# CHAPTER 5

# ELECTRICAL SYSTEM PROTECTION TECHNIQUES

## 5-1. Generator protection

Electrical power systems may include generators as alternate power sources or as emergency power sources. This paragraph will address the protection of single isolated generators, multiple isolated generators, and industrial generators.

*a. Single isolated generators.* Single isolated generators are normally operated in a standby mode and supply only emergency power. As such, they are usually connected to the electrical power system through an automatic transfer switch and are not operated in parallel with the main power supply. Hence, the name "isolated" generators. Minimum protection for a single isolated generator is shown in figure 5-1.

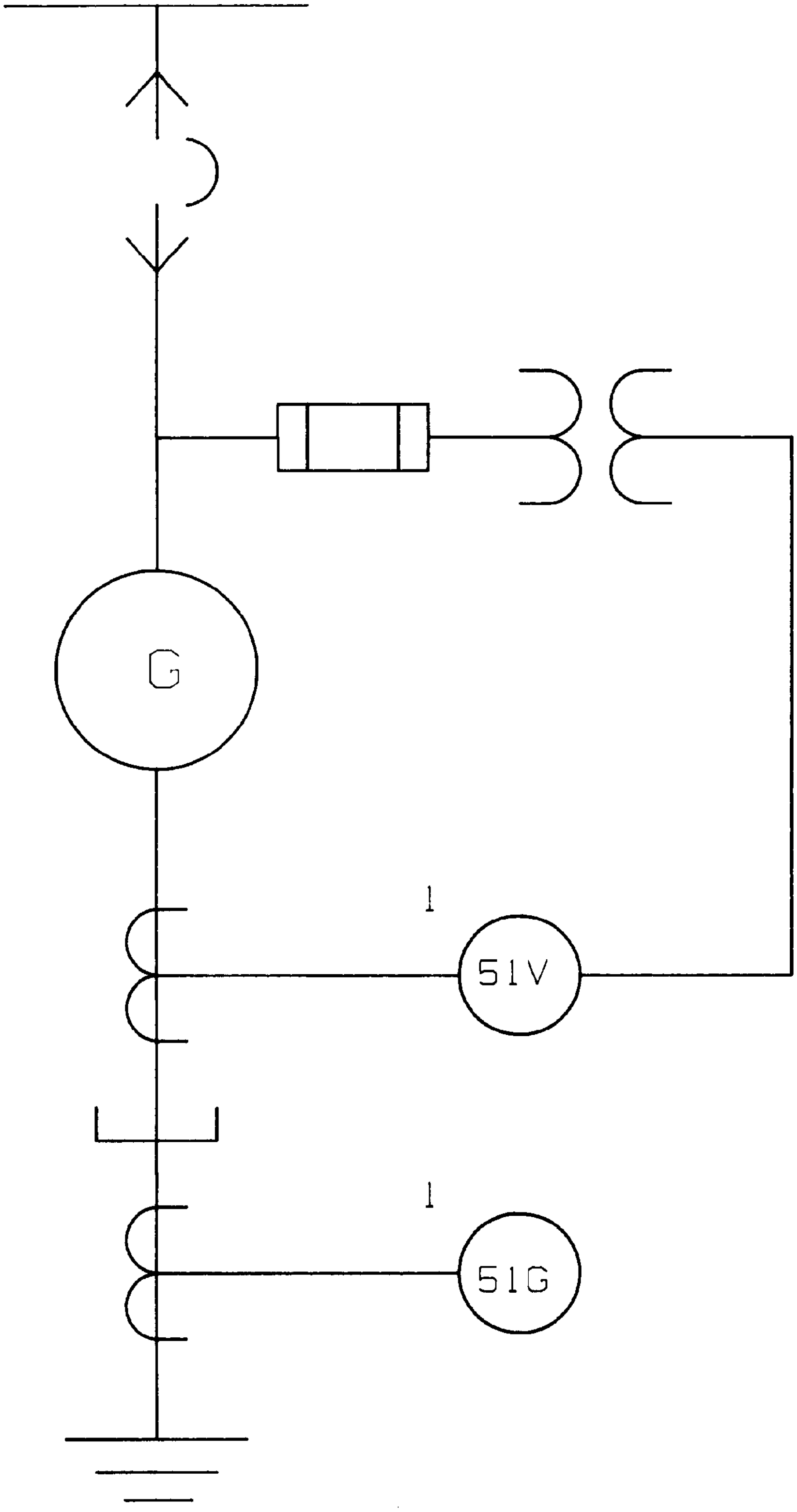

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*Figure 5-1. Single-isolated low-voltage generator.*

*b. Multiple isolated generators.* Multiple isolated generators are normally used at large commercial or industrial facilities. Generally, several generators will be operated in parallel to provide a total energy system not connected to the main power supply. Hence, the name "multiple-isolated" generators. Minimum protection for multiple isolated generators is shown in figure 5-2.

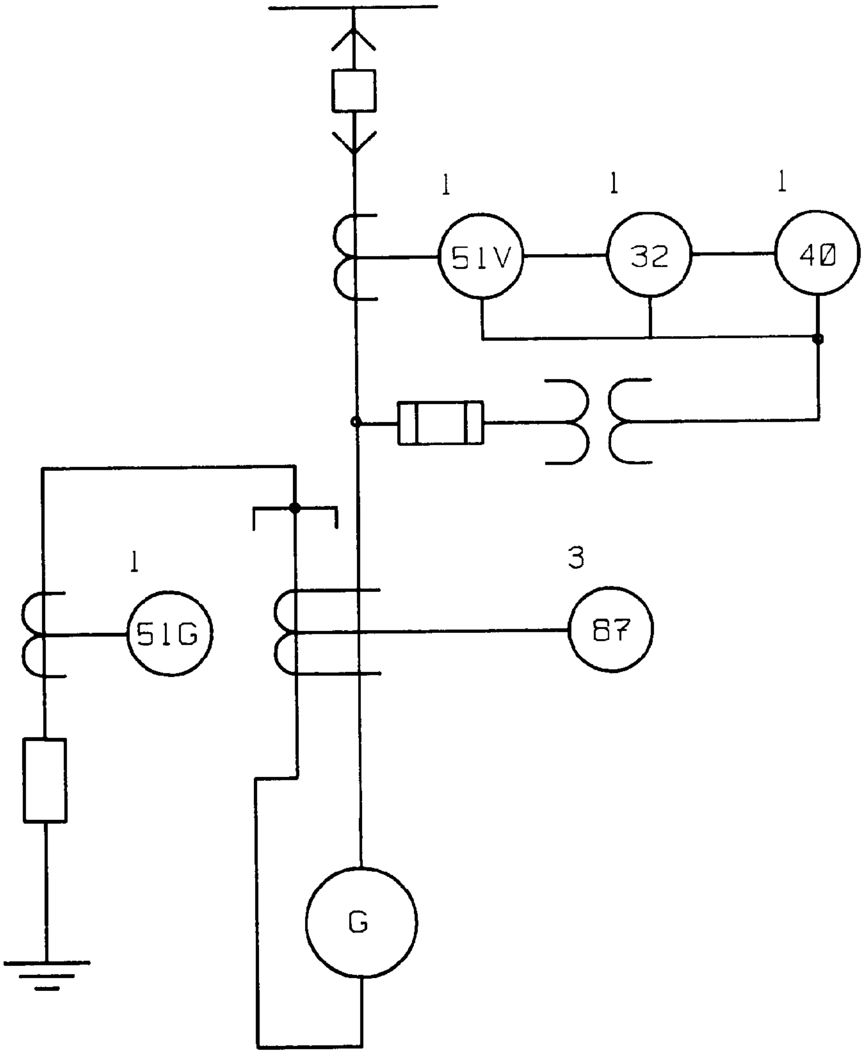

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*Figure 5-2. Multiple-isolated medium-voltage generator.*

*c. Industrial generators.* Industrial generators may range from 10-50MVA and operate continuously in parallel with the main power supply. Minimum protection for medium industrial generators (up to 12.5MVA) is shown in figure 5-3, and minimum protection for large industrial generators (greater than 12.5MVA) is shown in figure 5-4. With a CT in the neutral, the 51V device is effective immediately while the generator is running. With a CT at the breaker, the 51V device is operational only after the generator is on-line. Utilities will require special relaying to protect their system from generator contribution to utility faults.

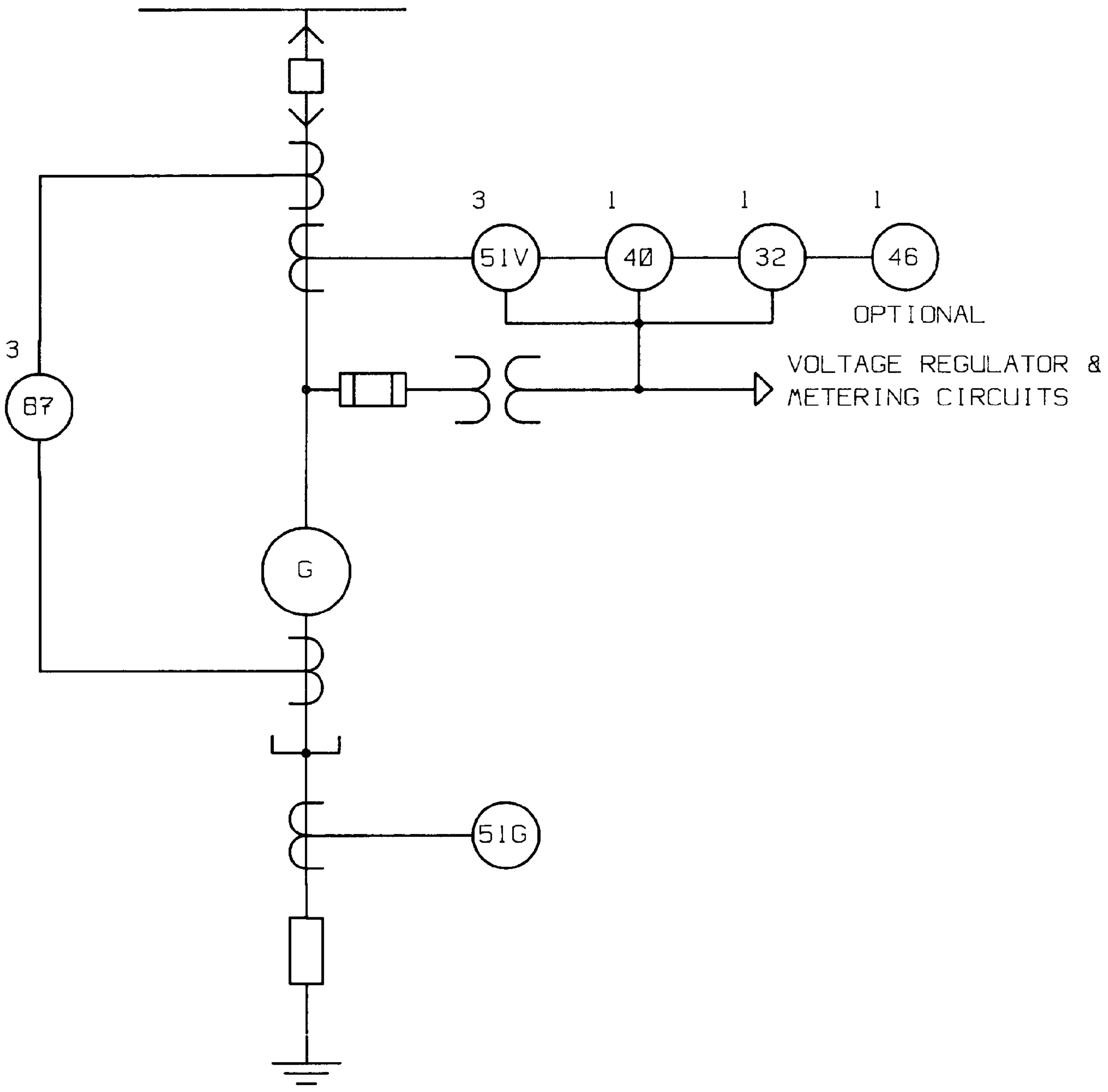

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*Figure 5-3. Medium industrial generators (up to 12.5MVA).*

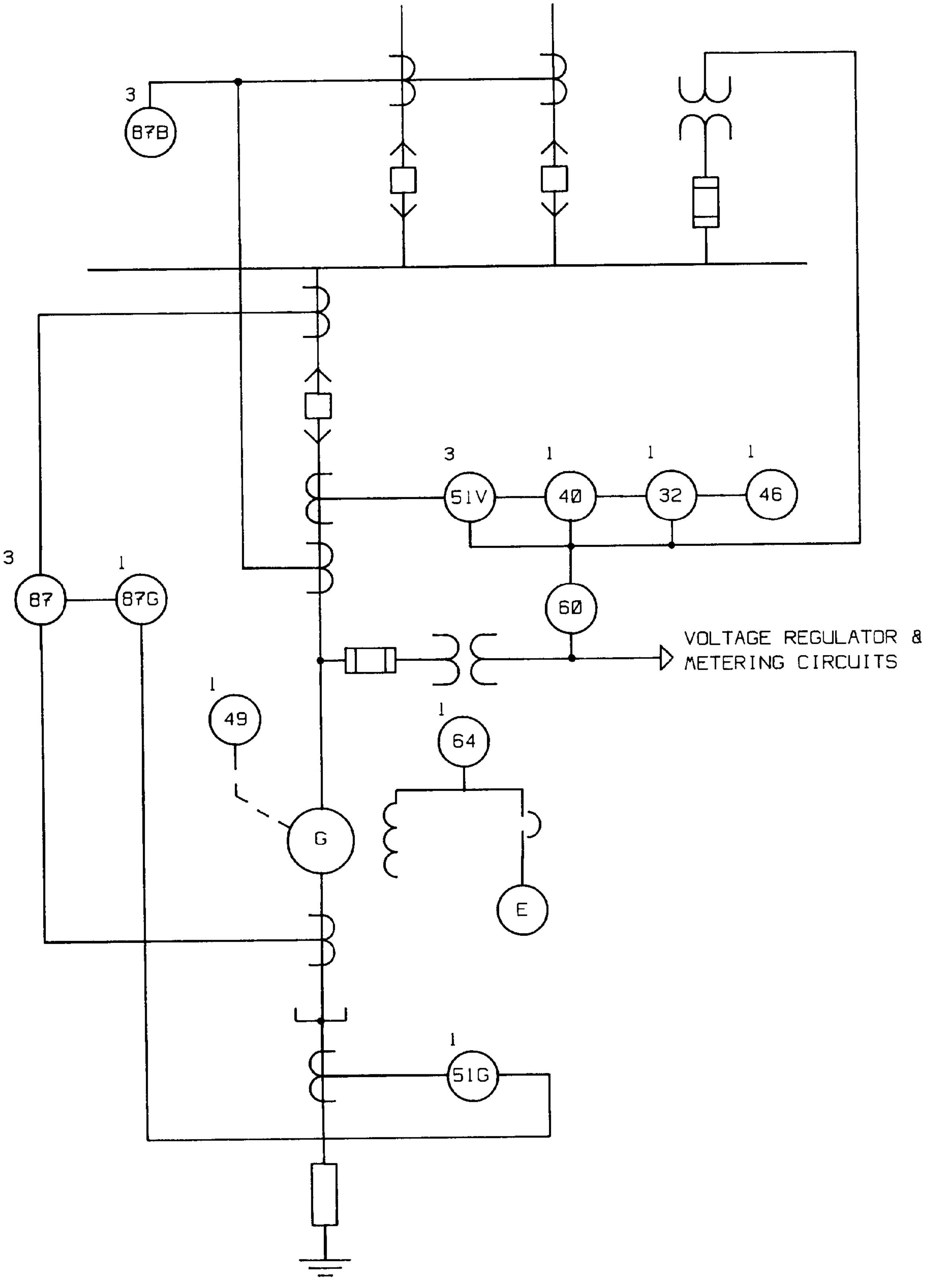

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*Figure 5-4. Large industrial generators (greater than 12.5MVA).*

*d. Generator protective devices.*

(1) Backup overcurrent protection *is* intended *to* protect the generator if a fault *is* not cleared by the primary protective devices. If the generator output bus is connected to equipment using overcurrent devices, device 51V is used. Application of overcurrent protection to generators is very sensitive since standard overcurrent relays may trip undesirably at large loads. As a result, special generator overcurrent relays are used. Voltage restraint and voltage controlled overcurrent relays provide operating characteristics that are a function of voltage as well as current, thus minimizing nuisance tripping. A 4 to 1 current pick-up range proportional to 100 percent to 0 percent of rated voltage are typical values.

(2) Backup ground overcurrent protection is provided by device 51G. Considerable time delay must often be set into this device in order to coordinate with all other ground relays on the system at the generator voltage level. The 51G device should also be set high enough to avoid pickup on normal harmonic currents flowing in the generator neutral. If the generator neutral is grounded through a resistance, device 59N may be connected in parallel with the neutral resistor to detect the voltage rise across the neutral resistor during a ground fault. A frequency sensitive overvoltage relay is required to differentiate between voltage produced by the fundamental and third harmonic currents.

(3) Differential relay protection is accomplished using device 87, and is similar to transformer differential protection described in this chapter.

(4) If the prime mover should lose its input, the generator will act like a motor and draw power from the downstream electrical distribution system. Therefore, a reverse power relay, device 32, must be applied which actually provides protection for the prime mover.

(5) other relays that can be used for generator applications include—

(a) Device 40 — Loss of field protection.
(b) Device 27 — Undervoltage relay.
(c) Device 49 — Overvoltage relay.
(d) Device 64F — Generator field protection.
(e) Overtemperature relays.

*e. Generator shutdown.* Total generator protection must include procedures for shutting down the prime mover in addition to disconnecting the generator from the electrical distribution system. Therefore, the generator manufacturer should be consulted to incorporate shutdown procedures into the coordination process. Basically, the shutdown procedure includes the following:

(1) Trip the generator circuit breaker.
(2) Trip the generator field circuit breaker.
(3) Remove prime mover input.
(4) Initiate alarms.

## 5-2. Transformer protection

This paragraph will address the proper protection methods for primary and secondary substation transformers. Primary substation transformers are generally rated 1 to 12MVA with secondary voltage of 15kV nominal. Secondary substation transformers are generally rated 300 to 2500kVA with secondary voltage of 600V nominal.

*a. Primary overcurrent protection.* An overcurrent protective device on the primary side of a transformer is intended to protect the transformer against internal faults (failure internal to the transformer) and through faults (abnormalities downstream of the transformer). The interrupting rating of the primary protective device should be rated for the maximum short-circuit current at the transformer primary. The primary protective device coordination curve should be below the through fault protection point but greater than the inrush excitation current. Additionally, NFPA 70 limits must be incorporated. Captive transformers, i.e., transformers supplied from a dedicated circuit breaker, do not require primary fusing but may require a disconnecting means. Where multiple transformers are supplied from a single circuit breaker, transformer primary protection may include fuses. On low-resistance grounded systems, transformer primary protection should incorporate a circuit breaker, not fuses. Low-resistance grounded systems are designed for ground-fault current to be approximately equal to full load amperes of the transformer. Ground-fault protection can, therefore, be applied easily with a circuit breaker arranged to trip from a neutral ground overcurrent relay.

(1) Overload protection. Transformers have a certain life expectancy based upon temperature ratings. Generally, a transformer is designed for a particular temperature rise above a certain ambient temperature. Overloading a transformer, whether accidentally or intentionally, will increase the temperature rise above the design limit, deteriorate the insulation, and reduce the transformer life expectancy. Transformer protection should consist of load limitation, overtemperature detection, and overcurrent protection.

(a) Load limitation may be accomplished by implementing manual or automatic load shedding schemes. The same effect may be accomplished by oversizing the transformer kVA rating or undersizing the transformer temperature rise rating. Both methods, although expensive, will give extra transformer capacity. Cooling fans are a less expensive means of increasing transformer capacity.

(b) Monitoring devices mounted directly on or within the transformer itself can be used to detect overtemperature conditions. Such devices include liquid temperature indicators, thermostats, and thermal relays.

(c) Fuses, circuit breakers and overcurrent relays should be rated or set to provide maximum transformer protection. Therefore, the manufacturer' s recommendations should always be consulted. If specific manufacturer's information is not available, overcurrent protection should be set below short-time loading limits. These limits are defined by the transformer through fault curves shown in figures 5-5 through 5-8. As can be seen from the figures, curves are provided for both frequently and infrequently occurring faults. This is because transformer damage is cumulative. Since transformer damage is cumulative, the number of through faults that a transformer can tolerate is a function of its application. For example, transformers with secondary-side conductors protected in conduit will experience fewer through faults than transformers with exposed secondary-side conductors. The frequent- or infrequent-fault-incidence curve should be selected as appropriate for the application. The through fault protection curves may be used directly for wye-wye and delta-delta connected transformers. For delta-wye transformer connections, the through fault curves must be reduced by 58 percent.

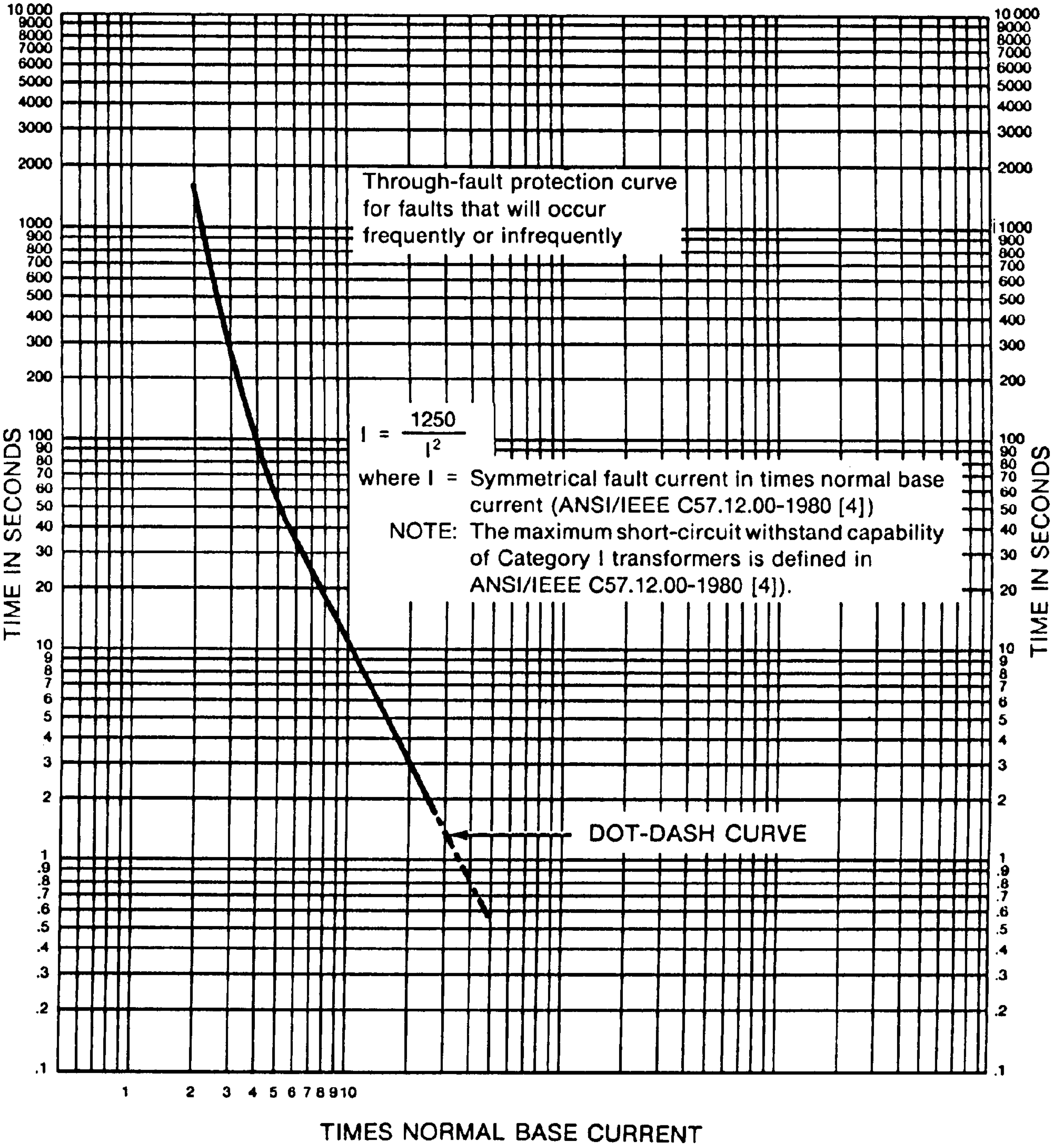

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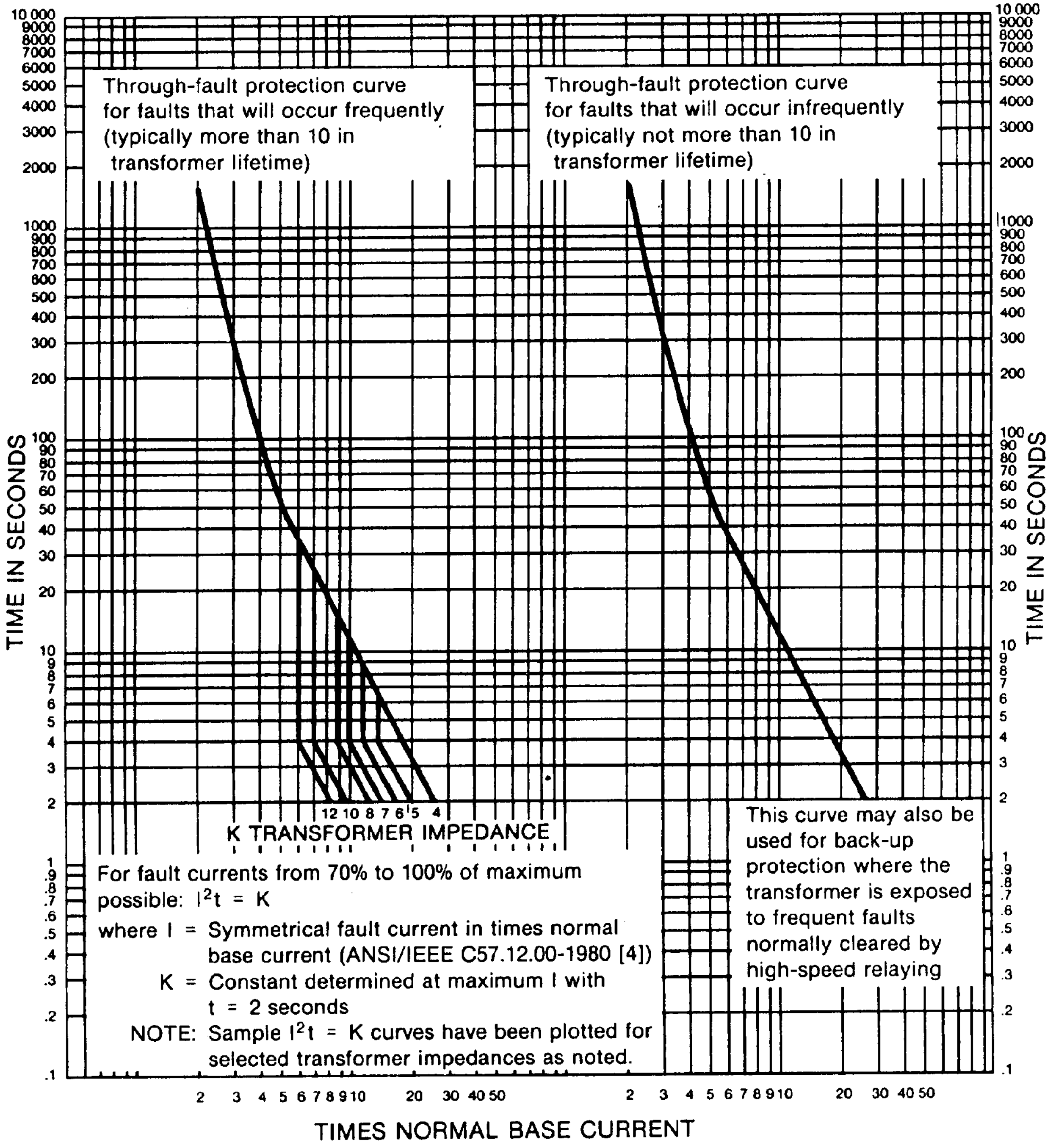
*Figure 5-5. Through-fault protection curves for liquid-immersed category I transformers (5kVA to 500kVA single-phase, 15kVA to 500kVA three-phase).*



Through-fault protection curve for faults that will occur frequently (typically more than 10 in transformer lifetime)

Through-fault protection curve for faults that will occur infrequently (typically not more than 10 in transformer lifetime)

For fault currents from 70% to 100% of maximum possible: $I^2t = K$

where I = Symmetrical fault current in times normal base current (ANSI/IEEE C57.12.00-1980 [4])

K = Constant determined at maximum I with t = 2 seconds

NOTE: Sample $I^2t = K$ curves have been plotted for selected transformer impedances as noted.

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

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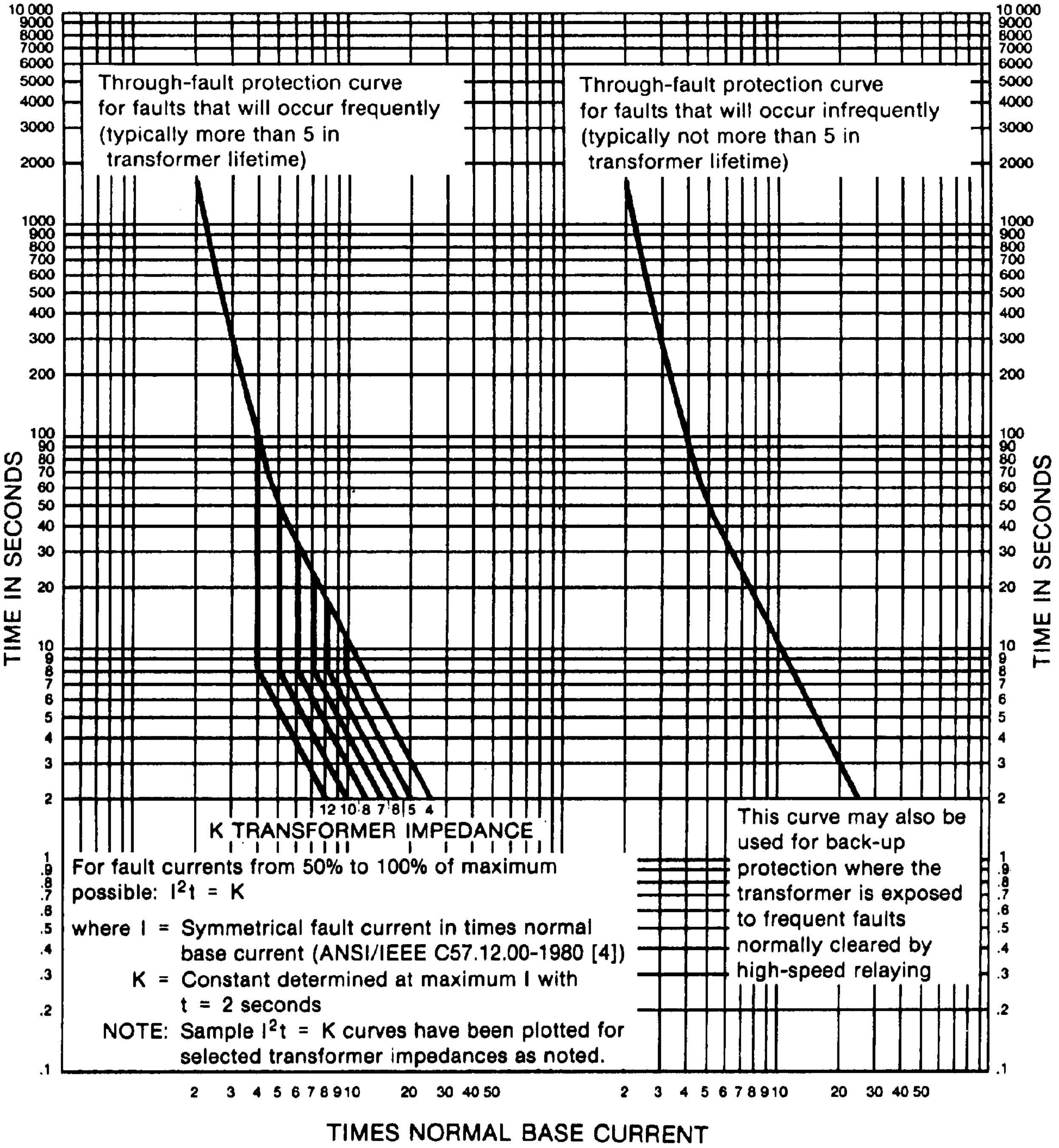
*Figure 5-6. Through-fault protection curves for liquid-immersed category II transformers (501kVA to 1667kVA single-phase, 501kVA to 5000kVA three-phase).*


Through-fault protection curve for faults that will occur frequently (typically more than 5 in transformer lifetime)

Through-fault protection curve for faults that will occur infrequently (typically not more than 5 in transformer lifetime)

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

For fault currents from 50% to 100% of maximum possible: $I^2t = K$

where I = Symmetrical fault current in times normal base current (ANSI/IEEE C57.12.00-1980 [4])

K = Constant determined at maximum I with t = 2 seconds

NOTE: Sample $I^2t = K$ curves have been plotted for selected transformer impedances as noted.

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*Figure 5-7. Through-fault protection curves for liquid-immersed category III transformers (1668kVA to 10,000kVA single-phase, 5001kVA to 30,000kVA three-phase).*

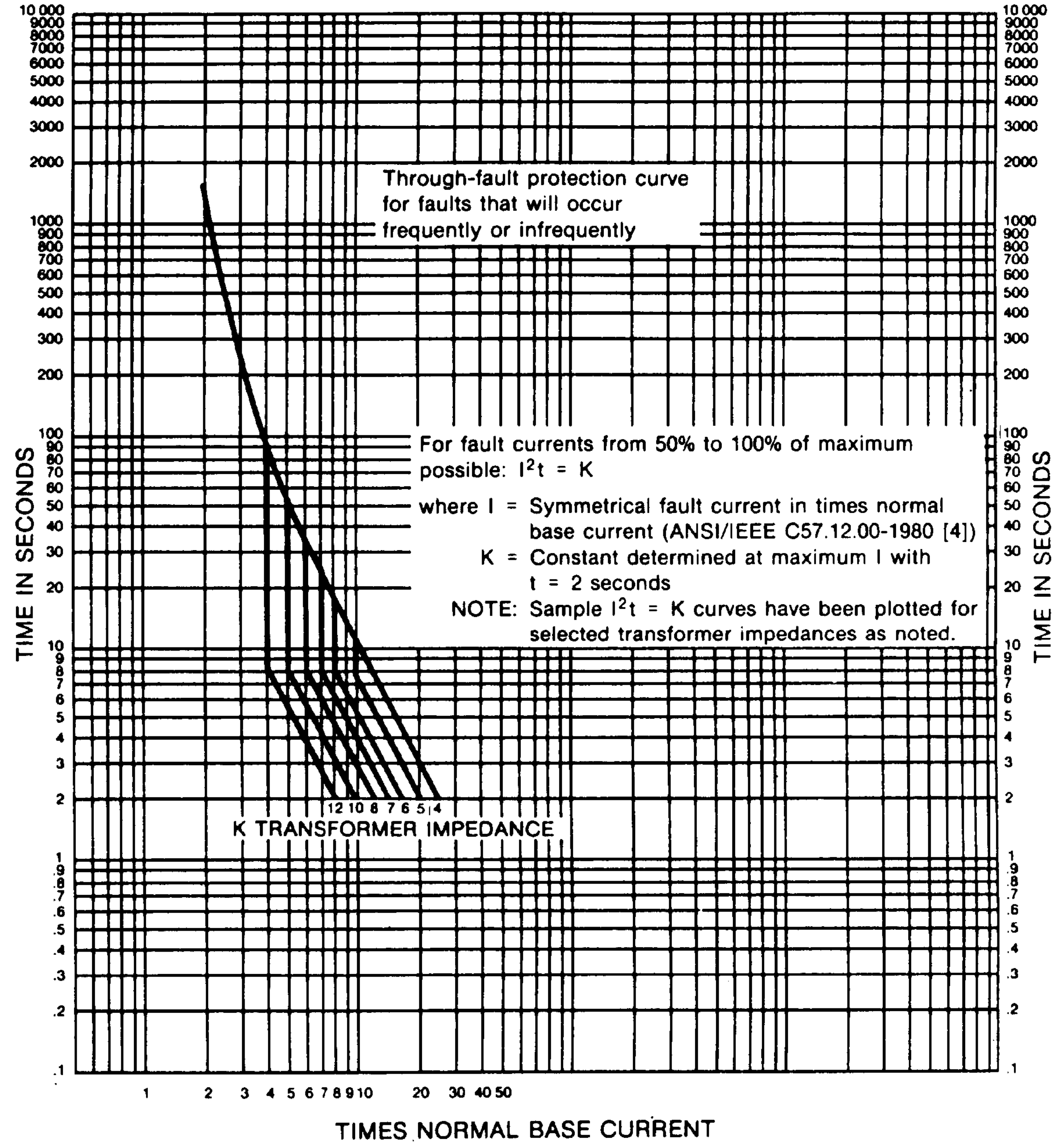

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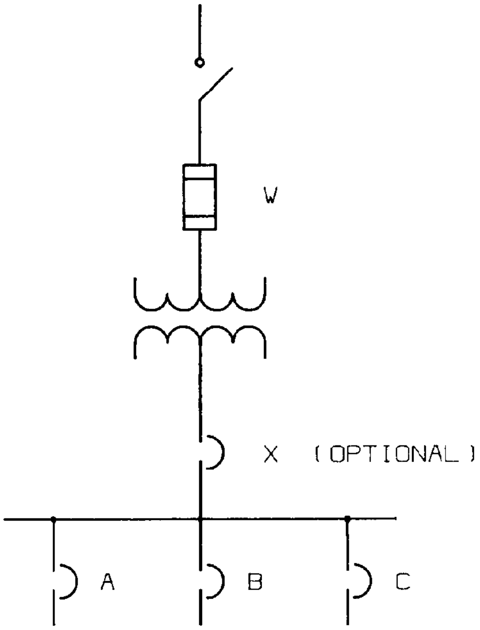
*Figure 5-8. Through-fault protection curves for liquid-immersed category IV transformers (above 10,000kVA single-phase, above 30,000kVA three-phase).*

(2) Internal and external short-circuits can subject transformers to extreme magnetic forces, high temperature rise, and extreme arcing energy. Since the transformer impedance is often the only limiter of short-circuit currents from downstream faults, low-impedance transformers may be subjected to extremely high short-circuit currents. Short-circuit protection may be accomplished by detecting the magnitude of short-circuit current or by detecting gases that may be present within the transformer as a result of an internal fault.

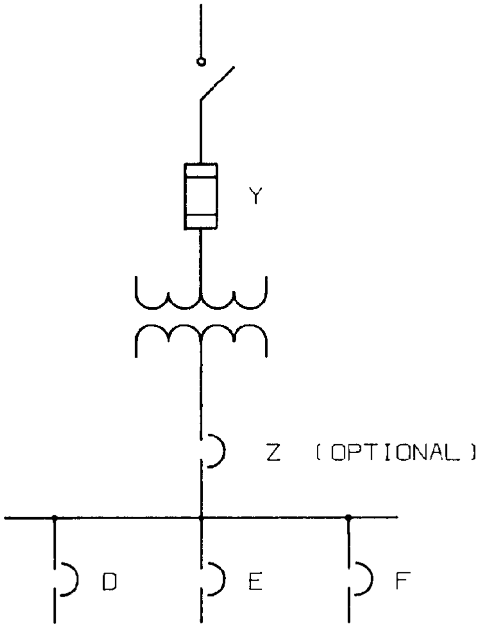
(a) Gas detection devices include pressure-relief valves, gas-detector relays, and high pressure relays.

(b) Short-circuit current detection devices include fuses, circuit breakers, and relays. These devices, like overload protective devices, should be rated or set to provide maximum protection and be rated to withstand and interrupt the maximum short-circuit current available at the fault point. Selective coordination, as described by the coordination examples in appendix G, may allow for some reduction.

*b. Secondary overcurrent protection.* Chapter 4 described the NFPA 70 limits for transformers with primary protection only, and for transformers with both primary and secondary protection. These guidelines must be followed in addition to the through fault protection curves described in this chapter. The location of the overcurrent protective devices must be considered in addition to the through fault incidence. Figure 5-9 shows two transformer applications. The transformer in figure 5-9(a) is subjected to frequent through; faults, while the transformer in figure 5-9(b) is subjected to infrequent through faults. Since the secondary feeder protection (devices A, B, and C in figure 5-9(a)) is the first-line of defense against through faults, these devices should be rated or set based on the frequent-fault curve. Furthermore, since the transformer primary and secondary protective devices (W and X in figure 5-9(a)) are intended to provide transformer protection and backup feeder protection, these devices may be rated or set based on the infrequent-fault curve. Now, consider figure 5-9(b). All devices (D, E, F, Y, and Z) should be rated or set based on the infrequent- fault curve.



( a ) FREQUENT FAULTS



( b ) INFREQUENT FAULTS

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*Figure 5-9. Transformer overcurrent protection.*

*c. Differential relaying.* Larger transformers should be protected by differential relays in addition to primary and secondary overcurrent protection, and overtemperature and overpressure detection. Phase differential relaying, illustrated in figure 5-10, compares the current entering the protected zone with the current leaving the protected zone. Operation of transformer differential relays is based on a percentage of entering current to through current, which is referred to as the relay slope. If the difference between the current entering and leaving the protected zone exceeds the relay slope, a fault is indicated and a relay operates the transformer primary device. Remote protective devices may be operated through pilot wire schemes. Modern pilot wire schemes are beginning to incorporate fibre optic technology. Phase differential relays should be supplemented with secondary ground differential relays on resistance-grounded transformers.

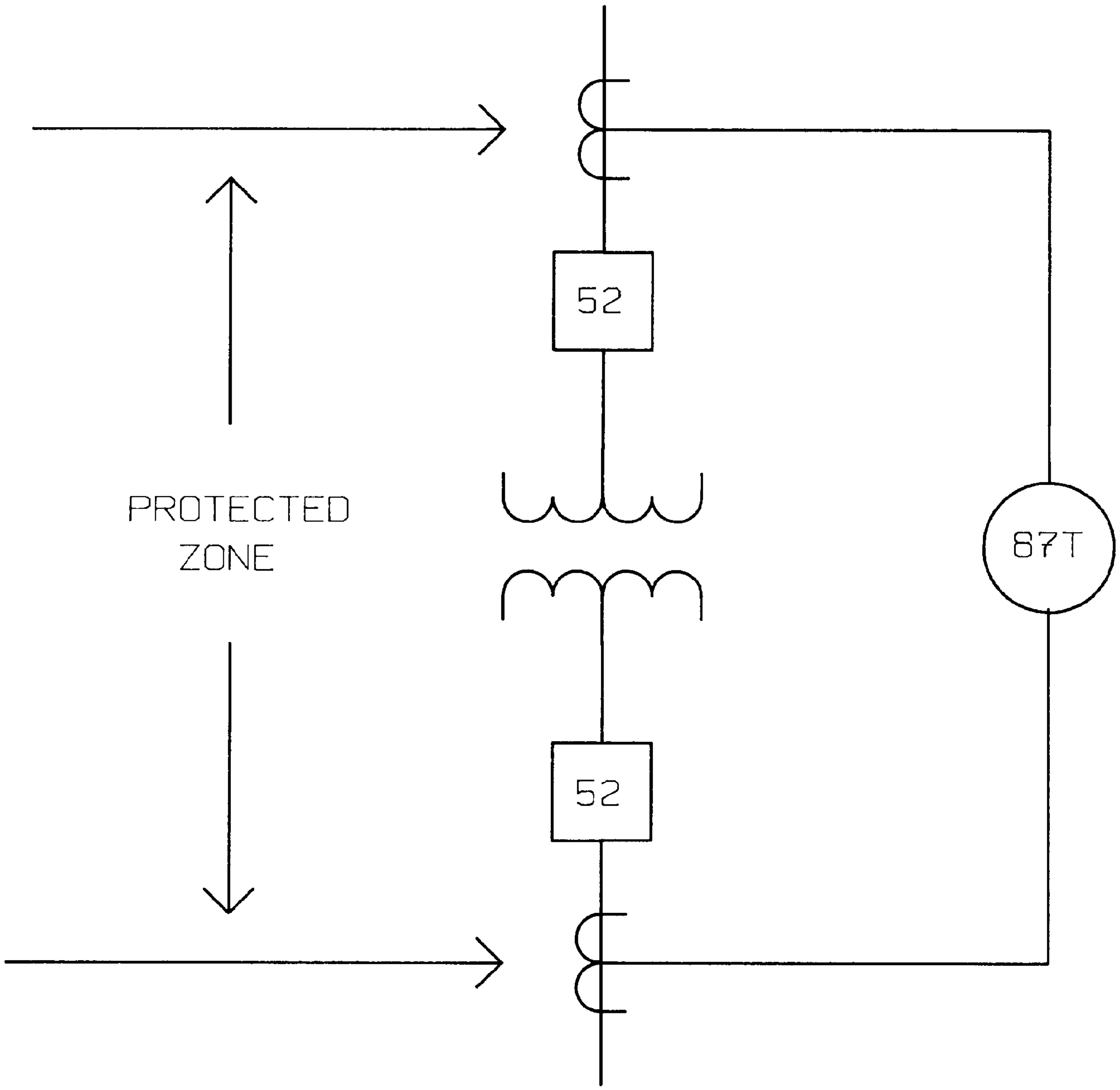

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*Figure 5-10. Phase differential relaying.*

## 5-3. Conductor protection

As with transformers, high conductor temperatures can result in shortened conductor life expectancy, or even failure. High conductor temperatures are caused by current flowing through conductor resistance ($I^2R$ losses), excessive ambient temperature, or both. This paragraph will address the proper protection methods for conductors and busways. Conductors require overload, short-circuit, and physical protection, while busways require only overload and short-circuit protection. The derating of conductors and busways will be covered in addition to the proper rating and setting of protective devices.

*a. Conductor ratings.* In addition to voltage and current ratings, modern conductors possess a percent insulation level (IL) rating. Time delays associated with overcurrent protective devices should be coordinated with these ratings as follows:

(1) 100 percent IL—Not required to operate longer than one minute under ground fault.

(2) 133 percent IL—Not required to operate longer than one hour under ground fault.

(3) 173 percent IL—Required to operate longer than one hour continuously under single line-to-ground fault.

*b. System grounding* The method of system grounding can affect the magnitude of overvoltages to which the system may be subjected. The magnitude of overvoltages, in turn, has an effect on the conductor insulation level rating. The line-to-ground voltage in an effectively grounded system will not exceed the line-to-neutral value under ground-fault conditions. The line-to-ground voltage in an ungrounded or high resistance grounded system may equal line-to-line voltage under bolted ground-fault conditions. Under arcing ground fault conditions or resonant conditions, line-to-ground voltage may be several times normal.

*c. Short-circuit protection.* Under short-circuit conditions, conductor temperatures should not be allowed to increase to the point of damage to conductor insulation. Since short-circuits are designed to be cleared very quickly, heat generated from conductor $I^2R$ losses is almost completely confined to the conductor metal. The heat has no time to be transferred to the conductor covering, raceway, or final surroundings. On that basis the temperature rise is a function of the cross-sectional area of the metallic conductor, the magnitude of the short-circuit current, and the time that the current is allowed to persist. Engineering curves based on this time-temperature-current relationship have been developed for conveniently selecting proper conductor sizes. Figure 5-11 shows typical curves for copper conductors from 75-200 degrees C. Protective devices should be selected by plotting the short-circuit time current curves of the protected conductors on the composite graph along with the time-current characteristic curve of the protective device.

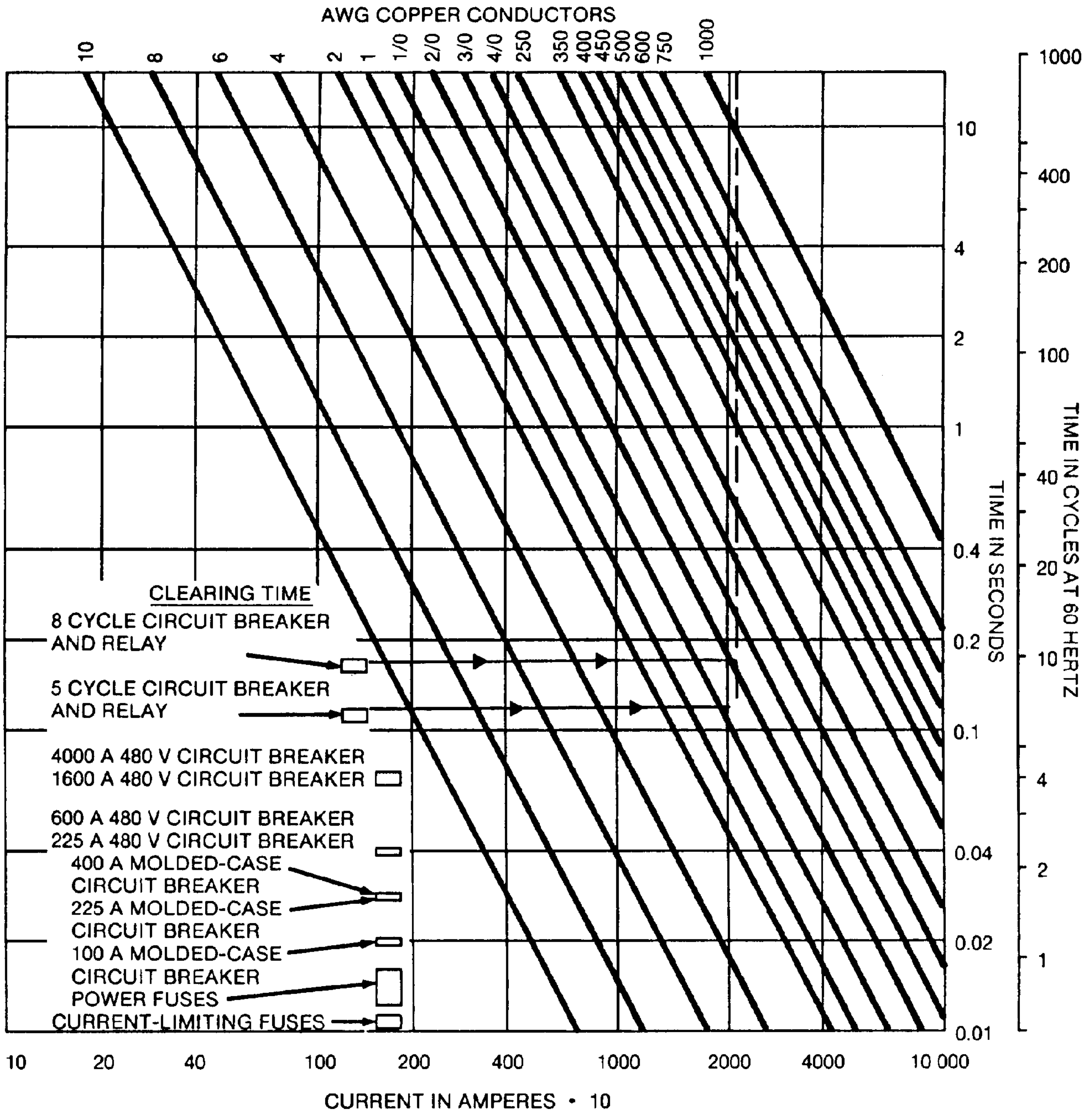

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*Figure 5-11. Maximum short-circuit current for insulated copper conductors; initial temperature 75 degrees C; final temperature 200 degrees C.*

*d.* Overload protection. As stated previously, temperature rise in conductors is a result of $I^2R$ losses. Conductor selection, then, is essentially a heat transfer problem. The heat must be transferred from the metallic conductor through the conductor insulation, surrounding air, raceway, and the final surroundings. The thermal resistance of the conductor insulation can be readily estimated, but the thermal insulation of the other items depends on a number of factors including raceway size, number of ducts, and number of cables. Protective devices should be selected and conductors sized by plotting the overload time-current curves of the protected conductors on the composite graph along with the time-current characteristic curve of the protective device. Overload time-current curves for typical conductors are shown in figure 5-12.

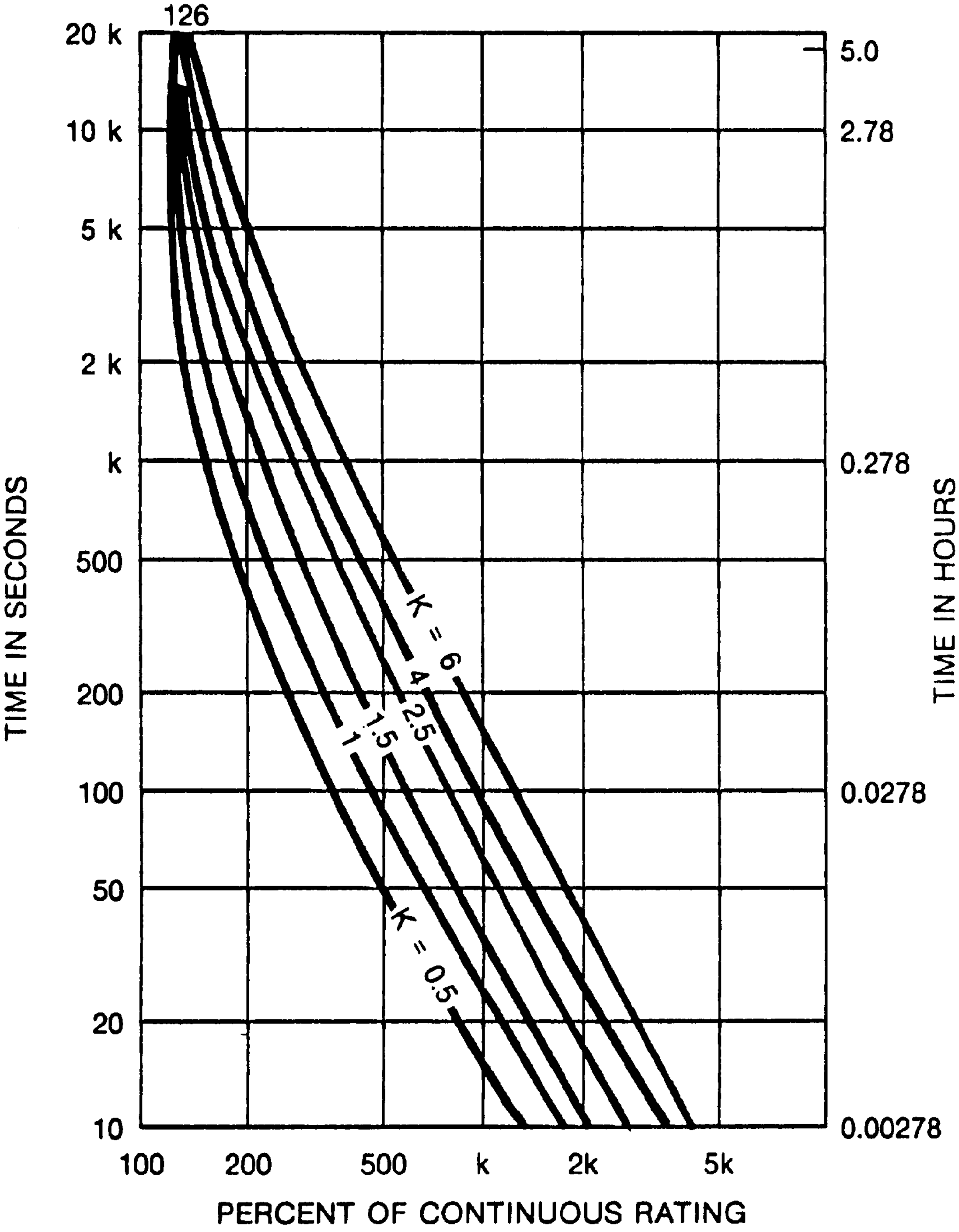

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*Figure 5-12. Emergency overload current percent of continuous rating EPR—XLP insulated 40 degrees C ambient.*

(1) Ampacity is defined as the current in amperes a conductor can carry continuously under the conditions of use without exceeding its temperature rating. NFPA 70 publishes ampacity tables, and guidelines for the proper selection of conductors. Ampacities of conductors not under the jurisdiction of NFPA 70 are published by the Insulated Cable Engineers Association (ICEA).

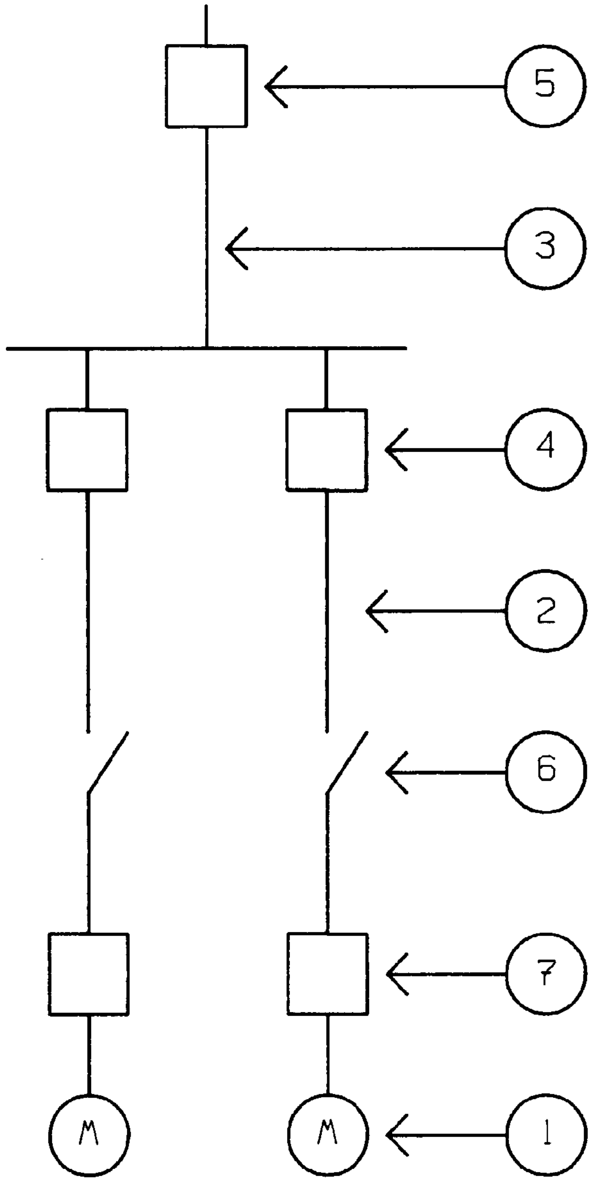
(2) NFPA 70 provides specific guidelines for derating conductors installed in areas with excessive ambient temperatures and for more than three current-carrying conductors in a single raceway. New NFPA 70 guidelines now cover derating of conductors installed in underground ductbanks and directly buried. Fill limits instead of derating factors for low-voltage cables installed in cable trays are also covered.

## 5-4. Motor protection

There are many variables involved in motor and motor circuit protection. These variables include motor characteristics, starting conditions, ambient and environmental conditions, motor loading, and the electrical distribution system itself. This paragraph will address protection for low-voltage and medium-voltage motors.

*a. Low-voltage motor&* NFPA 70 provides specific guidelines for low-voltage motor circuit protection. Two NFPA 70 articles make specific reference to motor circuit applications. Article 430 covers motors, motor circuits, and controllers in general, while Article 440 applies specifically to motor-driven air conditioning and refrigerating equipment.

(1) Figure 5-13 shows the basic motor circuit components which must be specified. Although all components are shown separately, NFPA 70 will, in certain instances, allow a single motor circuit component to serve multiple functions. For example, a switch or circuit breaker may serve as both disconnecting means and motor controller, based on certain NFPA 70 requirements.



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| STEP | REQUIREMENT | PROCEDURE |
|---|---|---|
| 1 | DETERMINE MOTOR PARAMETERS | FLA *<br>LRA *<br>NPA * |
| 2 | SELECT BRANCH CONDUCTORS | (1.25)(FLA) |
| 3 | SELECT FEEDER CONDUCTORS | (1.25)(LARGEST FLA)<br>+(REMAINING FLA) |
| 4 | SELECT BRANCH CIRCUIT SHORT-CIRCUIT PROTECTION | NFPA 70 |
| 5 | SELECT FEEDER SHORT-CIRCUIT PROTECTION | (LARGEST DEVICE)<br>+(REMAINING FLA) |
| 6 | SELECT DISCONNECTING MEANS | (1.15)(FLA) |
| 7 | SELECT OVERLOAD PROTECTION | USE NPA |

* FLA = FULL LOAD AMPERES
* LRA = LOCKED ROTOR AMPERES
* NPA = NAMEPLATE AMPERES

*Figure 5-13. Motor circuit requirements.*

(2) Overload protection (step 7, figure 5-13) for the motor, controller, disconnecting means, and circuit conductors may be provided by fuses, circuit breakers, overload relays, or motor integral thermal protectors. Article 430 of NFPA 70 establishes requirements for motor circuit overload protection.

(3) Short-circuit protection (steps 4 and 5, figure 5-13) may be provided by fuses or circuit breakers. These devices protect the motor, controller, disconnecting means, and circuit conductors against short-circuit currents. Article 430 of NFPA 70 covers the requirements for short-circuit protection.

(4) In practice, bolted short-circuits rarely occur. Most faults involve ground and are usually of the arcing type. Low-level, arcing ground faults, which usually fall below the protective range of standard overcurrent protective devices, can cause extensive damage in motor circuits. Furthermore, separate ground-fault protection designed specifically to respond to arcing ground-faults is not required for motor circuits. Ground-fault protection is required only at 480Y/277V services, and a maximum sensitivity limit of 1,200 amp is specified.

(5) Although the phrase "ground-fault protection” is also used in Article 430 of NFPA 70, it is not intended to require separate ground-fault protection for motor circuits in the same sense that it does for services. Standard overcurrent protective devices provide good protection against bolted ground-faults and limited protection against high level, arcing ground-faults. Therefore, these devices are referred to as “short-circuit and ground-fault protective devices" by NFPA 70.

(6) Low-voltage motor circuit protection techniques are covered in detail by the coordination examples in appendix G.

*b. Medium-voltage motors.* Medium-voltage motors generally range from above 1,000V to about 15kV. In addition to overload, short-circuit, and ground-fault protection, medium-voltage motors may also include undervoltage protection, phase unbalance protection, phase current differential protection, and winding overtemperature protection.

(1) Overload, short-circuit, and ground-fault protection are not motor-specific, and are applied to all components of the electrical distribution system described in this manual. Overload, short-circuit, and ground-fault protection for motors and other components are illustrated in detail by the coordination examples in appendix G. Figures 5-14 through 5-17 show minimum protection for medium-voltage induction and synchronous motors.

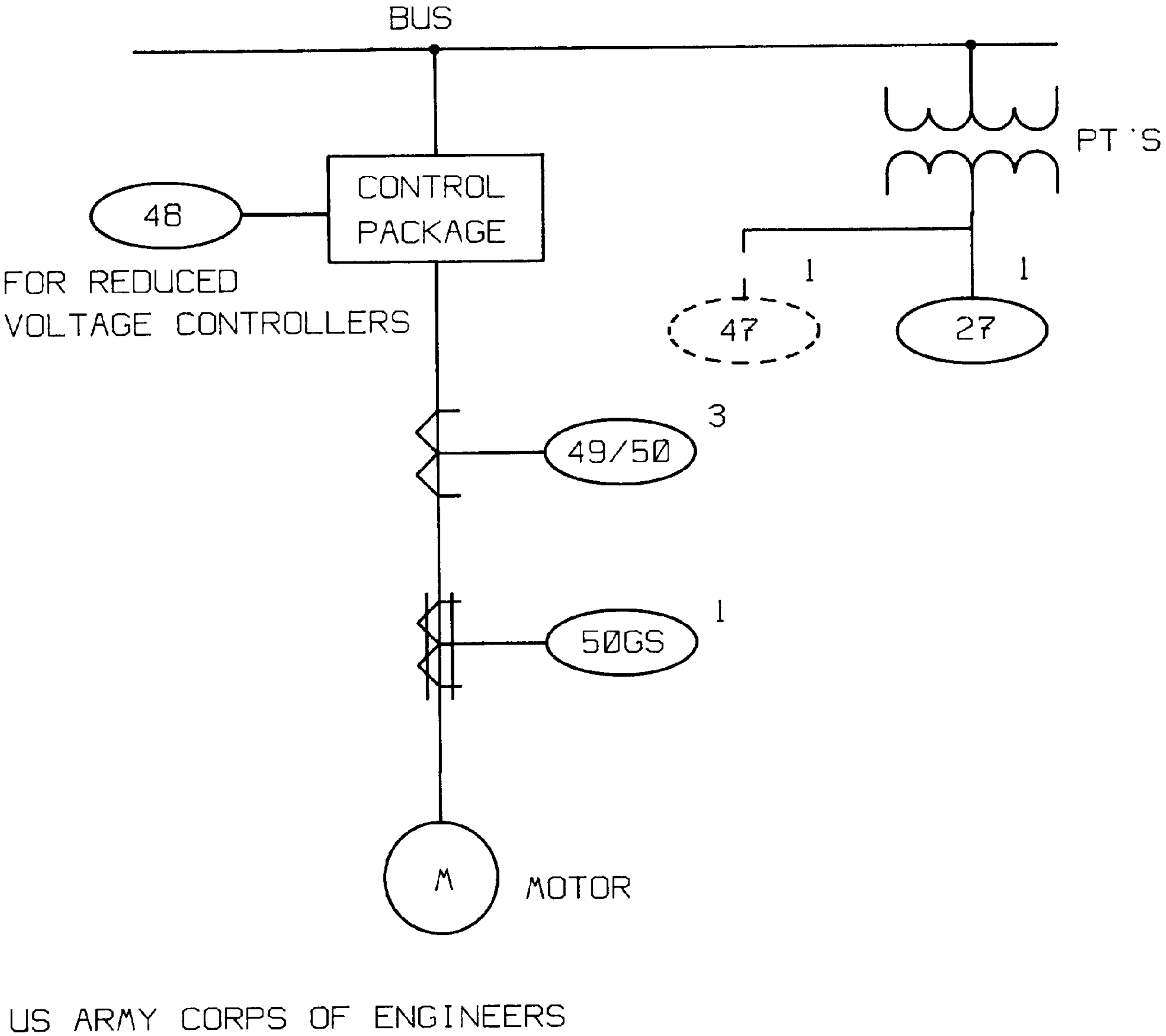

*Figure 5-14. Minimum protection for induction motor less than 1500 Hp.*

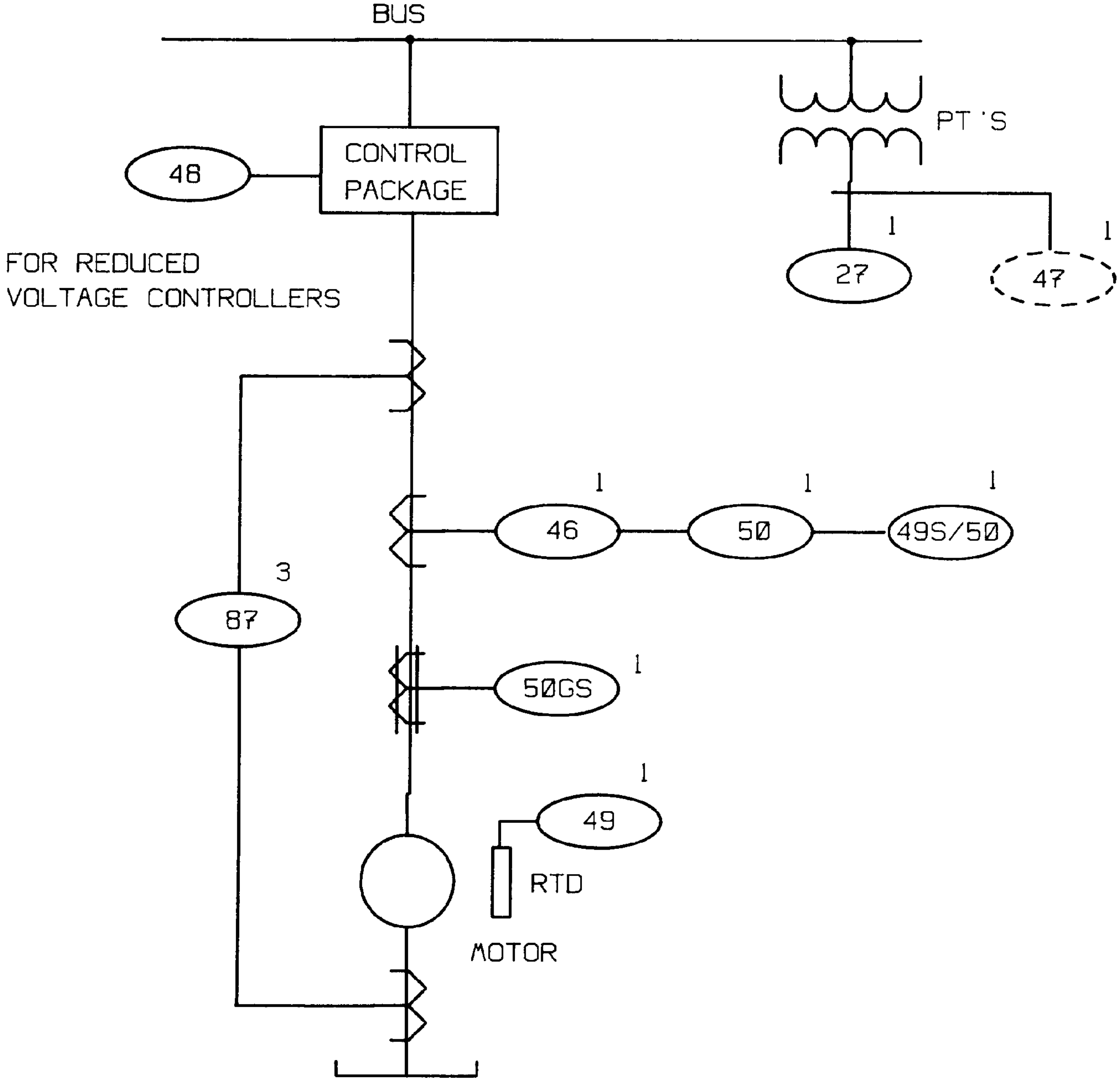

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***Figure 5-15. Minimum protection for induction motor 1500 Hp and larger.***

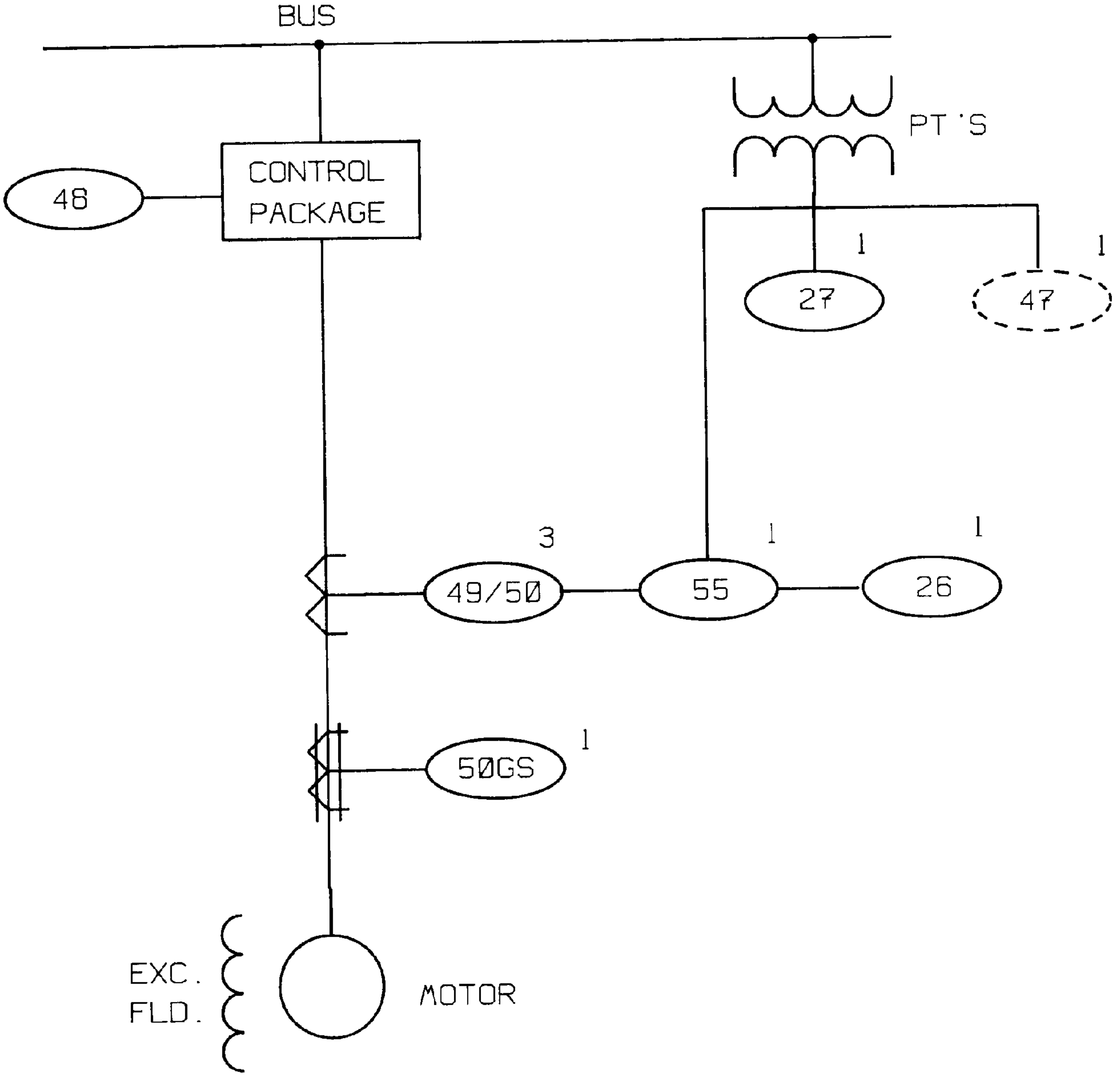

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*Figure 5-16. Minimum protection for MV, brushless synchronous motor less than 1500 Hp.*

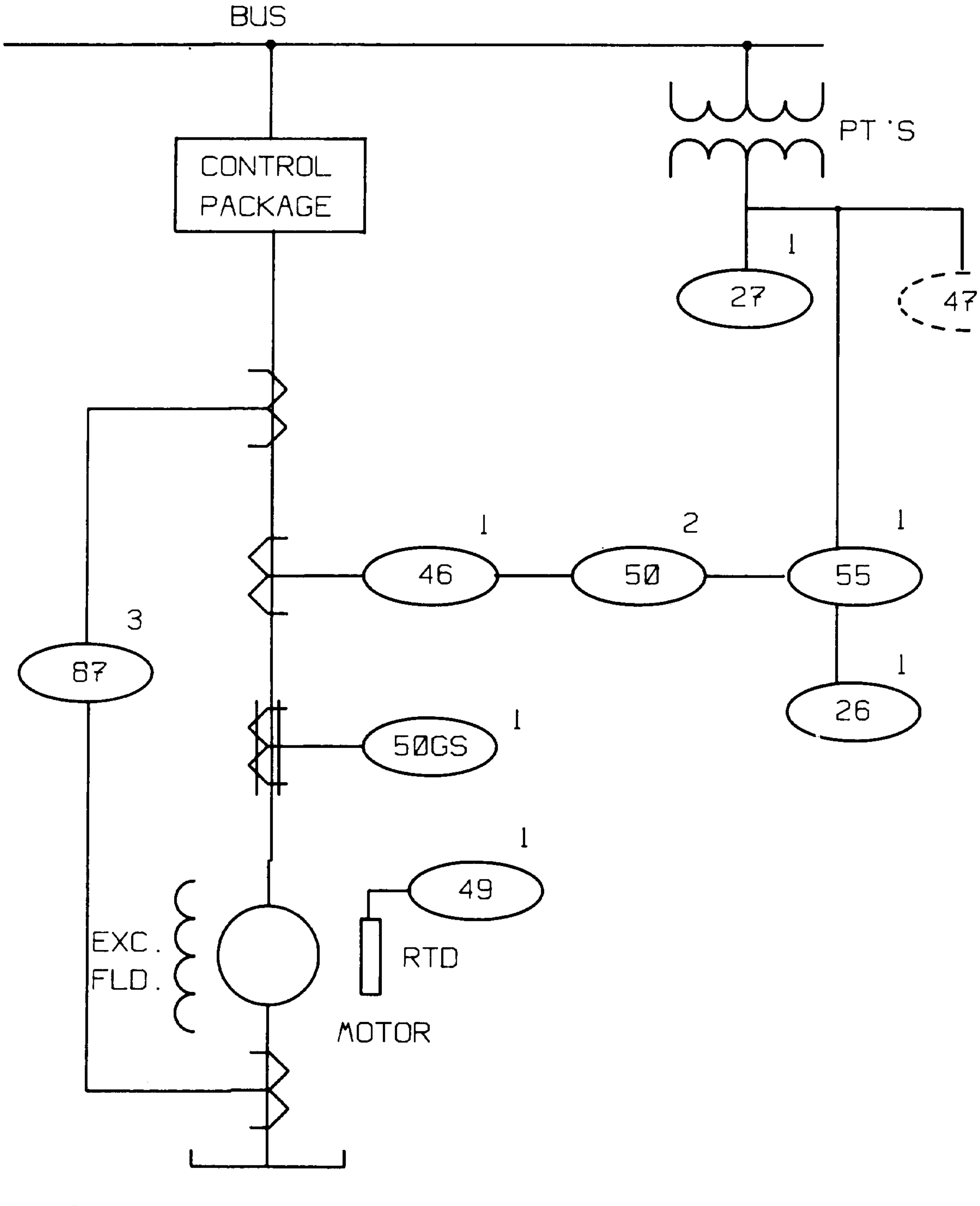

*Figure 5-17. Minimum protection for MV, brushless synchronous motor 1500 Hp and larger.*

(2) Undervoltage protection may he applied to motor circuits to prevent motor restarting when the system voltage is returned after a power interruption. Instantaneous and time-delay undervoltage relays are available depending upon the application.

(3) Phase unbalance protection for motors is necessary to prevent the motor from being damaged from overheating. When an unbalanced condition exists (single-phasing is an extreme example), increased phase currents result as the motor tries to deliver rated horsepower with the unbalanced

voltages. Phase unbalance protection should be applied where single-phasing is a distinct possibility, such as with upstream fuses or overhead lines. Phase unbalance protection is recommended for all motors rated 1,000 Hp and larger. For smaller motors, cost and the specific installation will dictate whether phase unbalance protection is included.

(4) Phase current differential protection is used to quickly detect abnormal fault conditions. Self-balancing differential protection is illustrated in figure 5-18. Three window-type CTs are normally installed at the motor. Line and neutral conductors of each phase winding are passed through a CT in such a way that the line and neutral currents of each phase winding cancel each other. A fault in one of the windings will result in a CT output and operate the associated relay.

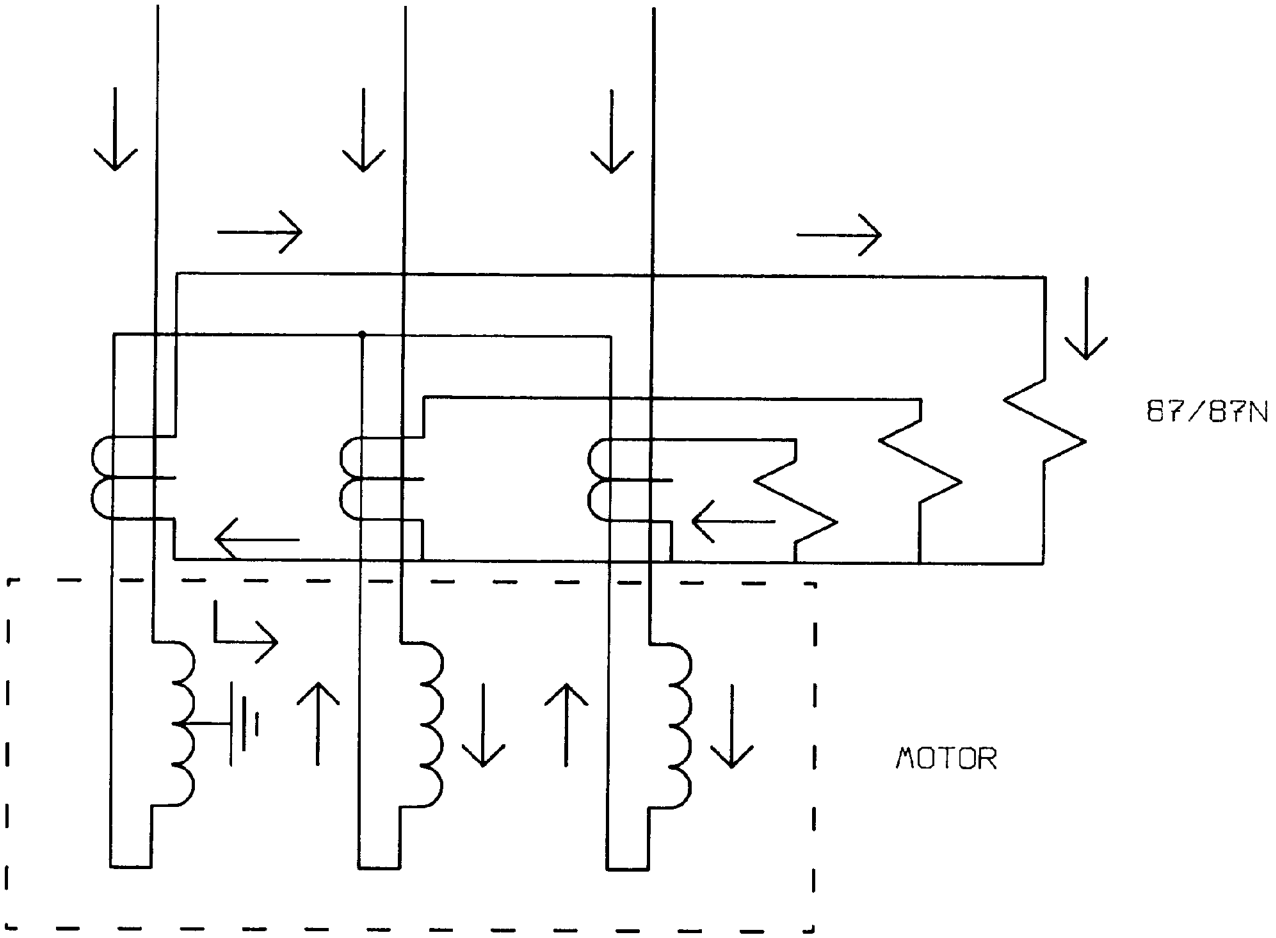

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*Figure 5-18. Motor self-balance differential protection.*

(5) Winding overtemperature protection can be applied to stator windings. Rotor winding overtemperature protection can be applied in close proximity to wind rotor induction motor starting resistors. The purpose of overtemperature protection is to detect excessive stator or rotor winding temperatures. Protection should be designed to alarm only on overtemperature since large motor installations are normally supervised. If supervision is

limited, two temperature settings can he specified, primary set to alarm, and back-up set to trip.

(6) Controllers for medium-voltage motors are designed as complete, self-contained units. Ratings are based on the maximum horsepower rating of the induction, synchronous, or multi-speed motor load using full- or reduced-voltage starting methods. Magnetic-fused-type controllers employ current-limiting power fuses and magnetic, air-break contactors. Medium-voltage controllers offer considerable cost advantages over switchgear and pro- vide more reliable short circuit protection on low current circuits. Combination motor controller/ switchgear assemblies are available.

(7) Single-phasing is one of the most common causes of motor failure. During single-phasing, the motor voltages, currents, and phase angles are severely unbalanced, and there is considerable harmonic content present. Single-phasing protection should be specified for motor protection which employs fuses.

## 5-5. Bus and switchgear protection

When protective devices are applied to the substation bus and switchgear components of an electrical distribution system, it must operate on bus and switchgear faults only. Modern bus and switchgear equipment is very reliable. Although bus faults are very rare, they can produce disastrous results when they do occur. Therefore, sensitive, high-speed protection can be applied.

*a. Differential protection.* Typical bus configurations employing differential relaying are shown in figures 5-19 through 5-22. Differential relaying is high-speed, sensitive, and can he overlapped with other relaying on the system. It can be used on 5kV to 15kV systems, but should not be used on Low-voltage systems. Differential relaying should supplement standard overcurrent protection, and should he applied where extra protection is needed such as:

(1) Open-type, outdoor busses.

(2) Installations where long, down-time periods cannot be tolerated.

(3) Where system coordination is difficult to achieve.

(4) Busses supplied by a local generator.

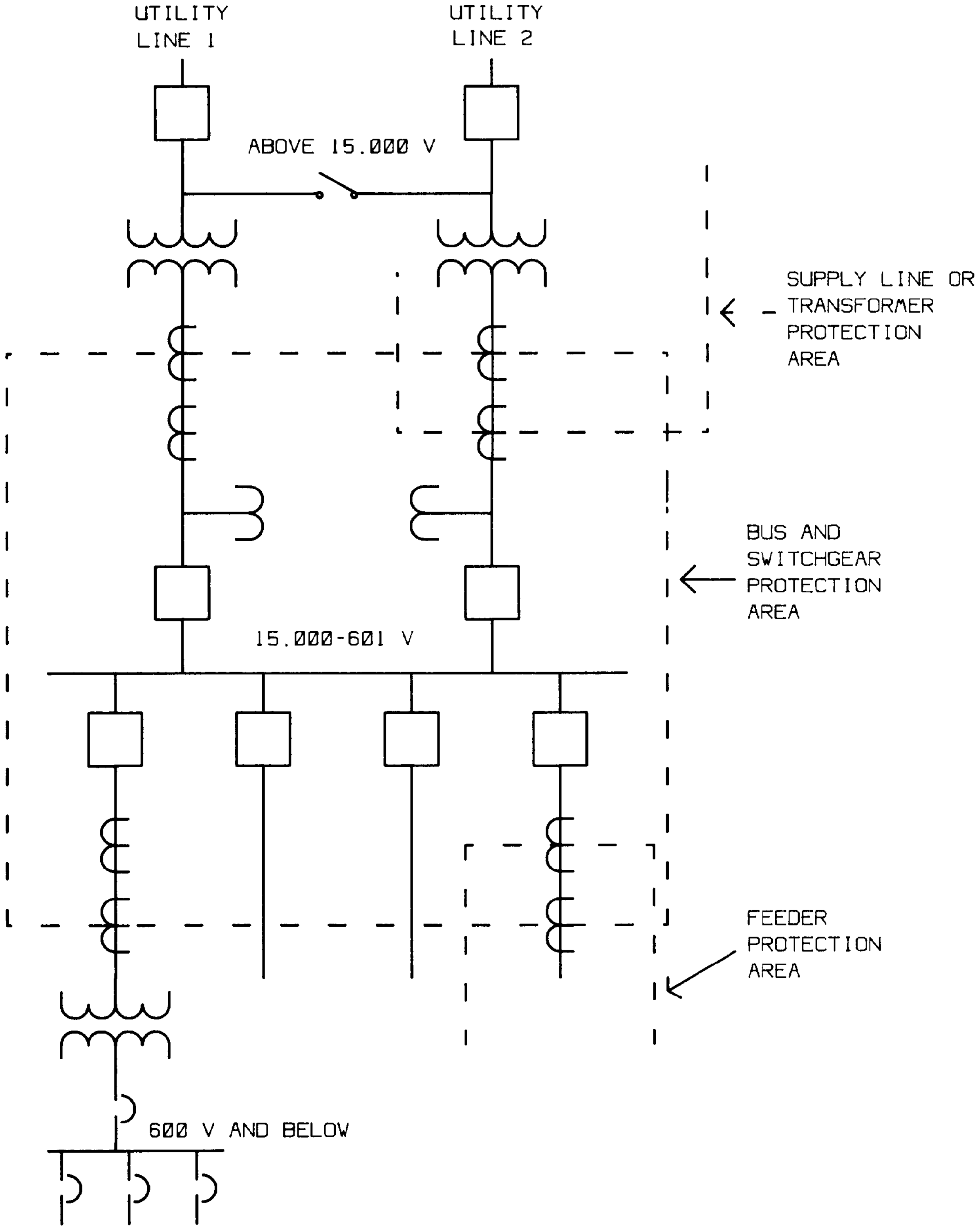

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*Figure 5-19. Single bus scheme with bus differential relaying.*

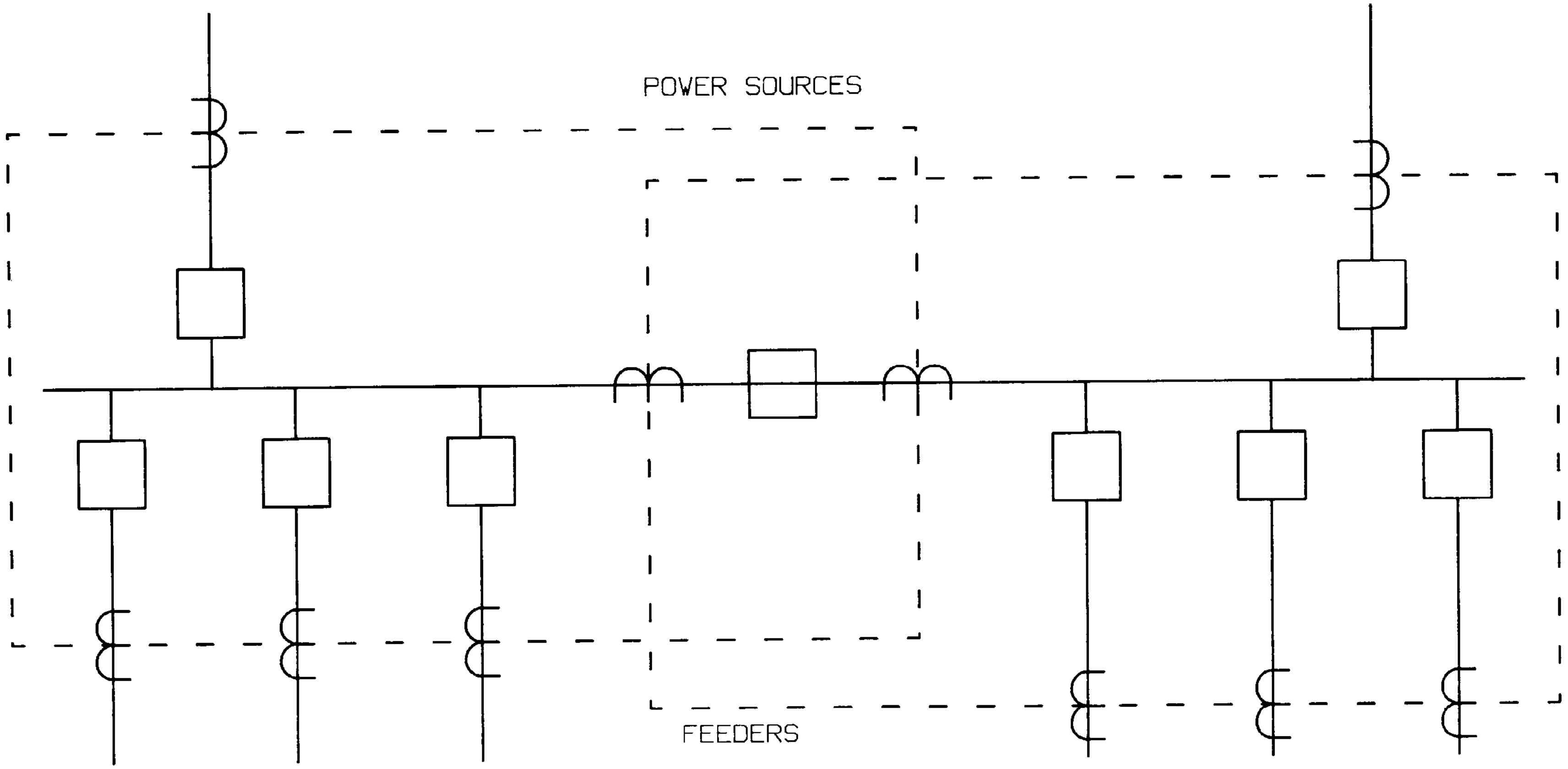

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*Figure 5-20. Sectionalized bus scheme with bus differential relaying.*

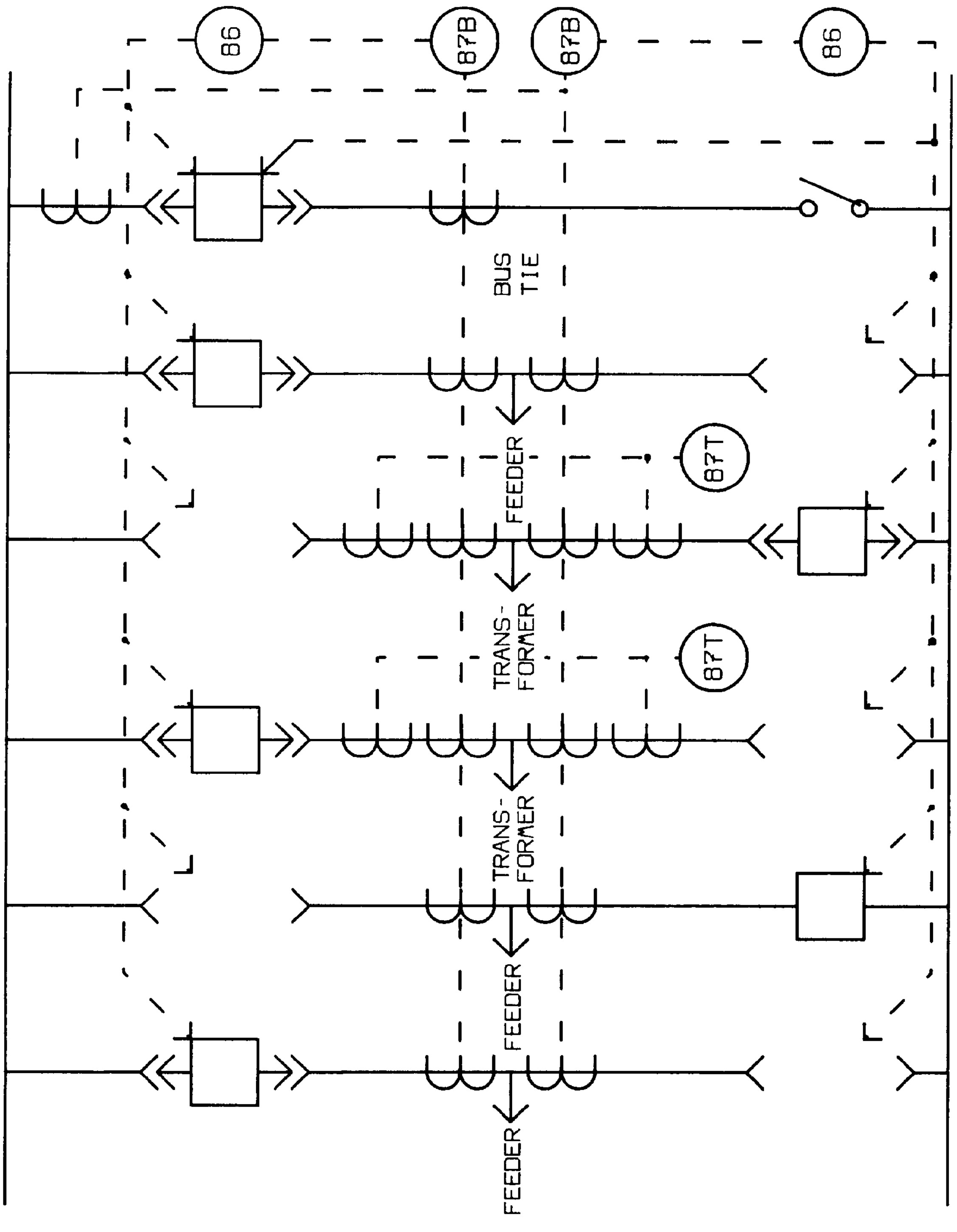

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*Figure 5-21. Double bus scheme with bus differential relaying.*

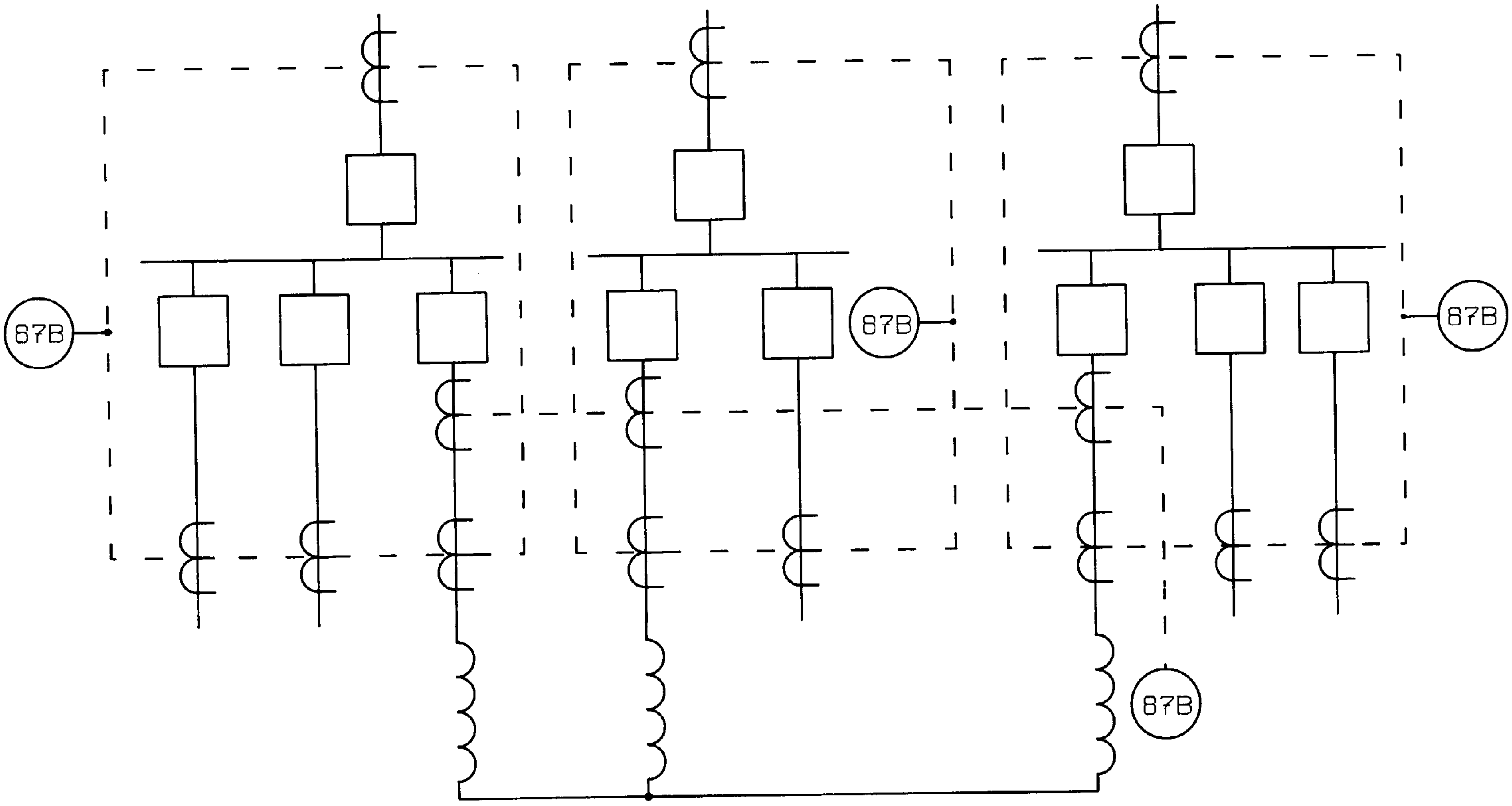

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*Figure 5-22. Synchronizing bus scheme with bus differential relaying.*

*b. Overcurrent protection.* On medium-voltage systems, fuses or overcurrent relays should be used. On low-voltage systems, fuses or circuit breakers should be used. Low-voltage switchgear cannot accommodate the CTs required for relay protection.

## 5-6. Ground-fault protection

Ground-fault protection of medium-voltage and high-voltage systems has been applied successfully for years using ground current relays (device 51G). Ground-fault protection of low-voltage systems is a considerable problem because of the presence and nature of low-level arcing ground faults. Chapter 2 classified ground-fault currents as leakage, arcing, and bolted. Leakage ground-fault current is low magnitude current (milliampere range) generally associated with portable tools and appliances. Leakage ground-fault current presents a hazard to personnel. Personnel protection from leakage ground-fault current is provided by ground-fault circuit interrupters (GFCI) and are required by the NFPA 70 in certain locations. Arcing and bolted ground-fault currents are higher magnitude currents, and are associated with equipment damage rather than personnel hazard. That doesn’t mean that arcing and bolted ground-fault currents don't present a personnel hazard. They do. But, the primary concern is with the equipment hazard since arcing and bolted ground-fault currents usually occur only on supervised commercial and industrial electrical systems. Equipment protection from arcing and bolted ground-fault currents is provided by ground-fault protection (GFP) devices. NFPA 70 differentiates between ground-fault protection of personnel and ground-fault protection of equipment.

*a. The ground-fault current mechanism.* When a short-circuit occurs between line and ground, ground-fault current will flow in the line, through the ground-fault connection (arc), and through the equipment grounding conductor back to the source transformer. The impedance of the Ground-fault current path may be high or low depending on many factors, such as conductor length, arc impedance, materials, and environment. The ground-fault current, therefore, may be high or low.

*b. Nature of arcing ground-faults.* The arc impedance is by far the most important variable in determining ground-fault current magnitude. As the arc impedance changes, so does the ground-fault current. The arc impedance itself is controlled by many variables. These include the physical length of the arc, arc elongation and blow-out, arc self-clearing and restrike, terminal shifts due to metal flow during the fault, and many others. As a result, ground-fault current may even go up and down as the fault persists. It is very difficult, then, if not impossible, to accurately calculate expected ground-fault current.

*c. Tolerable damage curves.* Although arcing ground-fault current magnitudes are difficult to determine, it is the arc, not the current, that causes the damage. As stated previously, arcing ground-fault current magnitudes may be below the setting of standard overcurrent devices. However, as the currents go undetected, the arc is releasing large amounts of thermal energy and causing severe equipment damage and perhaps presenting a personnel hazard. It is not really necessary to know the magnitude of arcing ground-fault current to coordinate protective devices. The arcing ground-fault problem becomes one of providing protection against any arcing ground-fault that is likely to occur. Therefore, some damage must be tolerated. NEMA PB2.2 assumes tolerable damage curves are shown in appendix C. These curves can be traced onto the composite time-current characteristic curve of the system under study and made a part of the coordination procedure. Ground-fault protection and coordination are covered in detail by the examples in appendix G.

*d. GFP techniques.* While numerous variations of ground-fault protection exist, all methods are really just variations of the following:

(1) Residual overcurrent relays are illustrated in figure 5-23. This method is used widely on medium-voltage systems.

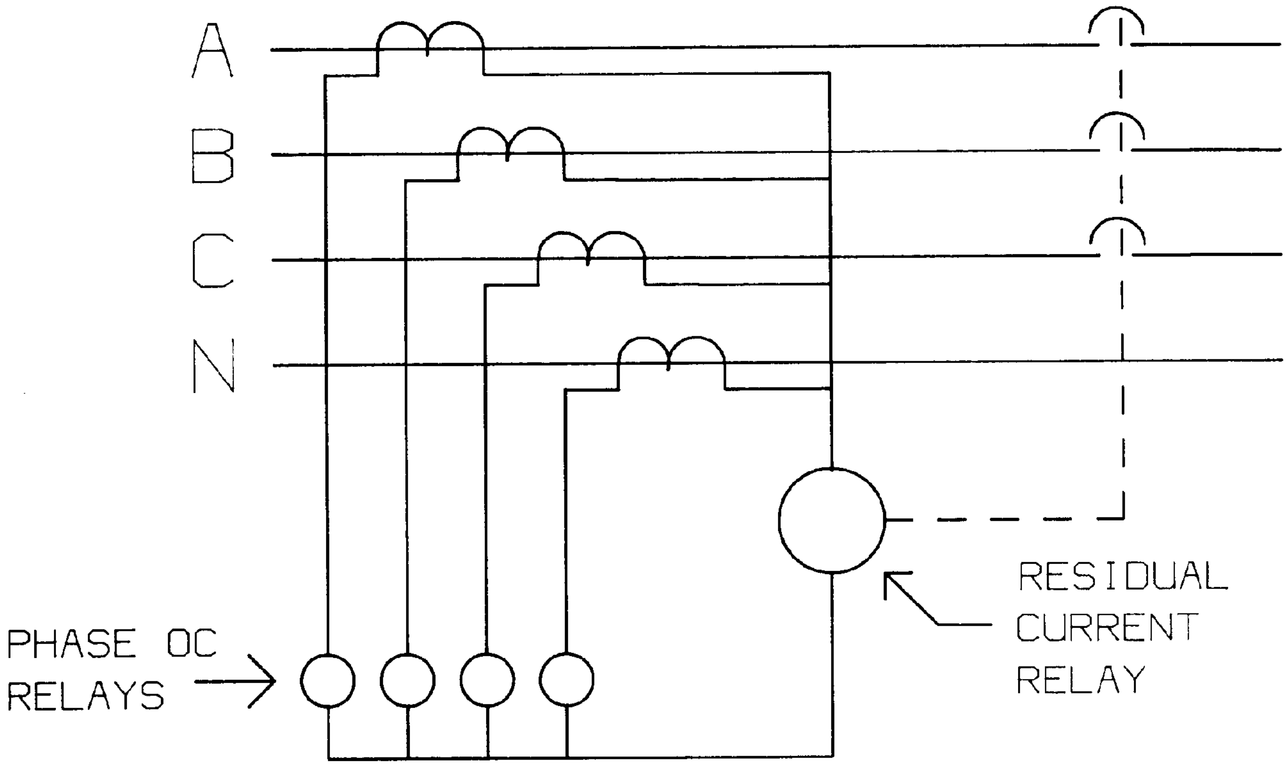

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*Figure 5–23. Residual or common relay.*

(2) The zero-sequence method is illustrated in figure 5-24. This method is widely used on low-voltage systems. The current-carrying conductors are passed through a common current transformer. The equipment grounding conductor must not be included. Under normal conditions, all current flowing to the load must equal all current returning to the source, and the CT is balanced and will not operate the relay. When a ground-fault occurs, some of the outgoing current returns on the equipment grounding conductor outside the CT, thus producing an unbalanced condition and operating the relay. The zero-sequence CT is also called "core-balance CT,” "window CT,” or "donut CT."

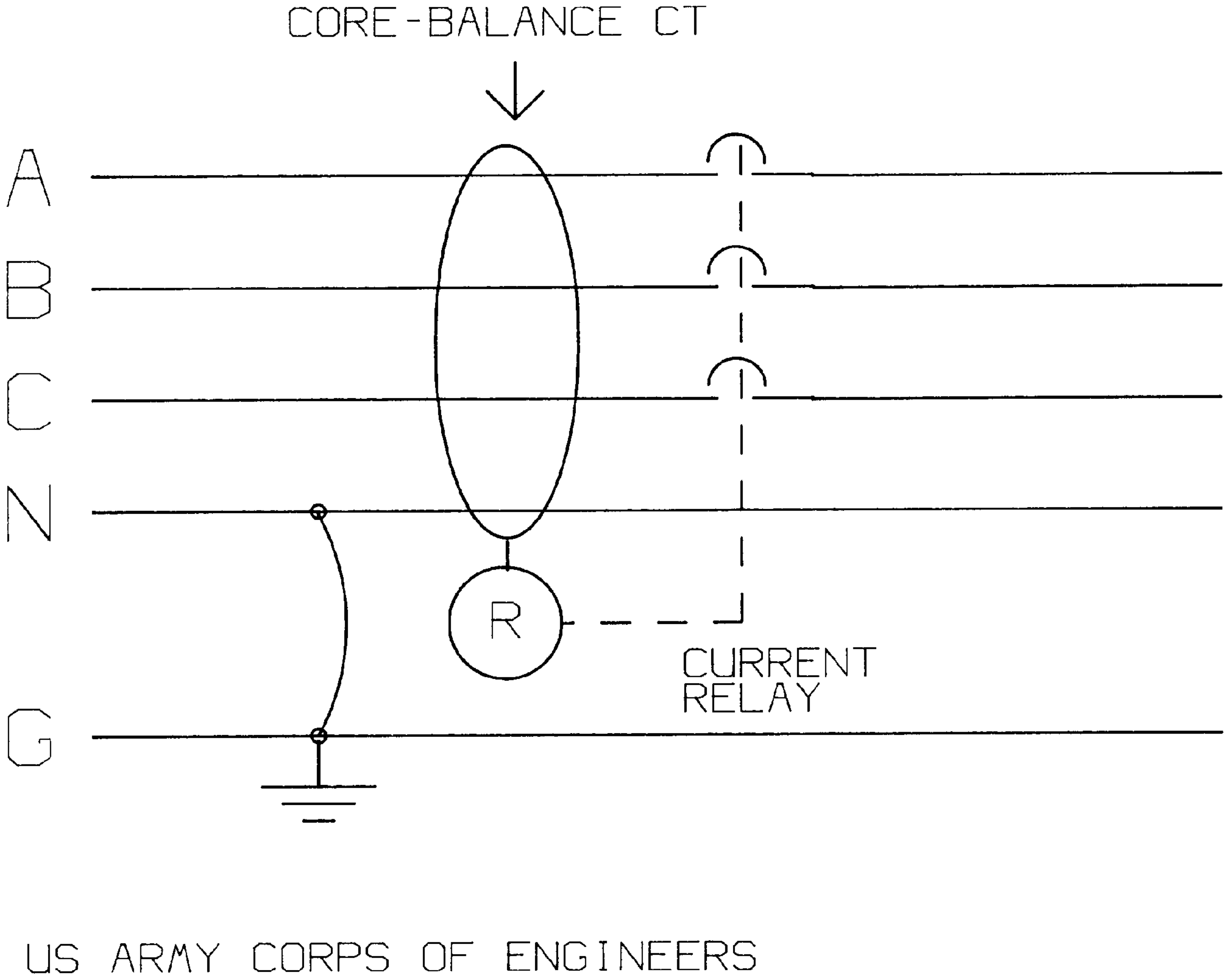

*Figure 5-24. Zero-sequence relay.*

(3) Ground-return relays are illustrated in figure 5-25. Since all ground-fault current must return to the source via the main bonding jumper (or grounding strap), this is a very convenient place to detect ground-fault current. However, this method is not recommended because multiple paths exist for the return of ground-fault current to the source.

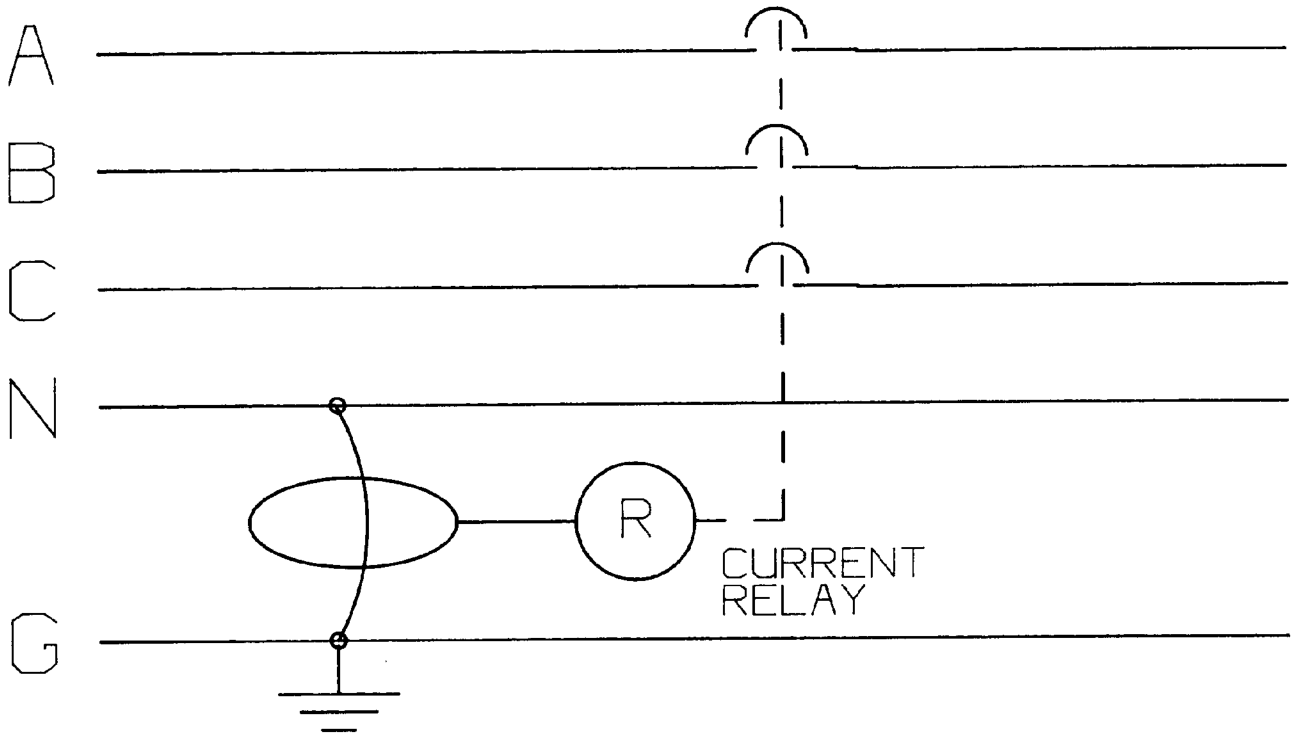

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*Figure 5-25. Ground return relay.*

(4) Differential ground-fault relaying is illustrated in figure 5-26. This method is very effective for main bus protection because of inherent selectivity. The CTs must be closely matched to prevent undesirable tripping for high-level faults downstream of the protected zone.

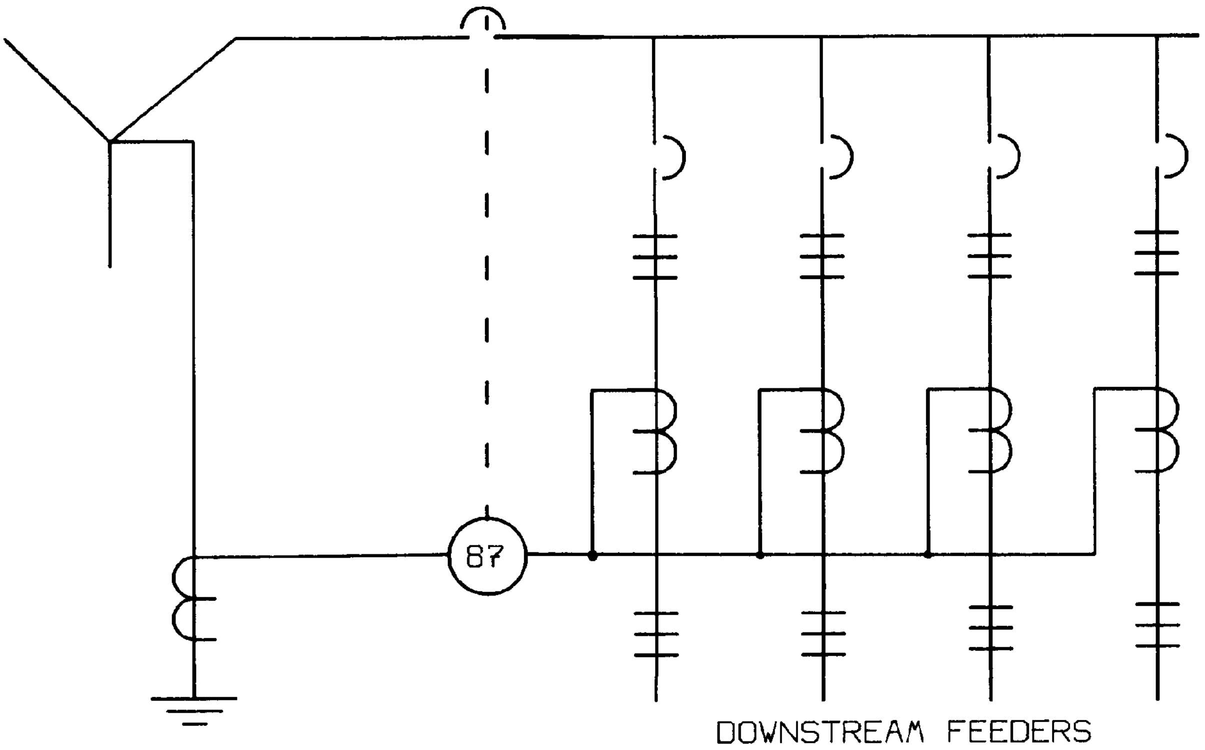

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*Figure 5-26. Ground differential relay.*

*e. Double-ended substations.* Three-phase, four-wire, double-ended substations are widely used on low-voltage systems. The application of ground-fault protection to double-ended substations is not without problems. NFPA 70 permits single-point grounding for double-ended substations. In accordance with NFPA 70, the substation transformers must be grounded only at the neutral tie point. Main ground-fault sensors are applied on the neutral of each transformer. All neutral loads associated with either transformer must be connected on the source side of the related ground-fault sensor. The ground-fault sensor for the tie circuit breaker is located directly on the grounding conductor between the neutral tie point and the grounding electrode. Zero-sequence sensing is used on the feeders. When the system is operated with the tie circuit breaker closed, supplementary interlocking is required to compensate for neutral currents in the main sensors. Due to the problems associated with applying ground-fault protection to three- phase, four-wire substations, it is recommended that the manufacturer always be contacted. It is further recommended that only three-phase, three- wire substations be used if at all possible. This will eliminate the ground-fault sensing problems discussed above. A step-down transformer can be used to supply line-to-neutral loads.

*f. NEMA damage example.* As discussed in this chapter, NEMA PB2.2 damage curves may be used as an alternative to calculating low-voltage arcing ground-fault current values. The NEMA PB2.2 damage curves are included in appendix C. Figure 5-27 shows the time-current characteristic curves of four, series-connected, standard circuit breakers used on a typical low-voltage system. The MAIN CB is rated 2000 amperes, the FDR CB is rated 800 amperes, the SUBFDR CB is rated 225 amperes, and the BRANCH CB is rated 100 amperes. NEMA PB2.2 damage curves for each level are also shown. NFPA 70 requires arcing ground-fault protection only at the service disconnect (2000A Main CB). Figure 5-28 shows the addition of ground-fault protection at the main only, and adjusted to the maximum setting permitted by NFPA 70 (1200A, 1 second time delay). For bolted ground-faults above about 7000A, the selected setting exceeds the 2000A NEMA damage curve. Also, the GFP setting will not coordinate with the downstream 800A FDR CB. A 2500A or less ground-fault on the 800A FDR CB will trip the main GFP device and shut down the entire system. Figure 5-29 shows improved protection by reducing the instantaneous setting of the 225A SUBFDR CB and the 100A BRANCH CB. Both devices are now below their respective NEMA damage curves, thus providing both short-circuit and ground-fault protection. Figure 5-30 shows further improved protection and coordination by reducing the MAIN GFP current and time settings. Ground-fault protection has also been added to the 800A feeder.

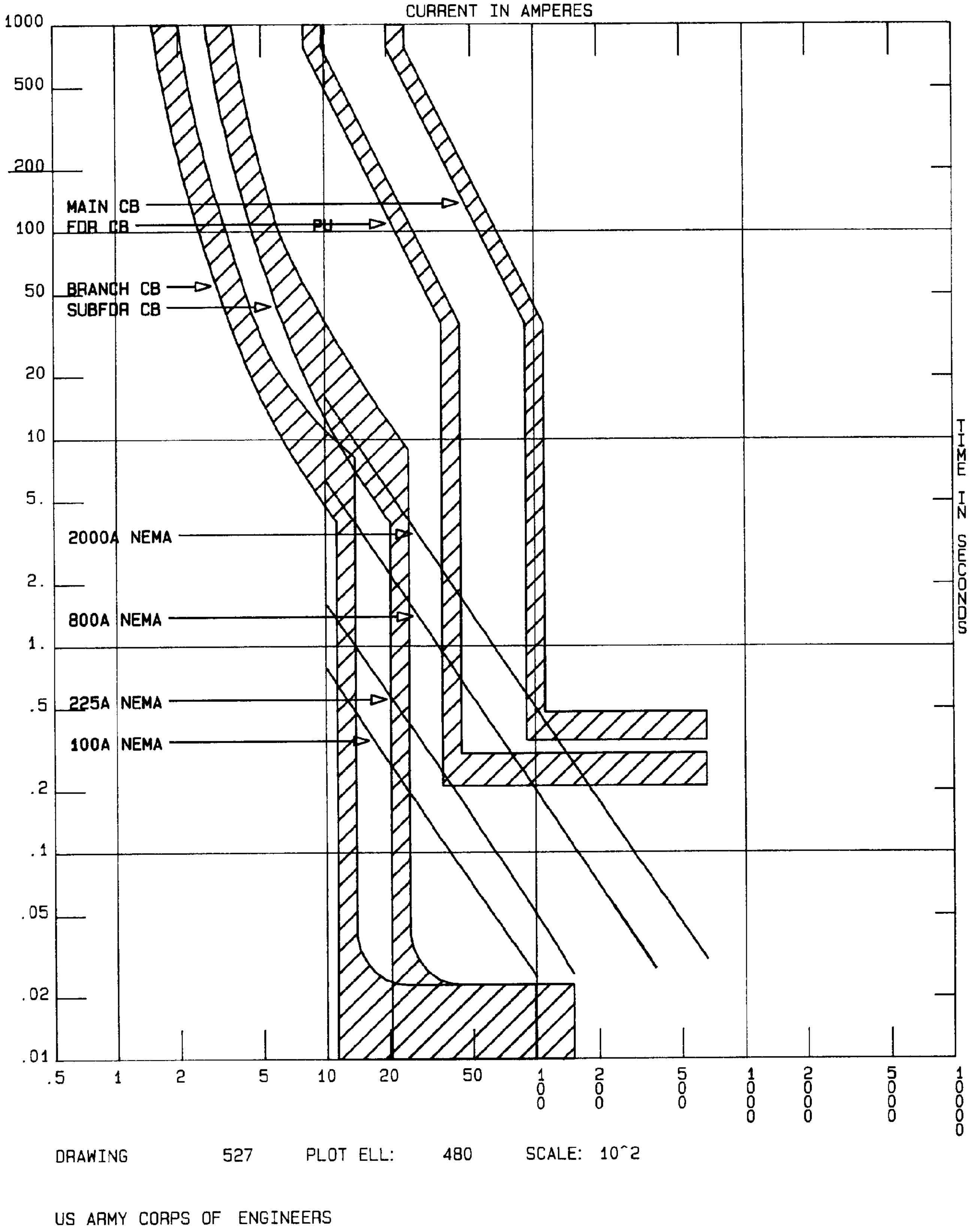

*Figure 5-27. Standard overcurrent protection.*

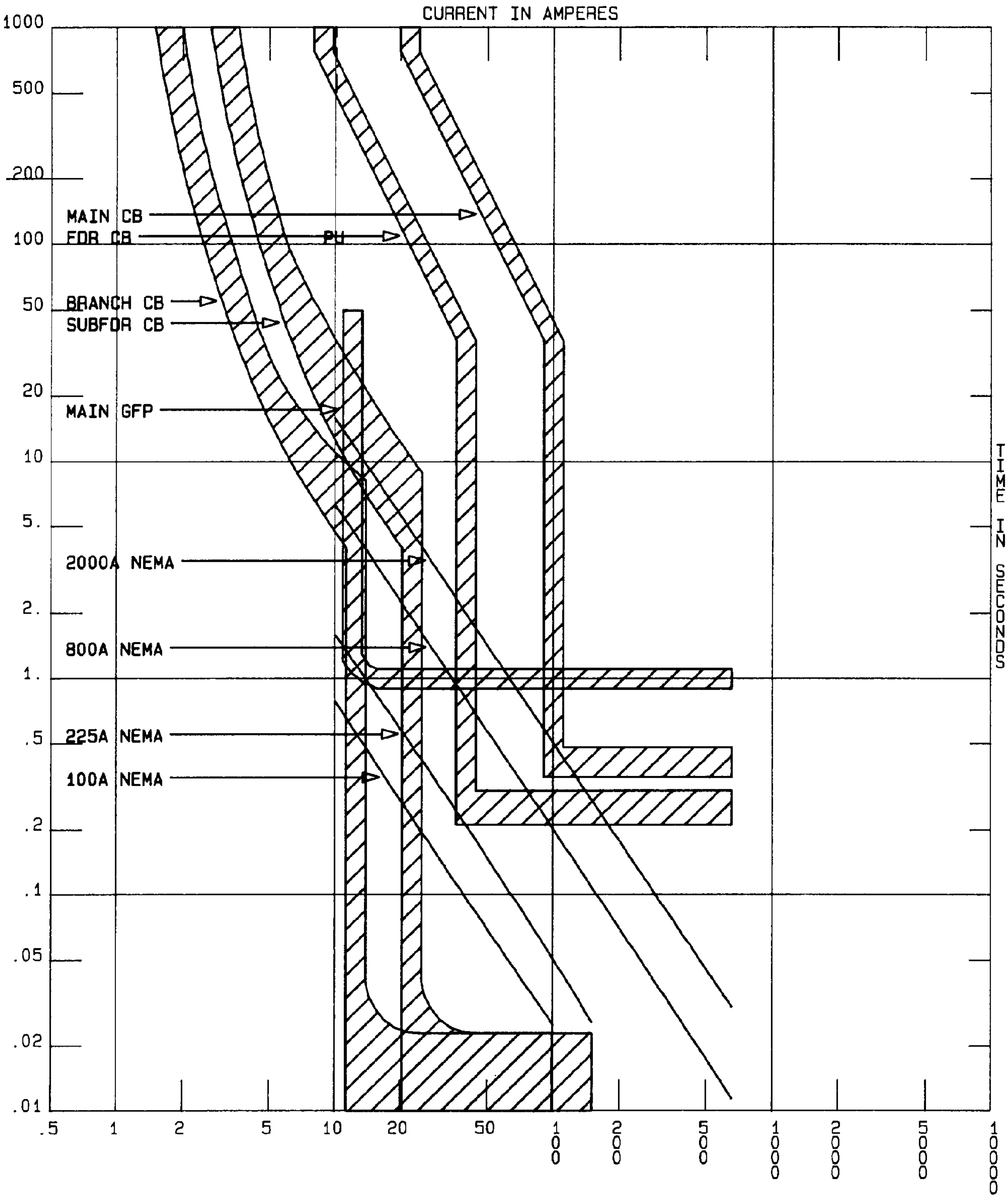

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*Figure 5-28. Main-only ground-fault protection.*

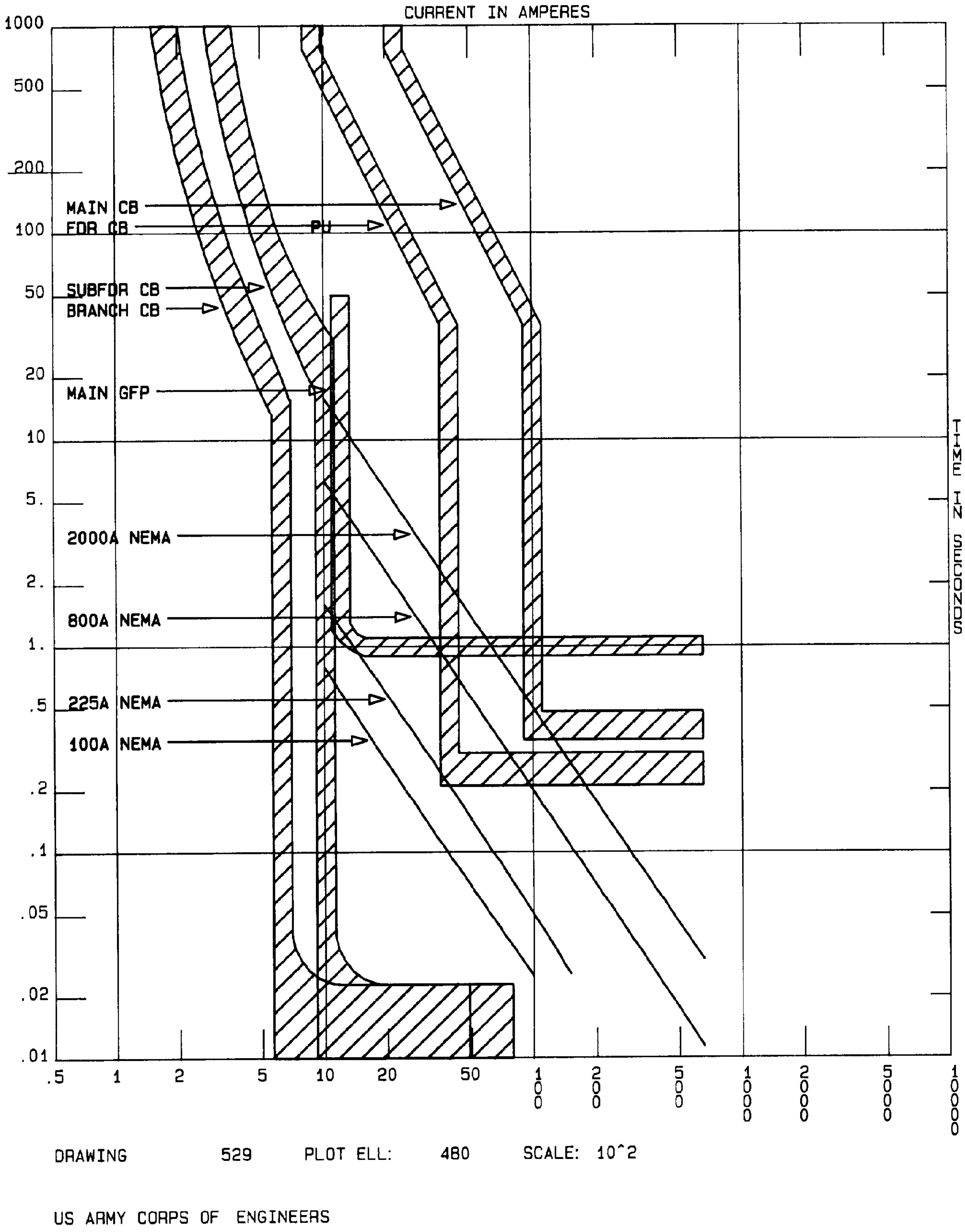

*Figure 5-29. Improved ground-fault protection and coordination.*

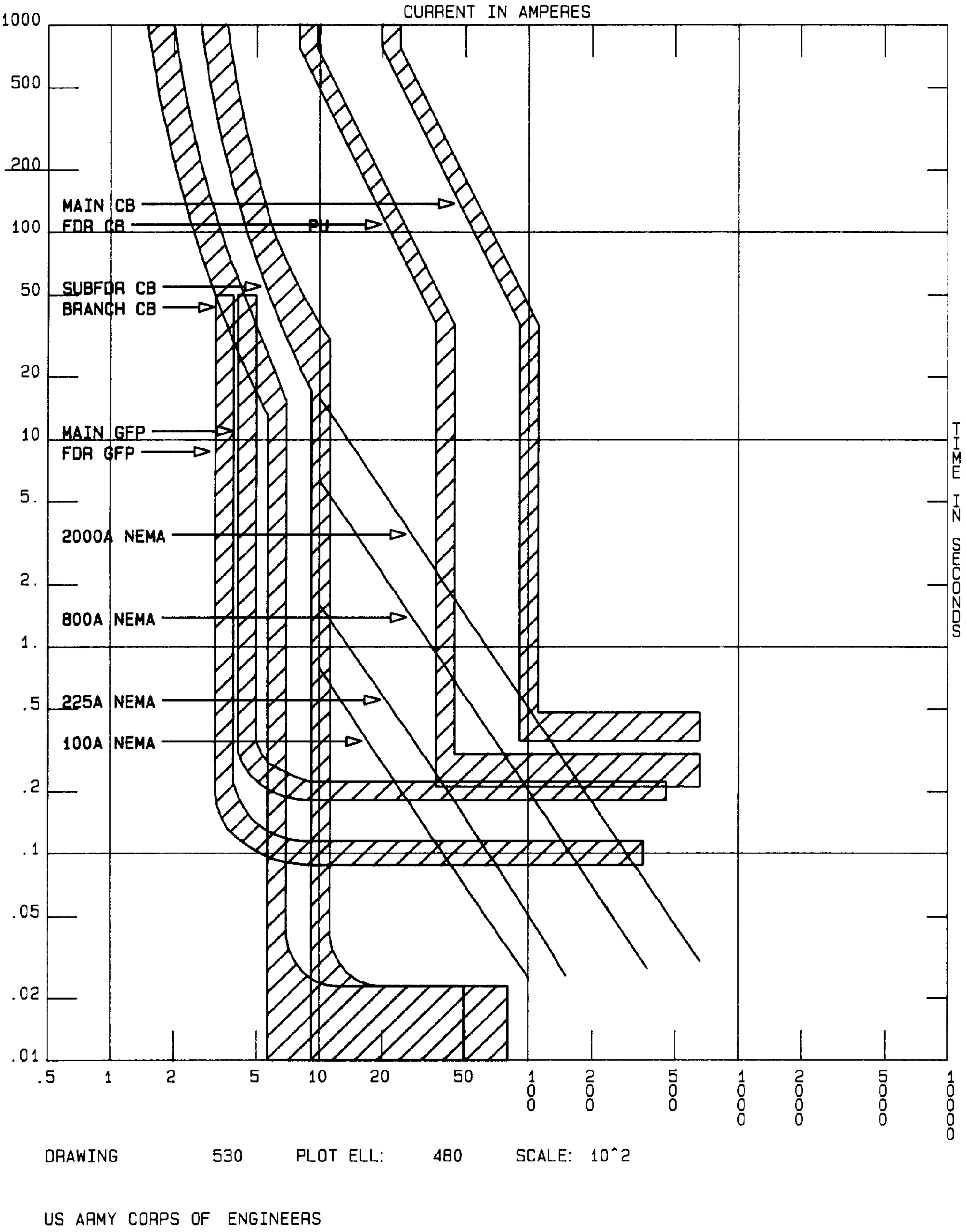

*Figure 5-30. Main and feeder ground-fault protection.*

## 5-7. Miscellaneous equipment protection

Miscellaneous electrical equipment, such as lighting fixtures, heaters, convenience outlets, and panelboards must include both overload and short-circuit protection. Such protection is provided by fuses or circuit breakers. High-level arcing and bolted ground-fault protection will normally be provided by the standard overcurrent protective devices (fuse and circuit breakers) on the system. Low-level arcing ground-faults will not be detected by the standard overcurrent devices, however. Although separate arcing ground-fault protection is required only at 480Y/277V services of 1000A and larger by NFPA 70, such protection should be evaluated on a project basis. Ground-fault protection on feeders as well as on the main service disconnect may be the only way to achieving a coordinated system. Ground-fault protection on the main only may be difficult to coordinate with downstream standard devices.