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IEEE Guide for Protective Relaying of Utility-Consumer Interconnections

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Abstract: IEEE C37.95-1989, *IEEE Guide for Protective Relaying of Utility-Consumer Interconnections*, is intended to cover applications involving service to a consumer that normally requires a transformation between the utility's supply voltage and the consumer's utilization voltage. Interconnections supplied at the ultimate utilization voltage are not covered.
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Foreword

(This Foreword is not a part of IEEE C37.95-1989, IEEE Guide for Protective Relaying of Utility-Consumer Interconnections.)

The principle value of this guide will be realized if it establishes a common ground of understanding among all of those involved in the process of supplying electric power from the utility to the consumer.

This guide was prepared by the Consumer-Utility Working Group of the Consumer Relaying Coordination Subcommittee of the IEEE Power System Relaying Committee. At the time this guide was approved, the Working Group membership was as follows:

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IEEE Guide for Protective Relaying of Utility-Consumer Interconnections

1. Introduction

The physical means by which electric energy is received from the electric utility is known as an interconnection tie. The primary elements include transmission or distribution circuits, transformers, and switching devices in the form of circuit breakers, fuses, and isolating disconnect switches. The secondary elements include sensing devices to obtain information to operate the primary equipment intelligently, and protective relays to initiate removal of equipment from service automatically and quickly when an electric fault or disturbance occurs.

It is important to remember that the physical laws of nature which govern the operating behavior of an electric power system do not recognize defined lines of electric facility ownership. Thus, for a well-engineered interconnection, it is suggested that problems in electric power system protection be studied and analyzed critically without regard to ownership.

From the viewpoint of service reliability and service continuity, it is basic to understand that the best conceived, best implemented protective relaying system is no substitute for an adequately designed power system. Indeed, inadequately applied protective relaying will contribute to inadequate and unsatisfactory performance of an otherwise well-designed power system. In considering a new installation, or changes to an existing arrangement, it is very important that protective relaying and safety be given careful attention in the early stages of planning.

2. Scope

This guide contains information on a number of different protective relaying practices for the utility-consumer interconnection. It is intended to cover applications involving service to a consumer that normally requires a transformation between the utility's supply voltage and the consumer's utilization voltage. Interconnections supplied at the ultimate utilization voltage are not covered.

This guide is not intended to supplant specific utility or consumer practices, procedures, or requirements, or any contractual agreement between the utility and consumer. The examples in Section 9 are used for illustrative purposes only and do not necessarily represent the preferred protection trader all conditions.

This guide addresses users (consumers), with or without generation, that are connected to utility subtransmission or transmission circuits. The specific control schemes associated with generation are not addressed. It is not intended to apply necessarily to consumer generation connected to utility distribution circuits.

3. Purpose

The primary purpose of this guide is to help those who are responsible for the application of protective relaying for the electrical interconnection between utility and consumer systems. It is anticipated that it will be used by representatives of the utility, the consumer, and their consultants who are responsible for the specification, design, and operation of the interconnection. Recognizing the diverse audience being addressed, background information and references are included in Section 4 to direct the reader to more complete treatment of the material.

4. References

[1] ANSI C2-1990, National Electrical Safety Code.[1]

[2] ANSI/IEEE C37.010-1979 (R1988), Application Guide for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis.[2]

[3] ANSI/IEEE C37.2-1987, Standard Electrical Power System Device Function Numbers.

[4] ANSI/IEEE C37.5-1979, Guide for Calculation of Fault Current for Application of AC High-Voltage Circuit Breakers Rated on a Total Current Basis.

[5] ANSI/IEEE C37.90-1978 (R1982), Relays and Relay Systems Associated with Electric Power Apparatus.

[6] ANSI/IEEE C37.91-1985, Guide for Protective Relay Applications to Power Transformers.

[7] ANSI/IEEE C37.93-1987, Guide for Power System Protective Relay Applications of Audio Tones over Telephone Channels.

[8] ANSI/IEEE C37.96-1988, Guide for AC Motor Protection.

[9] ANSI/IEEE C37.97-1979 (R1984), Guide for Protective Relay Applications to Power System Buses.

[10] ANSI/IEEE C37.99-1980 (R1985), Guide for Protection of Shunt Capacitor Banks.

[11] ANSI/IEEE C37.101-1985, Guide for Generator Ground Protection.

[12] ANSI/IEEE C57.13-1978 (R1986), Standard Requirements for Instrument Transformers.

[13] ANSI/IEEE Std 141-1986, Recommended Practice for Electric Power Distribution for Industrial Plants (IEEE Red Book).

[14] ANSI/IEEE Std 241-1983, Recommended Practice for Electric Power Systems in Commercial Buildings (IEEE Gray Book).

[1] ANSI publications are available from the Sales Department, American National Standards Institute, 1430 Broadway, New York, NY 10018.
[2] ANSI/IEEE publications are available from the Institute of Electrical and Electronics Engineers, Service Center, 445 Hoes Lane, Piscataway, NJ 08855-1331, or from the Sales Department, American National Standards Institute, 1430 Broadway, New York, NY 10018.

[15] ANSI/IEEE Std 242-1986, Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems (IEEE Buff Book).

[16] ANSI/IEEE Std 315-1975 (R1989), Graphic Symbols for Electrical and Electronics Diagrams.

[17] ANSI/IEEE Std 446-1987, Recommended Practice for Emergency and Standby Power for Industrial and Commercial Applications (IEEE Orange Book).

[18] ANSI/IEEE Std 493-1980, Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems (IEEE Gold Book).

[19] ANSI/IEEE Std 519-1981, Guide for Harmonic Control and Reactive Compensation of Static Power Converters.

[20] ANSI/NFPA 70-1987, National Electrical Code.[3]

[21] IEEE Std 80-1986, Guide for Safety in AC Substation Grounding.[4]

5. Establishing Consumer Service Requirements and Supply Methods

5.1 Interconnection

The utility-consumer interconnection provides the path for power flow between supplier (utility) and user (consumer). The interconnection may comprise one or more circuits and is assumed to include voltage transformation. For the purposes of this guide, the extent of the interconnection is defined to include the nearest source-side protective device for transformer high-side switching and the transformer low-side bus and switching devices.

5.2 General Process

The supply that is selected should satisfy the consumer's load requirements. Available utility supply options in the area as well as the utility's design standards and operating and maintenance practices should also be considered.

5.2.1 Consumer Defines Requirements

Prior to meeting with utility personnel, the consumer should define his present and future load requirements. He should establish the connected kVA along with the average and peak demand and reactive power requirements, the effect of interruptions and voltage dips on plant operation, the required dependability and security of the utility's electrical service, plus any other needs that may be unique to the operation. The consumer's engineer should be prepared to discuss these requirements in detail with utility engineers to ensure that there is a clear understanding of the consumer's requirements.

5.2.2 Utility Defines Service Availability

The utility should describe the supply voltages available in the area and estimate the initial and total costs of the various alternatives. Most utilities establish nominal limits on the kVA that can be supplied at different voltage levels. The availability of single- and multiple-line supply and the performance level of each should be discussed in detail. In addition, the utility should inform the consumer of any required studies, unusual problems, or future plans that may

[3]NFPA documents are published by the National Fire Protection Association, Publications Sales Division, Batterymarch Park, MA 02269. Copies are also available from the Sales Department of the American National Standards Institute, 1430 Broadway, New York, NY 10018.
[4]IEEE publications are available from the IEEE Service Center, 445 Hoes Lane, Piscataway, NJ 08855-1331.

affect the quality or continuity of supplying service. Some utilities publish standard information booklets detailing the requirements for service.

When the consumer has identified critical power requirements, the utility engineer should investigate their characteristics to be certain that both parties have a clear understanding of the effect of interruptions and voltage dips. The utility may then be able to suggest a supply system that will meet these requirements, or suggest plant control changes to make the operation more successful. It should be recognized that there is no electrical utility supply method that completely eliminates the possibility of momentary service interruptions or voltage dips. If the consumer cannot tolerate these service disruptions, consideration should be given to the installation of specific facilities to allow riding through these periods.

The primary cause of service complaints is the failure to adequately evaluate the effect of interruptions and voltage dips on the consumer's equipment. Depending on the type of operation, a voltage dip of only a few cycles can be very costly because it can disrupt an industrial process. It is especially critical that a careful evaluation be made by the consumer of the voltage requirements of his loads and the electronic systems that provide process control. In many instances, special means are available to make the loads tolerant of unavoidable voltage conditions on the power system.

5.3 Information Exchange

Once the supply method is established, a further exchange of information is required so that the station design can be completed and the utility can make the necessary preparations to supply the service. By establishing good communication between the utility and the consumer as early as possible for either a new or modified supply, specific requirements can be identified an included in the initial design before equipment is ordered.

5.3.1 Typical Information Furnished by Utility

- Available short-circuit current—range of single- and three-phase to ground-fault current and associated *X/R* ratios at the consumer's point of service. Values for normal and alternate supply facilities as well as any anticipated future values should be provided.
- Expected minimum, maximum, and nominal voltage at the consumer's point of service for available voltage levels.
- Outage history of the supply—both forced an maintenance outages
- Estimated frequency, duration, and magnitude of momentary voltage dips at the consumer's point of service
- Operating requirements and restraints
- Specific protection requirements to coordinate with the utility system
- Specific reclosing practices on both normal and alternate supply facilities
- Harmonic content, voltage fluctuation, and current unbalance constraints imposed by the utility. Also quantification of voltage waveform distortion and harmonic current injection from other sources on the utility system if requested by the consumer
- Additional information requested by the consumer, such as:
  - — Supply line construction and routing
  - — Supply substation arrangement and location
  - — Utility grounding and lightning protection practices
  - — Metering arrangements and data

5.3.2 Typical Information Furnished by Consumer

- Expected service date (when consumer will be ready for power)
- Complete one-line diagram of plant distribution system
- Preferred supply voltage
- Transformer ratings, connections, voltage taps, and impedances
- Power factor correction capacitor ratings and connections

- Switchgear specifications, including protective relay types and ranges
- Motor loads, types, sizes, and starting frequency
- Unusual load characteristics, such as those due to furnaces, thyristors, and other nonlinear loads (include flicker and harmonic producing equipment)
- Generation information, including short-circuit information
- Voltage balance requirements
- Protection and control schematic drawings, as appropriate
- Point of interconnection physical arrangement drawings
- Expansion plans, which include projected loads, future substation development, and estimated dates
- Station ground grid design
- Maintenance capability of consumer personnel

5.3.3 Future Utility System Changes

The utility should inform the consumer of any substantial utility system changes. For example, the installation of a large transformer that alters short-circuit currents at the supply point may affect the consumer's power system. In like manner, changes in regulator or capacitor location may also affect the consumer's power system.

5.4 Specific Supply Considerations

In determining the final supply method, consideration should be given to the design of the interconnection, the arrangement of the utility's supply system, its protective relaying requirements, and its maintenance requirements and responsibilities.

5.4.1 Division of Ownership

Individual operating and maintenance philosophies of the consumer and utility may impact electric system design. Proper engineering design should not be compromised. This guide places primary emphasis on principles and practices to be applied toward coordinated operation of an integrated system.

5.4.2 Nature of Interconnection

The utility-consumer interconnection tie may consist of one circuit or multiple circuits. Single service consists of a single line supplied from a single source and connected to a single transformer, with connections to the consumer's distribution system at the low-voltage side of the transformer. Such service is subject to interruption on forced or planned outage of the supply source, line, or transformer. If single line supply is not adequate, alternative supply facilities, such as a standby supply or multiple-line supply with or without multiple transformation, should be considered. A normally open standby supply from a second utility source can enable restoration of service by automatic or manual switching operations on failure of the principal single-line supply. Multiple, full-capacity interconnection lines routed over separate rights of way, with multiple transformation, will enhance continuity of service. Ideally, multiple lines should not originate at the same bus, since an outage of that bus would result in a consumer outage. Utility supply configurations, which provide two interconnection lines include:

- Two lines from separate utility sources
- Two lines derived by sectionalizing an existing utility tie line

Multiple supply lines may terminate at the consumer substation if a strong source is required to serve the consumer's load or other area loads.

As described in succeeding sections of this guide , the effects on service voltage of local and remote utility supply system faults will depend on the nature of the interconnection. Supply configurations are covered in more detail in Section 6

5.4.3 Interconnection Protection Requirements

The complexity of the protection used at an interconnection will vary depending upon voltage level, system configuration, the type and amount of consumer load, and specific requirements of either the consumer or utility. In a dual supply system, for example, additional relaying may be required to respond to undesirable power flow from one supply to the other. Special consideration must be given to consumers with large motors or generators connected to their system.

If a bus is installed at the consumer's location as part of the utility supply, the protective relaying for the supply lines and bus will normally be considered as part of the utility system. The consumer should be familiar with the effects of the protection applied to these facilities, since the duration of interruptions or voltage dips due to faults on the supply lines or buses has a direct effect on service.

Regardless of ownership, the protective equipment should be specified and designed to provide a coordinated system. If the consumer's facilities become an integral part of the utility system, protection requirements should assure the integrity of the supply system. This may result in some apparent duplication of protective equipment based on the philosophy and objectives of the utility and consumer in regard to protection. The protection of the utility-consumer interconnection facilities should satisfy the objectives of both parties. In all cases, the protection requirements, relay or fuse specification, relay setting or fuse size, and testing procedures should be discussed and agreed upon by both parties.

5.4.4 Maintenance

In determining the interconnection system and the associated protective equipment, it should be recognized that periodic maintenance of all facilities is required. Comprehensive maintenance includes operational testing of relays, control batteries, and interrupting devices. This applies to the utility supply system as well as the consumer's utilization system. During periods of maintenance, the reliability of the supply or possibly even the continuity of service may be affected. This work should be coordinated between the utility and consumer so as to minimize any adverse impact. If the consumer cannot tolerate the loss of service for periodic maintenance, the installation of an alternate supply will be required.

5.5 Load Considerations

The primary concern in applying protection for faults on the electrical supply or utilization systems is to minimize personnel hazard and equipment damage. However, the effect of the protective equipment on the load served should be considered. The operating time of fuses or protective relays and switching devices determines the time to isolate a faulted piece of equipment. During the fault, the electric system is subjected to abnormal currents and voltages. Abnormal voltages on unfaulted portions of the system can affect the operation of process controls, ac contactors, motors, computers, and other electronic devices. Reclosing practices of the utility can provide restoration of service to all facilities for a temporary fault, such as lightning-induced flashover of an overhead line. Reclosing can provide automatic restoration of service to a portion of the system once a permanently faulted section has been isolated. The consequences of reclosing vary and can be significant if the consumer's system includes generators or large motors. It is essential that the implications be understood and that designs be selected to meet the required objectives.

5.6 Other Supply Considerations

Harmonics, grounding, ferroresonance, and voltage regulation are discussed briefly in this section. Personnel responsible for the protection of the interconnection should recognize that these conditions can affect the quality of service and possibly even the performance of protective relays and their associated control circuits.

5.6.1 Harmonics

Harmonics are generated in an electric system by numerous devices. The consumer must be cognizant of the effect of harmonics on his equipment and the utility system (see IEEE Std 519-1981, Guide for Harmonic Control and Reactive Compensation of Static Power Converters [19]). Limits may be imposed on the acceptable level of harmonics beyond which corrective action should be taken. Capacitors do not create harmonics; but they can cause a change in harmonic distribution throughout the system. This can cause an increase in harmonics at a point different from the capacitor location or source of harmonics. It may be desirable, as part of the joint utility-consumer checkout of interconnection facilities, to measure and document harmonics present in the bus voltage before and after applying load to the station. The harmonic content of the load current should also be recorded.

5.6.2 Grounding

The utility and the consumer normally construct station ground grids as required by ANSI C2-1987, National Electrical Safety Code [1], and recommended in IEEE Std 80-1986, IEEE Guide for Safety in AC Substation Grounding [21]. Generally these two grids are connected together at a minimum of two locations. The mode of system neutral grounding employed by the consumer may differ from that used by the utility. Some consumers prefer to employ resistance grounding. The mode of neutral grounding should be discussed and an agreement should be reached on the practice to be followed and on important concerns such as ground relay settings and surge arrester ratings. If any low-voltage conductors (such as ct or vt secondaries, dc control circuits, station service circuits, or load management control circuits) connect equipment located in the utility station to equipment in the customer facility, consideration should be given to the difference in ground potential that may exist during faults. If the consumer and utility grounds are not interconnected, such low-voltage circuits need to be properly treated to avoid possible equipment damage and personnel hazards from transferred potential. For additional information, see IEEE Std 80-1986 [21].

5.6.3 Ferroresonance

Ferroresonance is a phenomenon that can produce high overvoltages. It can occur when a series or a parallel resonant circuit is established between capacitance and a nonlinear inductance. One of the necessary conditions for series resonance can arise when the capacitance to ground of a cable or transmission line is energized in series with the magnetizing impedance of an ungrounded lightly loaded transformer winding. This can result from the open phase(s) of a broken conductor, a fuse operation, or a single pole switch opening. An example of parallel resonance can occur when a weak source is isolated with a lightly loaded feeder containing power factor correction capacitors. Ferroresonance cannot always be avoided; but steps can be taken to reduce the probability of its occurrence, such as locating switches and fuses close to transformers, use of grounded wye transformer connections, three-phase switching, and using high-speed voltage and frequency sensors to isolate consumer generation.

5.6.4 Voltage Considerations

The utility electric supply may be regulated or unregulated. In general, service from a distribution system will be a regulated supply, whereas service from a transmission or subtransmission system will probably be unregulated. Consumer substations served by unregulated systems may require compensation for the variations in supply voltage and for voltage drop caused by load changes. The method of compensation can be by load-tap changing transformers or by power factor correction capacitors.

Flicker is defined as the rapid change in voltage produced by arc furnaces, welders, and other pulsating irregular loads. In this case, the concern is not only the magnitude of the voltage change but also the frequency of occurrence. Limits of operation are normally specified for flicker-producing loads, and these may require the installation of facilities designed to limit the voltage variation.

6. Typical Utility-Consumer Interconnection Configurations

In the typical service arrangements that follow, such aspects as dependability, security, and ease of maintenance range from minimal to optimal. The consumer load requirements will strongly influence the degree to which each of these aspects are considered. Protective relaying systems for certain selected examples are described in detail in Section 9 of this guide. Note that this is only a limited selection and that numerous other service arrangements are in general use.

6.1 Single Supply-Single Transformer

This is a common form of utility-consumer interconnection. It consists of a single transformer connected to a single source. The consumer will generally have multiple feeders connected to the low-voltage side of the transformer. Supply from this configuration is subject to interruption upon loss of the supply source, line, or transformer.

Figure 1 is a basic single supply-single transformer interconnection. The high side fuse provides protection for transformer primary and secondary side faults, as well as backup protection for low side feeder circuits. Protective relays on the supply source breaker will protect for line faults and also provide backup protection for the high side fuse. A consumer outage will be necessary if maintenance is required on any of the system components other than the consumer feeder devices.

In Fig 2, the fused disconnect switch has been replaced with a circuit breaker. Protective relays, measuring high side current, can now be utilized to provide additional protection for the transformer and low-voltage bus. Again, the consumer is subject to an outage when maintenance is required.

The system design of Fig 3 allows the interconnection circuit breaker to be removed from service for maintenance without a consumer outage, although additional protective relaying will be required at the utility source to maintain acceptable transformer protection. A maintenance outage of the supply line or transformer will still cause a consumer outage.

6.2 Dual Supply-Single Transformer

Two or more full capacity supply lines will greatly enhance continuity of service. Because of its extensive exposure, the supply line is generally the least reliable component of the utility-consumer interconnection. Ideally, duplicate supply lines should originate from separate utility supply buses and be routed over separate rights of way. Each line should have the capacity to serve the consumer's total requirements if complete redundancy is required. A dual supply allows dead line maintenance to be performed without an interruption to the consumer.

Figure 4 illustrates a dual supply with two manually operated switches located at the consumer load bus. System configuration may require the supplies to be looped together (i.e., both switches closed) or operated as two radial sources with one of the switches open.

- Looped mode—This mode dictates that both switches be closed during normal operation. A fault anywhere on the supply lines will cause a consumer outage. The switches can be used to isolate the faulted section and restore service to the consumer load bus via the remaining supply line. Outage time may be somewhat lengthy while switching is done to isolate the faulted section. Looped mode operation generally provides the consumer with a stronger source.
- Transfer mode—In this mode, one of the switches at the consumer load bus is operated normally open. If a fault occurs on the supply line feeding the consumer, it can be isolated and service restored by closing the normally open switch. It is recommended that the normally open supply line remain energized at all times to ensure the availability of that source.

In Fig 5, motor operators have been added to the switches at the consumer load bus. This system also may be operated in either the looped or transfer mode. Sectionalizing systems are available that will automatically isolate a faulted line section and restore consumer load, reducing the outage time.

In Fig 6, the motor-operated switches are replaced with circuit breakers. Now the consumer is served with two supply lines with separate protective equipment. Note that circuit breaker disconnect switches are provided for maintenance purposes. Bypasses may also be added if a looped system must be maintained.

6.3 Dual Supply-Dual Transformer

The addition of a second transformer will also increase reliability. If each transformer is sized to carry total consumer load requirements, plant production need not be affected by the loss of a single transformer. The addition of the second transformer allows flexibility in the operation of the low-voltage bus. With two supply sources now available, it is possible to selectively choose where plant feeders are to be connected.

Figure 7 illustrates a dual-supply, dual-transformer configuration. Operating the system with the low-voltage buses isolated from each other allows for improved transformer protection, minimizes fault current levels, and provides for the isolation of plant equipment.

If the low-voltage buses are not isolated but are operated in parallel, the transformer fuses or other relays should be able to respond to faults in both transformers if suitable protection is not available with the low-side overcurrent devices. Each transformer provides a path for fault current in the other unit. Because the impedance of both transformers limits fault current, it is difficult to choose a fuse or overcurrent relay that will provide adequate protection for both transformers and still be able to coordinate with low-voltage feeder protection. It is not a problem if the transformer's low-voltage sides are isolated from each other.

Maximum short-circuit fault current on the low-voltage system will approximately double if the buses are operated in parallel. This may be an important consideration when choosing the interruption rating of the feeder's overcurrent devices. Operating the buses isolated may allow application of lower rated, and thus less expensive, feeder overcurrent devices. Voltage transients from feeder or bus faults are less likely to impact total plant operation if the low-voltage buses are normally isolated. This may be particularly advantageous if there is voltage-sensitive equipment.

Improved transformer protection and service reliability may be obtained with the addition of high-side transformer circuit breakers or circuit switchers and differential relays (see Fig 8). With this configuration, a supply line fault does not require an outage of a transformer.

Operation in this mode will provide continuous service to all consumer load in the event of a transformer fault. Careful consideration of plant operation is necessary to determine the normal position of the high-voltage tie breaker. Bypass switches will be required on the supply-side breakers if supply lines A and B are to be looped together at all times. The relay systems should provide adequate protection for this situation.

Figure 9 uses a ring bus on the supply side of the intertie. With this system, transformer faults will not interrupt the remaining feed to the consumer or the connection between supply lines A and B. Maintenance may be performed on any of the supply-side breakers without the use of bypass switches. Service reliability to the consumer can be improved if sources and loads are alternately connected around the ring bus.

With this connection, the failure of a single breaker will not interrupt the total electric supply. The low-side buses may be operated in parallel as described in Fig 9. Again, careful consideration should be given to plant requirements to determine the optimum operating position of the low-side bus-tie breaker.

7. Brief Review of Protection Theory

7.1 Protection System Design Considerations

The philosophy in the implementation of any protection system should be to detect and isolate all failed or faulted components as quickly as possible, while minimizing disruption to the remainder of the electric system. This objective implies that a protection system should be dependable, i.e., operate when required; secure, i.e., not operate unnecessarily; selective, i.e., only the minimum required number of devices should operate; and fast, i.e., minimize hazards to personnel and damage to equipment. In addition, backup protection should clear any fault upon failure of the protective equipment in the primary protection system. These desired features can be achieved by properly designing the electric system and the protection schemes.

7.1.1 Zones of Protection

Any electric system can be divided into separate sections, or zones, through the application of interrupting devices (see Fig 10). Each zone consists of a specific type of electric facility with sensing devices at its boundaries. By proper application of sensing devices and protective relays, it is possible to detect faults within the zone and limit operation of the interrupting devices to those required to isolate the faulted component.

To ensure proper detection and clearing of faults that occur at the boundaries, zones are normally overlapped by connecting sensing devices and protective relays to overlapping current transformers.

Usually, the current transformers are located on both sides of the interrupting device; but they may be located on only one side. If this occurs, the interrupting device will be located in only one of the protective zones. Relative location of current transformers and interrupting devices must be carefully considered when designing the protective relaying.

If fuses are used, proper selection of ampere rating and speed will provide coordination.

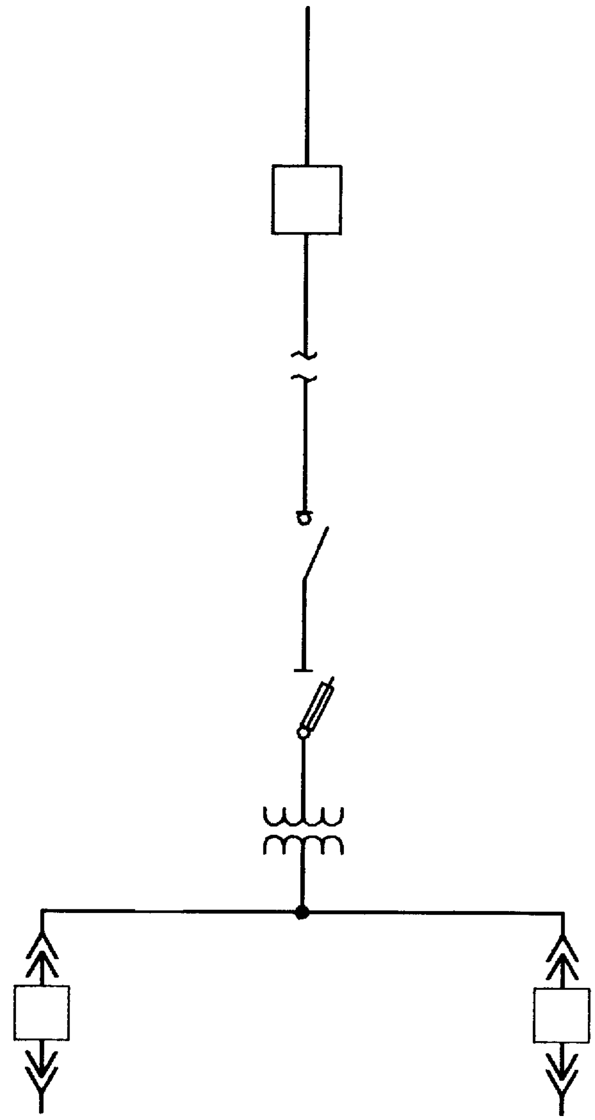

Figure 1—Single Supply-Single Transformer (transformer with high-side fuse)

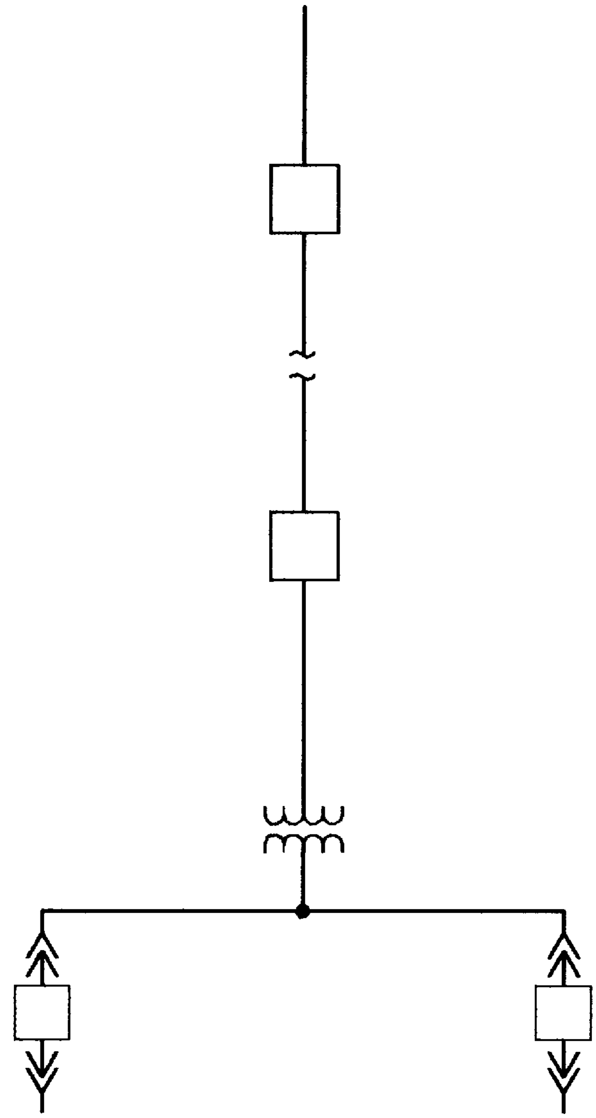

Figure 2—Single Supply-Single Transformer (transformer with high-side breaker)

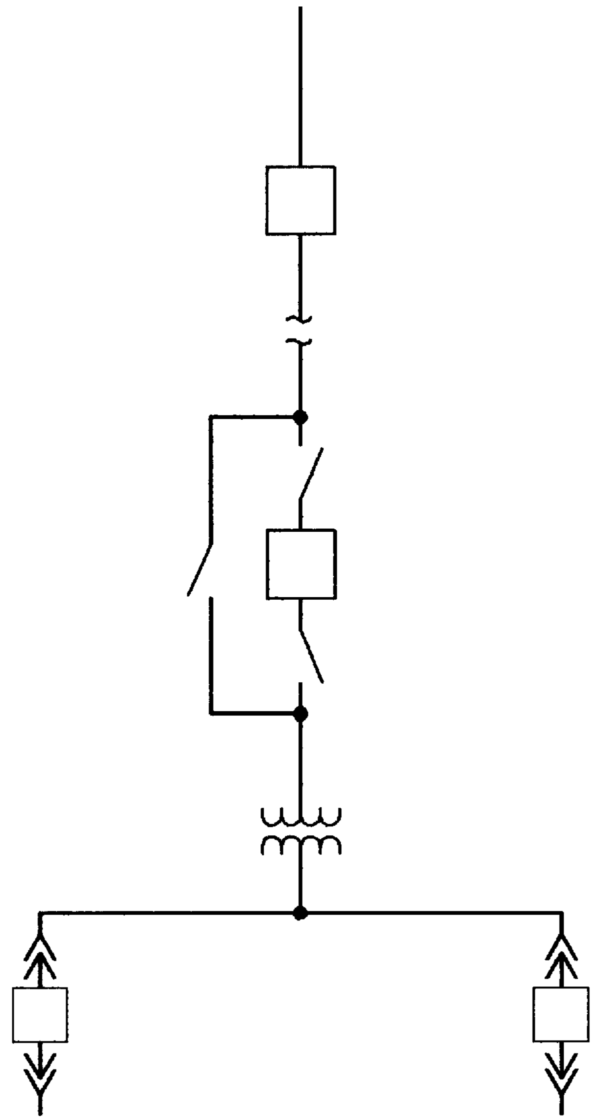

Figure 3—Single Supply-Single Transformer (transformer with high-side breaker and bypass switches)

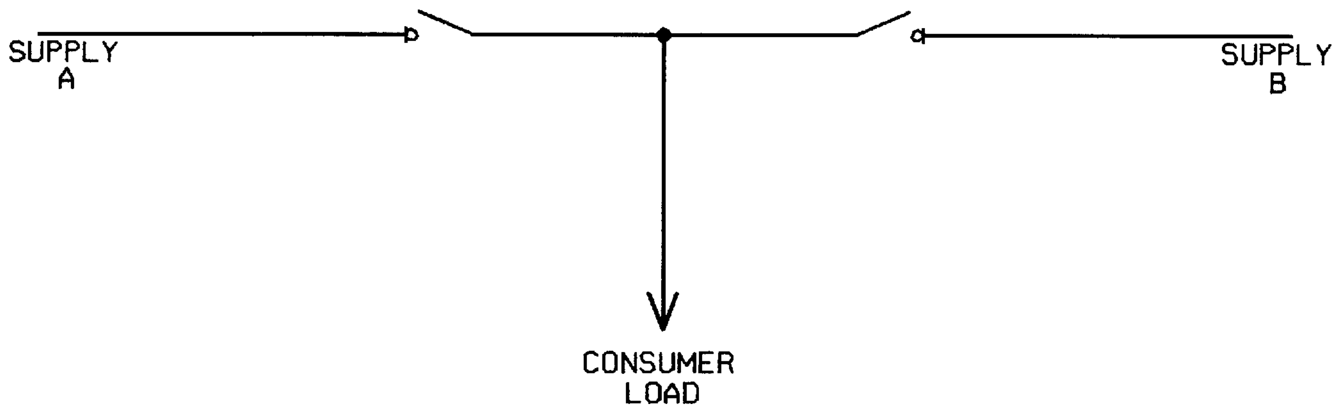

Figure 4—Dual Supply-Single Transformer (manually operated load break switches)

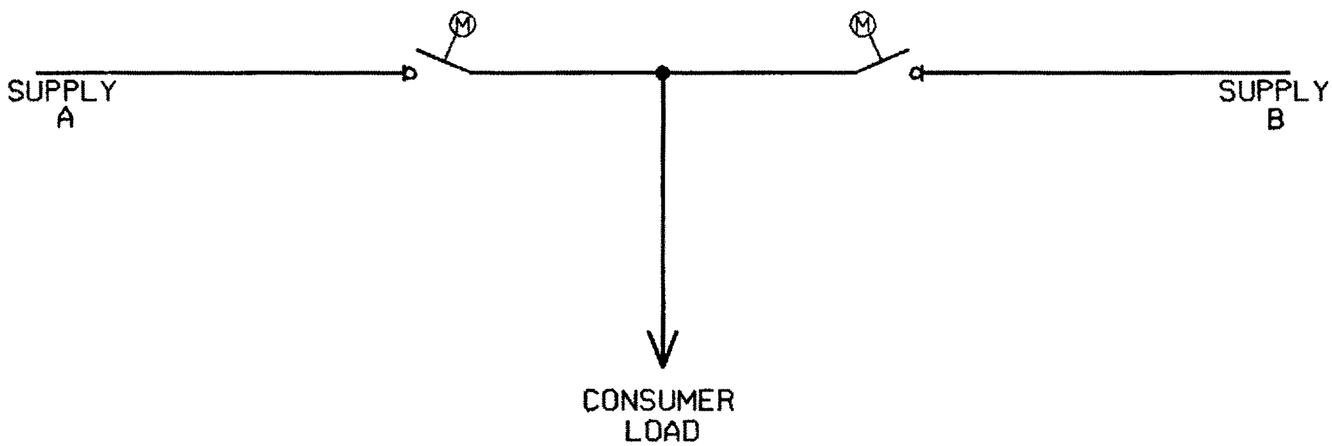

Figure 5—Dual Supply-Single Transformer (motor-operated load break switches)

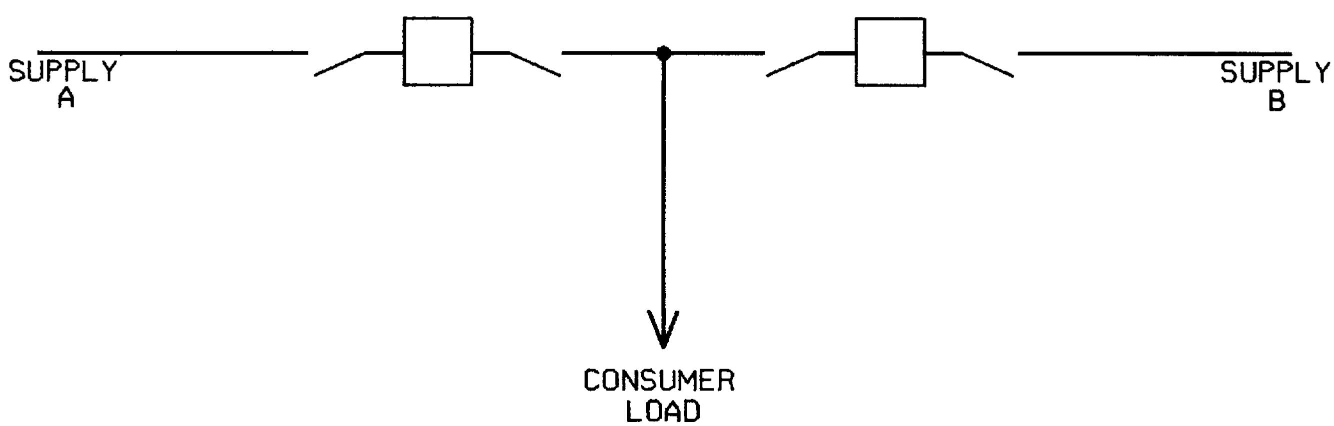

Figure 6—Dual Supply-Single Transformer (circuit breakers)

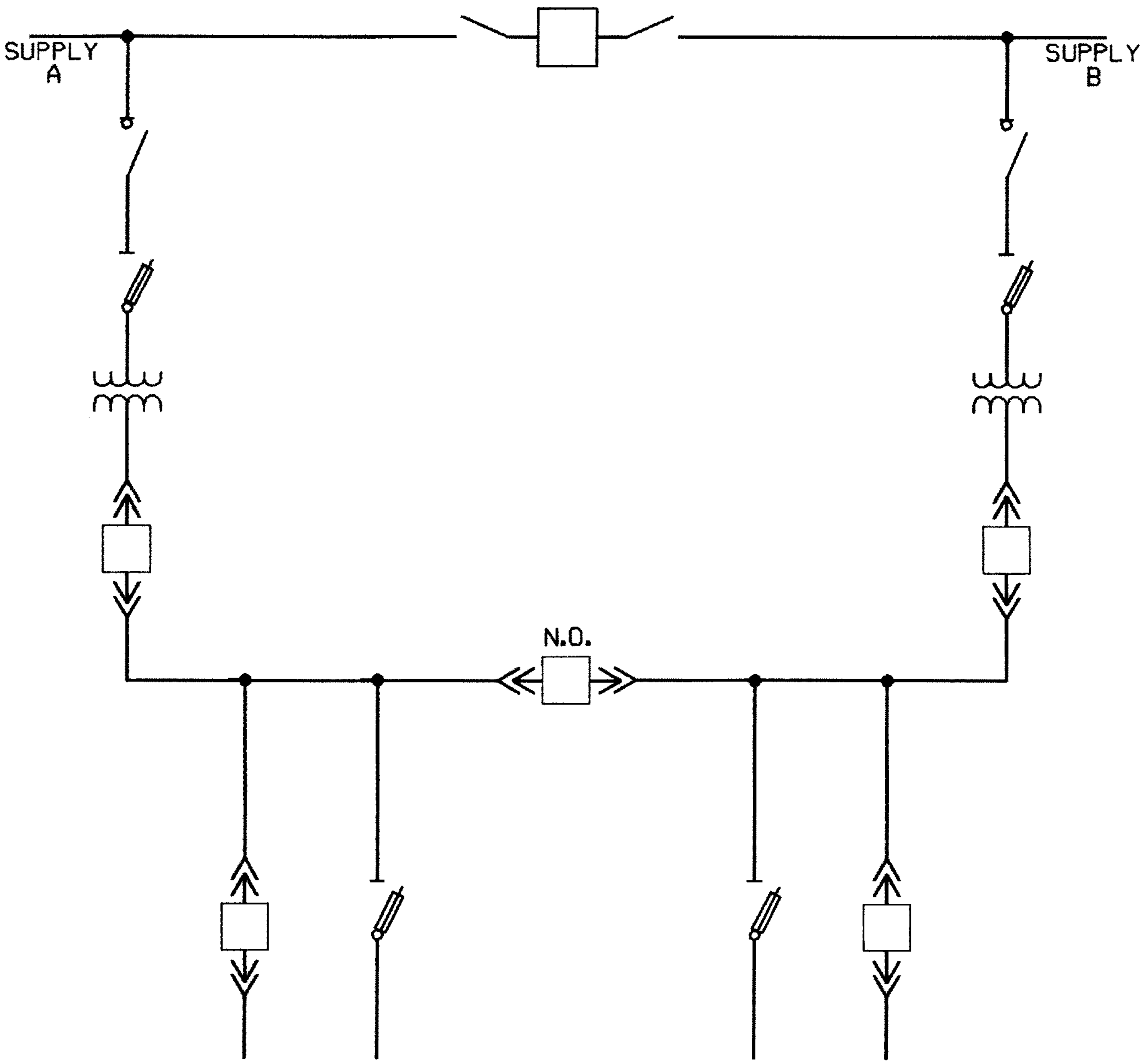

Figure 7—Dual Supply-Dual Transformer (single-supply circuit breaker)

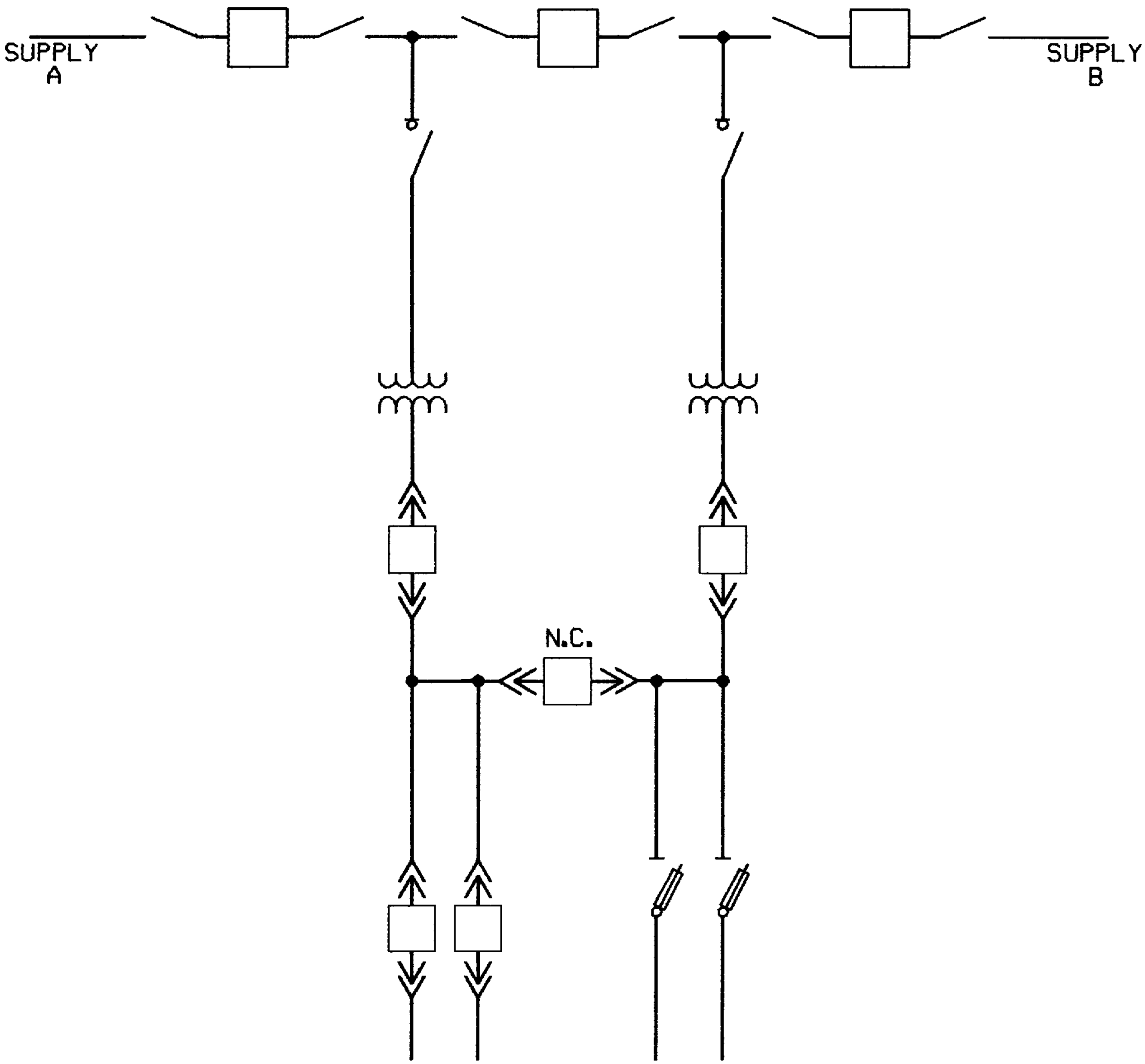

Figure 8—Dual Supply-Dual Transformer (multiple-supply circuit breakers)

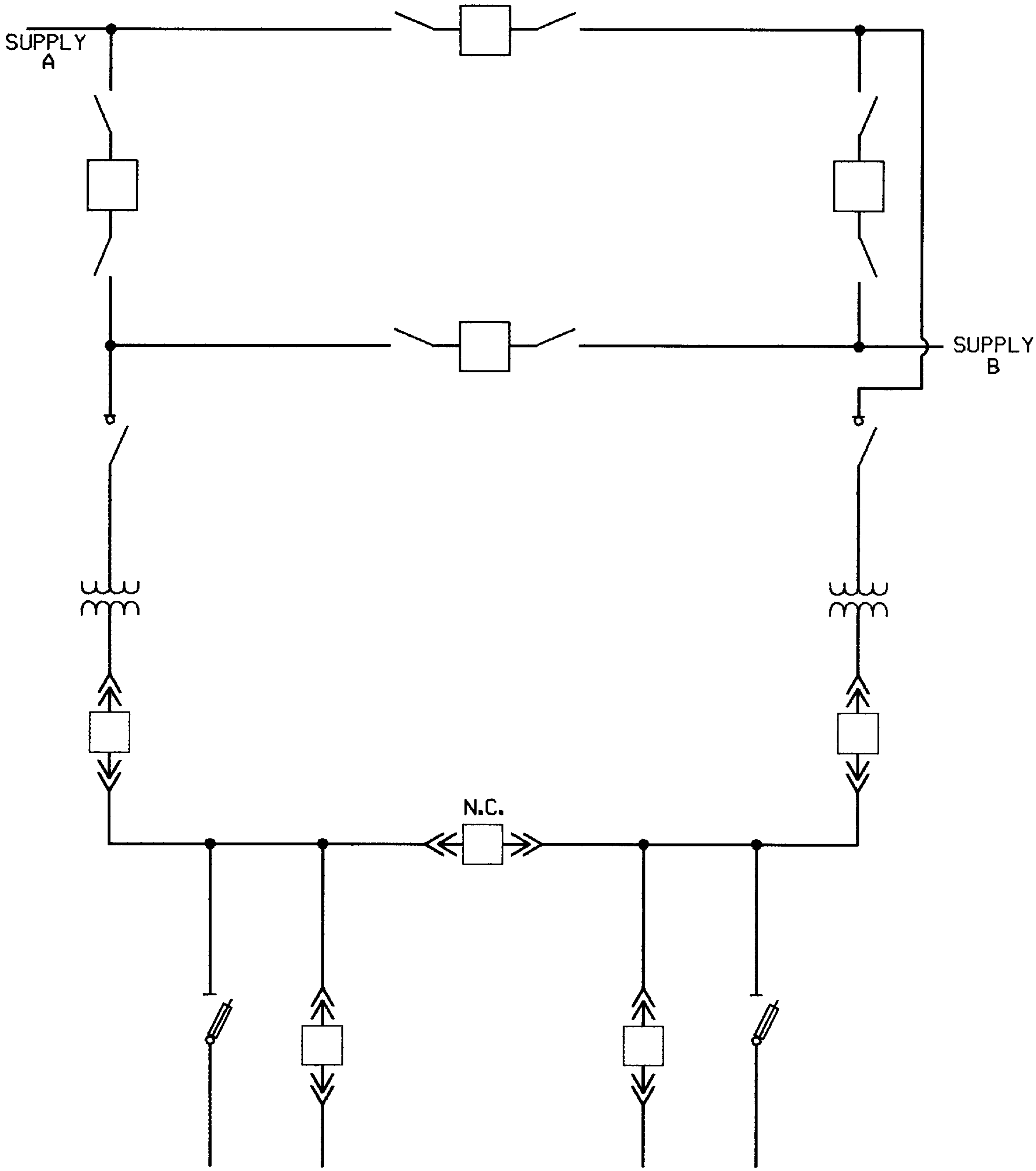

Figure 9—Dual Supply-Dual Transformer Ring Bus Configuration

7.1.2 Redundancy

The design of a protection system should allow for failures and for periodic maintenance of the interrupting devices, sensing devices, and protective relays. The importance of the electric service should dictate if backup or dual primary protection systems are required. Backup protection, particularly if it is located in the next zone (remote backup), is generally slower, since it should allow time for the primary system to operate. Remote backup may cause interruption to a larger portion of the electric supply system. Dual primary protection, if warranted, should include independent sensing devices, control circuits, and protective relays.

7.1.3 Fault Data

Protective relay systems measure the current, voltage, or a combination of current and voltage during fault conditions. Fault current magnitude, and the associated change in voltage, vary with the type of fault and with the location of the fault with respect to the sensing devices. Therefore, a study of the types of faults that can occur is suggested to ensure that the selected protection system can detect and isolate all faulted portions of the electric system. The types of faults that should be considered are: three phase, phase-to-phase, double-phase-to-ground, and single-phase-to-ground.

7.1.4 Fault Current versus Load Current

An important distinction can be made between normal load current, overload current, and fault current. In most cases, fault current exceeds normal load current by a factor of 2 or more. However, special consideration should be given to situations where load current is greater than fault current. A notable example of this is a ground-fault current lower than the normal load current magnitude. For this situation, the use of separate residual or ground fault relays is recommended. Phase overcurrent devices should not respond to maximum load current. Temporary overloads, such as motor-starting current, and the maximum circuit load should be considered when selecting and setting overcurrent devices. Chapter 2 of ANSI/NFPA 70-1987, National Electrical Code [20] and ANSI/IEEE 242-1986, Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems [15] cover this subject in greater detail.

7.2 Protection Systems Overview

It is not the intent of this guide to describe all of the application considerations for the fault interrupting device, sensing devices, and all types of protective relays that may be part of the utility-consumer interconnection. This section identifies some of the main considerations in the application of interrupting and sensing devices. Also, it includes a general discussion of the types and overall application considerations for specific protective relaying schemes used on the lines, transformers, and buses that typically comprise the utility-consumer interconnection. Section 9 of this guide provides a set of examples and related discussions of specific relaying application considerations.

7.2.1 Circuit-Interrupting Devices

Fuses are single-phase protective devices that combine sensing and interrupting functions into a single unit. Fuse operation is based on the magnitude and duration of current flowing in each phase of the circuit. Primary application considerations include the maximum load, the minimum and maximum fault current available, the operating time of the fuse relative to the operating time of protective devices on both the consumer and utility systems, and the effects of single-phase supply due to the operation of one fuse.

A circuit breaker is an interrupting device designed for normal switching functions as well as fault interruption. Circuit breakers offer considerable flexibility and are available in a variety of continuous voltage, current, and fault current interrupting ratings. Circuit breakers are usually equipped with separate electrically operated close and trip coils that can be controlled by any required protection and control package.

A circuit switcher is another type of interrupting device for load switching and limited fault interruption applications at higher voltages, usually 46 kV and above. Typically, they are used for switching and protection of transformers and station capacitor banks. Most circuit switchers employ an SF6 interrupter connected in series with a motor-operated disconnect switch. Control power for open and close operations may be either ac or dc depending upon specific application requirements. Circuit switcher fault interrupting capability is generally less than that of circuit breakers.

The bolted-contact switch is an interrupting device designed for application at 480 V. This switch, which can be manually or electrically operated, consists of movable blades and stationary contacts. These switches are designed specifically for use with ground-fault protection equipment and have a contact interrupting rating of 12 times their continuous rating. See 5.15 of ANSI/IEEE 241-1983, Recommended Practice for Electrical Power Systems in Commercial Buildings [14], for more detail.

A consideration in the application of these interrupting devices is the source of control power for the close and trip coils. A station battery is considered the most reliable source of dc control power, since battery output voltage is not affected by the ac voltage drop that can occur during short-circuit conditions.

7.2.2 Sensing Devices

Protective relays require low-magnitude current and voltage quantities proportional to those on the electric supply system. The standard ratings for protective relays in the United States are 5 A and 120 V, 60 Hz. These low-magnitude quantities are produced by current and voltage transformers.

Current transformers may be provided as part of a circuit breaker or transformer, or they may be separate devices. They are available in a variety of turn ratios and accuracy classes. Current transformer application requires consideration of available fault and load current magnitudes, secondary connections, and the effect of the burden of relays, meters, and other devices connected to the secondary windings.

Voltage transformers are also available in a variety of types, ratios, and accuracy classes. As with current transformers, the application of voltage transformers requires consideration of the voltage level to be measured, primary and secondary connections, and the burden of devices connected to secondary windings.

7.2.3 Protective Relaying Schemes

There are many types of protective relays and protection schemes available. This section addresses the functional application of protective relays to the primary areas, or zones that make up the utility-consumer interconnection.

Overcurrent relays are used for many protective applications. Operation is dependent on the magnitude, duration, and, in some cases, the relative direction of current in the circuit. These relays can be applied to protect lines, transformers, and buses. Their application may be complicated by changes in the fault current level, either due to fault type or supply system configuration changes. If improved speed of operation and selectivity with other protective relay systems is required, more complex protection schemes should be utilized.

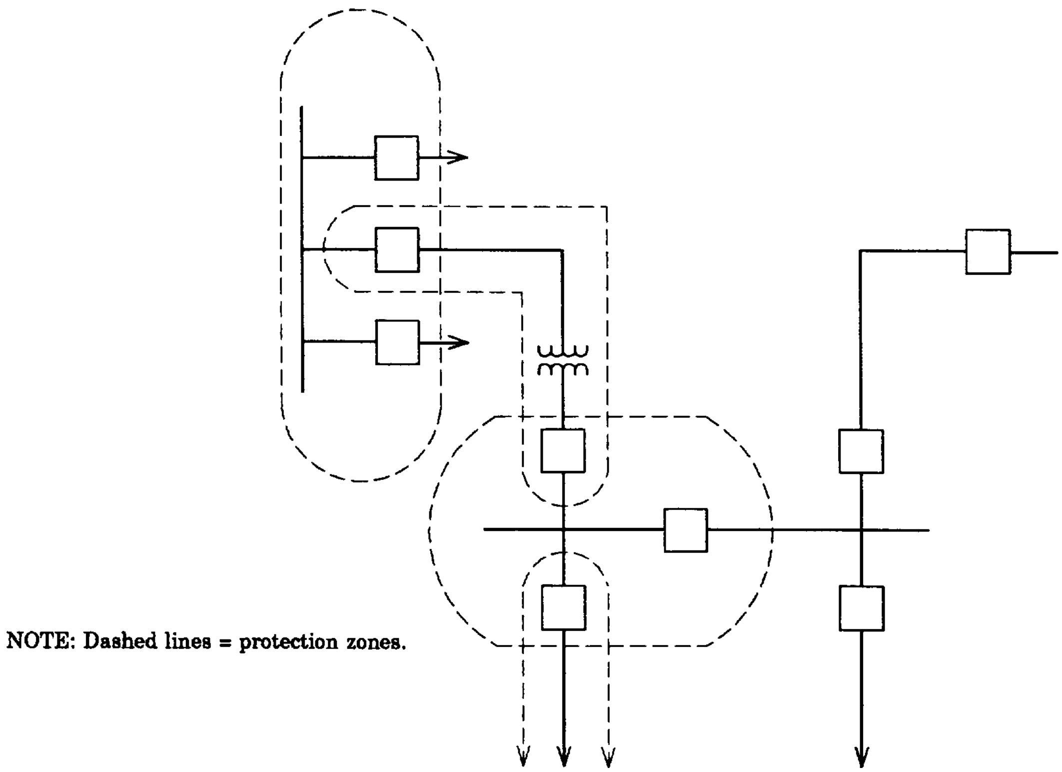

Figure 10—Protection Zones

For line protection applications, particularly at higher voltages, distance relays are often used. These relays, which respond to the ratio of current and voltage, are generally used for network lines, that is, lines with a source at each end. Impedance can be used as a measure of distance along a transmission line, thus the term *distance relays*. They offer selective high-speed protection, directional sensitivity, and the ability to be applied in areas with low-fault current/load current ratios.

For lines that require high-speed simultaneous clearing of all terminals, relays are used in pilot protection schemes that combine the protective relays with a communication link between line terminals. The communication links commonly used are power line carrier, microwave, fiber optics, pilot wire, and leased telephone lines. These pilot relay schemes provide high-speed operation for faults anywhere on the protected line section.

For bus and transformer protection, differential relays are often applied. Differential relay schemes establish a definite zone of protection, and they can be designed for high-speed response to faults within the zone of protection while refraining from operation for faults outside the zone.

7.2.4 Consumer-Owned Generation

The protection of generators is covered in other ANSI standards (see Section 4). However, the presence of consumer-owned generation will affect the protection of the interconnection, since power may flow back to the utility from consumer generation during normal operation, as well as under fault conditions. The contractual agreement between the consumer and the utility should dictate the modes of acceptable operation. Protection and control schemes applied to these interconnections should allow for all acceptable modes of operation. They should be able to detect faults on the utility system and in the interface substation, and they should ensure that the consumer (or his generator) is promptly disconnected from a faulted circuit.

8. System Studies

8.1 Types of Studies

Studies of an electric system should be conducted to provide the utility and the consumer with information regarding normal and abnormal conditions on the system. The two studies normally performed to determine requirements for design of the protection system are the short-circuit study and the stability study. These studies provide fault current magnitude; required clearing time data; data needed for proper selection of equipment, such as current transformers, interrupting devices, and protective relays; and data required for calculating the settings of protective devices.

Fault current data is required by the utility and the consumer for all protective device applications. The utility should provide the consumer with the minimum and maximum three-phase and phase-to-ground short-circuit duty (and associated *X/R* ratios) at the consumer's point of service for initial conditions (and any future conditions). Short-circuit contributions from consumer-owned generators and motors should be provided by the consumer. This information should be expressed in a form such that it is possible to determine the utility contribution alone.

Load flow studies are essential prior to performing stability studies; they are also important if there are multiple connections between the utility and the consumer. Stability studies that take into account system dynamic characteristics are typically performed by utilities when specific major changes occur in generation levels or transmission system configuration. The installation of a consumer facility with significant generation or load may justify a stability study of the new electric system configuration. A consumer who is adding generation or large synchronous motors may need to perform his own stability study.

Other studies may be required because of a consumer connection to a utility system. Utilities may perform load flow studies in order to determine the best method of supply, and to identify changes to their facilities or operating practices that may be required due to a large consumer installation. In some cases, a transient analysis study may be required to determine the impact of a change in the switching sequence for energizing or reclosing a transmission line or transformer, or because of the installation of capacitors or reactors. The application of underfrequency relays (for load shedding, or as protective devices for steam turbine generators or motors) may require a special study to determine the frequency variation and decay rate associated with particular system disturbances. Even if special studies are performed at the time of each utility-consumer interconnection, the database used for planning and operating studies should be updated as new facilities are installed, so that the cumulative effect of numerous interconnections will be considered in future studies.

8.2 Required Data

The basic data required for all electric system studies is the positive, negative, and zero-sequence impedance values of each system element including generators, transformers, motors, cables, and lines. For generators and synchronous motors, transient and subtransient reactances are also required. The most common method of presenting this required data is in per unit or percent.

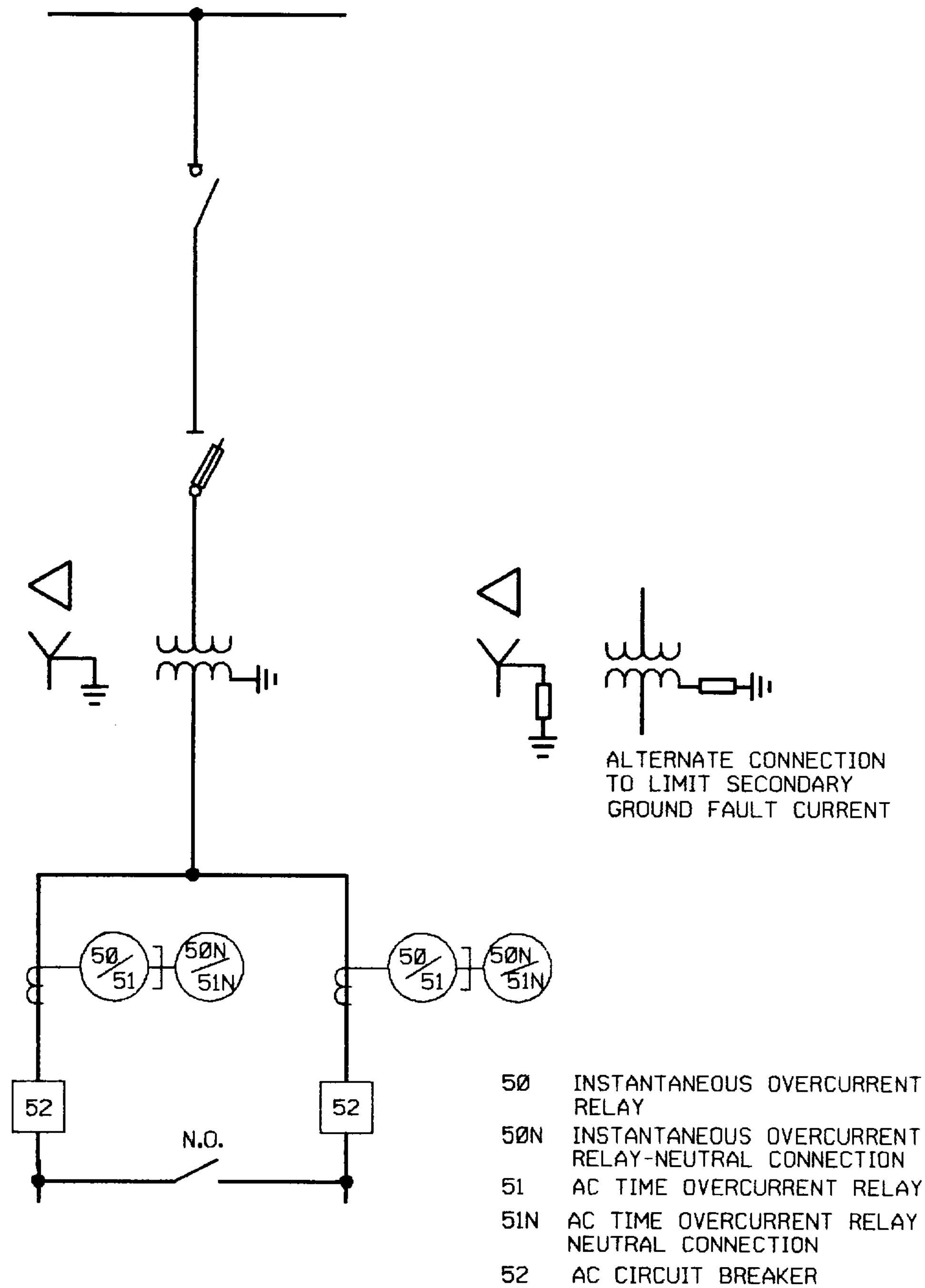

Figure 11—Single Supply from a Remote Utility Substation (single-transformer/single-bus configuration)

The required data is often shown on a one-line diagram covering all associated facilities.

8.3 Performance of Studies

Essentially, all system studies are conducted with computers using generalized application software. The type and complexity of studies to be performed will generally determine who will conduct the study.

Regardless of who performs the study, any results that impact upon the design or operation of the interconnections should be clearly communicated to the other party.

9. Interconnection Examples

This section provides four examples of interconnection protection of varying complexity. The figures utilize ANSI/IEEE 315-1975, Graphic Symbols for Electrical and Electronics Diagrams [16], and ANSI/IEEE C37.2-1987, Standard Electric Power System Device Function Numbers [3].

9.1 Single Supply from a Remote Utility Substation

See Fig 11 for a detailed look at this interconnection.

9.1.1 General Description

The utility supply voltage will vary depending upon availability and consumer requirements.

The consumer transformer is connected delta high side, grounded-wye low side. A fused disconnect switch provides three-phase switching and protection for the transformer, as well as physical isolation of the transformer during maintenance.

The consumer voltage may range from 480 V to 34.5 kV. A normally open feeder bus-tie switch is included to facilitate low-side circuit breaker maintenance.

9.1.2 Transformer Protection

Several factors are involved in selecting the transformer high-side fuses.

1) In general, the voltage rating of the fuse should be equal to or greater than the system phase-to-phase voltage. Solid material expulsion-type fuses are not “voltage critical” and may, therefore, be applied on systems rated less than the voltage rating of the fuse. In contrast, current-limiting fuses, which are available in ratings through 34.5 kV, inherently develop an overvoltage during fault-current interruption. This overvoltage typically restricts application of current-limiting fuses to the same system voltage class as the maximum voltage rating of the current-limiting fuse.
2) The fuse interrupting rating should be equal to or greater than the maximum anticipated fault duty including possible utility system expansion.
3) The fuse continuous current rating should be equal to or greater than the maximum anticipated emergency loading of the transformer. Note that the overload capability of power fuses may vary from 0% to 40% with different fuse types and with different ampere ratings of the same fuse type.
4) The fuse ampere rating and melting time current characteristics should be selected to provide optimum transformer protection as well as to coordinate with the low side as well as upstream protective breaker relaying or fuses, taking into account the effect of ambient temperature and preload (load current heating). In the interest of keeping the fuse size to a minimum for faster fault clearing, it may be necessary to accept fuse melting along with tripping of the low-side breaker for faults near the maximum available. For further information, refer to ANSI/IEEE C37.91-1985, Guide for Protective Relay Applications to Power Transformers [6]. If two transformers are involved, as in Fig 7, the fuse size and relay setting or fuse coordination should be selected based on the normal maximum loading level of both transformers. Coordination with the low-side breaker may be sacrificed under emergency loading conditions with one transformer out of service.

Primary fusing as the only means of transformer protection may not be recommended when the secondary ground-fault current is limited by the use of low- or high-resistance grounding of the neutral. This is because the primary current resulting from a phase-to-ground secondary side fault may not be sufficient to melt the fuse. If low-resistance grounding is used, several relay schemes can be employed to clear a ground fault between the transformer and feeder breakers, or beyond the feeder breakers if one fails to open. All of these use a neutral current transformer and overcurrent relay.

Relay trip output can be arranged to do one of the following:

- Close a high-side grounding switch to force tripping of the remote utility breaker.
- Open a high-side motor-operated switch that is rated to interrupt such faults.
- Transfer trip the remote utility breaker.

9.1.3 Transformer Low-Side Bus and Feeder Protection

The fuse provides protection for the transformer against high-side, as well as low-side, faults. It will also provide limited backup protection for low-side feeder relays and breakers.

Feeder phase protection is provided by non-directional instantaneous and time overcurrent relays. The purpose of the instantaneous relays is high-speed detection of close-in faults. Coordination may be difficult, if not impossible, on short feeders where fault current magnitude variation is minimal. The time overcurrent relays should coordinate with the largest protective device on the feeder. The time current characteristics of the relays should be selected accordingly. For coordination with branch fuses, the very inverse or extremely inverse time characteristic should be selected. Relay pickup should be greater than the expected full load current on the feeder. It is also important to check coordination of the time overcurrent relay with the transformer high-side fuse. Under special situations, when the load side tie switch is closed, coordination should be reviewed. The phase relay pickup should be high enough to carry the load of both feeders and still provide adequate fault protection while maintaining coordination with the high-side fuse.

Feeder ground-fault protection may be provided by nondirectional instantaneous and time overcurrent relays. A ground relay, connected in the neutral circuit, is not sensitive to balanced three-phase load current. Only currents resulting from an unbalanced load, if a four-wire system, or unbalanced faults involving ground will flow in the ground relay. Thus, feeder full load need not be a direct consideration when determining relay pickup. The following are two different methods for setting ground relays:

1) Maximum coordination—The ground relay has a setting identical to that of the phase relays. This ensures the same degree of coordination with downstream protective devices as with the phase relay. The ground relay will provide redundancy in the event of phase relay failure for a line-to-ground fault.
2) Maximum ground-fault sensitivity—The ground relay instantaneous and time overcurrent pickup may be set much lower than phase relay pickup. This provides sensitive protection for ground faults; but it may also result in feeder outages on a four-wire system that would normally be cleared by downstream protective devices. For greater sensitivity, the ground relay may also be set with a time overcurrent pickup of about one-half that of the phase relay but with high-time dial setting so as to coordinate with downstream fuses over a reasonable fault current range.

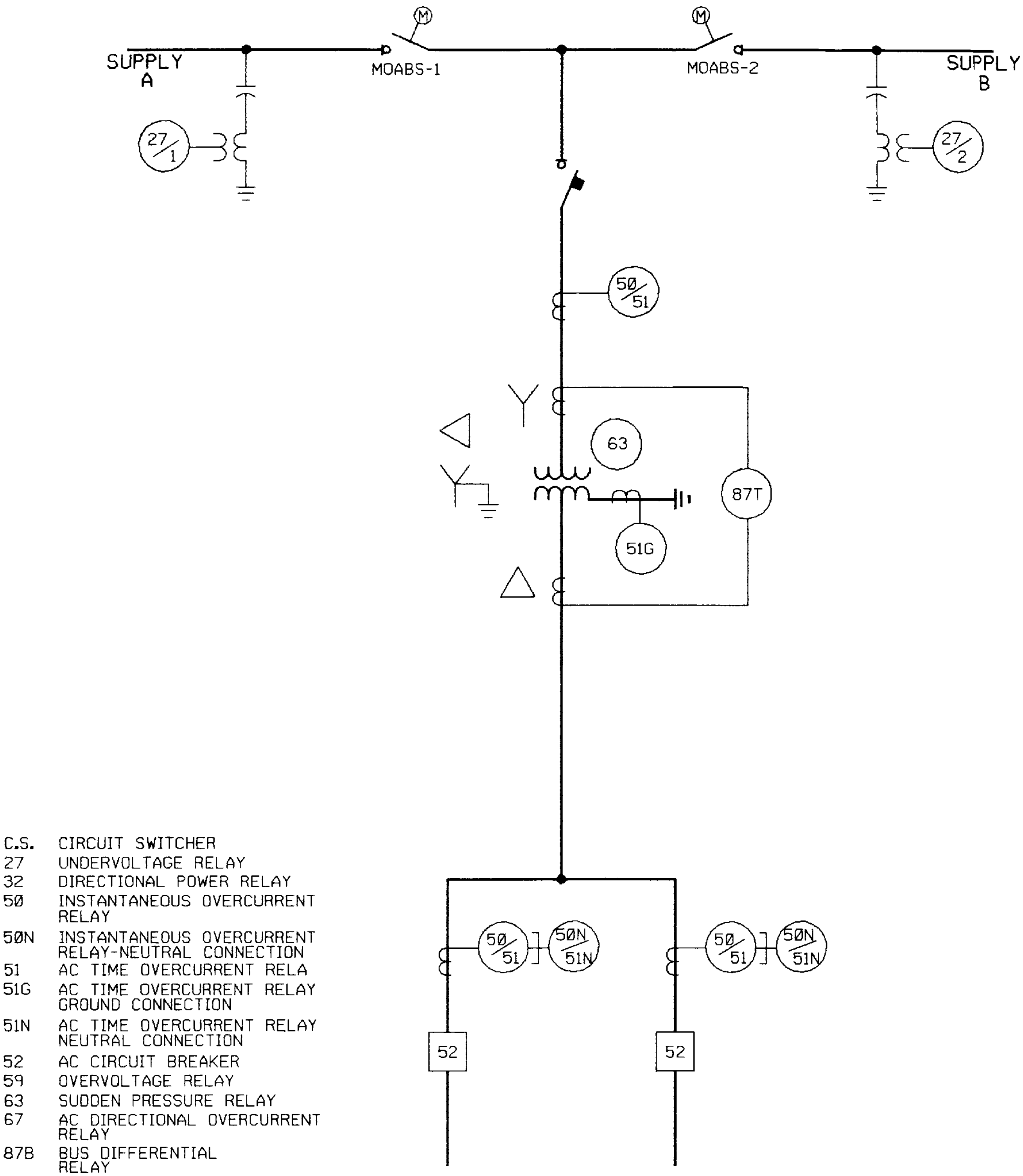

Figure 12—Dual Supply from a Remote Utility Substation (single-transformer/single-bus configuration)

9.1.4 Protection of the Supply Line

Different supply voltage levels generally dictate different levels of utility line protection. Most of these systems will trip instantaneously for all line faults. This instantaneous relaying may reach into the consumer's transformer, but not completely through it. Ideally, transformer faults that are detected by instantaneous line relaying should permit the transformer fuse to operate as well. This allows for line reenergization and easy fault location. Transformer isolation in this manner may not always be possible, particularly if the utility system limits ground-fault levels, either by design or due to a weakly grounded system.

The supply line may also be protected with time-delayed relays. These relays may reach completely through the transformer, depending upon other relay setting restraints on the utility system. If the relays do respond to low-side faults, coordination is necessary with the transformer fuses.

9.2 Dual Supply from a Remote Utility Substation/Single-Transformer Configuration

See Fig 12 for a detailed look at this interconnection.

9.2.1 General Description

The utility supplies may come from a variety of sources. Section 6.2 discusses alternate configurations. The motor-operated air break switches (MOABS) provide for automatic load transfer of the utility sources. The transformer size will typically justify application of a high-side circuit switcher and protective relays.

9.2.2 Transformer Protection

Faults in the transformer should be detected by transformer differential relays (87T) and a sudden pressure relay (63). These relays will trip the circuit switcher through a lockout relay. The combination transformer differential and sudden pressure relay scheme provides greater sensitivity than the fuse discussed in 9.1 (see ANSI/IEEE C37.91-1985 [6]).

9.2.3 Transformer Low-Side Bus and Feeder Protection

Phase overcurrent relays (50/51) are connected to current transformers located on the high-side of the power transformer to provide protection for low-side bus faults. These relays also provide backup protection for the transformer differential relays and feeder breakers. The time-overcurrent unit (51) must coordinate with all downstream devices. The instantaneous unit (50) must not respond to low-side fault current levels to ensure coordination with feeder protection. This requires a setting of nearly 200% of the maximum low-side symmetrical three-phase fault current to avoid tripping for an asymmetrical fault. The relays trip the transformer circuit switcher. It is recommended that these relays trip through a separately fused lockout relay.

An overcurrent relay (51G) is added to the transformer neutral to improve low-side ground-fault protection, since phase overcurrent relays (50/51) located on the transformer high side are relatively insensitive to these faults. This relay must also coordinate with feeder ground-fault protection. The ground relay will trip the transformer circuit switcher through a lockout relay. Feeder phase and ground-fault protection has been previously described in 9.1.3.

9.2.4 Protection of the Supply Line

The relay system employed by the utility to protect the supply line will trip instantaneously for most line faults. Transformer faults in the high-side winding may be of sufficient magnitude to trip the remote utility breaker. In this case, transformer relaying should also respond, isolating the transformer from the supply line, that will then be available for reenergization.

The motor-operated air break switches (MOABS) may be operated in the looped or transfer mode, which are described below:

1) Looped mode—In this mode, MOABS-1 and MOABS-2 are normally closed. Undervoltage relays (27-1, 27-2) monitor line potential for each switch. The supply line circuit breakers (not shown in Fig 12) provide the necessary interrupting capability for line faults. To properly sectionalize a fault, coordination between the MOABS relays and those controlling the supply line breakers is essential.
   Assume that a fault occurs between supply line B and MOABS-2. Supply line breakers at sources A and B will interrupt the fault. The line circuit breakers may be reclosed, assuming the fault is not permanent in nature. If permanent, both circuit breakers will trip again and remain open long enough for MOABS-1 and MOABS-2 to open when both undervoltage relays 27-1 and 27-2 drop out. These relays must be set with sufficient delay to allow the single reclose attempt. After the MCABS are open, the supply line circuit breakers are allowed an additional reclose. Source A breaker will close successfully; but source B breaker will trip and remain open.

Upon reenergization from source A, undervoltage relay 27-1 will initiate a return-of-potential timer to close MOABS-1. When MOABS-1 closes, service will be restored to the consumer. MOABS-2 will remain open until the fault is removed and the source B breaker is closed. It will then close via a return-of-potential timer associated with undervoltage relay 27-2.

2) Transfer mode—In this mode, one of the motor-operated air break switches is operated normally open, the other is normally operated closed. Both sources are normally energized. With an outage of the normal source, the load may be switched automatically to the alternate source.
   If the switches are not capable of interrupting load current, the operation of at least two undervoltage relays connected to different phases, with their contacts in series, is suggested to initiate transfer to avoid opening a switch underload due to a single relay failure, fuse operation, or line failure.
   The undervoltage relays should have a low set point to avoid operation for an open-phase condition unless the switches can interrupt load current; then it would be desirable to transfer for this condition. The transfer should be delayed until after the first reclosure of the source line breaker to avoid unnecessary transfer for temporary faults on the line. The time delay should be coordinated with the line reclosing to avoid switching at the time of a reclosure.
   Assume MOABS-1 is normally closed, and MOABS-2 normally open. Assume a permanent fault occurs between supply line A and MOABS-1. After the supply breaker has deenergized the line, MOABS-1 will open after undervoltage relay 27-1 has dropped out. Again, dropout delay is necessary if a single reclose attempt is required. Then MOABS-2 will close to pickup consumer load when MOABS-1 is completely open, if supply line B is energized (27-2 is energized).
   Logic is available to automatically transfer back to supply line A once the line is restored. This transfer is made with a close/open sequence to avoid service interruption.

NOTE — The switches must be suitable for separating the closed loop connection.

Looped or transfer sectionalizing sequences normally require between 15 and 30 seconds, although faster transfer can be achieved, especially at 34.5 kilovolts and below, where transfer times of 2 seconds or less are common. To prevent repeated tripping and lockout of both lines for a fault in the lead substation, control logic may be added to lock open both switches if the line voltage relay drops out within a few seconds of closing the associated switch.

9.3 Dual Supply from a Remote Utility Sub- station/Dual-Transformer Configuration.

See Fig 13 for a detailed look at this interconnection.

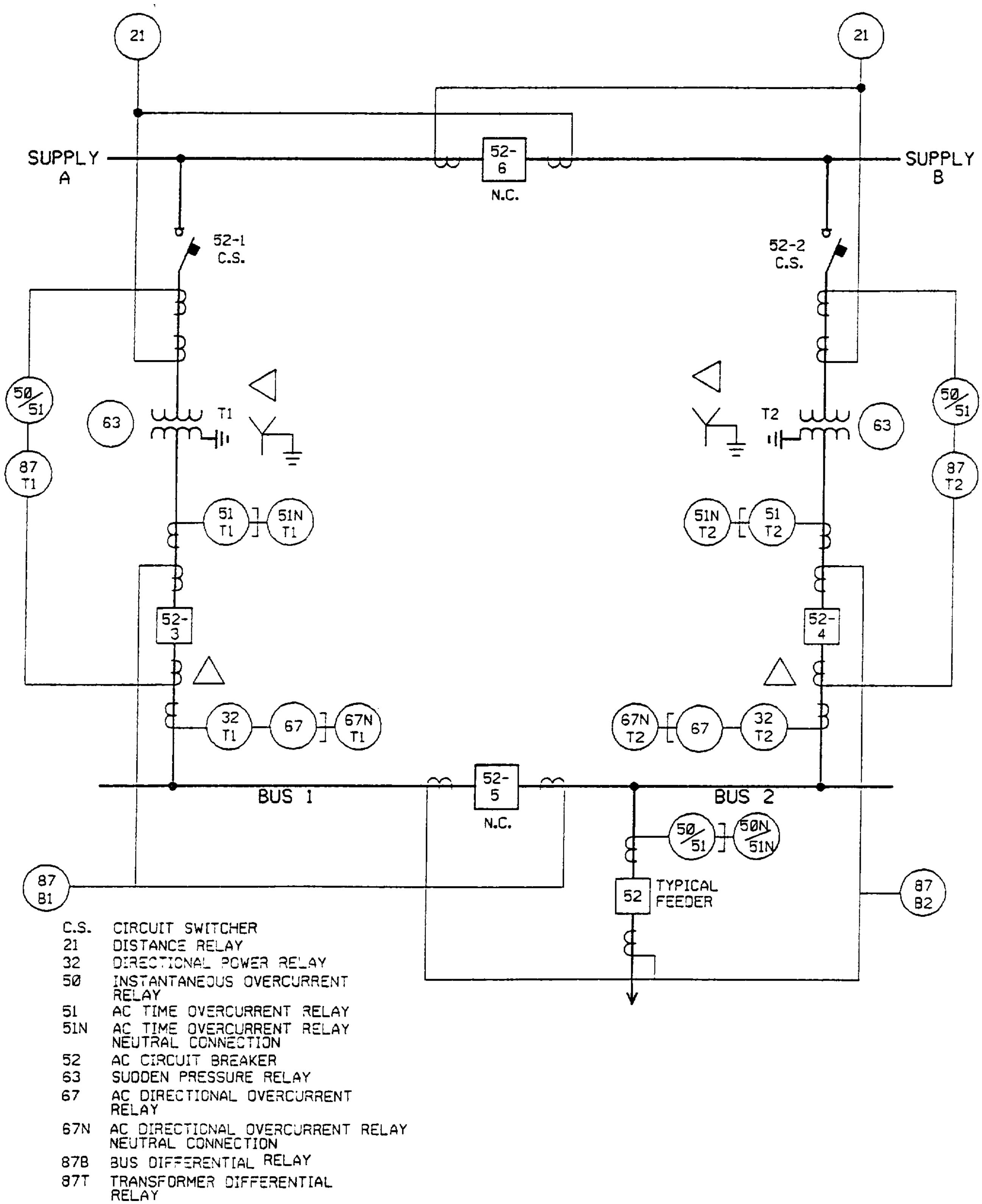

Figure 13—Dual Supply from a Remote Utility Substation (single high side breaker/dual-transformer configuration)

9.3.1 General Description

The utility dual supply may come from a variety of sources. Breaker 52-6 is common to both supply lines and consumer transformers.

Reliability is improved with the addition of a second transformer and consumer load bus. The addition of breaker 52-6 and appropriate protection eliminates a total consumer outage for a supply line fault.

Consumer service requirements will dictate the transformer's capacity. If full-capacity plant operation is critical at all times, each transformer should be sized to carry the total lead. Thus, the failure of a transformer or a supply line will not seriously affect plant operation.

Line breaker 52-6 and low-voltage bus-tie breaker 52-5 are both normally closed. When breaker 52-6 is open for maintenance, it may also be necessary to open breaker 52-5 to avoid unwanted power flow from one utility supply line to the other through the consumer transformers.

9.3.2 Transformer Protection

Differential (87T), sudden pressure (63), and high-side overcurrent (50/51) relays should be applied for transformer fault protection. Operation of any of these relays will open the transformer circuit switcher and low-side main breaker. It is recommended that these relays trip through a lockout relay (86).

9.3.3 Transformer Low-Side Bus and Feeder Protection

Each transformer low-side bus is protected with differential relays (87B1, 87B2). These will provide selective tripping, isolating the faulted bus from the system. Consumer lead connected to the other bus will remain in service. Additional bus and feeder backup protection is provided by nondirectional phase and ground overcurrent relays (51T1, 51NT1, 51T2, 51NT2) located on the low side of each transformer. These will be set with a delayed trip to allow sufficient time for the bus differential or feeder protection to operate.

A partial differential overcurrent relay system may also be used for low-side bus protection. Unlike a full differential, there is no current transformer input from the feeder breakers. This, in turn, makes the partial differential sensitive to feeder faults. Coordination with feeder relays is recommended. Current transformers with similar performance ratings are recommended. This system will provide bus-fault protection as well as backup protection for the feeder breakers.

9.3.4 Protection of the Supply Line

Each of the supply lines will be protected with a separate set of relays. It is necessary to parallel current transformers from transformer T1 and 52-6 for the relays protecting supply line A. Supply line B requires current transformer paralleling from transformer T2 and 52-6. This will ensure that all current flowing on each supply line is properly measured.

Current transformers should have similar performance characteristics when paralleled in this manner. The supply line relays trip breaker 52-6 and usually the associated transformer low-side breaker, rather than the transformer circuit switcher.

The specific type of line protection will vary depending on such factors as voltage level, consumer requirements, line configuration and length, and utility line protection standards. It is reasonable to expect a primary system that will respond to all line faults with little, if any, time delay.

A secondary protection system may be employed on each line to provide backup tripping if the primary system fails. Communication systems with the remote line breakers may be needed with one or both relay systems.

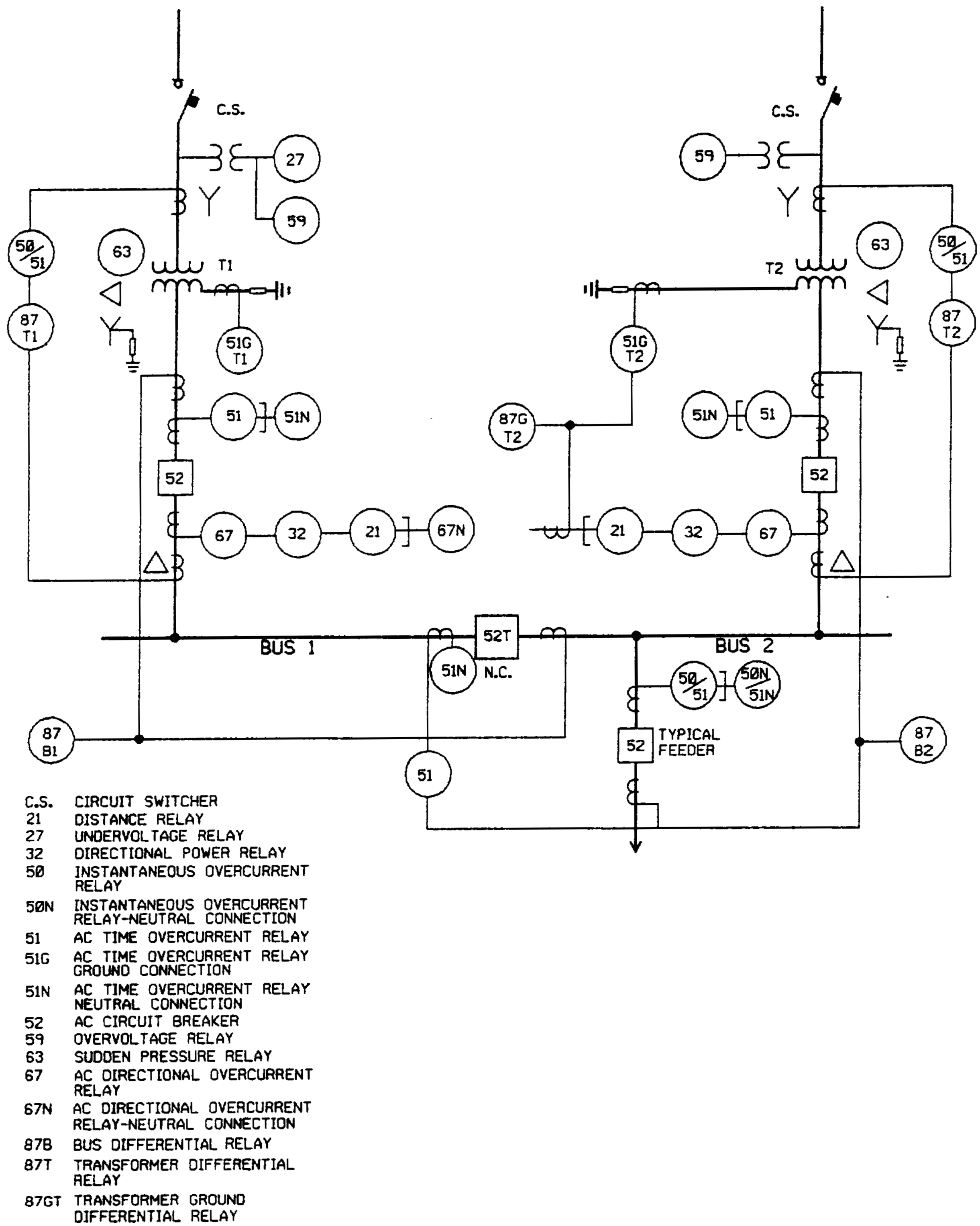

Figure 14—Dual Supply from a Remote Utility Substation (dual high-side circuit switcher/dual-transformer configuration)

A fault on supply line A will trip breakers 52-3 and 52-6. To avoid unnecessary power transfer through the consumer transformers, breaker 52-6 should be closed first after the fault is cleared. This will connect the two utility sources back together. Then breaker 52-3 can be reclosed, allowing transformer T1 to pick up the load.

Reverse power relays (32) added to each transformer will alarm or trip in response to backward power flow. The directional overcurrent relays (67) will provide limited backup protection for transformer and supply line multiple-phase faults. These relays are directionally polarized to permit settings below consumer feeder relays and the transformer's full-load rating.

With breaker 52-6 open, neither the supply line relays nor the directional overcurrent relays (67) will operate for transmission line-to-ground faults, since the transformer high-side windings are delta-connected. Reverse power relays (32) will be suitable for clearing ground faults if they can be set fast enough to coordinate with the line reclosing and if they are sensitive enough to respond to the in-phase component of transformer core losses.

If this is not the case, then zero-sequence overvoltage relays should be applied to the primary side of each transformer to detect ground faults on the supply lines when breaker 52-6 is open. See 9.4.4 for a more complete discussion of these relay systems.

9.4 Dual Supply from a Remote Utility Trans- former/Dual-Circuit Switcher/Transformer Configuration.

See Fig 14 for a detailed look at this interconnection.

9.4.1 General Description

Many variations may exist with this basic arrangement. The supply line voltage may be from 34.5 kilovolts to 345 kilovolts with corresponding variations in protection requirements. The lines may be supplied from a single bus or they may be network lines interconnecting utility substations.

Transformer capacity requirements will vary depending upon consumer load requirements. If full-capacity plant operation is critical at all times, each transformer should be able to carry the total load. In Fig 14, the transformer connection is assumed to be delta on the high side and resistance-grounded wye on the low side.

The low-side bus-tie breaker can be operated normally closed, assuming the utility supply lines originate from the same substation. If the supply lines originate from separate sources, undesirable power may flow from one transformer to the other requiring the low-side bus-tie breaker to be operated normally open. See 6.3 for additional comments concerning low-side bus-tie breaker operation.

9.4.2 Transformer Protection

Transformer differential relays (87T) and sudden pressure relay (63) provide primary protection for transformer faults. These relays trip both the circuit switcher and low-side breaker through a lockout relay (86).

With resistance-grounded systems, the fault current is often so low that transformer differential relays will not operate. This requires the addition of either low set ground directional overcurrent relays (67N) for each transformer breaker, or a ground differential overcurrent relay (87GT2) for the transformer/breaker zone to operate for ground faults in the transformer low-voltage winding or leads to the breaker. A backup ground overcurrent relay (51GT) in the transformer neutral also responds to reduced ground-fault current.

Current polarizing for these directional ground relays may be obtained from a current transformer in the neutral of the opposite transformer; but the ground relays will not respond to faults if the bus-tie breaker (52T) is open.

9.4.3 Transformer Low-Side Bus and Feeder Protection

Each low-voltage bus is protected with a set of differential relays. Each breaker connected to the bus requires a set of current transformers for the differential.

The transformer low-side breakers and the bus-tie breaker should be provided with phase time overcurrent relays (51) and ground time overcurrent relays (51N). The bus-tie relays should be set for the maximum load through the bus-tie breaker, with one transformer out of service, and should coordinate with the relaying on the feeder circuits and the transformer directional overcurrent relays (67). Likewise, the transformer breaker phase relays (50/51) should be set above the maximum load current of one transformer and should coordinate with the bus-tie and feeder breaker relays.

The instantaneous relays (50) should not respond to faults on the low side of the transformer. Note that no instantaneous overcurrent relays are permitted on the low-side breakers since time delay is required to coordinate with a downstream fault protective device.

Feeder phase protection is provided by nondirectional instantaneous and time overcurrent relays (50/51N). The instantaneous relays should not be sensitive to faults intended to be cleared by other downstream protective devices. Their function is high-speed detection of close-in faults. The time overcurrent relays should coordinate with the largest downstream protective device, and they should be set to carry the maximum expected full load on the feeder. Feeder ground protection is also provided by nondirectional instantaneous and time overcurrent relays (50/51N).

9.4.4 Protection of the Supply Line

The utility will normally provide instantaneous operation of the supply line breaker(s) for all line faults. This protective relaying will normally reach into the consumer's transformer but not through it. If the time-delayed phase relays on the supply line can detect low-side faults, they should coordinate with the transformer and low-side protective relays. Supply line ground relays will not operate for low-side faults because the transformer high-side winding is delta-connected.

High-magnitude faults in the upper portions of the transformer high-side winding may be expected to trip the line instantaneously. Normally, the transformer relays will also have sufficient time to operate. The fault can now be easily located and permits the isolation of the faulted transformer before the line is automatically reenergized.

Faults in the transformer, low-voltage leads or on the transmission line should also be cleared from the load bus as quickly as possible. Each transformer low-side breaker should have a set of directional overcurrent relays (67) “facing” toward the transformer and line.

These relays should have a pickup setting of 25% to 50% of the transformer rating and operate as fast as possible, but with enough time delay to coordinate with other relays on the utility source bus. Operating times should be agreed upon by the consumer and utility. A moderately inverse time characteristic is suggested for this application. The relays should have a thermal or continuous current rating equal to or greater than the maximum transformer load and the phase angle characteristic should prevent tripping on reactive power flowing from the consumer toward the utility. If this is a problem, consideration should be given to using relays with a 45° maximum torque angle instead of the usual 30° torque angle, or increasing the relay pickup setting.

Standard power directional relays (32) are not suitable for phase fault relaying since line faults will be nearly zero power factor due to the high X / R ratio of the transformer impedance. However, very sensitive power directional relays, designed to operate on the transformer exciting current losses may be applied to deenergize the transformer and prevent backfeed when the utility source is lost. This may occur as a result of a ground fault on the utility line where there is no ground-fault current contribution from the consumer substation due to the high-side delta-connected transformer winding. Time delay should be used with the sensitive power directional relays to avoid undesired tripping for reverse power flow during faults on the utility system.

In recent years, there has been a conscious effort made to reduce core losses in transformers. Some newer transformers may not have sufficient core losses for this scheme to work.

For greater reliability and minimum disturbance, the two supply lines should not originate from the same bus. If served from different substations, or with heavy utility loading over part of one or both lines, there may well be a small amount of power flow through the low-voltage bus (in one transformer and out the other) at times when the consumer load is light. This may cause an operation of the power directional relay monitoring the breaker with outgoing power. If this is objectionable, other methods, such as ground detection or transfer trip, may be used to detect loss of supply. The amount of load required on the consumer substation bus to avoid this undesirable operation depends on the connections and load flow pattern of the utility lines.

Ground faults on the utility line may be detected by a zero-sequence overvoltage relay (59) connected in the broken-delta secondary of voltage transformers on the high side of the power transformer. An alternative method is undervoltage and overvoltage relays (27, 59) connected to a voltage transformer that is connected one phase to ground. The voltage transformer will be exposed to full line-to-line voltage for some supply line ground faults. This should be considered when determining its primary voltage rating. The relays should be set for a safe margin below (80%–85% for relay 27) and above (115%–120% for relay 59) the normal line-to-ground voltage. The time setting should be independent of the voltage setting and should be just sufficient to coordinate with ground-fault relaying at the utility source bus.

If it is desirable to clear line faults more quickly in order to reduce the duration of the voltage dip on the load bus during phase faults, zone one (instantaneous) distance relays (21) should be applied if the line length and arrangement permit. A distance relay connected on the low side of the power transformer will include the transformer in its protective zone and, therefore, will include the transformer impedance in its setting. If the transformer size is relatively small or the line short, there may be little coverage of the line. Although not a transformer protective relay, a distance relay applied on the low side of the transformer may provide instantaneous relaying from the load bus for faults in the transformer or low-voltage leads. Greater line coverage can be obtained by using high-side voltage, so that impedance measurement is made from the transformer high-voltage terminals rather than from the low-voltage bus. Relay current should be obtained from the low-voltage breaker so as to retain the transformer and leads in the relay zone and allow the relay to operate for some transformer faults. The relay impedance measurement is made from the point of the voltage measurement; but direction is sensed from the point of current measurement. If distance relays are applied to a delta-wye transformer, using high-side voltage and low-side current, then a 30° phase shift must be introduced in either the voltage or current circuit to compensate for the 30° phase shift through the transformer. A delta-connected current transformer circuit will accomplish this and also avoid the possible misoperation of some impedance relays for low-side system ground faults.

The requirement for a high-side voltage source adds to the cost unless it is also used for other purposes, such as metering. Transformer bushing voltage devices are a relatively low-cost option, and may be used with bushings of 115 kV and above. Coupling capacitor voltage transformers (ccvt) may also be used. Resistance voltage devices may also be used but should be rated for line-to-line voltage, or operated at reduced voltage to avoid flashover of the protective gap at line-to-line voltage when one phase is grounded. If voltage transformers are used, consideration should be given to the possibility of ferroresonance when the line switch is open and the transformer energized from the low side. A voltage transformer secondary resistance burden will usually solve this problem.

The available voltage signal should be matched to the requirements of the protective relays, whether distance, directional overcurrent, or power directional. Auxiliary voltage transformers may be required in some cases.

If the two supply lines originate at the same remote utility substation, a fault on either line, or other line connected to the same utility substation bus, will result in depressed voltage at the consumer bus until that fault is cleared from both the utility and consumer buses. The consumer substation relaying may not function until after the first utility breaker has cleared. This is known as sequential clearing of the consumer's breaker. If high-speed and simultaneous clearing of the utility and consumer terminals is required, a direct transfer trip or other pilot relaying scheme may also be required. It is desirable to make the consumer breaker high-speed, trip-permissive upon the operation of a local fault detector to help minimize the possibility of a false trip by misoperation of the transfer trip scheme. However, it should be recognized that there may be no fault current flow through the low-voltage bus and an overcurrent fault detector may not operate until after the utility breaker has opened. Therefore, instantaneous voltage relays are required to obtain high-speed operation for any line fault.

Undervoltage relays, that are connected to measure line-to-line voltage on the high side of the power transformer, may be set low to minimize operation for low-side feeder faults where pilot relaying of the transformer is not desired. A zero-sequence overvoltage relay will operate for high-side line-to-ground faults and will not respond to low-side faults.

Three undervoltage relays may also be used for this permissive function. They should be connected line-to-neutral using high-side voltage to detect both phase and ground faults. A line-to-line fault collapses the line-to-neutral voltage only to 50% so the relay dropout setting must be well above 50% of the normal voltage. If the two lines are relatively short, both lines will have essentially the same voltage for a fault on either line, until the first breaker on the faulted line opens. The instantaneous undervoltage relays should be of a type rated for continuous operation.

If there is no generation present at the consumer substation, increased security against false tripping may be obtained by interlocking the line relaying of each breaker through a 52a switch of the opposite breaker. Therefore, when one transformer is out of service, the second cannot be falsely tripped. If, however, generation is present that requires tripping of a single-source transformer for a line fault, such an interlock cannot be used.

If the consumer station process requirements are critical, i.e., high-speed relaying is required, and the utility system does not otherwise require pilot relaying of the supply line, it may be necessary to negotiate with the utility to install pilot relaying in addition to the direct transfer trip of the consumer's breaker. However, it should be recognized that the addition of complex equipment increases maintenance requirements and the possibility of misoperation. Before such facilities are requested, the plant equipment should be checked to determine that it is not the cause of critical requirements.

Motors should have enough reserve capacity to ride through voltage dips during fault clearing. Motor starters or motor-starter controls should not drop out for momentary voltage dips that the motors and process can accept.