Individual circuit overcurrent devices can perform basic protection for most ac motors. The power source would be protected by facility undervoltage/overvoltage protective devices as well as overcurrent devices set to coordinate with the primary overcurrent devices of those individual motor circuits.

Most electrical equipment has thermal limits beyond which some failures can be predicted to occur. These limits determine the selection and setting (where appropriate) of the overcurrent protective devices. Although only one phase will be shown for most figures in this chapter, a three-phase system is implied. For instance, Fig. 1 illustrates the type of limits for induction motors. (Please note that the time versus current magnitude is on a log–log scale.) For convenience, the safe stall time is shown as a single point in time above the starting current [locked rotor current (LRC)], whereas other failures can occur at lower current values. On this basis, there is need to protect the motor during starting, as well as when running. This phenomenon has been recognized for years, and protective devices can be applied to prevent the motor current from reaching these limits. It is further assumed that the motor winding temperature is approximated by the temperature curves of the time–inverse-overcurrent relays used in this figure. By adding the tripping characteris-

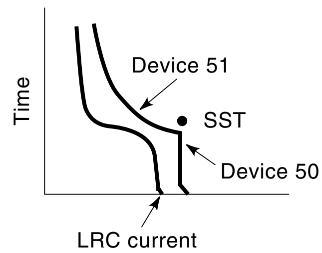


Figure 2. Motor protection using time-overcurrent relay with instantaneous trip element for short-circuit protection.

tics of an inverse-time–overcurrent device 51 (5) below the motor thermal characteristics, the motor will be allowed to start and to accelerate to its rated speed where it is then protected by overcurrent means while running. Regardless of the cause, the motor will be protected for overcurrent conditions.

A drawback using this overcurrent protection scheme is that it does not adequately protect for short circuits in the cable from the distribution equipment to the motor. Therefore, a protective element must be added to the overcurrent device to sense a trip whenever there is an abnormally high current during starting. This device 50 is shown in Fig. 2 to the extreme right of the inverse curve. In order to allow starting, the setting for this instantaneous tripping device must be higher than the magnitude of the inrush current to the motor. The motor locked rotor current (LRC) can be estimated at six times the full load current, although some locked rotor currents may be as high as eight times the root mean square (rms) value of the full load current. In addition, there are asymmetrical peaks that could inadvertently trip a protective overcurrent device set too closely. This is reason to suggest setting the instantaneous element to some value of at least twice the LRC. When possible, obtain the actual current values from the motor manufacturer, especially for the new energy efficient motors, which may require a trip setting equal to three times LRC. It is important to be able to estimate the approximate current settings in the design stage of the application, in order to select the range of the protective device.

Overcurrent Protection

As mentioned above, the principal means for overcurrent protection is the use of overcurrent devices that replicate to thermal limits established for a particular motor. This method is used for both low-voltage motors (systems below 1000 V) and medium-voltage motors (nominal voltages greater than 1000 V). However, devices manufactured for low-voltage motors and equipment are generally of a different nature due to the lower fault duty imposed upon them, with resulting smaller spacing required between the energized buses and other parts of the equipment. In many cases, motors are supplied from switchgear, particularly when the number of start/stop operations is limited. For those applications where very frequent start/stop operations are required, combination controllers are used for low-voltage motors as well as for medium-voltage motors.

Medium-Voltage Motors. Medium-voltage (MV) motors are to be protected from all the previously mentioned failures. Because these motors are closer to the source, they are more subject to changes in power quality. Depending upon source transformers and their protection, MV motors would be more vulnerable to surges due to circuit switching or lightning on the power source. They would also be exposed to higher values of fault current than would lower-voltage systems. Overcurrent protection is applied to all three phases, and the normal differences between applications will be due to the motor torque–speed characteristics, very evident during starting and acceleration of the connected equipment. For instance, the normal protection of Fig. 2 could satisfy many requirements.

However, motors with high inertia loads have different torque characteristics, and long acceleration times of 30 s to 40 s before reaching rated speed. Thus the overcurrent protection must change in order to permit starting of these motors. Figure 3 illustrates one method of protection that utilizes several overcurrent elements. The relay must be able to distinguish between an actual fault and a starting current that contains high transient asymmetrical peak currents over a very brief time period. Therefore a time delay of 50 ms to 100 ms has been shown on device HD50, which pickup has been set above the LRC value. The standard instantaneous trip element, device 50, has been set at two to three times the LRC. The inverse-time-overcurrent element, device 51, protects the motor for running conditions. There exists a practice within some companies to set the device 51 at a lower value on one phase only to alarm, such as 1.2 X FLC, while the device 51 on the other two phases would trip on some higher value, such as 1.35 or 1.40 X FLC. This takes advantage of the redundancy of having protection on each of the three phases.

Differential Overcurrent Protection of MV Motors. Differential overcurrent protection of motors is an established method to detect low-level faults before they cause much damage. One scheme locates the current transformers (CTs) at the switchgear, such that the motor conductors are included in

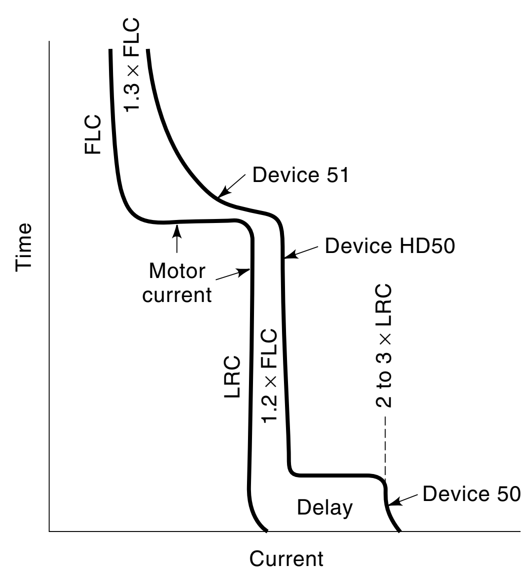


Figure 3. Overcurrent protection of large motor with high inertia load with long acceleration time.

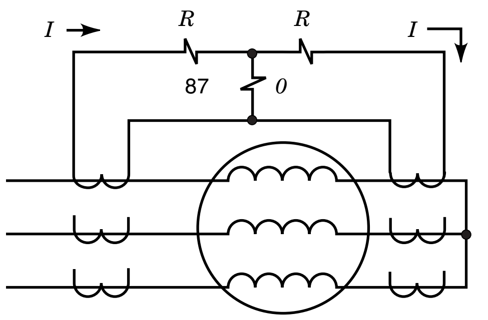


Figure 4. Differential protection of motor, prefault.

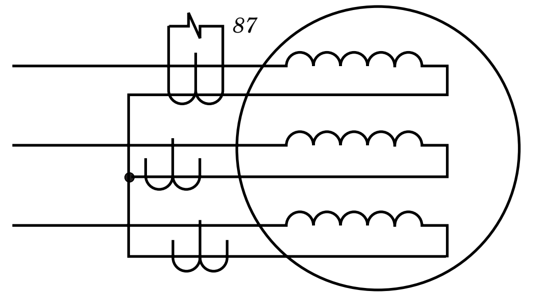


Figure 6. Differential protection using self-balancing CTs at the motor.

the differential zone. Figures 4 and 5 illustrate that method. While more embracing, this scheme lacks the speed and resolution of the self-balancing method, which follows.

Differential overcurrent protection is often used on MV motors, especially on the higher horsepower ratings. This type of protection measures current entering a motor and then matches this current with the value of the current exiting the motor. Figure 4 illustrates the normal condition where current is stepped down by the CT to a range of 0 A to 5 A on its secondary. Normally in the selection of the CT primary, a value equal to 150% of motor FLC will be adequate for running as well as starting current. For example for an FLC of 200 A, a 300 : 5 A CT will be selected. The starting current (e.g., 1200 A) may then produce a secondary current of 20 A which will circulate through both CTs and the relay restraint windings. Assuming that the connected relay and metering burden is normal, the secondary voltage on the CT will not lead to CT saturation. Standard CT burdens and voltages will be used to select the actual CT.

Figure 5 shows what happens when there is a fault in the motor windings. The secondary current from CT1 produces more current than that from CT2. This produces a current difference, which returns to CT1 through an operating winding, which initiates tripping action. Although this scheme represents the actual elements in earlier electromechanical relays, it is only a schematic for solid-state relays. Because there may be a difference in CT ratios, there must be some threshold percentage difference current to operate the tripping action. In older relays, it was necessary to exceed a 10% difference at low values of current before tripping was initiated.

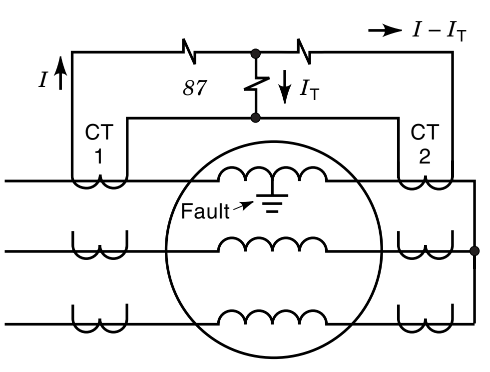


Figure 5. Differential protection of motor, following fault.

Another method to provide differential overcurrent protection is to use self-balancing CTs at the motor. Figure 6 illustrates how this is achieved. The CT for each phase is self-balancing where flux from the current entering the motor is balanced in the CT core by flux produced by the current leaving the motor. This results in a very sensitive relay that can detect ground faults in the motor winding much easier than the schemes of Figs. 4 and 5. There is no need to allow for differences in the CT performances, and, as such, this scheme is faster. While able to be set at low values of current, there is a need to recognize the type of system grounding and what device the relay will signal to trip. On a large MV distribution system there may be surge protection at the motor terminals, and this will require a delay in action to allow for the surge devices to carry the surge current to ground. Another consideration is when motor starters are used to open and close the motor circuit. If the self-balancing device is too fast, the motor contactor may open during a developing fault for which it is not rated to interrupt. Some schemes use a delay so that a circuit breaker opens or a fuse operates to limit the fault current.

Voltage Protection of MV Motors. There are several considerations for voltage protection that necessitate an approach not related to the overcurrent devices. As mentioned earlier, MV motors are more sensitive to power quality, and they certainly justify the application of devices which would not normally be used on low-voltage motors. For instance, surge protection is one application that fits here. Protection against voltage sags (a term which describes a momentary decrease in the supply voltage) is another. For strictly induction motors, there may be a dropout of contactors if magnetically held by its circuit ac power. One method is to use a dc control voltage that is not affected by the source sag. Alternately, a reliable ac control voltage would be used, possibly requiring a UPS or some other means.

Mentioned earlier is the loss of one phase or reverse connection of the supply voltage. Either of these scenarios can cause negative sequence voltage and current. Even a negative sequence voltage as low as or equal to a 5% value of the normal positive sequence voltage can cause a negative sequence current that overheats certain components on the motor rotor. The best way to envision this is to recognize that the ac windings generate a magnetic field that rotates in a prescribed direction, with the rotor lagging by the slip of only 2% to 3%. To the contrary, the negative sequence voltage will develop a field that rotates in the opposite direction, causing an opposing move that generates heat in the rotor. Positive, negative,

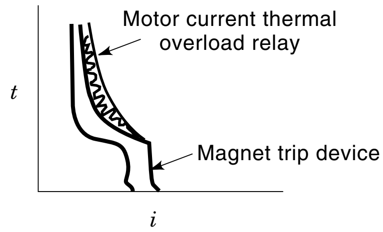


Figure 7. Protection of low-voltage motor using a combination controller.

and zero sequence terms are derived from symmetrical components, a method to analyze power circuits. A negative sequence overvoltage relay can be located near the bus to protect a group of motors. Negative sequence overcurrent relays are more sensitive, and can be applied on individual motor circuits to protect large motors. Generators have a definite constant (k) to be used in protection against these negative sequence currents. No standard presently exists for motor protection (k) constant, although values of 30–40 have been used to apply the negative sequence relay.

Low-Voltage Motors. Most low voltages will be fed from motor control centers or some similar configuration of grouped devices. Most protection consists of a combination motor controller that includes short-circuit protection and motor protection for overloads and ground faults. Figure 7 is typical and consists of a circuit protective device, such as either a fuse or molded case circuit breaker, an overload relay which protects the motor, and a contactor which opens and closes the circuit upon command from the process or manual signal.

The circuit protection may be a single-element fuse or a dual-element fuse that can also protect the motor. The circuit breaker needs to have only an instantaneous trip element, although circumstances may force the use of a circuit breaker which has an inverse tripping element, as well.

Ground Fault Current Protection. This term is generally shortened to ground fault protection (GFP), with current implied. Most faults start as a single line to ground faults, and early detection may prevent the fault from developing into a phase-to-phase fault. A ground fault is generally caused by an insulation failure due to temperature, vibration, or a similar environmental condition. The failure could also be caused by poor workmanship during installation of the motor or its conductors from the power source. When a ground fault develops in a motor circuit, the value of the normal phase current may not change appreciably, but a differential current is created which will return to the source via ground and not via the phase conductors. Assuming the fault to be in the motor insulation, its core and frame provide low-resistance paths for the fault current. While the current may initially be in milliamperes, it can develop into more measurable and destructive values of current, very much dependent upon the type of system neutral grounding. The major reason for early detection of ground faults is to limit the damage to coil replacement, rather than permit the fault current to grow, causing damage to the motor steel. The system designer determines the type of system grounding, which will affect how motors are protected, the type of insulation needed for voltage transformers, and the voltage rating of surge protective devices. This article will discuss only the application, and not the factors used to select the type of neutral grounding.

High-Resistance Grounding. If the neutral is not grounded or is high-resistance grounded, the ground fault current magnitude may be limited to 5 A or less, a value normally equal to the capacitive charging current of a MV plant distribution system. High-resistance grounding of the system neutral is a common approach to protection for low-voltage (1000 V maximum) or MV systems, especially where the process continuance requires that the motors remain connected until an operator trips off the power as part of the procedure following an alarm. For 13.8 kV and higher voltage systems, the charging current may exceed 10 A, and this could lead to combustion of the insulation when arcing; thus, the current practice is to trip whenever the ground fault occurs at the higher MV systems.

Figure 8 illustrates the phasor relation of a 13.8 kV MV system where the motor circuit capacitive current exists due to the capacitance in the motor, the cables, and surge protection. Phasors are similar to vectors, except phasors have magnitude and time difference in electrical degrees, as opposed to vector magnitude and direction. The V_A represents the "A" phase to neutral voltage, and leads the "B" phase voltage by 120 electrical degrees, and leads "C" phase voltage by 240 electrical degrees. The capacitive current leads its respective phase voltage by 90 electrical degrees, and has been designated as I_{ac}, I_{bc}, and I_{cc}, respectively. In a normal industrial installation, there would be actual load current fed into the motor, and this load current would be of considerably higher magnitude than the capacitive current shown.

Figure 9 illustrates the effect of a ground fault on B phase, and how the capacitive current combines to a charging current equal in magnitude to three times the pre-fault phasor value. Figure 9 can also be applied to a low-voltage system, although the magnitude of the charging current would be lower, approximately equal to a magnitude of 1 A per 1000 kVA. By measuring this low-amplitude current, a ground-fault relay can initiate automatic tripping of circuits or to alarm only so that the operator may manually trip the circuits as part of the normal process control shutdown. The presence of a ground fault raises the potential from the normal phase voltage to ground to a value equal to line-to-line voltage or 1.732 times phase voltage. The significance of this is that the operator must be aware of the increased potential for a major fault of line-to-line voltage and should handle system shutdown expeditiously.

Figures 10 and 11 show two methods for measuring the ground fault current in a high-resistance grounded neutral

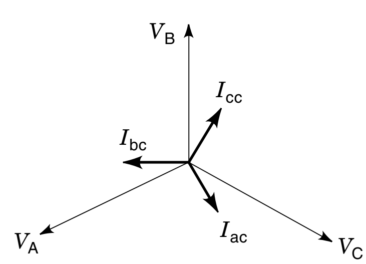
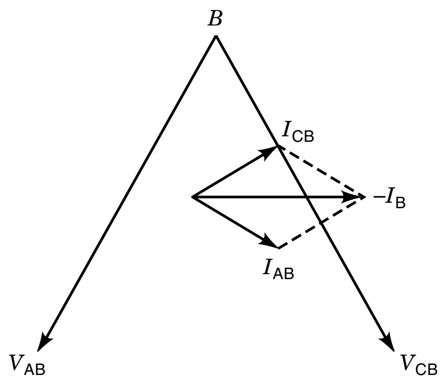


Figure 8. Phasor relation of a 13.8 kV MV system where the motor circuit capacitive current exists due to the capacitance in the motor, the cables, and surge protection. Load current not shown.



$I_{AB} = \sqrt{3}\,|I_{AC}|\ \underline{/330^*} = \sqrt{3}\ ^*0.75)\ \underline{/330}$

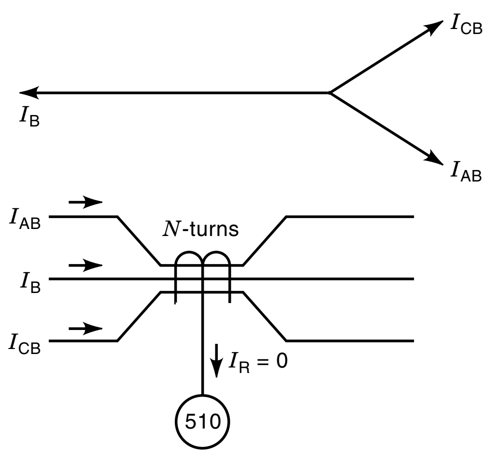
$I_{CB} = \sqrt{3}\,|I_{CC}|\ \underline{/30^*} = \sqrt{3}\ ^*0.75)\ \underline{/30}$

$-I_B = I_{AC} + I_{CB} = \sqrt{3}\ (0.75)\ (0.866 - j0.5 + 0.866 + j0.5)$

$= \sqrt{3}\ (0.75)\ (\sqrt{3}) = 3\ (0.75) = 2.25$ A

Charging current in faulted phase = 2.25 A

(**a**)



(**b**)

Figure 9. Effect of a ground fault on B phase, and how the capacitive current combines to a charging current equal in magnitude to three times the pre-fault phasor value.

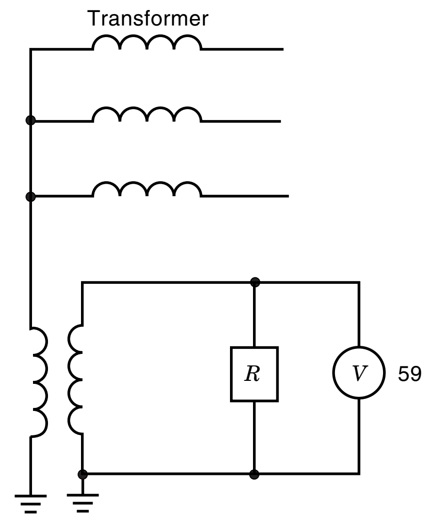


Figure 11. Typical high-resistance neutral grounding scheme.

system. Figure 10 has a toroidal current transformer, which encircles all current carrying conductors. For three-phase balanced loads, this consists of the three-phase leads. A neutral conductor may also be so grouped with the phase conductors on low voltage in order to account for any single phase to neutral loads. The sum of magnetic flux in the current transformer core during a pre-fault condition will equal zero, as illustrated in Fig. 8. Figure 11 is a typical high-resistance neutral grounding scheme, which connects a distribution transformer between the neutral and ground. A resistor is connected on this transformer secondary to provide a path for the ground fault current, and is monitored by a voltage relay sensitive to the voltage drop across the resistor. This scheme would be used to back up ground fault protection on individual motor circuits, and it could be used to alarm or trip after a time delay in the event of failure to act by an individual circuit protective device such as shown in Fig. 10.

There are variations on these schemes, such as having a residually connected CT configuration with the three-phase leads tied together after carrying current to their respective protective relay and metering devices. The ground fault device is now connected between the residual connection and the neutral connection of the CTs. This is shown in Fig. 12. An advantage to this scheme is the simplicity of not needing

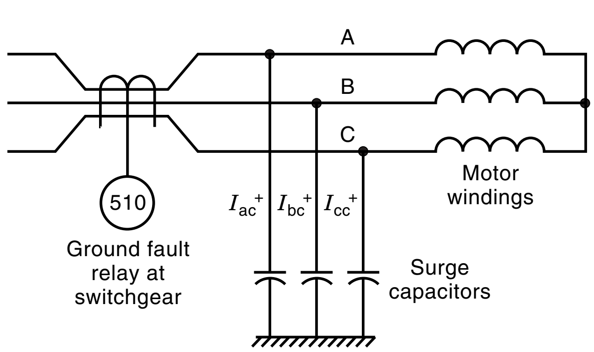


Figure 10. Core-balance CT for measuring the ground fault current in a high-resistance grounded neutral system.

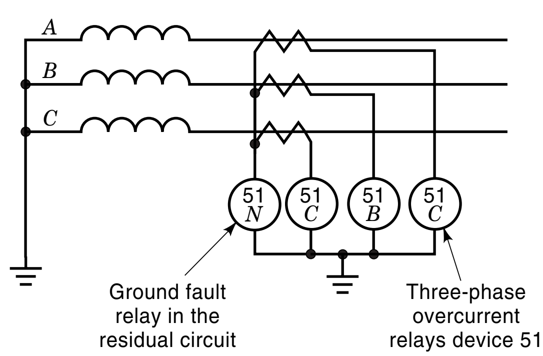


Figure 12. Residual connection of overcurrent relays to obtain ground fault current.

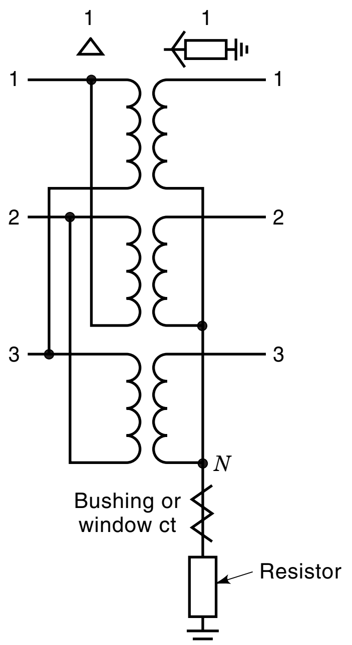


Figure 13. Neutral to ground resistor for low-resistance GFP scheme.

a fourth CT for the low-voltage systems neutral or one large-core balance current transformer as shown in Fig. 10. The disadvantage is that the residual current may contain unbalanced current due to CT differences. This latter disadvantage can be troublesome when coordinating several stages of protective relays.

Many low-voltage circuit protective devices have an integral residual current circuit. Where close coordination is required, a neutral CT may also be needed, or it may be necessary for the source to use the Fig. 10 connection with the neutral conductor also enclosed by the core balance CT. At medium voltage where there is no neutral conductor, many users of microprocessor-based protection recognize the increased capability that is gained from using the Fig. 10 connection for deriving the unbalanced current.

Low-Resistance Grounded Neutral System. This approach in Figure 13 is used to protect MV systems and motors from ground faults by tripping without intentional delay, except for (1) the need to distinguish between current unbalances and charging current effect and (2) coordination of protection of large motor loads and backup systems. The advantage of rapid tripping is balanced by the possibility of more extensive damage, because the neutral is grounded through a resistor that permits a higher current to flow on a ground fault. The magnitude would be in the range of 150 A to 1500 A as opposed to 5 A to 10 A with high-resistance grounding. The resistor will normally be rated for 10 s operation. The selection of this resistor is discussed in another article. Consideration must be given to the resistor current value, because setting the relay at 15 A pickup on a 150 A neutral resistor source will provide ground fault protection down to 90% of the neutral winding. Should there be surge arrestors and capacitors, the GFP pickup sensitivity may be retained by adding a tripping time delay of a few cycles in order to preclude false tripping on a surge.

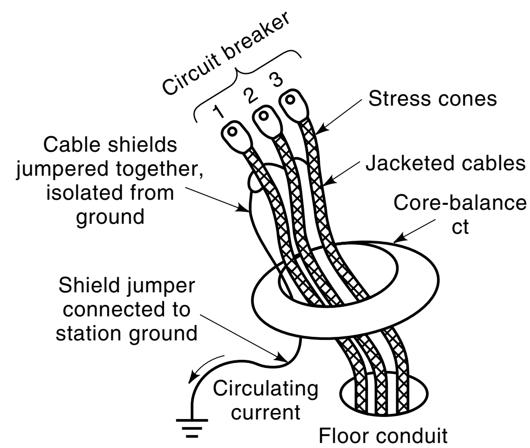


Figure 14. GFP at source to protect cable and motor.

Two schemes are normally used with this approach: The first one has the GFP at the switchgear, and the other one has the GFP at the motor in the form of a differential core balance CT. Figure 14 illustrates the use of the GFP at the switchgear and thus being able to protect for ground faults in the cable as well as in the motor. Figure 15 illustrates the differential approach. Although only the motor is protected, this configuration is more sensitive than that in Fig. 14 scheme. For the configuration shown in Fig. 15, it is important that there be coordination with the motor contactor because motor contactors have limited capability to open fault current, generally up to 10 times its continuous current rating. If the differential GFP operated too swiftly, the contactor could open on a major fault, leading to failure of both the protective device and the motor.

Solidly Grounded Neutral Systems. This method is used primarily for low-voltage schemes, although certain rare solidly grounded neutral MV schemes exist. Low-voltage schemes, however, operate to trip the motor in a manner similar to overcurrent protection. For coordination purposes, each motor branch circuit should have its own GFP device. When a ground fault develops, the circuit breaker or fused load switch should open to remove the fault. In the event of failure of the individual circuit protection, backup protective devices will operate to remove a larger section of the system in addition to the faulted motor circuit. Some of the motor controllers include this protection inherently, but there is not universal agreement on the minimum size motor circuit for which there is no need to have an individual GFP. A zone interlock scheme can be utilized which prevents the backup device from operating until after a time delay. Zone interlock is a protection system that relies upon relay operating time differences

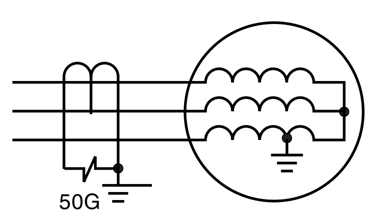


Figure 15. GFP using a core balance CT at the motor, connected to an instantaneous relay.

between downstream protective devices and upstream (backup) protective devices. For example, on a low voltage circuit, a ground fault protective device 50 G may operate in 1 s for a 100 A ground fault. Towards the power source would be a ground fault device protecting the bus from which the protected circuit had been fed. This upstream device could be set for a 100 A pickup, delayed for 1 s to 3 s in order to permit the primary protection initiate clearing the fault within 1 s. If the ground fault fails to be cleared by the primary protection, the backup device would operate in 1 s to 3 s. As in phase overcurrent applications, the backup protection would remove all circuits from the systems when it tripped the source circuit breaker or load switch.

Undervoltage Protection. Undervoltage tripping is necessary to protect the motor from overheating when the voltage is too low. Both the efficiency and the power factor are affected by an undervoltage condition. MV motors can be protected by many methods, but often a bus undervoltage relay is adequate. However, it can be hazardous to rely solely on this method, because if the source were disconnected during periods of low voltage, large motors continue to rotate and even supply power to the smaller motors on the bus. There are combination relays that include an undervoltage relay element for the normal positive sequence voltage and an overvoltage for the negative sequence voltage. Motors supplied by magnetically held controllers could also trip open in order to protect the motor. If this action is not desirable, the contactor can be held in from a battery supplied voltage or from a reliable ac source, such as a UPS.

Overtemperature Protection. In addition to overcurrent protection, there are direct methods of overtemperature protection. For MV motors, there are thermal relays that replicate the effects of current by plotting a temperature versus time curve that has memory. This can also be accomplished by new techniques in which stored temperature can be factored. The older overcurrent electromechanical relays had no memory; and if a motor were being tested, as is often done during plant commissioning, the overcurrent relay would reset when the motor is tripped off. When restarting, the effects of the previous tests would not show on the overcurrent relay, and excessive, damaging current could be permitted to continue.

Another method is the application of thermal devices that are placed in low-voltage motor windings and carry load current. When the temperature reaches a limit for its insulation class, the device would open, and power would be removed from the motor.

For long-term protection, motor windings will be furnished with temperature sensors, such as thermocouples (TCs) and resistance temperature detectors (RTDs). Certain standards exist which define the number of these devices that will be inserted automatically into the motor windings during manufacturing.

Synchronous Motors

These motors are similar to induction motors with the main difference being that the rotor has a field winding into which a dc current is applied after the synchronous motor has been started and has reached a certain speed. Induction motors have a slip in motor speed from synchronous speed, such as a 2-pole motor (3600 rpm synchronous) operating at 3450 rpm, a 4-pole machine operating at 1725 instead of 1800 rpm, and a 6-pole machine operating at 1150 rpm instead of 1200 rpm. Synchronous motors, on the other hand, operate at synchronous speed (e.g., 3600, 1800, 1200 rpm), relying on the rotor field to keep in synchronism with the stator rotating field. Thus the principle difference in protection is to ensure the field integrity and its field supply, such as a remote exciter, motor-generator set, or electronic type.

When the excitation is applied to the field, the motor will pull into synchronism with the applied voltage. Preparatory to starting the motor, the availability of the excitation system is determined, then the motor is started, and a sequence device will permit the excitation to be applied to the field at the right time. If the sequence is not complete within a certain time reference, the field closure will be blocked.

Once running, protection is applied to detect a ground in the dc field circuit, generally to alarm. Field failure is also monitored, because this would result in the motor slipping (pullout) from synchronism. Protective devices for these applications are changing with the new power electronics capability. Often the synchronous motor manufacturer would specify what protection to use.

Surge Protection. Surge protection can generally be limited to MV motors, except for those installations where there is exposure of the low-voltage distribution system. In normal plants, surges would appear on the MV system, and that is where surge devices would divert the surges to ground and thus protect the connected electrical equipment. In the past, lightning protection was the term used, but in recent years switching surges have generated destructive surges. One example is the switching of capacitor banks for power factor improvement. While the switching surge and lightning surges may differ, the means for protection have also changed. For many years, lightning arresters consisted of an air gap across which the surge jumped. Since lighting was of a brief time period, follow-through 60 Hz current reset to zero during the normal sinusoidal cycle. In today's applications, the metal oxide varistor (MOV) predominates by providing a low resistance path for surges to ground by changing from a normal quiescent high resistance characteristic, generally not using an air gap.

Surge capacitors are often used with motor applications and function by slowing the rate of rise of the surge. Coupled with this phenomenon is the increased capacitance in extruded cables. Both cable capacitance and motor exposure must be considered. Surge protective devices are generally mounted at the motor terminals with the shortest leads as practical in order to minimize the lead inductance. As a result, surge protection may require an oversized terminal box. When applying ground fault protection to motors that have surge protection, it is necessary to allow a short time delay in order for the surge to be cleared. Otherwise the GFP would assume that the surge were a ground fault and cause a false tripping of the circuit.

BIBLIOGRAPHY

1. IEEE Standard 399-1990, *Recommended Practice for Industrial and Commercial Power Systems Analysis.*
2. ANSI C84.1-1989, *American National Standard Voltage Ratings for Electric Power Systems and Equipment* (60 Hz).

3. IEEE Standard 242-1986, *Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems.*
4. IEEE Standard 141-1993, *Recommended Practice for Electric Power Distribution for Industrial Plants.*
5. ANSI/IEEE Standard 31.2-1991, *Standard Electrical Power Systems Device Function Numbers.*

DANIEL J. LOVE
Consultant

AC NETWORK ANALYSIS. See NETWORK ANALYSIS, SINUSOIDAL STEADY STATE.
ACOUSTIC BIOEFFECTS. See BIOLOGICAL EFFECTS OF ULTRASOUND.