a) All circuit breakers in the industrial plant are capable of interrupting the increased short-circuit current.
b) Each plant feeder circuit breaker is equipped with inverse-time or very inverse-time overcurrent relays with instantaneous units.
c) Each of the generators is protected by differential relays and also has external fault backup protection in the form of generator overcurrent relays with voltage-restraint or voltage-controlled overcurrent relays, as well as negative-sequence current relays for protection against excessive internal heating for line-to-line faults.
d) The utility company end of the tie line will be automatically reclosed through synchronizing relays following a trip-out.
e) The utility system neutral is solidly grounded and the neutrals of one or both plant generators will be grounded through resistors.
f) The plant generators are of insufficient capacity to handle the entire plant load; therefore, no power is to be fed back into the utility system under any condition.

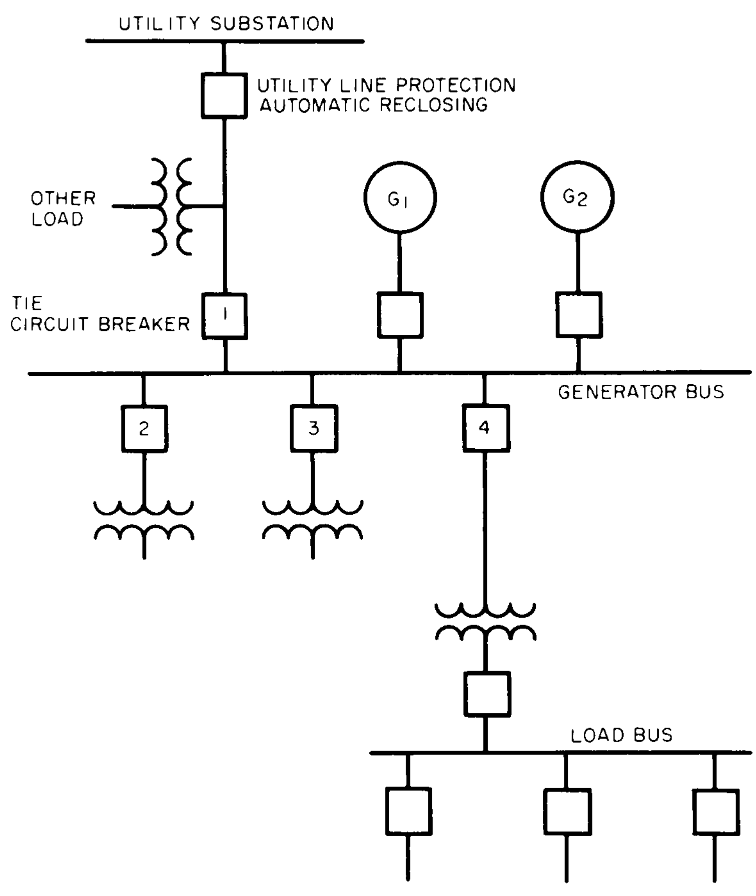


Figure 5-20—Industrial plant system with local generation

Protection at the utility end of the tie line might consist of three distance relays or time overcurrent relays without instantaneous units. If the distance relays were used, they would be set to operate instantaneously for faults in the tie line up to 10% of the distance from the plant, and with time delay for faults beyond that point in order to allow one step of instantaneous relaying in the plant on heavy faults. If time overcurrent relays were used, they would be set to coordinate with the time delay and instantaneous relays at the plant. At the industrial plant end of the tie at circuit breaker 1, there should be a set of directional overcurrent relays for faults on the tie line, or reverse power relaying to detect and trip for energy flow to other loads on the utility system should the utility circuit breaker open, or both.

The directional overcurrent relays are designed for optimum performance during fault conditions. The tap and time dial should be set to ensure operation within the short-circuit capability of the plant generation, and also to be selective to the extent possible with other fault-clearing devices on the utility system.

The reverse power or power directional relay is designed to provide maximum sensitivity for flow of energy into the utility system where coordination with the utility protective devices is not a requisite of proper performance. A sensitive tap setting can be used, although a small time delay is required to prevent nuisance tripping that may occur from load swings during synchronizing.

Due to this time delay a reverse power relay trip of circuit breaker 1 alone may be too slow to prevent generator overload in the event of loss of the utility power source. Further, the amount of power flowing out to the other utility loads may not at all times be sufficient to ensure relay pickup. A complete loss of the plant load can only be prevented by early detection of generator frequency decay to immediately trip not only circuit breaker 1, but also sufficient nonessential plant load so that the remaining load is within the generation capability. An underfrequency relay to initiate the automatic load shedding action is considered essential protection for this system. For larger systems, two or more underfrequency relays may be set to operate at successively lower frequencies. The nonessential loads could thereby be tripped off in steps, depending on the load demand on the system.

The proposed relay protection for a tie line between a utility system and an industrial plant with local generation should be thoroughly discussed with the utility to ensure that the interests of each are fully protected. Automatic reclosing of the utility circuit breaker with little or no delay following a trip-out is usually normal on overhead lines serving more than one customer. To protect against the possibility of the two systems being out of synchronism at the time of reclosure, the incoming line circuit breaker l can be transfer-tripped when the utility circuit breaker trips. The synchro-check relaying at the utility end will receive a dead-line signal and allow the automatic reclosing cycle to be completed. Reconnection of the plant system with the utility supply can then be accomplished by normal synchronizing procedures.

Generator external-fault protective relays, usually of the voltage-restraint or voltage-controlled overcurrent type, and negative-sequence current relays provide primary protection in case of bus faults and backup protection for feeder or tie line faults. These generator relays will also operate as backup protection to the differential relays in the event of internal generator faults, provided there are other sources of power to feed fault current into the generator.

5.6 Protection requirements

The primary purpose of a coordination study is to determine satisfactory ratings and settings for the distribution system protective devices. The protective device settings should be chosen so that pickup currents and operating times are short, but sufficient to override system transient overloads such as inrush currents experienced when energizing transformers or starting motors. Further, the devices should be set for selective operation so that the circuit interrupter closest to the fault opens before other devices.

Determining the ratings and settings for protective devices requires familiarity with the NEC [B10] requirements for the protection of cables, motors, and transformers, and with IEEE Std C57.12.00-1987 [B45] for transformer magnetizing inrush current and transformer thermal and magnetic stress damage limits.

5.6.1 Transformers [B43]

5.6.1.1 Maximum overcurrent protection

The NEC [B10], Article 450-3, specifies the maximum overcurrent level at which the transformer protective devices may be set. If there is no secondary protection, transformers with primaries rated for more than 600 V require either a primary circuit breaker that will operate at no more than 300% or a fuse sized not greater than 250% of transformer full-load current. Better protection will be realized with breaker settings or fuse ratings lower than these NEC maximum levels. The actual value depends on the nature of the specific load involved and the characteristics of the downstream protective devices. When both primary and secondary protective devices are provided, the maximum protective levels depend on the transformer impedance and secondary voltage. These maximum levels of protection, taken from NEC, table 450-3(a)(2)(b), are shown in table 5-1.

Transformers with primaries rated 600 V or less require primary protection rated at 125% of full-load current when no secondary protection is present, and 250% as the maximum rating of the primary feeder overcurrent device when secondary protection is set at no more than 125% of transformer rating. Certain exceptions to these requirements for smaller-sized transformers, detailed in NEC, Article 450-3, are intended to permit the application of protective devices having standard ratings normally available. The permissible circuit breaker setting is generally higher than the fuse rating setting due to their differences in the circuit opening characteristics in the overload region.

Table 5-1—Maximum overcurrent protection (in percent)

Transformer rated impedance	Transformers with primary and secondary protection				
	Primary Over 600 V		Secondary		
			Over 600 V		600 V or below
	Circuit breaker setting	Fuse rating	Circuit breaker setting	Fuse rating	Circuit breaker setting or fuse rating
No more than 6%	600	300	300	250	250
More than 6% but no more than 10%	400	300	250	225	250

5.6.1.2 Transformers withstand limits

In the years prior to the adoption of IEEE Std C57.109-1985 [B51], the time limits defining transformer withstand capability were based on the following values of time and current, shown in Table 5-2.

Table 5-2—Transformer withstand limits prior to IEEE Std C57.109-1985

Impedance (percent)	Current (time base value)	Time (seconds)
4	25	2
5	20	3
6	16.6	4
7 and above	14.3 or less	5

At levels of current in excess of about 400–600% of full load, the transformer withstand characteristic can be conservatively approximated by a constant I^2t (heating) plot, which is represented by a straight line of minus 2 slope extending to and terminating at the appropriate short-circuit withstand point.

It has been widely recognized that damage to transformers from through faults is the result of mechanical and thermal effects. The former, in fact, has gained increased recognition as a major factor in transformer failures. Accordingly, two standards significantly revise the familiar ANSI withstand point: IEEE Std C57.109-1985 [B51] for liquid-filled transformers and IEEE Std C57.12.59-1989 [B47] for dry-type transformers. A complete discussion of this subject is given in Chapter 10 of IEEE Std 242-1986 [B57], and in the Appendix of IEEE Std C37.91-1985 [B43].

The following discussion briefly reviews the through-fault protection guidelines for Category I, dry-type transformers (5–500 kVA single-phase, and 15–500 kVA three-phase); Category II of dry and liquid-filled transformers (501–1667 kVA single-phase, and 501–5000 kVA three-phase); and Category III of liquid-filled transformers (1668–10 000 kVA single-phase, and 5001–30 000 kVA three-phase). The through-fault protection curves take into consideration the fact that transformer damage due to mechanical effects is cumulative, and the number of through-faults to which a transformer can be exposed is different, depending on the transformer application.

A straight line curve having an I^2t constant of 1250 from 2–100 s has been established for Category I transformers for both frequently and infrequently occurring faults. Two through-fault protection curves have been established for both Category II [figures 5-21(a) and 5-21(b)] and Category III (figure 5-22) transformers. One curve is for those applications where faults occur frequently, typically more than 10 in a transformer lifetime, and the second is for infrequently occurring faults, typically not more than 10.

Where secondary-side conductors are enclosed in conduit, busway, or otherwise isolated, as found in industrial, institutional, and commercial systems, the incidence of faults is extremely low and the infrequent fault curve may be used to determine the settings of main secondary devices, primary devices, or both. In contrast, transformers with secondary-side overhead lines have a relatively high exposure to through-faults, and the use of reclosing-type protective devices may subject the transformer to repeated current surges from each fault. In these cases, the frequent fault withstand curve should be used.

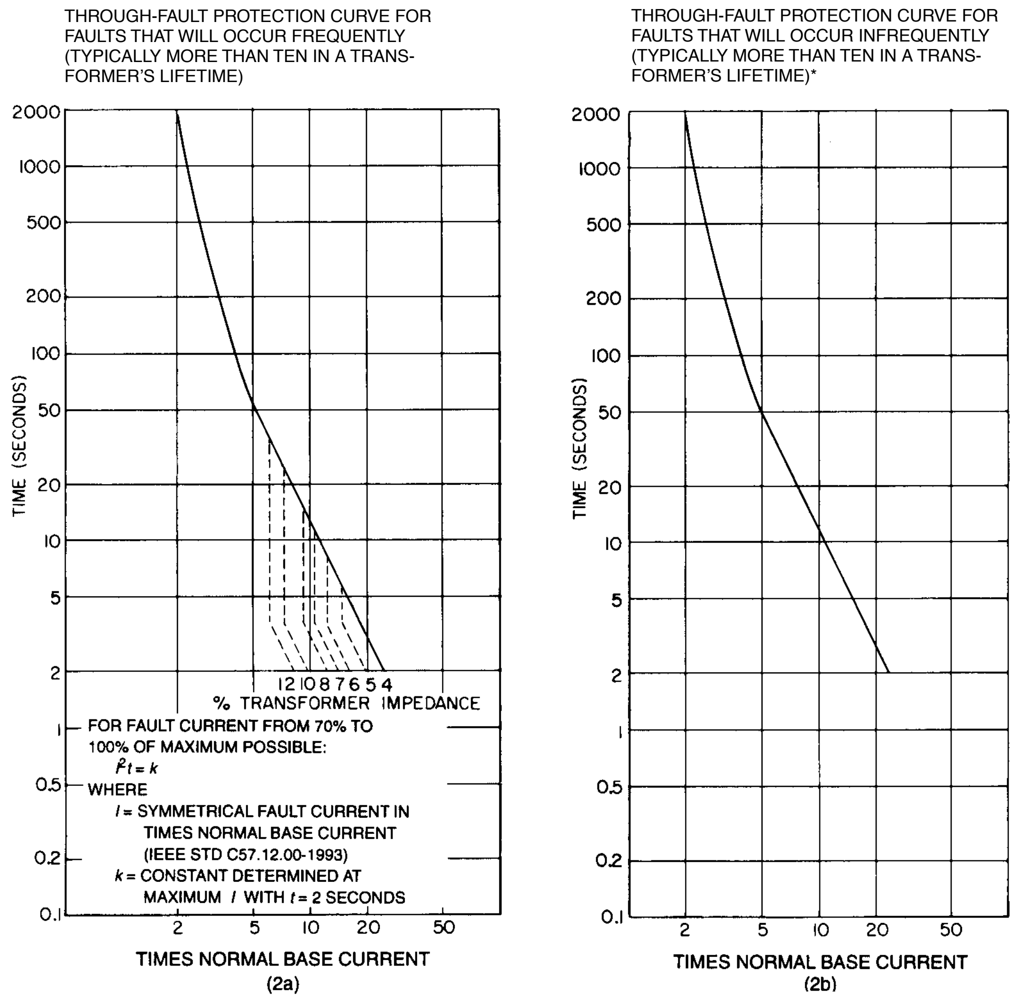
Another consideration is a relative shift in the damage point that occurs in delta-wye transformers with the wye connected secondary and its neutral point grounded. A secondary single-phase-to-ground fault of one per unit value (using the three-phase fault values as a base) will produce a fault current of one per unit in the delta of the primary winding, but results in only 0.58 per unit current in the line to the delta winding that contains the protective device. Therefore, a second damage characteristic, corresponding to that provided by IEEE Std C57.109-1993 [B51] and derated for a wye-wound solidly grounded neutral should be plotted at 0.58 per unit of the normal characteristic.

5.6.1.3 Other protection considerations

In selecting the settings or ratings of the primary protective device, the following items should be known and considered:

a) Voltage rating of the system
b) Rated load and inrush current of the transformer
c) Short-circuit duty of the supply system in kilovoltamperes
d) Type of load, whether steady, fluctuating, nonlinear, or subject to heavy motor, welding, furnace, or other starting surges
e) Selective coordination with other protective devices

Relays, when used in combination with power circuit breakers for protection of a transformer primary circuit, should have a time–current characteristic similar to that of the first down-

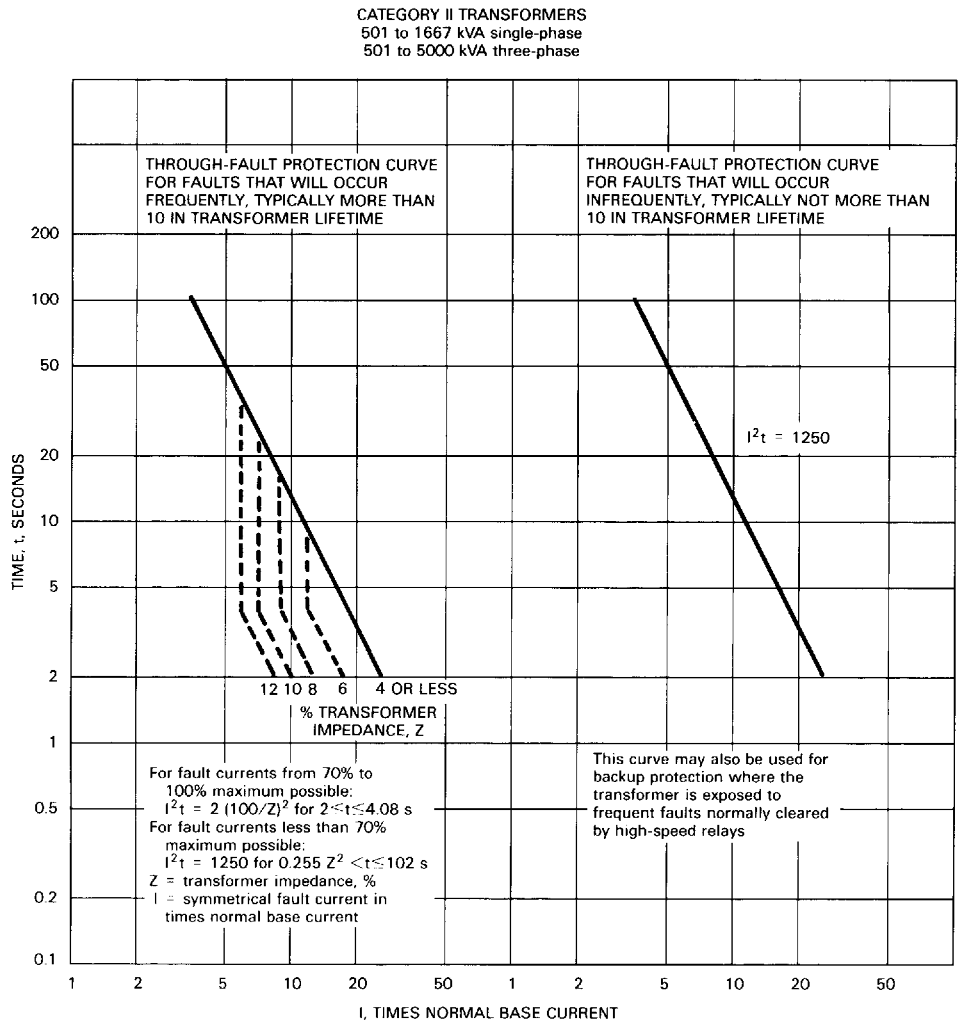


*This curve may also be used for backup protection where the transformer is exposed to frequent faults normally cleared by high-speed relaying.

Source: IEEE Std C57.109-1993.

NOTES
1—Sample $I^2t = k$ curves have been plotted for selected transformer short-circuit impedances as noted in 2a.
2—Low current values of 3.5 and less may result from overloads rather than faults. An appropriate loading guide should be referred to for specific allowable time durations.

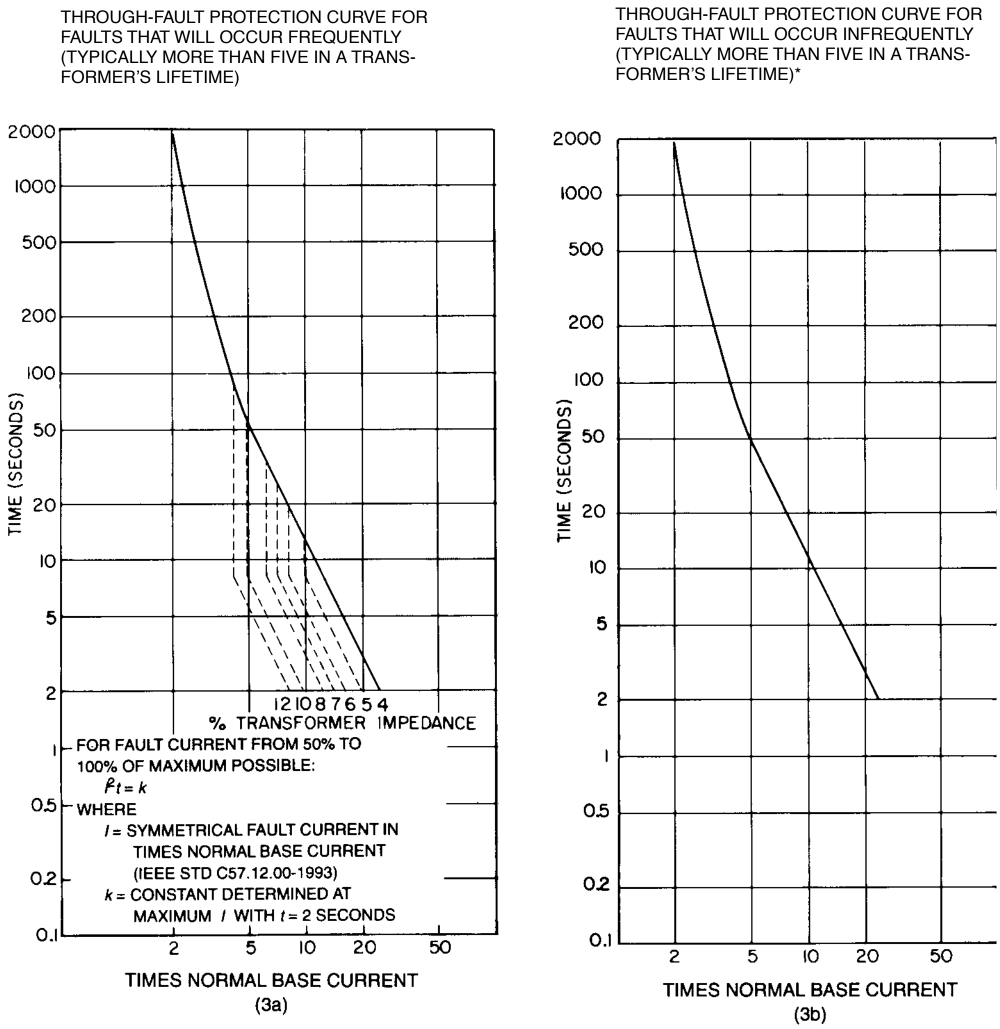
Figure 5-21(a)—Category II liquid-filled transformers



Source: IEEE Std C57.12.59-1989.

Figure 5-21(b)—Category II dry-type transformers

stream device. Pickup of the time-delay element may typically be 150–200% of the transformer primary full-load current rating. The instantaneous pickup setting should be set at 150–160% of equivalent maximum secondary three-phase symmetrical short-circuit current to allow for the dc component of fault current during the first half-cycle. The setting should also permit the magnetizing inrush current to flow. In general, the transformer inrush current is approximately 8 to 12 times the transformer full-load current for a maximum period of 0.1 s. This point should be plotted on the time–current curve, and it should fall below the transformer primary protection device curve. If there is more than one transformer connected to this feeder, the pickup of the time-delay element should not exceed 600% full-load current



*This curve may also be used for backup protection where the transformer is exposed to frequent faults normally cleared by high-speed relaying.

Source: IEEE Std C57.109-1993.

NOTES

1—Sample $I^2t = k$ curves have been plotted for selected transformer short-circuit impedances as noted in 3a.

2—Low current values of 3.5 and less may result from overloads rather than faults. An appropriate loading guide should be referred to for specific allowable time durations.

Figure 5-22—Category III transformers

of the smallest transformer, assuming that the transformers have secondary protection and an impedance of 6% or less. When used in the transformer secondary circuit, the pickup of the time-delay element should also be between 150 and 200% full-load current of the transformer secondary rating. A typical circuit configuration is illustrated by the one-line diagram insert in figure 5-27.

5.6.2 Feeder conductors

Restrictions that apply are provided in the NEC [B10]. Protection of feeders or conductors rated 600 V or less shall be in accordance with their current-carrying capacity as given in NEC [B10] tables, except where the load includes motors. In this case it is permissible for the protective device to be set higher than the continuous capability of the conductor (to permit coordination on faults or starting the largest connected motor while the other loads are operating at full capacity), since running overload protection is provided by the collective action of the overload devices in the individual load circuits. Where protective devices rated 800 A or less are applied that do not have adjustable settings that correspond to the allowable current-carrying capacity of the conductor, the next higher device rating may be used. Other exceptions are allowed in the NEC, Article 240-3, such as capacitor and welder circuits and transformer secondary conductors.

Feeders rated more than 600 V are required to have short-circuit protection, which may be provided by a fuse rated at no more than 300% of the conductor ampacity or by a circuit breaker set to trip at no more than 600% of the conductor ampacity. Although not required by the NEC [B10], improved protection of these circuits is possible when running overload protection is also provided in accordance with the conductor ampacity.

The flow of short-circuit current in an electric system imposes mechanical and thermal stresses on cable as well as circuit breakers, fuses, and the other electric components. Consequently, to avoid severe permanent damage to cable insulation during the interval of short-circuit current flow, feeder conductor damage characteristics should be coordinated with the short-circuit protective device. The feeder conductor damage curve should fall above the clearing-time curve of its protective device.

This damage curve represents a constant I^2t limit for the insulated conductor. It is dependent upon the maximum temperature that the insulation can be permitted to reach during a transient short-circuit condition without incurring severe permanent damage. Recommended short-circuit temperature limits, which vary according to the insulation type, are published by cable manufacturers. For any particular magnitude of current, the time required to reach the temperature limit can be determined from one of the following equations.

For copper conductors:

$$\left(\frac{I}{A}\right)^2 t = 0.0297 \log_{10}\frac{(T_2 + 234)}{(T_1 + 234)}$$

For aluminum conductors:

$$\left(\frac{I}{A}\right)^2 t = 0.0125 \log_{10}\frac{(T_2 + 228)}{(T_1 + 228)}$$

where

I = rms current in amperes
t = time in seconds
A = conductor cross-sectional area in circular mils
T_1 = initial conductor temperature in °C
T_2 = final conductor temperature in °C (short-circuit temperature limit)

If the initial and short-circuit temperatures are known, these equations can be used to construct a conductor damage curve which is valid for time intervals up to approximately 10 s. Since the initial temperature depends upon the cable loading and ambient conditions, and therefore cannot usually be determined accurately, it is common to conservatively assume that the initial temperature is equal to the rated maximum continuous temperature of the conductor.

5.6.3 Motors

5.6.3.1 Large alternating-current rotating apparatus

(See IEEE Std C37.96-1988 [B44].) The protection of an ac induction motor is a function of its type, size, speed, voltage rating, application, location, and type of service. In addition, a motor may be classified as being in essential or nonessential service, depending upon the effect of the motor being shut down on the operation of the process or plant. Although the discussion earlier in this chapter on the different types of protective devices indirectly touches on some of the problems associated with protecting motors, it is worthwhile to examine such an important subject from the standpoint of the machine itself.

Unscheduled motor shutdowns may be caused by the following:

a) Internal faults
b) Sustained overloads and locked rotor
c) Undervoltage
d) Phase unbalance or reversal
e) Voltage surges
f) Reclosure and transfer switch operations

The ideal relay scheme for an induction motor must provide protection against all these hazards. In the following text, the relaying approach to protect against each of these problems will be discussed in general terms. Later in the chapter, several specific applications will be discussed in detail. For a complete discussion on motor protection, see Chapter 9 of IEEE Std 242-1986 [B57].