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# **IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems**

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of the  
IEEE Industry Applications Society**

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## Foreword

(This Foreword is not part of ANSI/IEEE Std 242-1986, IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems.)

At the October 1965 IEEE Industrial and Commercial Power Systems Conference in Buffalo, a paper was presented to the attendees by Tom Higgins and Norman Peach. That paper, resulting from a suggestion by A. C. Friel (deceased), proposed a new IEEE publication covering protection and coordination for industrial and commercial power systems. The first sentence of that paper states, "The proposed publication is intended for the plant electrical engineer with broad responsibilities for the plant electric system. He is familiar with the general principles of industrial system design, but has not had an opportunity to specialize in system protection." The Power Systems Protection Subcommittee (now Committee) of the Industrial and Commercial Power Systems (ICPS) Committee (now Department) accepted the responsibility of preparing the new book.

During the next seven years, thirteen of the fifteen chapter subjects were presented formally at sessions of IEEE conferences in which the ICPS Department participated. The last three years were occupied in reviewing and updating the papers and obtaining the necessary approvals. Copies of the manuscript were forwarded to each of the 74 ICPS Department members and approved through the usual IEEE Standards procedures.

The content of this standards document is evident from an inspection of the title of each chapter. The value of proper and adequate protection in electric power distribution systems has been emphasized by the provisions of the Occupational Safety and Health Act of 1969. Good coordination helps to ensure the availability of electric energy, a requirement of steadily increasing economic importance.

The ICPS Department will maintain this document current with the state of developing technology, and revisions of this book will be issued at reasonable intervals in order to maintain all chapters current with the rapidly changing techniques of circuit protection. Suggestions for improvements are welcomed. These should be directed to:

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

Recommended Practice for Grounding of Industrial and Commercial Power Systems (IEEE Green Book), ANSI/IEEE Std 142-1982.

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

Recommended Practice for Industrial and Commercial Power System Analysis (IEEE Brown Book), ANSI/IEEE Std 399-1980.

Recommended Practice for Emergency and Standby Power for Industrial and Commercial Applications (IEEE Orange Book), ANSI/IEEE Std 446-1980.

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

Recommended Practice for Electric Systems in Health Care Facilities (IEEE White Book), ANSI/IEEE Std 602-1986.

Recommended Practice for Energy Conservation and Cost-Effective Planning in Industrial Facilities (IEEE Bronze Book), ANSI/IEEE Std 739-1984.

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# Protection and Coordination of Industrial and Commercial Power Systems

Second Edition

## Protection and Coordination of Industrial and Commercial Power Systems

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# IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems

## 1. First Principles

### 1.1 Objectives

The objectives of electrical system protection and coordination are to prevent injury to personnel, to minimize damage to the system components, and to limit the extent and duration of service interruption whenever equipment failure, human error, or adverse natural events occur on any portion of the system. The circumstances causing system malfunction are usually unpredictable, though sound design and preventive maintenance can reduce the likelihood of their happening. The electrical system, therefore, should be designed and maintained in such a way as to protect itself automatically.

#### 1.1.1 Safety

Prevention of human injury is the most important objective of electrical system protection. Interrupting devices should have adequate interrupting capability and energized parts should be sufficiently enclosed or isolated so as not to expose personnel to explosion, fire, arcing, or shock. Safety has priority over service continuity, equipment damage, or economics.

These fundamental principles of safety have always been adhered to by responsible engineers engaged in the design and operation of electrical systems. ANSI/NFPA 70-1984 [4]<sup>1</sup> (National Electrical Code [NEC]) and state and local codes have prescribed practices intended to enhance the safety of electrical systems. In recent years an increased concern about safety has led to many studies resulting in detailed recommendations and regulations relating to electrical systems. Prominent among these are the regulations of the Occupational Safety and Health Administration (OSHA) of the United States Department of Labor. Engineers engaged in the design and operation of electrical system protection should familiarize themselves with the most recent OSHA regulations and all other applicable codes and regulations relating to human safety.

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<sup>1</sup>The numbers in brackets correspond to those of the references listed at the end of this chapter.

### 1.1.2 Equipment Damage Versus Service Continuity

Whether minimizing the risk of equipment damage or preserving service continuity is the more important objective depends on the operating philosophy of the particular plant or business. Some operations can afford limited service interruptions to minimize the possibility of equipment repair or replacement costs, while others will regard such an expense as small compared with even a brief interruption of service. The latter attitude is dominant in the process industries that have developed, from experience, practices in system design, operation, and maintenance that make it possible to operate with sustained overloads and reduce the likelihood of minor faults rapidly turning into major ones. A case in point is ungrounded systems that require special regard to maintenance, fault detection, and fault location to clear the first ground fault before a second ground fault occurs. In such installations this basic approach is applied throughout the electric system and all other systems impinging on the critical process. While generally considered obsolete, ungrounded systems are still preferred by some designers of electrical systems where process interruption is critical.

In industries where the process is not highly critical, electrical protection should be designed for the best compromise between equipment damage and service continuity. Keeping in mind that a prime objective is to obtain selectivity so as to minimize the extent of equipment shutdown in case of a fault, most operations probably would prefer that faulted equipment be deenergized as soon as the fault is detected.

### 1.1.3 Economic Considerations

The cost of system protection can never be ignored, and it will determine the degree of system protection that can be feasibly designed into a system. Many features can be added that will improve system performance, reliability, and flexibility, but at increased initial cost. On the other hand, failure to design into a system at least the minimum safety and reliability requirements will inevitably result in unsatisfactory performance with the probability of expensive downtime. Modifying a system that proves inadequate will be more expensive and in most cases less satisfactory than designing these features into a system at the outset.

## 1.2 Scope

This publication presents in a step-by-step, simplified, yet comprehensive, form the principles of system protection and the proper application and coordination of those components that may be required to protect industrial and commercial power systems against any abnormalities that could reasonably be expected to occur in the course of system operation.

Coverage is limited to system protection and coordination as it pertains to system design treated in ANSI/IEEE Std 141-1986 [1]<sup>1</sup> and ANSI/IEEE Std 241-1983 [3]. No attempt is made to cover utility systems or residential systems, though much of the material presented is applicable to these systems.

## 1.3 Planning System Protection

The designer of electric power systems has available several techniques to minimize the effects of abnormalities occurring on the system itself or on the utilization equipment that it supplies. One can design into the electric system features that will:

- 1) Quickly isolate the affected portion of the system and in this manner maintain normal service for as much of the system as possible and minimize damage to the affected portion of the system
- 2) Minimize the magnitude of the available short-circuit current and in this manner minimize potential damage to the system, its components, and the utilization equipment it supplies
- 3) Provide alternate circuits, automatic throwovers or automatic reclosing devices, or both, where applicable, and in this manner minimize the duration or the extent, or both, of supply and utilization equipment outages.

System protection encompasses all of the above techniques; however, this text deals mainly with the prompt isolation of the affected portion of the system. Accordingly, the function of system protection may be defined as “the detection and prompt isolation of the affected portion of the system whenever a short circuit or other abnormality occurs that might cause damage to, or adversely affect, the operation of any portion of the system or the load that it supplies.”

Coordination is the selection or setting, or both, of protective devices so as to isolate only that portion of the system where the abnormality occurs. It is a basic ingredient of well-designed electric distribution system protection and is mandatory in certain health care and continuous process industrial systems.

System protection is one of the most essential features of an electrical system and must be considered concurrently with all other essential features. There is too often a tendency to consider system protection after all other design features have been determined and the basic system design established. Such an approach can result in an unsatisfactory system that cannot be adequately protected, except by a disproportionately high expenditure. System protection is so basic to the safety of personnel and the reliability of electrical supply, and can have such profound influence on the economics of system design, that examining system protection needs only after all other design features have been determined is a completely unrealistic approach. It would, therefore, seem that any competent designer should thoroughly examine the question of system protection at each stage of the planning and incorporate in the final system a fully integrated protection plan that is capable of being coordinated and is flexible enough to grow with the system.

In laying out electric power systems the designer should endeavor to keep the final design as simple as would be compatible with safety, reliability, maintainability, and economic considerations. Designing additional reliability or flexibility, or both, into a system may lead to a more complex system requiring more complex coordination of the protective system. Such additional complexity should be avoided except where the requisite personnel, equipment, and know-how are known to be available to adequately service and maintain a complex electric power system.

## 1.4 Abnormalities to Protect Against

The principal abnormalities to protect against are short circuits and overloads. Short circuits may be caused in many ways, including failure of insulation due to excessive moisture, mechanical damage to electrical distribution equipment, and failure of utilization equipment as a result of overloading or other abuse. Circuits may become overloaded simply by connecting larger or additional utilization equipment to the circuit. Overloads may be caused by improper installation and maintenance, such as misaligned shafts and worn bearings. Improper operating procedures are also a cause of equipment overload or damage. These include too frequent starting, extended accelerating periods, and obstructed ventilation.

Short circuits may occur between two phase conductors, between all phases of a polyphase system, or between one or more phases and ground. The short circuit may be “solid” (bolted) or welded, in which case the short circuit is permanent and has a relatively low impedance. Or (under 250 V) the short circuit may burn itself clear, probably opening one or more conductors in the process. The short circuit may involve an arc having relatively high impedance. Such an arcing short circuit can do extensive damage without producing exceptionally high current. An arcing short circuit may or may not extinguish itself. Another type of short circuit is one with a high impedance path, such as the dirt accumulated on an insulator, in which a flashover occurs. The flashover may be harmlessly extinguished or the ionization produced may lead to a more extensive short circuit. These different types of short circuits produce somewhat different conditions in the system. Electric systems should be protected against the highest current short circuits that can occur, keeping in mind, however, that this maximum fault protection may not simultaneously provide adequate protection against lower current faults that may involve an arc and that are potentially very destructive.

Other sources of abnormality, such as lightning, load surges, and loss of synchronism, usually have little or no effect on system overcurrent selectivity, but should not be ignored. They usually can be best handled on an individual basis for the specific equipment involved, such as transformers, motors, generators, etc.

Reference should be made to texts dealing with these problems.

## 1.5 Basic Protective Equipment

The isolation of short circuits and overloads requires the application of protective equipment that will both sense that an abnormal current flow exists and then remove the affected portion from the system. In some types the sensing device and the interrupting device are completely separate, interconnected only through external control wiring. In other types the sensing and interrupting functions are combined in the same device. In still other types, the sensing and interrupting devices, although actually separate, are included in the same equipment and mechanically coupled so as to function as a single device.

A fuse is both a sensing and interrupting device. It is connected in series with the circuit and responds to thermal effects produced by the current flow through it. Its fusible element is designed to open at a predetermined time depending on the amount of current that flows. Different types are available having the time-current characteristics required for the proper protection of the circuit components. Fuses may be noncurrent-limiting or current-limiting, depending upon their design and construction. Fuses are not resettable since their fusible elements are consumed in the process of interrupting current flow. Fuses, their characteristics, applications, and limitations are described in detail in Chapter 5.

Circuit breakers are interrupting devices only and must be used in conjunction with sensing devices to fulfill the detection function. In the case of medium-voltage (1-72.5 kV) circuit breakers, the sensing devices are separate protective relays or combinations of relays, covered in Chapter 4. In the case of low-voltage (under 1000 V) circuit breakers, sensing devices may be external protection relays or combinations of relays. In most applications, either molded-case circuit breakers or other low-voltage circuit breakers have sensing devices built into the equipment. These sensors may be thermal or magnetic series devices, or they may be integrally mounted but otherwise separate protective relays. Low-voltage circuit breakers, their applications, characteristics, and limitations are covered in Chapter 6.

Overcurrent relays used in conjunction with medium-voltage circuit breakers are available with different functional characteristics. They may be either directional or nondirectional in their action. They may be instantaneous or time-delay in response. Various time-current characteristics, such as inverse time, very inverse time, extremely inverse time, and definite minimum time, are available over a wide range of current settings. For specific applications, various types of differential overcurrent relays are available. Overcurrent relays and their selection, application, and settings are covered in detail in Chapter 4. Such relays generally are used in conjunction with instrument transformers, which are covered in Chapter 3.

## 1.6 Preliminary Design

The designer of an electric power system should first determine the load requirement, including the sizes and types of loads, and any special requirements. He should also determine the available short-circuit current at the point of delivery, the time-current curves and settings of the nearest utility company protective device, and any contract restrictions on ratings and settings of protective relays in the user's system. (See Fig 1.)

The designer can then proceed with a preliminary system design. Chapter 2 covers the fundamentals of short-circuit behavior and the calculation of short-circuit duty requirements that will permit evaluation of the preliminary design for compatibility with available ratings of circuit breakers and fuses. At this point some modification of the design may be necessary because of economic considerations or equipment availability. Preliminary design should be evaluated from the standpoint of system coordination, as covered in Chapter 14. If the protection provided in the preliminary design cannot be selectively coordinated with utility company settings and contractual restrictions on protective device settings, the design should be modified to provide proper selective coordination.

Ground-fault protection is an essential part of system protection and is given detailed coverage in Chapter 7 for two reasons. First, although many of the devices used to obtain ground-fault protection are similar to those covered in Chapters 3 through 6, the need for protection and the potential problems of proper applications are frequently not fully appreciated. Second, proper selective coordination of ground-fault protection seldom has any significant effect on overall system selectivity, although its effect should be taken into consideration in the same general manner covered in Chapter 14.

## 1.7 Special Protection

In addition to developing a basic protection design, the designer may also need to develop protective schemes for specific pieces of equipment or for specific portions of the system. Such specialized protection should be coordinated with the basic system protection. Specialized protection applications include:

Chapter 8      Conductor Protection

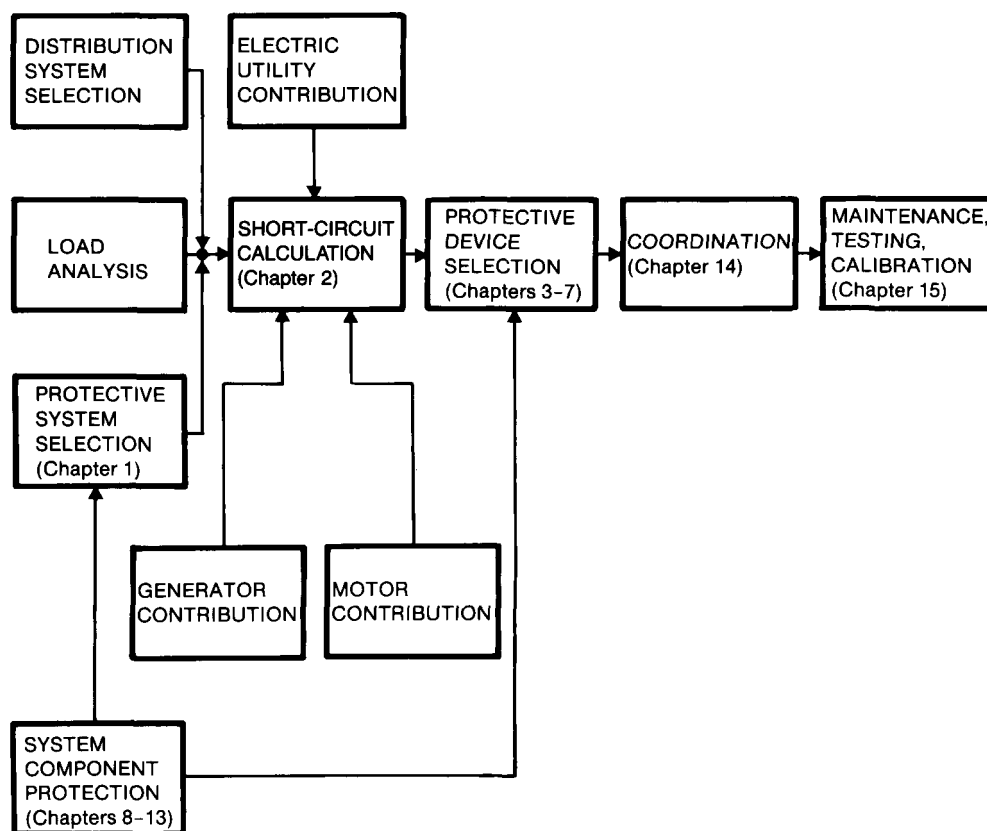


**Figure 1—Sequence of Steps in System Protection and Coordination**

Chapter 9      Motor Protection  
 Chapter 10     Transformer Protection  
 Chapter 11     Generator Protection  
 Chapter 12     Bus and Switchgear Protection  
 Chapter 13     Service Supply Line Protection

## 1.8 Field Follow-up

Proper application of the principles covered in the first 14 chapters of this book will result in the installation of system protection capable of coordinated selective isolation of system faults. But this capability will be to no avail if the proper field follow-up is not planned and executed. This followup has three elements: proper installation, including testing and calibration of all protective devices; proper operation of the system and its components; and a proper preventive maintenance program, including periodic retesting and recalibration of all protective devices. A separate chapter, Chapter 15, has been included to cover testing and maintenance.

## 1.9 References

The following publications shall be used in conjunction with this chapter.

- [1] ANSI/IEEE Std 141-1986, IEEE Recommended Practice for Electric Power Distribution for Industrial Plants.<sup>2</sup>
- [2] ANSI/IEEE Std 142-1982, IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems.
- [3] ANSI/IEEE Std 241-1983, IEEE Recommended Practice for Electric Power Systems in Commercial Buildings.
- [4] ANSI/NFPA 70-1984, National Electrical Code.<sup>3</sup>

## 2. Calculation of Short-Circuit Currents

### 2.1 General Discussion

Short-circuit currents introduce large amounts of destructive energy in the forms of heat and magnetic force into a power system. Calculations should be made to ensure that the short-circuit ratings of the equipment are adequate to handle the currents available at their locations. In general, the procedure is to (1) develop a graphical representation of the system with symbolic voltage sources and circuit impedances, then (2) determine the total equivalent impedance from the source to designated points, and (3) at each point divide the voltage by the total impedance to that point to derive the short-circuit current.

#### 2.1.1 Basic Assumptions

Certain simplifying assumptions are customarily made when calculating fault current. An important assumption is that the fault is “bolted,” that is, it has zero impedance. This assumption simplifies calculation, since the resulting calculated values are a maximum, and equipment selected on this basis will always have an adequate rating. Furthermore, a three-phase fault is customarily assumed, because this type of fault generally results in the maximum short-circuit current available in a system. In most systems the three-phase fault is frequently the only one calculated.

The actual fault current is usually less than the calculated bolted three-phase value because most faults involve arcing resistance or other undefined impedances, or both, not used in the calculations. Faults which are not three-phase will usually be less. Bolted line-to-line currents are about 87% of the three-phase value, while bolted line-to-ground currents can range from about 25–125% of the three-phase value, depending on system parameters. However, line-to-ground currents of more than 100% of the three-phase value rarely occur in industrial and commercial systems. Line-to-ground arcing fault currents in low-voltage systems are sometimes less than normal load currents and yet can be extremely destructive. This has led to techniques specifically directed to ground-fault protection (see Chapter 8).

Several assumptions which simplify the calculations are usually made. First, load currents are ignored. Second, the voltages of power company and generator sources are assumed to be equal to their nominal values at no load, although the actual voltages may be in a range of  $\pm 5\%$  of the nominal values. Third, motors are assumed to be running with their rated voltage at the terminals when a fault occurs. Fourth, the transformer percent impedance values used may be actual values or are often nominal values possibly subject to their  $\pm 7.5\%$  tolerance to anticipate the worst case. Fifth, when source  $X/R$  ratios are unknown, a relatively high value is generally assumed. This normally results in calculated values of short-circuit current that are slightly high. Sixth, switchboard and panelboard bus impedances can be

<sup>2</sup>ANSI/IEEE publications can be obtained from the Sales Department, American National Standards Institute, 1430 Broadway, New York, NY 10018, or from Publication Sales, the Institute of Electrical and Electronics Engineers, Service Center, Piscataway, NJ 08854.

<sup>3</sup>ANSI/NFPA publications can be obtained from the Sales Department, American National Standards Institute, 1430 Broadway, New York, NY 10018, or from Publication Sales, National Fire Protection Association, Batterymarch Park, Quincy, MA 02269.

ignored. These impedance values are usually small enough to only slightly increase the calculated values and are difficult to determine with any reasonable degree of accuracy. Furthermore, integrated equipment short-circuit ratings of panelboards and switchboards already involve consideration of their bus impedances. Other assumptions about source contributions and circuit element impedances are discussed later in this chapter.

### 2.1.2 Sources of Fault Current

The basic sources of fault current are the power company system, generators, synchronous motors, and induction motors.

- 1) A typical modern electric utility represents a large and complex interconnection of generating plants. In a typical system, the individual generators are not affected by a maximum short circuit in an industrial plant. Transmission lines, distribution lines, and transformers introduce impedances between the utility generators and the industrial customer. Were it not for such impedances, the utility system would be an infinite source of fault current. Before performing calculations, accurate values of present and projected available short-circuit currents and the  $X/R$  ratio, or the  $R + jX$  source impedance, at the delivery point must be obtained from the supplying utility.
- 2) In-plant generators react to system short circuits in a predictable way. Fault current from a generator decreases exponentially from a high initial value to a lower steady-state value some time after the initiation of the fault. Since a generator continues to be driven by its prime mover, and to have its field energized from its separate exciter, the steady-state fault current will persist unless interrupted by some circuit interrupter. For purposes of fault current calculation, the variable generator reactance can be represented by three values.  $X''_d$ , the direct-axis subtransient reactance, usually determines the current magnitude during the first cycle after the fault occurs. In some cases, the time constant is so short that the magnitude of the first peak may actually be determined by the direct-axis transient reactance.  $X'_d$ , the direct-axis transient reactance, determines the current magnitude in the range up to 1 or 2 s.  $X_d$ , the direct-axis synchronous reactance, determines the current flow after a steady-state condition is reached. Most fault protective devices, such as circuit breakers or fuses, operate before steady-state conditions are reached. Therefore, generator synchronous reactance is seldom used in calculating fault currents for the application of these devices.
- 3) Synchronous motors supply current to a fault in much the same manner as do synchronous generators. The drop in system voltage due to a fault causes the synchronous motor to receive less power from the system for driving its load. The inertia of the motor and its load acts as a prime mover, and with field excitation maintained, the motor acts as a generator. This fault current diminishes as the motor slows down and the motor field excitation decays.  
The variable reactance of a synchronous motor is described with the same designation as for a generator. However, numerical values of the three reactances  $X''_d$ ,  $X'_d$ , and  $X_d$  will often be different for motors than for generators.
- 4) The fault current contribution of an induction motor results from generator action produced by inertia driving the motor after the fault occurs. In contrast to the synchronous motor, the field flux of the induction motor is produced by induction from the stator rather than from a direct-current field winding. This flux decays on removal of source voltage resulting from a fault, and so the contribution of an induction motor drops off at a rapid exponential rate and soon disappears. As a consequence, induction motors are assigned only a reactance that is about equivalent to the synchronous machine subtransient reactance  $X''_d$ . This value will be about equal to the locked-rotor reactance, and hence the initial fault current contribution will be about equal to the full-voltage starting current of the machine. However, the resistance in small motors may be large enough to cause significant decay in their fault current contribution before the first peak of fault current is experienced.

Wound-rotor induction motors normally operate with their rotor rings short circuited and will contribute fault current in the same manner as a squirrel-cage induction motor. Occasionally, large wound-rotor motors are operated with external resistance maintained in their rotor circuits. This gives them short-circuit time constants that are so low that their fault contribution is insignificant. However, a specific investigation should be made before neglecting the contribution from a wound-rotor motor.

Capacitor discharge currents, because of their very short-time constant, can be neglected in most cases. However, there are some applications in which very high transitory currents can be developed when a short circuit occurs close to a bank of energized capacitors. These currents, generally of much higher frequency than normal operating frequency, may exceed in magnitude the power-frequency short-circuit currents and persist long enough to impose severe duty on the circuit components that carry this current. If a problem is anticipated, the capacitor currents could be calculated the same way as for back-to-back switching and compared to the short-circuit ratings of the devices [B5]<sup>4</sup>.

### 2.1.3 Total Short-Circuit Current as a Function of Time

When a short circuit occurs, a new circuit is established with lower impedance, most of which is inductance, and the current consequently increases. In the case of a bolted short circuit the impedance is drastically reduced, and the current increases to a very high value in a fraction of a cycle. Figure 2 represents a symmetrical short-circuit current, that is, a short-circuit current that has the same axis as the normal current that was flowing before the fault occurred. To produce a symmetrical short-circuit current under the assumption that the short-circuit power factor is zero, the fault should occur exactly when the normal voltage is maximum. In Fig 2 the system voltage is assumed to remain constant although the current increases.

The total short-circuit current is made up of components from all sources connected to the circuit. The contributions from rotating machinery decrease at various rates, so that the symmetrical current is initially at a maximum, then decreases until a steady-state value is reached. This decrease is known as the alternating-current decrement of the short-circuit current. Figure 3 shows a decreasing symmetrical short-circuit current.

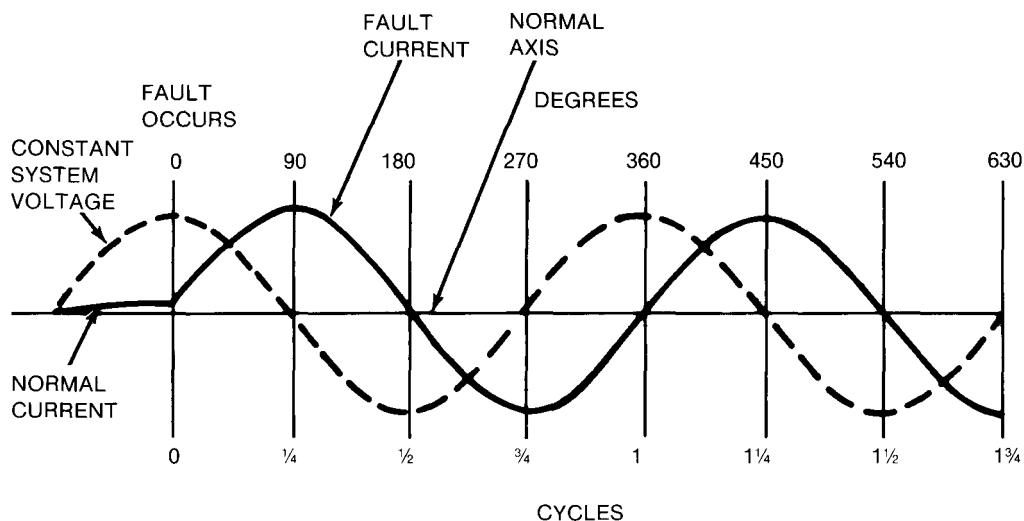


**Figure 2—A Symmetrical Short-Circuit Current Wave for a Totally Reactive System**

Most short-circuit currents are not symmetrical; they are offset from the normal-current axis for a period of several cycles. If the power factor is essentially zero until a steady-state value is reached and the short circuit occurs at a zero point on the voltage wave, the current starts to build up from zero, but cannot follow the normal-current axis because the current should lag behind the voltage by  $90^\circ$ . Although the current is symmetrical with respect to a new axis, it is asymmetrical with respect to the original axis. Figure 4 illustrates the case where a short circuit with low power factor produces the highest first peak of short-circuit current. The magnitude of current offset for a typical fault will be between the two extremes of complete symmetry and complete asymmetry because the odds are against the fault occurring exactly at a voltage peak or a voltage zero.

<sup>4</sup>The numbers in brackets correspond to those of the references listed at the end of this chapter. The numbers in brackets with the prefix "B" corresponds to those of the bibliography listed at the end of this chapter.

An analysis of a typical asymmetrical current wave is made in Fig 4. The offset of the asymmetrical current wave from a symmetrical wave having equal peak-to-peak displacement is a positive value of current that may be considered as a direct current. The asymmetrical current, therefore, may be thought of as the sum of an alternating-current component  $b$  and a direct-current component  $a$ . At the instant of fault initiation (0 cycles in Fig 4),  $b$  is negative and  $a + b = 0$ . Just before quarter-cycle the symmetrical alternating-current component is zero, and the total current is equal to the direct-current component. At near half-cycle the total current is maximum, being the sum of the maximum positive alternating-current component and the direct-current component.

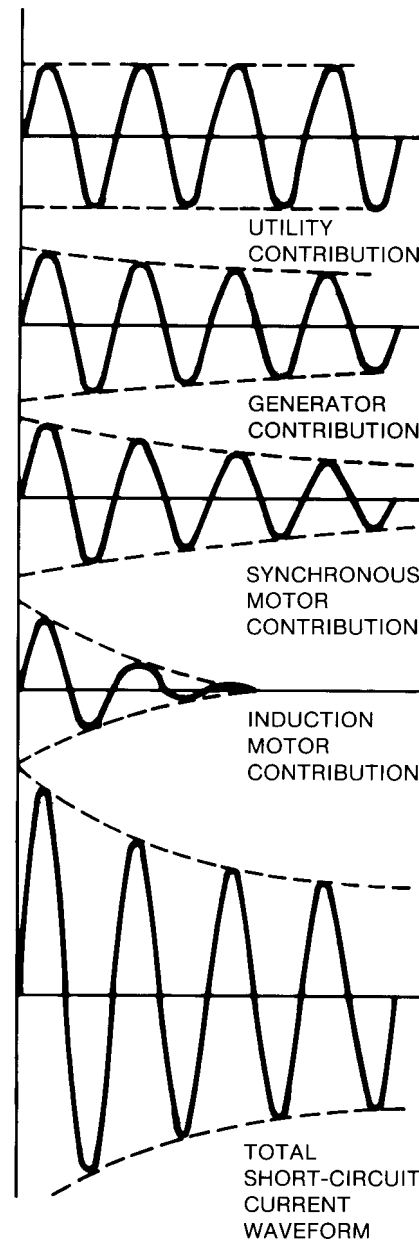


**Figure 3—Decreasing Symmetrical Short-Circuit Current Waveform**

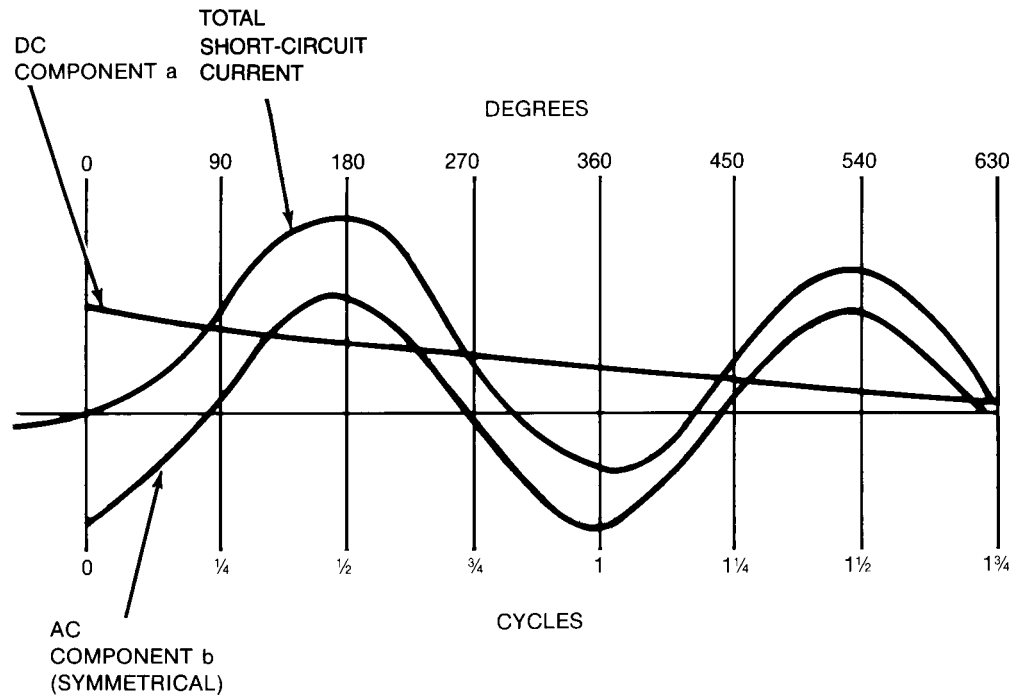


**Figure 4—Analysis of Asymmetrical Current Waveform**

The direct-current component decreases eventually to zero as the stored energy it represents is expended in the form of  $I^2R$  losses in the resistance of the system. The initial rate of decay of the direct-current component is inversely proportional to the  $X/R$  ratio of the system from the source to the fault. The lower the  $X/R$  ratio, the more rapid is the decay. This decay is called the “direct-current decrement.” The total short-circuit current is thus affected by both an alternating-current decrement and a direct-current decrement before reaching its steady-state value.

#### 2.1.4 Short-Circuit Ratings of Equipment

From the foregoing it can be seen that short-circuit currents may act differently in the first few cycles than later, if allowed to persist. Former practice was to establish rms asymmetrical short-circuit ratings of equipment. Calculations for symmetrical values of short-circuit currents were made, and asymmetrical values were then determined by applying simple multipliers to the symmetrical values. The trend in recent years to rate protective equipment on an rms symmetrical basis is now nearly complete. Under the new rating basis, asymmetry is accounted for by various application formulas depending on the class of equipment. Some of these application formulas, embodied in national standards, are quite involved [6].

Short-circuit current calculation concepts are also examined from another point of view. While the symmetrical equipment rating concept was gaining acceptance, the operating times of interrupting devices were being reduced. The interrupting period of protective devices became crowded into the first few cycles and even into the first half-cycle for current-limiting fuses. To an increasing number of engineers, therefore, maximum symmetrical values of short-circuit current have not appeared fully adequate to define short-circuit conditions.

The concept of  $I^2t$  has been introduced to supplement the symmetrical current concept because it represents the actual thermal stresses imposed on equipment carrying short-circuit current in the first few cycles [11]. The quantity  $I^2t$  represents  $\int i^2 dt$ , the time integral of the current squared for the time under consideration (Fig 5). It is quite possible that in the future some pieces of protective equipment may be time-current coordinated and rated on an  $I^2t$  basis rather than a maximum symmetrical current basis.

## 2.2 Calculation Preliminaries

### 2.2.1 One-Line Diagram

A one-line diagram is a graphical representation of the power system and should be prepared as the first step in making a short-circuit current study. This diagram should show all sources of short-circuit current and all significant circuit elements. Reactance and resistance values of all these elements should be included in the diagram. Reactance and resistance data can be obtained from Tables 1–14, or preferably from the equipment supplier. In any case, the calculations cannot be more accurate than the data used.

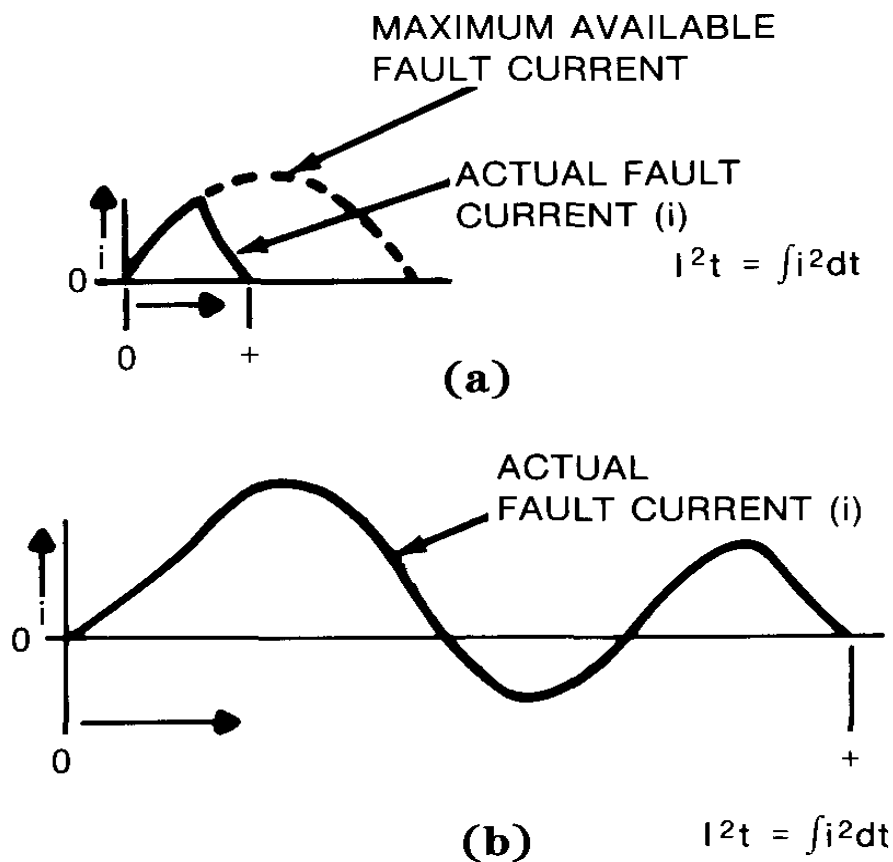


Figure 5—Finding  $I^2t$  in Fault-Current Waveforms  
 (a) Current-Limiting Fuse  
 (b) 1.5 Cycle Circuit Breaker

**Table 1—Impedance Data for Three-Phase Transformers With Primaries of Up to 15 000 V and Secondaries of 600 V or Less**

| kVA<br>3 $\phi$ | Suggested X/R<br>Ratio for<br>Calculation | Normal Range of Percent<br>Impedance (see notes) |
|-----------------|-------------------------------------------|--------------------------------------------------|
| 112.5           | 3.0                                       | 1.6 – <u>2 Min</u> – 6.2                         |
| 150.0           | 3.5                                       | 1.5 – <u>2 Min</u> – 6.4                         |
| 225.0           | 4.0                                       | 2.0 – <u>2 Min</u> – 6.6                         |
| 300.0           | 4.5                                       | 2.0 – <u>4.5 Min</u> – 6.0                       |
| 500.0           | 5.0                                       | 2.1 – <u>4.5 Min</u> – 6.1                       |
| 750.0           | 6.0                                       | 3.2 – <u>5.75 – 6.75</u> – 6.8                   |
| 1000.0          | 7.0                                       | 3.2 – <u>5.75 – 6.75</u> – 8.0                   |
| 1500.0          | 7.0                                       | 3.5 – <u>5.75 – 6.75</u> – 6.8                   |
| 2000.0          | 8.0                                       | 3.5 – <u>5.75 – 6.75</u> – 6.8                   |
| 2500.0          | 9.0                                       | 3.5 – <u>5.75 – 6.75</u> – 6.8                   |

## NOTES:

1 — Underlined values are from ANSI C57.12.10-1977 [1], ANSI C57.12.22-1980 [2], and NEMA 210-1976 [10].

2 — Network transformers (with three-position switches) have 5.0%Z for 300–1000 kVA, 7.0% Z for 1500–2500 kVA, (with two-position switches) 4.0% Z for 500–750 kVA. See ANSI C57.12-40-1982 [3].

3 — Three-phase banks with three single-phase transformers may have values as low as 1.2%.

**Table 2—Data for Three-Phase Transformers With Secondaries of 2400 V or More (750–60 000 kVA)**

| Primary<br>kV | Primary<br>kV BIL | Standard Percent Impedance<br>(see notes) |
|---------------|-------------------|-------------------------------------------|
| 2.4–22.9      | 60–150            | 5.5 or 6.5                                |
| –34.4         | –200              | 6.0 or 7.0                                |
| –43.8         | –250              | 6.5 or 7.5                                |
| –67.0         | –350              | 7.0 or 8.0                                |
| –115.0        | –450              | 7.5 or 8.5                                |
| –138.0        | –550              | 8.0 or 9.0                                |

## NOTES:

1 — Actual values are generally within  $\pm 7.5\%$  of the standard values [1].

2 — Add 0.5% for load tap changing [8].

3 — Lower values are usually for OA 55 °C or OA 55/65 °C rise transformers.

4 — Higher values are usually for OA 65 °C rise transformers.

5 — X/R values are similar to those in Table 1. Consult manufacturer or use the values in [4] for transformers rated over 2500 kVA.

**Table 3—Constants of Medium-Voltage Copper Conductors for 1 Ft Delta Spacing**

| Conductor Size |          | Resistance $R$<br>at 25 °C, 50 Hz<br>(mΩ/conductor/100 ft) | Reactance $X_A$ at 1 ft<br>Spacing, 60 Hz<br>(mΩ/conductor/100ft) |
|----------------|----------|------------------------------------------------------------|-------------------------------------------------------------------|
| (MCM or kcmil) | (AWG No) |                                                            |                                                                   |
| 1000.00        |          | 1.19                                                       | 7.58                                                              |
| 900.00         |          | 1.30                                                       | 7.69                                                              |
| 800.00         |          | 1.45                                                       | 7.82                                                              |
| 750.00         |          | 1.53                                                       | 7.90                                                              |
| 700.00         |          | 1.63                                                       | 8.00                                                              |
| 600.00         |          | 1.88                                                       | 8.18                                                              |
| 500.00         |          | 2.24                                                       | 8.39                                                              |
| 450.00         |          | 2.49                                                       | 8.54                                                              |
| 400.00         |          | 2.80                                                       | 8.67                                                              |
| 350.00         |          | 3.17                                                       | 8.83                                                              |
| 300.00         |          | 3.71                                                       | 9.02                                                              |
| 250.00         |          | 4.44                                                       | 9.22                                                              |
| 211.60         | 4/0      | 5.24                                                       | 9.53                                                              |
| 167.80         | 3/0      | 6.60                                                       | 9.81                                                              |
| 133.10         | 2/0      | 8.31                                                       | 10.10                                                             |
| 105.50         | 1/0      | 10.49                                                      | 10.30                                                             |
| 83.69          | 1        | 13.22                                                      | 10.60                                                             |
| 66.37          | 2        | 16.51                                                      | 10.80                                                             |
| 52.63          | 3        | 20.70                                                      | 11.10                                                             |
| 41.74          | 4        | 26.27                                                      | 11.30                                                             |
| 33.10          | 5        | 33.01                                                      | 11.60                                                             |
| 26.25          | 6        | 41.31                                                      | 12.10                                                             |
| 20.80          | 7        | 51.98                                                      | 12.30                                                             |
| 16.51          | 8        | 65.66                                                      | 12.60                                                             |

NOTE — For a three-phase circuit the total impedance, line-to-neutral, is  
 $Z = R + j(X_A + X_B) \cdot M$   
 To determine  $X_B$ , use Tables 5–8. For overhead lines,  $M = 1$ .  
 For cable in conduit, determine  $M$  from Table 9.

**Table 4—Constants of Medium-Voltage Aluminum Cable Steel Reinforced for 1 Ft Delta Spacing**

| Conductor Size |          | Resistance $R$<br>at 25 °C, 50 Hz<br>(mΩ/conductor/100ft) | Reactance $X_A$ at 1 ft<br>Spacing, 60 Hz<br>(mΩ/conductor/100ft) |
|----------------|----------|-----------------------------------------------------------|-------------------------------------------------------------------|
| (MCM or kcmil) | (AWG No) |                                                           |                                                                   |
| 1590.0         |          | 1.18                                                      | 6.79                                                              |
| 1431.0         |          | 1.31                                                      | 6.92                                                              |
| 1272.0         |          | 1.47                                                      | 7.04                                                              |
| 1192.5         |          | 1.56                                                      | 7.12                                                              |
| 1113.0         |          | 1.67                                                      | 7.19                                                              |
| 954.0          |          | 1.94                                                      | 7.38                                                              |
| 795.0          |          | 2.22                                                      | 7.44                                                              |
| 715.5          |          | 2.49                                                      | 7.56                                                              |
| 636.0          |          | 2.80                                                      | 7.68                                                              |
| 556.5          |          | 3.21                                                      | 7.86                                                              |
| 477.0          |          | 3.38                                                      | 8.02                                                              |
| 397.5          |          | 4.06                                                      | 8.24                                                              |
| 336.4          |          | 4.80                                                      | 8.43                                                              |
| 266.8          |          | 6.04                                                      | 11.45                                                             |
|                | 4/0      | 7.62                                                      | 10.99                                                             |
|                | 3/0      | 9.59                                                      | 11.75                                                             |
|                | 2/0      | 12.13                                                     | 12.12                                                             |
|                | 1/0      | 15.27                                                     | 12.42                                                             |
|                | 1        | 19.33                                                     | 12.59                                                             |
|                | 2        | 24.35                                                     | 12.15                                                             |
|                | 3        | 30.73                                                     | 12.51                                                             |
|                | 4        | 38.67                                                     | 12.40                                                             |
|                | 5        | 48.70                                                     | 12.59                                                             |
|                | 6        | 61.47                                                     | 12.73                                                             |

NOTE — For a three-phase circuit the total impedance, line-to-neutral, is  
 $Z = R + j(X_A + X_B) \cdot M$   
 To determine  $X_B$ , use Tables 5–8. For overhead lines,  $M = 1$ .  
 For cable in conduit, determine  $M$  from Table 9.

**Table 5—60 Hz Reactance Spacing Factor  $X_B$ , in Milliohms per Conductor per 100 Ft**

| (feet) | Separation (inches) |       |       |       |       |       |       |       |       |       |       |       |
|--------|---------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|        | 0                   | 1     | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9     | 10    | 11    |
| 0      | —                   | −5.71 | −4.12 | −3.19 | −2.52 | −2.01 | −1.59 | −1.24 | −0.93 | −0.66 | −0.42 | −0.20 |
| 1      | 0.00                | 0.18  | 0.35  | 0.51  | 0.61  | 0.80  | 0.93  | 1.06  | 1.17  | 1.29  | 1.39  | 1.49  |
| 2      | 1.59                | 1.69  | 1.78  | 1.86  | 1.95  | 2.03  | 2.11  | 2.18  | 2.55  | 2.32  | 2.39  | 2.46  |
| 3      | 2.52                | 2.59  | 2.65  | 2.71  | 2.77  | 2.82  | 2.88  | 2.93  | 2.99  | 3.04  | 3.09  | 3.14  |
| 4      | 3.19                | 3.23  | 3.28  | 3.33  | 3.37  | 3.41  | 3.46  | 3.50  | 3.54  | 3.58  | 3.62  | 3.66  |
| 5      | 3.70                | 3.74  | 3.77  | 3.81  | 3.85  | 3.88  | 3.92  | 3.95  | 3.99  | 4.02  | 4.05  | 4.09  |
| 6      | 4.12                | 4.15  | 4.18  | 4.21  | 4.24  | 4.27  | 4.30  | 4.33  | 4.36  | 4.39  | 4.42  | 4.45  |
| 7      | 4.47                | 4.50  | 4.53  | 4.55  | 4.58  | 4.60  | 4.63  | 4.66  | 4.68  | 4.71  | 4.73  | 4.76  |
| 8      | 4.78                |       |       |       |       |       |       |       |       |       |       |       |

**Table 6—60 Hz Reactance Spacing Factor  $X_B$ , in Milliohms per Conductor per 100 Ft**

| Separation<br>(inches) | Factor $X_B$ | (inches) | Separation<br>(quarter inches) |        |        |        |
|------------------------|--------------|----------|--------------------------------|--------|--------|--------|
|                        |              |          | 0                              | 1/4    | 2/4    | 3/4    |
| 0.40                   | −7.95        | 2        | −4.12                          | −3.840 | −3.590 | −3.390 |
| 0.50                   | −7.29        | 3        | −3.19                          | −3.010 | −2.820 | −2.670 |
| 0.60                   | −6.95        | 4        | −2.52                          | −2.380 | −2.250 | −2.120 |
| 0.70                   | −6.58        | 5        | −2.01                          | −1.795 | −1.795 | −1.684 |
| 0.75                   | −6.36        | 6        | −1.59                          | −1.494 | −1.399 | −1.323 |
| 0.80                   | −6.22        | 7        | −1.24                          | −1.152 | −1.078 | −1.002 |
| 0.90                   | −5.95        | 8        | −0.93                          | −0.852 | −0.794 | −0.719 |
| 1.00                   | −5.71        | 9        | −0.66                          | −0.605 | −0.529 | −0.474 |
| 1.10                   | −5.48        | 10       | −0.42                          | —      | —      | —      |
| 1.20                   | −5.25        | 11       | −0.20                          | —      | —      | —      |
| 1.25                   | −5.19        | 12       | —                              | —      | —      | —      |
| 1.30                   | −5.08        |          |                                |        |        |        |
| 1.40                   | −4.90        |          |                                |        |        |        |
| 1.50                   | −4.77        |          |                                |        |        |        |
| 1.60                   | −4.62        |          |                                |        |        |        |
| 1.70                   | −4.50        |          |                                |        |        |        |
| 1.75                   | −4.43        |          |                                |        |        |        |
| 1.80                   | −4.37        |          |                                |        |        |        |
| 1.90                   | −4.28        |          |                                |        |        |        |
| 2.00                   | −4.12        |          |                                |        |        |        |

**Table 7—Typical Conductor Spacings for Overhead Lines**

| Nominal System Voltage<br>(volts) | Equivalent Delta Spacing<br>(inches) |
|-----------------------------------|--------------------------------------|
| 120                               | 12                                   |
| 240                               | 12                                   |
| 480                               | 18                                   |
| 600                               | 18                                   |
| 2400                              | 30                                   |
| 4160                              | 30                                   |
| 6900                              | 36                                   |
| 13 800                            | 42                                   |
| 23 000                            | 48                                   |
| 34 500                            | 54                                   |
| 69 000                            | 96                                   |
| 115 000                           | 204                                  |

NOTE — When conductors are not arranged in a delta, the following formula may be used to determine the equivalent delta:

$$d = 3\sqrt{A \cdot B \cdot C}$$

When the conductors are located in one plane and the outside conductors are equally spaced from the middle conductor, the equivalent is 1.26 times the distance between the middle conductor and an outside conductor. For example,

$$\begin{aligned} \text{equivalent delta spacing} &= 3\sqrt{A \cdot A \cdot 2A} \\ &= 1.26A \end{aligned}$$

O—A—O—A—O  
—2A—

**Table 8—  
Approximate Minimum Conductor Spacings for Medium-Voltage Cable  
(Copper and Aluminum) in Conduit\***

| Conductor Size<br>(MCM or kcmil) | (AWG No) | Spacings for 5 kV<br>Single-Conductor<br>Cable<br>in Conduit <sup>†</sup><br>(inches) | Spacings for 5 kV<br>Multiconductor Conduit <sup>‡</sup><br>(inches) |
|----------------------------------|----------|---------------------------------------------------------------------------------------|----------------------------------------------------------------------|
|                                  |          |                                                                                       |                                                                      |
| 1000                             |          | 1.4                                                                                   | 1.0                                                                  |
| 750                              |          | 1.3                                                                                   | 0.9                                                                  |
| 500                              |          | 1.1                                                                                   | 0.8                                                                  |
| 350                              |          | 0.9                                                                                   | 0.7                                                                  |
| 250                              |          | 0.8                                                                                   | 0.6                                                                  |
|                                  | 4/0      | 0.8                                                                                   | 0.6                                                                  |
|                                  | 3/0      | 0.7                                                                                   | 0.6                                                                  |
|                                  | 2/0      | 0.7                                                                                   | 0.6                                                                  |
|                                  | 1/0      | 0.6                                                                                   | 0.5                                                                  |
|                                  | 1        | 0.6                                                                                   | 0.5                                                                  |
|                                  | 2        | 0.5                                                                                   | 0.5                                                                  |
|                                  | 4        | 0.5                                                                                   | 0.5                                                                  |
|                                  | 6        | 0.4                                                                                   | 0.4                                                                  |
|                                  | 8        | 0.4                                                                                   | 0.4                                                                  |

\*Use actual cable outside diameter, if known.

<sup>†</sup>Add 0.3 for 8 kV, 0.5 for 15 kV.

<sup>‡</sup>Add 0.1 for 8 kV, 0.2 for 15 kV.

**Table 9—Medium-Voltage Cable in Conduit—Reactance Factor  $M$  for Various Constructions and Installations**

| Conductor Size<br>(MCM or kcmil) | Multiple-Conductor Cable in Conduit or Armor |          |              |          | Three Single-Conductor in Conduit with Random Lay |          |              |          |
|----------------------------------|----------------------------------------------|----------|--------------|----------|---------------------------------------------------|----------|--------------|----------|
|                                  | Nonshielded                                  |          | Shielded     |          | Nonshielded                                       |          | Shielded     |          |
|                                  | Non-magnetic                                 | Magnetic | Non-magnetic | Magnetic | Non-magnetic                                      | Magnetic | Non-magnetic | Magnetic |
| 250 and Smaller                  | 1.0                                          | 1.149    | 0.945        | 1.086    | 1.2                                               | 1.5      | 1.320        | 1.650    |
| 300                              | 1.0                                          | 1.146    | 0.946        | 1.084    | 1.2                                               | 1.5      | 1.302        | 1.628    |
| 350                              | 1.0                                          | 1.140    | 0.947        | 1.080    | 1.2                                               | 1.5      | 1.298        | 1.623    |
| 400                              | 1.0                                          | 1.134    | 0.949        | 1.076    | 1.2                                               | 1.5      | 1.295        | 1.619    |
| 450                              | 1.0                                          | 1.128    | 0.951        | 1.073    | 1.2                                               | 1.5      | 1.292        | 1.616    |
| 500                              | 1.0                                          | 1.122    | 0.952        | 1.068    | 1.2                                               | 1.5      | 1.290        | 1.613    |
| 600                              | 1.0                                          | 1.111    | 0.955        | 1.061    | 1.2                                               | 1.5      | 1.285        | 1.607    |
| 700                              | 1.0                                          | 1.100    | 0.957        | 1.053    | 1.2                                               | 1.5      | 1.282        | 1.602    |
| 750                              | 1.0                                          | 1.095    | 0.959        | 1.050    | 1.2                                               | 1.5      | 1.278        | 1.598    |
| 1000                             | 1.0                                          | 1.070    | 0.962        | 1.029    | 1.2                                               | 1.5      | 1.271        | 1.589    |

**Table 10—60 Hz Low-Voltage Cable in Conduit-Resistance (*R*) and Reactance (*X*) Data for Insulation Types THW, RHW, RHH, and Use in Milliohms per Conductor per 100 Ft at 25 °C Copper Conductor**

| Cable Size | Several Single-Conductor Cables (1/C) |          |          |          |          |          | One Multiple-Conductor Cable (3/C) |          |          |          |          |          |
|------------|---------------------------------------|----------|----------|----------|----------|----------|------------------------------------|----------|----------|----------|----------|----------|
|            | Steel                                 |          | Aluminum |          | Plastic  |          | Steel                              |          | Aluminum |          | Plastic  |          |
|            | <i>R</i>                              | <i>X</i> | <i>R</i> | <i>X</i> | <i>R</i> | <i>X</i> | <i>R</i>                           | <i>X</i> | <i>R</i> | <i>X</i> | <i>R</i> | <i>X</i> |
| 14         | 257.00                                | 5.60     | 257.00   | 4.48     | 257.00   | 4.48     | 257.00                             | 4.29     | 257.00   | 3.73     | 257.00   | 3.73     |
| 12         | 162.00                                | 5.23     | 162.00   | 4.18     | 162.00   | 4.18     | 162.00                             | 4.01     | 162.00   | 3.49     | 162.00   | 3.49     |
| 10         | 101.80                                | 4.90     | 101.80   | 3.92     | 101.80   | 3.92     | 101.80                             | 3.76     | 101.80   | 3.27     | 101.80   | 3.27     |
| 8          | 64.04                                 | 5.14     | 64.04    | 4.12     | 64.04    | 4.12     | 64.04                              | 3.94     | 64.04    | 3.43     | 64.04    | 3.43     |
| 6          | 41.00                                 | 5.04     | 41.00    | 4.03     | 41.00    | 4.03     | 41.00                              | 3.86     | 41.00    | 3.36     | 41.00    | 3.36     |
| 4          | 25.90                                 | 4.77     | 25.90    | 3.82     | 25.90    | 3.82     | 25.90                              | 3.65     | 25.90    | 3.18     | 25.90    | 3.18     |
| 3          | 20.50                                 | 4.58     | 20.50    | 3.66     | 20.50    | 3.66     | 20.50                              | 3.50     | 20.50    | 3.05     | 20.50    | 3.05     |
| 2          | 16.40                                 | 4.49     | 16.40    | 3.59     | 16.20    | 3.59     | 16.40                              | 3.44     | 16.40    | 2.99     | 16.20    | 2.99     |
| 1          | 13.03                                 | 4.58     | 13.03    | 3.66     | 12.90    | 3.66     | 13.03                              | 3.50     | 13.03    | 3.05     | 12.90    | 3.05     |
| 1/0        | 10.40                                 | 4.46     | 10.40    | 3.56     | 10.20    | 3.56     | 10.40                              | 3.41     | 10.40    | 2.97     | 10.20    | 2.97     |
| 2/0        | 8.35                                  | 4.35     | 8.35     | 3.48     | 8.12     | 3.48     | 8.35                               | 3.33     | 8.35     | 2.90     | 8.12     | 2.90     |
| 3/0        | 6.68                                  | 4.22     | 6.68     | 3.37     | 6.43     | 3.37     | 6.68                               | 3.23     | 6.68     | 2.81     | 6.43     | 2.81     |
| 4/0        | 5.34                                  | 4.14     | 5.34     | 3.31     | 5.11     | 3.31     | 5.34                               | 3.17     | 5.34     | 2.76     | 5.11     | 2.76     |
| 250        | 4.57                                  | 4.23     | 4.57     | 3.38     | 4.33     | 3.38     | 4.57                               | 3.24     | 4.57     | 2.82     | 4.33     | 2.82     |
| 300        | 3.85                                  | 4.14     | 3.85     | 3.31     | 3.62     | 3.31     | 3.85                               | 3.16     | 3.85     | 2.76     | 3.62     | 2.76     |
| 350        | 3.33                                  | 4.07     | 3.33     | 3.25     | 3.11     | 3.25     | 3.33                               | 3.09     | 3.33     | 2.71     | 3.11     | 2.71     |
| 400        | 2.97                                  | 4.04     | 2.97     | 3.23     | 2.73     | 3.23     | 2.97                               | 3.05     | 2.97     | 2.69     | 2.73     | 2.69     |
| 500        | 2.44                                  | 3.96     | 2.44     | 3.17     | 2.20     | 3.17     | 2.44                               | 2.96     | 2.44     | 2.64     | 2.20     | 2.64     |
| 600        | 2.09                                  | 4.01     | 2.09     | 3.21     | 1.85     | 3.21     | 2.09                               | 2.97     | 2.09     | 2.68     | 1.85     | 2.68     |
| 750        | 1.74                                  | 3.94     | 1.74     | 3.15     | 1.50     | 3.15     | 1.74                               | 2.88     | 1.74     | 2.63     | 1.50     | 2.63     |
| 1000       | 1.40                                  | 3.86     | 1.40     | 3.09     | 1.15     | 3.09     | 1.40                               | 2.74     | 1.40     | 2.57     | 1.15     | 2.57     |

## Aluminum Conductor

| Cable Size | Several Single-Conductor Cables (1/C) |      |          |      |         |      | One Multiple-Conductor Cable (3/C) |      |          |      |         |      |
|------------|---------------------------------------|------|----------|------|---------|------|------------------------------------|------|----------|------|---------|------|
|            | Steel                                 |      | Aluminum |      | Plastic |      | Steel                              |      | Aluminum |      | Plastic |      |
|            | R                                     | X    | R        | X    | R       | X    | R                                  | X    | R        | X    | R       | X    |
| 14*        | 422.00                                | 5.60 | 422.00   | 4.48 | 422.00  | 4.48 | 422.00                             | 4.29 | 422.00   | 3.73 | 422.00  | 3.73 |
| 12         | 266.00                                | 5.23 | 266.00   | 4.18 | 266.00  | 4.18 | 266.00                             | 4.01 | 266.00   | 3.49 | 266.00  | 3.49 |
| 10         | 167.00                                | 4.90 | 167.00   | 3.92 | 167.00  | 3.92 | 167.00                             | 3.76 | 167.00   | 3.27 | 167.00  | 3.27 |
| 8          | 105.00                                | 5.14 | 105.00   | 4.12 | 105.00  | 4.12 | 105.00                             | 3.94 | 105.00   | 3.43 | 105.00  | 3.43 |
| 6          | 67.40                                 | 5.04 | 67.40    | 4.03 | 67.40   | 4.03 | 67.40                              | 3.86 | 67.40    | 3.36 | 67.40   | 3.36 |
| 4          | 42.40                                 | 4.77 | 42.40    | 3.82 | 42.40   | 3.82 | 42.40                              | 3.65 | 42.40    | 3.18 | 42.40   | 3.18 |
| 3          | 33.60                                 | 4.58 | 33.60    | 3.66 | 33.60   | 3.66 | 33.60                              | 3.50 | 33.60    | 3.05 | 33.60   | ,05  |
| 2          | 26.60                                 | 4.49 | 26.60    | 3.59 | 26.60   | 3.59 | 26.60                              | 3.44 | 26.60    | 2.99 | 26.60   | 2.99 |
| 1          | 21.10                                 | 4.58 | 21.10    | 3.66 | 21.10   | 3.66 | 21.10                              | 3.50 | 21.10    | 3.05 | 21.10   | 3.05 |
| 1/0        | 16.80                                 | 4.46 | 16.80    | 3.56 | 16.80   | 3.56 | 16.80                              | 3.41 | 16.80    | 2.97 | 16.80   | 2.97 |
| 2/0        | 13.30                                 | 4.35 | 13.30    | 3.48 | 13.30   | 3.48 | 13.30                              | 3.33 | 13.30    | 2.90 | 13.30   | 2.90 |
| 3/0        | 10.60                                 | 4.22 | 10.60    | 3.37 | 10.50   | 3.37 | 10.60                              | 3.23 | 10.60    | 2.81 | 10.50   | 2.81 |
| 4/0        | 8.44                                  | 4.14 | 8.44     | 3.31 | 8.38    | 3.31 | 8.44                               | 3.17 | 8.44     | 2.76 | 8.38    | 2.76 |
| 250        | 7.22                                  | 4.23 | 7.22     | 3.38 | 7.09    | 3.38 | 7.22                               | 3.24 | 7.22     | 2.82 | 7.09    | 2.82 |
| 300        | 6.02                                  | 4.14 | 6.02     | 3.31 | 5.92    | 3.31 | 6.02                               | 3.16 | 6.02     | 2.76 | 5.92    | 2.76 |
| 350        | 5.20                                  | 4.07 | 5.20     | 3.25 | 5.07    | 3.25 | 5.20                               | 3.09 | 5.20     | 2.71 | 5.07    | 2.71 |
| 400        | 4.60                                  | 4.04 | 4.60     | 3.23 | 4.44    | 3.23 | 4.60                               | 3.05 | 4.60     | 2.69 | 4.44    | 2.69 |
| 500        | 3.75                                  | 3.96 | 3.75     | 3.17 | 3.56    | 3.17 | 3.75                               | 2.96 | 3.75     | 2.64 | 3.56    | 2.64 |
| 600        | 3.19                                  | 4.01 | 3.19     | 3.21 | 2.98    | 3.21 | 3.19                               | 2.97 | 3.19     | 2.68 | 2.98    | 2.68 |
| 750        | 2.64                                  | 3.94 | 2.64     | 3.15 | 2.40    | 3.15 | 2.64                               | 2.88 | 2.64     | 2.63 | 2.40    | 2.63 |
| 1000       | 2.11                                  | 3.86 | 2.11     | 3.09 | 1.82    | 3.09 | 2.11                               | 2.74 | 2.11     | 2.57 | 1.82    | 2.57 |

\*Size 14 for type "use" not listed in 1984 NEC.

**Table 11—60 Hz Low-Voltage Cable in Conduit-Resistance (*R*) and Reactance (*X*) Data for Insulation Types THWN and THHN in Milliohms per Conductor per 100 Ft at 25 °C Copper Conductor**

| Cable Size | Several Single-Conductor Cables (1/C) |          |          |          |          |          | One Multiple-Conductor Cable (3/C) |          |          |          |          |          |
|------------|---------------------------------------|----------|----------|----------|----------|----------|------------------------------------|----------|----------|----------|----------|----------|
|            | Steel                                 |          | Aluminum |          | Plastic  |          | Steel                              |          | Aluminum |          | Plastic  |          |
|            | <i>R</i>                              | <i>X</i> | <i>R</i> | <i>X</i> | <i>R</i> | <i>X</i> | <i>R</i>                           | <i>X</i> | <i>R</i> | <i>X</i> | <i>R</i> | <i>X</i> |
| 14         | 257.00                                | 4.93     | 257.00   | 3.94     | 257.00   | 3.94     | 257.00                             | 3.51     | 257.00   | 3.05     | 257.00   | 3.05     |
| 12         | 162.00                                | 4.68     | 162.00   | 3.74     | 162.00   | 3.74     | 162.00                             | 3.33     | 162.00   | 2.90     | 162.00   | 2.90     |
| 10         | 101.80                                | 4.63     | 101.80   | 3.71     | 101.80   | 3.71     | 101.80                             | 3.37     | 101.80   | 2.93     | 101.80   | 2.93     |
| 8          | 64.04                                 | 4.75     | 64.04    | 3.80     | 64.04    | 3.80     | 64.04                              | 3.51     | 64.04    | 3.05     | 64.04    | 3.05     |
| 6          | 41.00                                 | 4.37     | 41.00    | 3.49     | 41.00    | 3.49     | 41.00                              | 3.24     | 41.00    | 2.82     | 41.00    | 2.82     |
| 4          | 25.90                                 | 4.41     | 25.90    | 3.53     | 25.90    | 3.53     | 25.90                              | 3.28     | 25.90    | 2.85     | 25.90    | 2.35     |
| 3          | 20.50                                 | 4.30     | 20.50    | 3.44     | 20.50    | 3.44     | 20.50                              | 3.20     | 20.50    | 2.79     | 20.50    | 2.79     |
| 2          | 16.40                                 | 4.20     | 16.40    | 3.36     | 16.20    | 3.36     | 16.40                              | 3.13     | 16.40    | 2.73     | 16.20    | 2.73     |
| 1          | 13.03                                 | 4.27     | 13.03    | 3.42     | 12.90    | 3.42     | 13.03                              | 3.19     | 13.03    | 2.77     | 12.90    | 2.77     |
| 1/0        | 10.40                                 | 4.17     | 10.40    | 3.34     | 10.20    | 3.34     | 10.40                              | 3.12     | 10.40    | 2.72     | 10.20    | 2.72     |
| 2/0        | 8.35                                  | 4.09     | 8.35     | 3.27     | 8.12     | 3.27     | 8.35                               | 3.06     | 8.35     | 2.66     | 8.12     | 2.66     |
| 3/0        | 6.68                                  | 4.00     | 6.68     | 3.20     | 6.43     | 3.20     | 6.68                               | 3.00     | 6.68     | 2.61     | 6.43     | 2.61     |
| 4/0        | 5.34                                  | 3.93     | 5.34     | 3.14     | 5.11     | 3.14     | 5.34                               | 2.95     | 5.34     | 2.57     | 5.11     | 2.57     |
| 250        | 4.57                                  | 3.99     | 4.57     | 3.19     | 4.33     | 3.19     | 4.57                               | 2.99     | 4.57     | 2.61     | 4.33     | 2.61     |
| 300        | 3.85                                  | 3.93     | 3.85     | 3.14     | 3.62     | 3.14     | 3.85                               | 2.95     | 3.85     | 2.57     | 3.62     | 2.57     |
| 350        | 3.33                                  | 3.83     | 3.33     | 3.11     | 3.11     | 3.11     | 3.33                               | 2.90     | 3.33     | 2.54     | 3.11     | 2.54     |
| 400        | 2.97                                  | 3.85     | 2.97     | 3.08     | 2.73     | 3.08     | 2.97                               | 2.86     | 2.97     | 2.52     | 2.73     | 2.52     |
| 500        | 2.44                                  | 3.79     | 2.44     | 3.03     | 2.20     | 3.03     | 2.44                               | 2.79     | 2.44     | 2.49     | 2.20     | 2.49     |
| 600        | 2.09                                  | 3.82     | 2.09     | 3.05     | 1.85     | 3.05     | 2.09                               | 2.78     | 2.09     | 2.50     | 1.85     | 2.50     |
| 750        | 1.74                                  | 3.76     | 1.74     | 3.01     | 1.50     | 3.01     | 1.74                               | 2.71     | 1.74     | 2.47     | 1.50     | 2.47     |
| 1000       | 1.40                                  | 3.70     | 1.40     | 2.96     | 1.15     | 2.96     | 1.40                               | 2.60     | 1.40     | 2.43     | 1.15     | 2.43     |

**Aluminum Conductor**

| Cable Size | Several Single-Conductor Cables (1/C) |      |          |      |         |      | One Multiple-Conductor Cable (3/C) |      |          |      |         |      |
|------------|---------------------------------------|------|----------|------|---------|------|------------------------------------|------|----------|------|---------|------|
|            | Steel                                 |      | Aluminum |      | Plastic |      | Steel                              |      | Aluminum |      | Plastic |      |
|            | R                                     | X    | R        | X    | R       | X    | R                                  | X    | R        | X    | R       | X    |
| 14         | 422.00                                | 4.93 | 422.00   | 3.94 | 422.00  | 3.94 | 422.00                             | 3.51 | 422.00   | 3.05 | 422.00  | 3.05 |
| 12         | 266.00                                | 4.68 | 266.00   | 3.74 | 266.00  | 3.74 | 266.00                             | 3.33 | 266.00   | 2.90 | 266.00  | 2.90 |
| 10         | 167.00                                | 4.63 | 167.00   | 3.71 | 167.00  | 3.71 | 167.00                             | 3.37 | 167.00   | 2.93 | 167.00  | 2.93 |
| 8          | 105.00                                | 4.75 | 105.00   | 3.80 | 105.00  | 3.80 | 105.00                             | 3.51 | 105.00   | 3.05 | 105.00  | 3.05 |
| 6          | 67.40                                 | 4.37 | 67.40    | 3.49 | 67.40   | 3.49 | 67.40                              | 3.24 | 67.40    | 2.82 | 67.40   | 2.82 |
| 4          | 42.40                                 | 4.41 | 42.40    | 3.53 | 42.40   | 3.53 | 42.40                              | 3.28 | 42.40    | 2.85 | 42.40   | 2.85 |
| 3          | 33.60                                 | 4.30 | 33.60    | 3.44 | 33.60   | 3.44 | 33.60                              | 3.20 | 33.60    | 2.79 | 33.60   | 2.79 |
| 2          | 26.60                                 | 4.20 | 26.60    | 3.36 | 26.60   | 3.36 | 26.60                              | 3.13 | 26.60    | 2.73 | 26.60   | 2.73 |
| 1          | 21.10                                 | 4.27 | 21.10    | 3.42 | 21.10   | 3.42 | 21.10                              | 3.19 | 21.10    | 2.77 | 21.10   | 2.77 |
| 1/0        | 16.80                                 | 4.17 | 16.80    | 3.34 | 16.80   | 3.34 | 16.80                              | 3.12 | 16.80    | 2.72 | 16.80   | 2.72 |
| 2/0        | 13.30                                 | 4.09 | 13.30    | 3.27 | 13.30   | 3.27 | 13.30                              | 3.06 | 13.30    | 2.66 | 13.30   | 2.66 |
| 3/0        | 10.60                                 | 4.00 | 10.60    | 3.20 | 10.50   | 3.20 | 10.60                              | 3.00 | 10.60    | 2.61 | 10.50   | 2.61 |
| 4/0        | 8.44                                  | 3.93 | 8.44     | 3.14 | 8.38    | 3.14 | 8.44                               | 2.95 | 8.44     | 2.57 | 8.38    | 2.57 |
| 250        | 7.22                                  | 3.99 | 7.22     | 3.19 | 7.09    | 3.19 | 7.22                               | 2.99 | 7.22     | 2.61 | 7.09    | 2.61 |
| 300        | 6.02                                  | 3.93 | 6.02     | 3.14 | 5.92    | 3.14 | 6.02                               | 2.95 | 6.02     | 2.57 | 5.92    | 2.57 |
| 350        | 5.20                                  | 3.88 | 5.20     | 3.11 | 5.07    | 3.11 | 5.20                               | 2.90 | 5.20     | 2.54 | 5.07    | 2.54 |
| 400        | 4.60                                  | 3.85 | 4.60     | 3.08 | 4.44    | 3.08 | 4.60                               | 2.86 | 4.60     | 2.52 | 4.44    | 2.52 |
| 500        | 3.75                                  | 3.79 | 3.75     | 3.03 | 3.56    | 3.03 | 3.75                               | 2.79 | 3.75     | 2.49 | 3.56    | 2.49 |
| 600        | 3.19                                  | 3.82 | 3.19     | 3.05 | 2.98    | 3.05 | 3.19                               | 2.78 | 3.19     | 2.50 | 2.98    | 2.50 |
| 750        | 2.64                                  | 3.76 | 2.64     | 3.01 | 2.40    | 3.01 | 2.64                               | 2.71 | 2.64     | 2.47 | 2.40    | 2.47 |
| 1000       | 2.11                                  | 3.70 | 2.11     | 2.96 | 1.82    | 2.96 | 2.11                               | 2.60 | 2.11     | 2.43 | 1.82    | 2.43 |

**Table 12—60 Hz Low-Voltage Busway-Resistance (*R*) and Reactance (*X*) Data in Milliohms per 100 Ft at 25 °C**

| Ampere Rating | Feeder   |          |          |          | Plug-In  |          |          |          |
|---------------|----------|----------|----------|----------|----------|----------|----------|----------|
|               | Copper   |          | Aluminum |          | Copper   |          | Aluminum |          |
|               | <i>R</i> | <i>X</i> | <i>R</i> | <i>X</i> | <i>R</i> | <i>X</i> | <i>R</i> | <i>X</i> |
| 100           | —        | —        | —        | —        | 11.82    | 4.00     | 21.96    | 4.00     |
| 225           | —        | —        | —        | —        | 7.15     | 3.42     | 6.12     | 3.42     |
| 400           | —        | —        | —        | —        | 1.78     | 2.30     | 3.11     | 2.60     |
| 600           | —        | —        | 2.56     | 0.99     | 1.78     | 2.30     | 1.71     | 1.59     |
| 800           | 1.26     | 0.99     | 1.78     | 0.81     | 1.05     | 2.17     | 1.80     | 2.17     |
| 1000          | 1.05     | 0.82     | 1.59     | 0.50     | 1.05     | 2.17     | 1.20     | 1.43     |
| 1350          | 0.76     | 0.65     | 1.06     | 0.44     | 0.71     | 1.43     | 0.84     | 1.00     |
| 1600          | 0.70     | 0.53     | 0.89     | 0.40     | 0.49     | 1.00     | 0.75     | 0.90     |
| 2000          | 0.52     | 0.41     | 0.63     | 0.31     | 0.43     | 0.90     | 0.60     | 0.72     |
| 2500          | 0.38     | 0.32     | 0.47     | 0.25     | 0.35     | 0.72     | 0.42     | 0.50     |
| 3000          | 0.35     | 0.30     | 0.46     | 0.20     | 0.24     | 0.50     | 0.40     | 0.48     |
| 4000          | 0.25     | 0.20     | 0.31     | 0.16     | —        | —        | —        | —        |
| 5000          | 0.19     | 0.15     | —        | —        | —        | —        | —        | —        |

**Table 13—Multipliers for Source Short-Circuit Current Contributions**

| Type of Source(s)                             | Type of Calculation                 |                                    |                                     |                                    |                                                 |                                    |
|-----------------------------------------------|-------------------------------------|------------------------------------|-------------------------------------|------------------------------------|-------------------------------------------------|------------------------------------|
|                                               | First-Cycle                         |                                    | Interrupting                        |                                    | Medium-Voltage Circuit Breaker Close and Latch* |                                    |
|                                               | Multiply SCA or SCA <sub>M</sub> by | Multiply <i>X<sub>d</sub></i> ' by | Multiply SCA or SCA <sub>M</sub> by | Multiply <i>X<sub>d</sub></i> ' by | Multiply SCA or SCA <sub>M</sub> by             | Multiply <i>X<sub>d</sub></i> ' by |
| Utility or Power Company                      | 1.0                                 | 1.0                                | 1.0                                 | 1.0                                | 1.0                                             | 1.0                                |
| Generators <sup>†</sup>                       | 1.0                                 | 1.0                                | 1.0                                 | 1.0                                | 1.0                                             | 1.0                                |
| Synchronous Motors                            | 1.0                                 | 1.0                                | 0.667                               | 1.5                                | 1.0                                             | 1.0                                |
| Induction motors<br>Above 1000 hp at 1800 rpm | 1.0                                 | 1.0                                | 0.667                               | 1.5                                | 1.0                                             | 1.0                                |
| Above 250 hp at 3600 rpm                      | 1.0                                 | 1.0                                | 0.667                               | 1.5                                | 1.0                                             | 1.0                                |
| All others, 50 hp and above                   | 1.0                                 | 1.0                                | 0.333                               | 3.0                                | 0.833                                           | 1.2                                |
| All smaller than 50 hp                        | 1.0                                 | 1.0                                | NEGLECT                             | NEGLECT                            | NEGLECT                                         | NEGLECT                            |

\*Refers to calculations for medium-voltage circuit breakers as developed in national standards (see [5] and [4]).

<sup>†</sup>Use 0.75*X<sub>d</sub>*' for hydrogenerators without amortisseur windings.

**Table 14—Impedance Data for Single-Phase Transformers**

| kVA<br>1 $\phi$ | Suggested<br>X/R Ratio for<br>Calculation | Normal Range of<br>Percent Impedance<br>(%Z)* | Impedance Multipliers <sup>†</sup><br>for Line-to-Neutral Fault |        |
|-----------------|-------------------------------------------|-----------------------------------------------|-----------------------------------------------------------------|--------|
|                 |                                           |                                               | for %X                                                          | for %R |
| 25.0            | 1.1                                       | 1.2–6.0                                       | 0.6                                                             | 0.75   |
| 37.5            | 1.4                                       | 1.2–6.5                                       | 0.6                                                             | 0.75   |
| 50.0            | 1.6                                       | 1.2–6.4                                       | 0.6                                                             | 0.75   |
| 75.0            | 1.8                                       | 1.2–6.6                                       | 0.6                                                             | 0.75   |
| 100.0           | 2.0                                       | 1.3–5.7                                       | 0.6                                                             | 0.75   |
| 167.0           | 2.5                                       | 1.4–6.1                                       | 1.0                                                             | 0.75   |
| 250.0           | 3.6                                       | 1.9–6.8                                       | 1.0                                                             | 0.75   |
| 333.0           | 4.7                                       | 2.4–6.0                                       | 1.0                                                             | 0.75   |
| 500.0           | 5.5                                       | 2.2–5.4                                       | 1.0                                                             | 0.75   |

\*National standards do not specify %Z for single-phase transformers. Consult manufacturer for values to use in calculation.

<sup>†</sup>Based on rated current of the winding (one-half nameplate kVA divided by secondary line-to-neutral voltage).

## 2.2.2 Calculation Method

Two methods of making short-circuit calculations are presented. They are identified as the *direct method* and the *per-unit method*. While they represent different calculation concepts, if both use the same data, they produce results of the same degree of accuracy.

The direct method of short-circuit calculation presented here is so designated because, for the most part, it uses the system one-line diagram directly, uses system and equipment data such as volts, amperes, and ohms directly, and uses basic electrical equations and relationships directly without utilizing special diagrams, abstract units, or mathematical techniques.

The per-unit method is more representative of conventional electrical circuit analysis. It involves converting the system one-line diagram into an equivalent impedance diagram and reducing this to a single impedance value. This is best accomplished especially when several voltage levels are involved by using a special mathematical technique that establishes base (or reference) values for volts, current, kVA, and ohms and then refers the actual parameters to these bases in special equations to derive per-unit (or sometimes percent) values. Applying these values in special equations produces the short-circuit values.

For those who do not specialize in short-circuit calculation work, the direct method is usually easier to comprehend since it uses the familiar system one-line diagram and is compatible with the intuitive analogy of water flowing from sources to point of fault. Also, it instills confidence since system and equipment data are applied directly to familiar electrical equations producing recognizable values that can be immediately appraised.

The direct method is particularly adapted to progressive analysis of a whole or portion of a system starting at the source, considering each eschelon step by step, and determining short-circuit values at each location out to the end of the various circuits. Such an analysis is typically associated with planning an entire power system of a new building or facility where short-circuit values at all points must be determined before proper equipment can be selected.

The per-unit method with its special mathematical technique is particularly adapted to calculating short-circuit values at one or more specific points in the system, especially when several voltage levels exist between the source and the short-circuit point. In the per-unit method each point of fault is considered separately. A system equivalent impedance

diagram is developed using those parameters that will have an effect on short-circuit current at that point. The diagram is reduced by delta and wye conversion equations to a single impedance, which applied to the appropriate equation produces the short-circuit value. Each fault location requires its own separate equivalent impedance diagram, subsequent reduction, and calculation. It is not dependent on short-circuit values obtained from a proceeding circuit section. Since each point is considered separately, the per-unit method may be more expedient when a single specific remote location is being analyzed (perhaps in an existing system) since progressive calculation at interim points would not be involved.

In the evolution of short-circuit calculation techniques, most of the major short-circuit studies have pertained to systems where the characteristics of the per-unit method were of an advantage—typically, existing medium- and high-voltage systems with many voltage levels, such as power company systems. As a result, the per-unit method is generally considered the official standard method of calculation, as presented in great detail in many references, including ANSI standards and other IEEE publications and books. It is not the intent of this discussion to duplicate the voluminous material presented in these references. Instead, a brief discussion of the per-unit method is presented here in comparison with the direct method and the reader is encouraged to study these other references if the per-unit method is chosen for calculation.

### 2.2.3 Calculation Times

Because some protective devices operate after a few cycles and others after a time delay, short-circuit currents may need to be calculated at the following recommended times.

- 1) *The First-Cycle Considerations.* Maximum symmetrical values immediately after fault initiation are always required and are often the only values needed. In this chapter these values are referred to as first-cycle current and are symmetrical rms short-circuit amperes of alternating current unless otherwise noted. These values are used in selecting proper short-circuit ratings for low-voltage equipment and when converted to asymmetrical values are the basis for selecting circuit medium-voltage switch and fuse ratings and circuit breaker close and latch ratings. They often are used in the process of selecting medium-voltage circuit breaker interrupting ratings. The first-cycle values are also required for coordinating protective devices according to their time-current characteristics. Even if a device does not interrupt until several cycles after fault initiation, thus allowing the fault current to decay, the protective devices and all series devices should withstand the maximum current as well as the total energy. A device that interrupts in less than one-half cycle (and before the first current peak is attained) reduces the withstand requirements of series devices. The let-through current for such a device can be determined from the maximum symmetrical values in the first one-half cycle usually referred to as prospective short-circuit current.
- 2) *After 1.5–8 Cycles (Interrupting Considerations).* Maximum values after a few cycles are required for comparison with the interrupting ratings of medium-voltage circuit breakers. Only the basic considerations and calculations are discussed in this chapter. (They are discussed fully in [6] and [7] and referred to in the example.)
- 3) *About 30 Cycles.* These reduced fault currents are sometimes needed for estimating the performance of time-delay relays and fuses. Often, minimum values should be calculated to determine whether sufficient current is available to open the protective devices within a satisfactory time.

### 2.2.4 Impedance Tables

Tables 1–12 give impedance data for three-phase transformers, medium-voltage cable, low-voltage cable, and low-voltage busway. When specific data cannot be obtained from the manufacturer, these tables can be used and should provide satisfactory results.

It should be noted that transformers usually provide the most critical impedances in any system. A small difference between an assumed transformer impedance and the actual impedance can significantly alter the calculated fault current and consequently the equipment selected. Therefore, percent impedance values for transformers being built should be obtained from the supplier (manufacturer or power company).

## 2.3 Calculating Three-Phase Short-Circuit Currents by the Direct Method

With the one-line diagram of the actual power system, refer to Figs 6–16, which present the direct method of calculation. The pictorial representation in each figure clearly shows where in the one-line diagram it applies. The format shows what data must be acquired and how they are used to calculate the results. Supplemental comments and explanations appear on the right side of the figures. The method is based on familiar concepts. Visualize current flow as if it were water flowing from sources to fault. Fundamental ohms law is the basis for most calculations, but the concept of *percent impedance* is used when data warrant. Percent impedance represents the percent of normal voltage that, applied to the primary of a transformer, etc, will cause full-load current to flow in a shortcircuited secondary. Maximum short-circuit current occurs when full (100%) voltage is applied and is equal to full-load current times the ratio of 100% divided by the total percent impedance value. Throughout the procedure, resistances are totaled separately, reactances are totaled separately, and these used to determine resulting impedance; mathematical conversion of one to the other (vectorially) is done with simple trigonometric equations easily performed on popular small inexpensive calculators.

### 2.3.1 Description of Procedure

Fault calculation points on the system one-line diagram are marked with *bus* numbers. The various sources are next analyzed to determine the total source short-circuit current available at the various busses. Each segment from one bus to another is then handled separately to determine the short-circuit current at the *start* and *finish* of that segment, beginning with the service point and working through the system until every segment has been analyzed. Each circuit segment is handled separately according to one of the following sections.

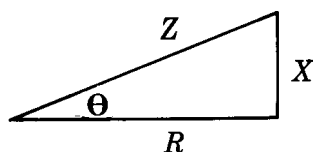
### 2.3.2 Basic Equations

To calculate the available short-circuit current at a given point in the system, the following fundamental equations may be used:

$$\text{kVA}_{\text{SC}} = \frac{\sqrt{3} \cdot V_{\text{LL}} \cdot I_{\text{SC}}}{1000} = \sqrt{3} \cdot \text{kV}_{\text{LL}} \cdot I_{\text{SC}}$$

$$I_{\text{SC}} = \frac{V_{\text{LN}}}{Z}$$

from the right triangle relationship



$$Z^2 = R^2 + X^2$$

$$X = \frac{Z (X/R)}{\sqrt{(X/R)^2 + 1}}$$

$$\frac{X}{R} \text{ ratio} = \frac{X}{R} = \tan \theta$$

$$\theta = \arctan \frac{X}{R}$$

$$R = Z \cos \theta$$

$$X = Z \sin \theta$$

$$X = Z \sin \left( \arctan \frac{X}{R} \right)$$

$$Z = \frac{X}{\sin \left( \arctan \frac{X}{R} \right)}$$

where

$kVA_{SC}$  = three-phase first-cycle short-circuit rms symmetrical kilovolt-amperes (also denoted as SCKVA; see 2.3.3)

$I_{SC}$  = three-phase first-cycle short-circuit rms symmetrical current amperes (also denoted as SCA; see 2.3.3)

$V_{LL}$  = line-to-line volts

$kV_{LL}$  = line-to-line kilovolts

$V_{LN}$  = line-to-neutral volts

$R$  = resistance in ohms, on a line-to-neutral basis

$X$  = reactance in ohms, on a line-to-neutral basis

$Z$  = impedance in ohms, on a line-to-neutral basis

$\frac{X}{R}$  ratio = reactance divided by resistance

### 2.3.3 Determining Source Contributions for First-Cycle Calculations

In using the direct method of short-circuit calculation, the total source current at each bus should be determined before the short-circuit currents can be calculated. This procedure for first-cycle calculations is detailed in the next several paragraphs. Note that certain abbreviations are used for simplicity and to avoid excessive subscripting:

SCKVA = Short-Circuit kilovolt-Amperes =  $kVA_{SC}$

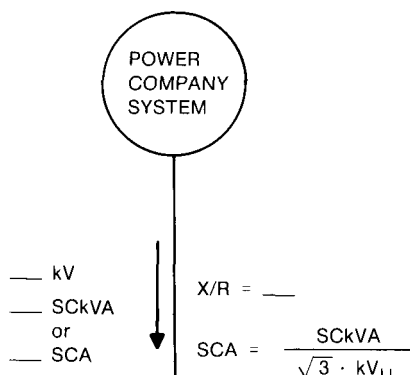
SCA = Short-Circuit Amperes =  $I_{SC}$

### 2.3.4 Determining Source Contributions for Medium-Voltage Circuit Breaker Interrupting and Close and Latch Capacity Calculations

Many factors have an influence on proper application of medium-voltage circuit breakers. Persons involved in such applications are advised to study ANSI/IEEE C37.010-1979 [5] and other appropriate references. The great detail presented in these standards is not repeated in this text, but portions are briefly discussed to provide some understanding of the procedure relating medium-voltage circuit breaker application to system short-circuit calculations.

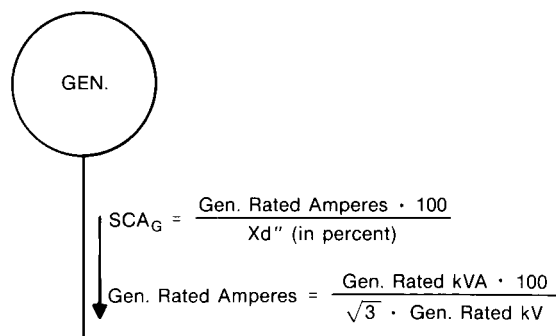
Devices that interrupt after a few cycles, such as medium-voltage circuit breakers, may be required to interrupt less current than the available first-cycle short circuit. This is due to the rapid decrease of some source short-circuit contributions by the time the circuit breaker interrupts. Data in Table 13 are used in these calculations.

Both the short-circuit current and  $X/R$  ratio are important in medium-voltage circuit breaker application. However, if the available symmetrical short-circuit current at time of interruption (or the higher first-cycle symmetrical short-circuit current) is not more than 80% of the circuit breaker symmetrical current interrupting rating, any  $X/R$  ratio will be satisfactory and therefore need not be calculated. This 80% condition is often sufficient to justify the circuit breaker interrupting rating. If this does not suffice, the available short-circuit current may be as great as 100% of the circuit breaker interrupting rating as long as the  $X/R$  ratio does not exceed  $X/R = 15$  for 5- and 3-cycle circuit breakers and 10 for 8-cycle circuit breakers. But if the  $X/R$  ratio is greater than these limits, multipliers from curves in ANSI/IEEE C37.010-1979 [5] should be applied. These evaluations require calculating or conservatively estimating the system  $X/R$  ratio at point of fault.



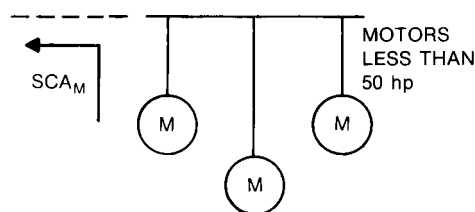
The Power Company will advise the maximum available symmetrical short-circuit kVA or amperes that its system can produce at the user's service connection. This is the maximum fault possible at that point expressed in terms of normal voltage and steady-state short-circuit current. It influences the size of short circuits in the user's distribution system. If this information is not available, be guided by the interrupting rating of the nearest circuit breaker or fuse intended to clear this fault.

**Figure 6—Power Company Source**



Values vary widely, depending on design. Consult generator manufacturer for data.  $X_d''$  is the subtransient reactance. If  $X_d''$  is given in per-unit, multiply by 100 to yield percent.

**Figure 7—Generator**

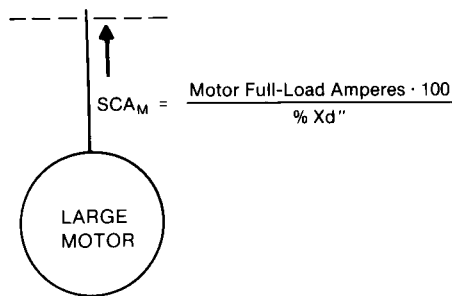


$$SCA_M = 4 \cdot \text{Sum of Motor Full-Load Amperes}$$

It is not practical to consider each small motor separately, and so it is usual practice to combine them all at each location. Consider all motors at each location which may be running even though at partial load. ANSI standards permit neglecting motors less than 50 hp when considering medium-voltage circuit breaker applications—see Table 13.

A multiplier of 4 is used throughout the industry. This is generally lower than for large motors to account for the rapid decay of their short-circuit contribution.

**Figure 8—Small Motors (Less Than 50 hp)**



Motor Rated kVA  $\cong$  Motor Rated hp (for 80% power factor)

Motor Rated kVA  $\cong$  0.8  $\cdot$  Motor Rated hp (for 100% power factor)

$$\text{Motor Full-Load Amperes} = \frac{\text{Motor Rated kVA}}{\sqrt{3} \cdot \text{Motor Rated kV}}$$

#### APPROXIMATIONS

##### (a) Large Induction Motors

$$SCA_M \cong \text{Locked-Rotor Amperes}$$

or

$$SCA_M \cong \frac{\text{NEC (and NEMA) Coded Letter Multiple} \cdot \text{hp}}{\sqrt{3} \cdot \text{Motor Rated kV}}$$

or

$$SCA_M \cong 5 \cdot \text{Full-Load Amperes}$$

##### (b) Large Synchronous Motors

$$SCA_M \cong 6.7 \cdot \text{Motor Full-Load Amperes for 1200 rpm}$$

$$\cong 5 \cdot \text{Motor Full-Load Amperes for 514-900 rpm}$$

$$\cong 3.6 \cdot \text{Motor Full-Load Amperes for 450 rpm or less}$$

Handle each motor separately, unless several of identical type are connected to the same bus.

The exact short-circuit contribution can be determined from the subtransient reactance ( $X_d''$ ), if known. If  $X_d''$  is given in per-unit, multiply by 100 to obtain percent.

1 hp = .746 kW but .8 usually used in determining kVA

New individual motors are rated at 200, 230, 460, 575, 2300, 4000, 6600 and 13 200 volts. Older motors may be rated lower, and new motors included in a complete unit (such as a chiller unit) may be rated at the system voltage.

If subtransient reactance cannot be determined, the approximations will be close.

Locked-rotor current is nearly the same as short-circuit contribution.

Code letter on motor nameplate identifies range of ratio of locked-rotor kVA  $\div$  hp. Maximum values are as follows:

| Letter | Multiple | Letter | Multiple  |
|--------|----------|--------|-----------|
| A      | 3.15     | L      | 10.0      |
| B      | 3.55     | M      | 11.2      |
| C      | 4.0      | N      | 12.5      |
| D      | 4.5      | P      | 14.0      |
| E      | 5.0      | R      | 16.0      |
| F      | 5.6      | S      | 18.0      |
| G      | 6.3      | T      | 20.0      |
| H      | 7.1      | U      | 22.4      |
| J      | 8.0      | V      | Over 22.4 |
| K      | 9.0      |        |           |

Assumes motor impedance is 20% (usual range 15-25% with 20% more popular).

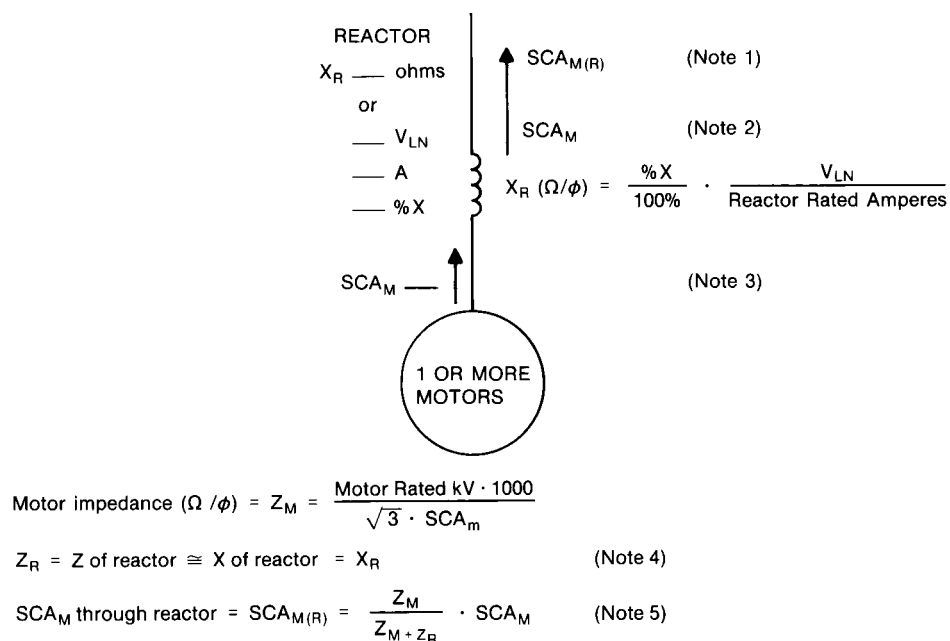
Assumes  $X_d'' = 15\%$

Assumes  $X_d'' = 20\%$

Assumes  $X_d'' = 28\%$

If rpm is unknown, assume 514-900 rpm, since 1200 rpm is uncommon.

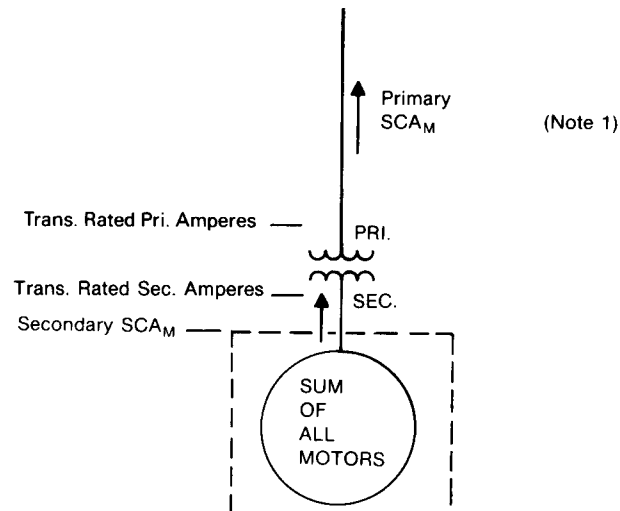
**Figure 9—Large Motors (50 hp or More)**



## NOTES:

- 1 — Reactor impedance significantly reduces motor short-circuit contribution.
- 2 — If system has no neutral, use  $V_{LN}$  equal to  $V_{LL}$  divided by  $\sqrt{3}$ .
- 3 —  $SCA_M$  is total short-circuit amperes from motors (obtained from Figs 8 and 9).
- 4 — Impedance is virtually reactance, very high X/R ratio.
- 5 — Usually can add these impedances arithmetically instead of vectorially since both reactor and motor will have high X/R ratio.

**Figure 10—Motor Contribution Through Reactor**

APPROXIMATION

(Note 2)

$$\text{Primary SCA}_M = \frac{\text{Trans. Rated Pri. Amperes}}{\text{Trans. Rated Sec. Amperes}} \cdot \text{Secondary SCA}_M$$

When L.V. is 240 V or higher Pri.  $\text{SCA}_M = 3.5 \cdot \text{transformer primary A}$  (Note 3)

When L.V. is 208 V or lower Pri.  $\text{SCA}_M = 2 \cdot \text{transformer primary A}$

MORE EXACT DETERMINATION

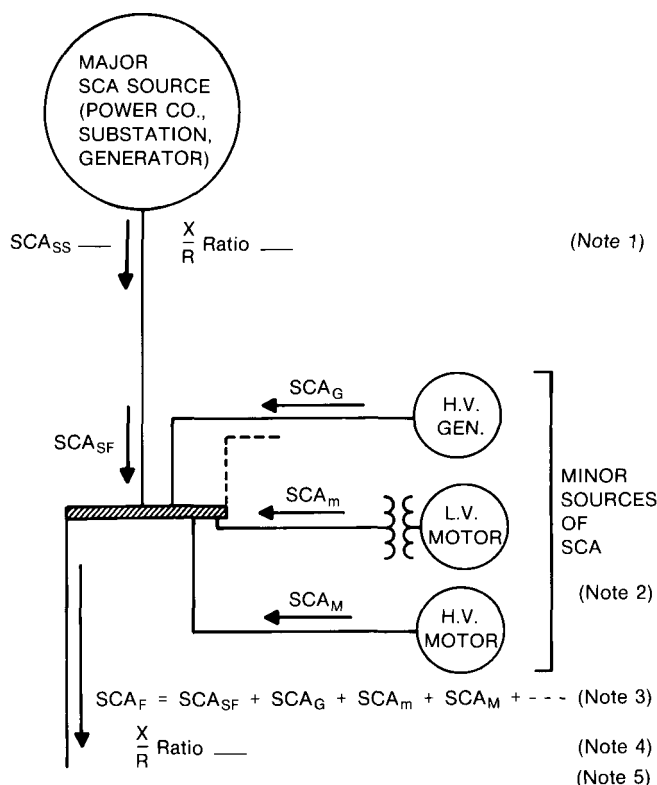
(Note 4)

$$\text{Primary SCA}_M = \frac{\text{Trans. Rated Pri. Amperes}}{\frac{\text{Trans. \%Z}}{100\%} + \frac{\text{Trans. Rated Sec. Amperes}}{\text{Secondary SCA}_M}}$$

## NOTES:

- 1 — Motors generate short circuit current which can be transmitted through transformer to primary system.
- 2 — Simple estimate yielding somewhat high results by ignoring transformer impedance.
- 3 — Based on only small motors (see Fig 8) normal transformer impedance, all transformer load being motors if L.V. is 240 volts and above and  $1/2$  transformer load being motors if voltage is 208 volts or lower.
- 4 — Yields more accurate results when transformer impedance is known.

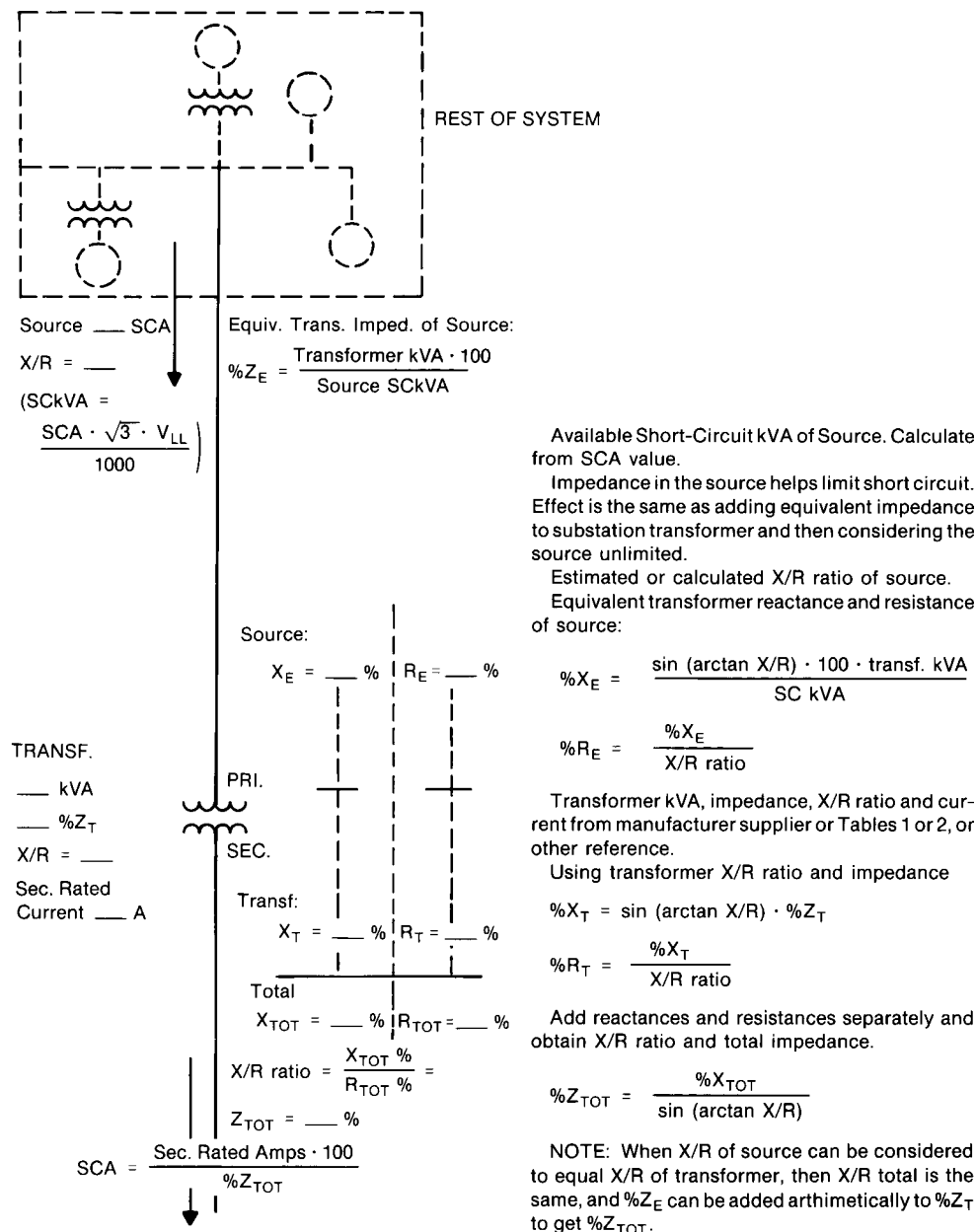
**Figure 11—Transformer Secondary Motor Contribution to Primary System**



## NOTES:

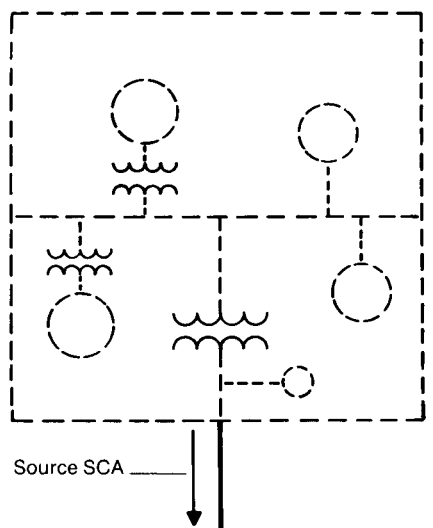
- 1 — The  $SCA_M$  at the start of the feeder is the combination of the SCA from the various sources which supply this feeder.
- 2 — The SCA values from the various sources (as determined in Figs 6 through 11) will be reduced by the impedance of the conductors from these sources. However, the impedance of some and perhaps all of these conductors is often ignored (considered zero) to make calculation easier and data may not be available. This produces calculated SCA values which are higher than the actual values and are safe but may require larger capacity equipment than necessary. Generally, the impedance of short conductor segments and conductors from minor sources are often ignored. When the conductor impedance is to be considered the calculations are as indicated in Figs 14, 15, 16, and perhaps 13.
- 3 — Add arithmetically.
- 4 — The X/R ratio at the start of the feeder is determined mostly by the X/R ratio of the major sources.
- 5 — Short circuit ampere values from the various sources should, for maximum accuracy, be added vectorily and can be, using the X/R ratios. However, since the SCA values from the major sources are usually influenced by high X/R ratios and minor sources contributions are usually estimates anyway, adding these arithmetically produces sufficiently accurate results. This is much easier and safe since arithmetic addition will not produce SCA values lower than more precise vector addition.

Figure 12—Total Short-Circuit Available at Beginning/Start of A Feeder



NOTE — When X/R of source can be considered to equal X/R of transformer, then X/R total is the same, and  $\%Z_E$  can be added arithmetically to  $\%Z_T$  to get  $\%Z_{TOT}$ .

Figure 13—Transformer Secondary Short-Circuit Current



CONSOLIDATED  
SOURCE TO  
FEEDER

Feeder Voltage \_\_\_\_\_ V      Voltage Line-Neutral \_\_\_\_\_  $V_{LN}$

$Z$  = Source Impedance ( $m\Omega/\phi$ )

$$Z = \frac{V_{LN} \cdot 1000}{SCA}$$

Source X/R ratio \_\_\_\_\_

| Reactance                     | Resistance            |
|-------------------------------|-----------------------|
| Source: $X =$ _____ $m\Omega$ | $R =$ _____ $m\Omega$ |

Available Short-Circuit Amperes from Source.

Short-circuit analysis is performed on a per-phase basis. Necessary to use line-to-neutral voltage. Even if system has no neutral use  $V_{LN}$  equal to voltage line-to-line divided by  $\sqrt{3}$ .

Ohm's Law. Effective impedance is obtained by dividing known voltage by available short-circuit current.

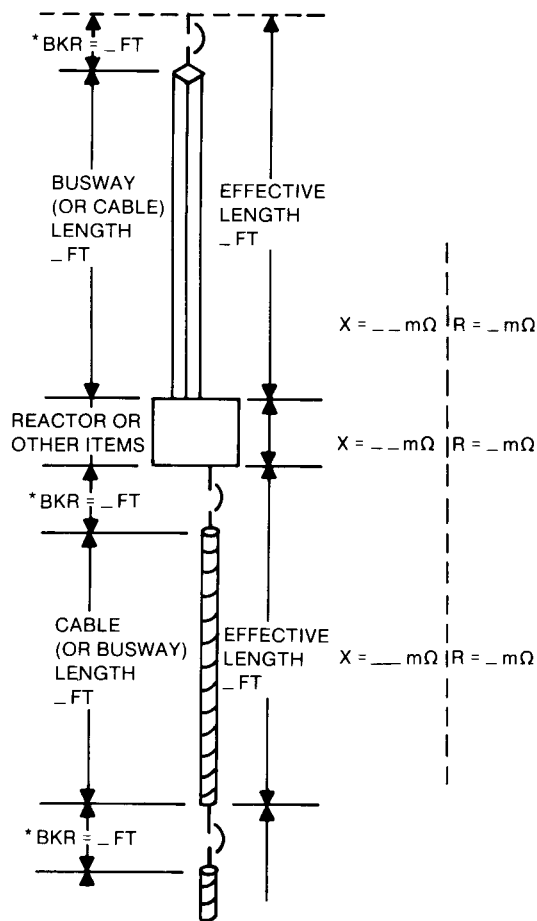
Impedance, reactance, and resistance are expressed in milliohms, instead of ohms, for greater convenience. One milliohm =  $1 m\Omega = 1/1000$  ohm = .001 ohm. This accounts for 1000 factor in equation.

X/R ratio value determined from previous calculations or estimate of supply. (In low voltage [600 V max] systems X/R = 12 is often used if more specific information is not available.)

$$X = Z \cdot \sin(\arctan \frac{X}{R} \text{ ratio})$$

$$R = \frac{X}{\frac{X}{R} \text{ ratio}}$$

Figure 14—Effective Impedance (Reactance and Resistance) of System Supplying Feeder



Determine milliohms reactance and resistance per phase of each circuit section by considering length and reactance and resistance data in manufacturer's literature or accompanying tables.

For parallel conductors per phase divide milliohms values of one conductor by number of identical conductors.

Short-circuit analysis is performed on a per-phase (line-to-neutral) basis. Circuit length is overall three-phase length, not the sum of the individual conductor lengths.

Reactance (X) and resistance (R) values are expressed in milliohms (mΩ) for convenience.

Busway data in Table 12.

Cable data in Tables 3 through 11.

Reactance and resistance milliohms for any miscellaneous devices, components, switchboard bussing, etc, may be considered if available.

Use reactor actual milliohms for X and X/80 for R (assumes  $X/R = 80$ ).

Circuit breaker impedances are usually ignored for ease of calculation. When calculated current values slightly exceed equipment rating it may be beneficial to consider circuit breaker impedance. Circuit breaker reactance and resistance values depend on breaker size, design, and manufacturer. However, these values usually are similar to those of the circuit supplied by the breaker (feeder breaker) or supplying the breaker (main breaker). From this and for convenience, circuit breakers are represented here as equivalent lengths of cable or busway. A similar relationship for switch and fuse devices has not yet been established.

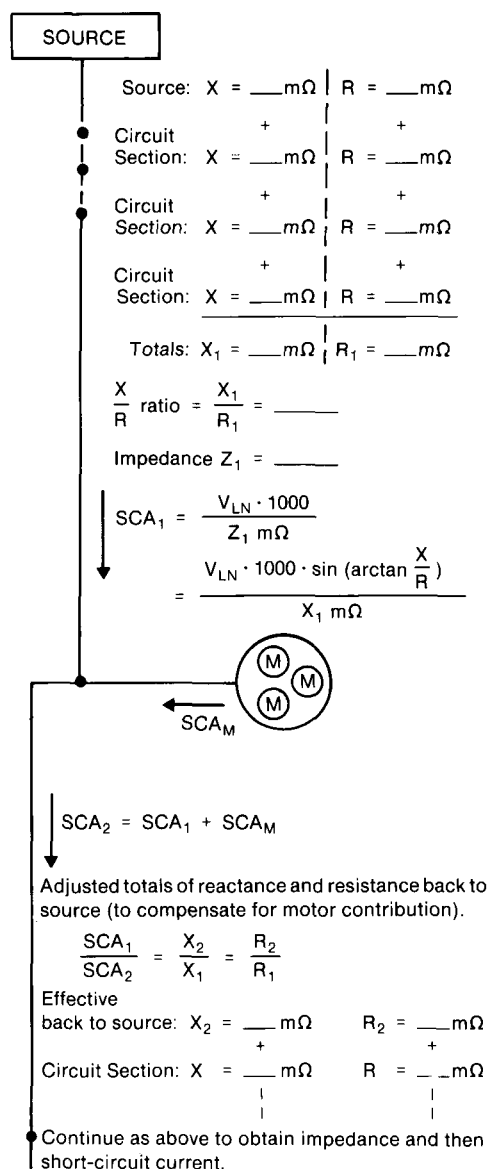
\*If circuit breaker impedances are considered, then treat each circuit breaker other than at point of assumed fault as equal to —

or 5 ft of cable or plug-in busway  
or 10 ft of feeder busway

Use load side cable/busway for feeder bkr's; line side cable/busway for equipment main bkr's.

NOTE — The reactance and resistance of a circuit breaker help determine its interrupting rating. Therefore, circuit breaker reactance and resistance cannot be used in determining the system short-circuit current at the point where that breaker is considered for use. Circuit breakers at other points can be considered.

Figure 15—Reactance and Resistance of Circuit Segments



Often, medium-voltage cable impedance is ignored, especially since it has very little effect on calculations in the subsequent low-voltage system. This is easier and faster, and usually sufficiently precise, and produces safe values. However, if the short-circuit values obtained at remote locations on medium-voltage feeders are higher than the ratings of the equipment proposed for use there, it may be desirable to consider the medium-voltage cable impedance. Values can be obtained from the cable manufacturer or from Tables 3 through 9.

Low-voltage conductor impedance has significant effect and should be considered unless the conductor segment is very short.

Reactance and resistance milliohm values from Figs 14 and 15.

Add arithmetically all reactance values, then all resistance values — keeping reactances separate from resistances.  $X/R$  ratio is total reactance divided by total resistance. Obtain resultant impedance  $Z$  by using total reactance and  $X/R$  ratio.

$$Z_1 = \frac{X_1}{\sin(\arctan X/R)}$$

Ohm's Law: Phase voltage divided by phase impedance equals available short-circuit amperes in each phase.

Motor contribution explained in Figs 8 and 9.

Add short-circuit currents from source and motors arithmetically (assumes  $X/R$  ratio of supply feeder and motor circuit are equal). This is a safe approximation and easier than more rigorous vector addition.

With voltage considered a constant, the increased short-circuit (due to addition from motors) can be considered a result of reducing the impedance of the supply feeder circuit, then ignoring the motors. In Ohm's Law, impedance (also reactance and resistance) varies inversely as the short-circuit current, permitting the proportion equations at left. Knowing four values, the other two are easily found.

To the new reactance and resistance milliohm values representing effective totals back to the source add  $X$  and  $R$  values of subsequent circuit sections. Procedure is same as above; totaling reactances, resistances; determining impedance; applying Ohm's Law to get available short-circuit amperes.

**Figure 16—Determination of Short-Circuit Current on Feeder**

A satisfactory, safe  $X/R$  ratio can be obtained from vector analysis of the short-circuit currents and  $X/R$  ratios of the various sources. One way is to factor the various source short-circuit currents into effective reactance and resistance components by considering: reactance component = short-circuit current  $\sin(\arctan X/R \text{ ratio})$ ; the resistance component = reactance component divided by  $X/R$  ratio. The arithmetic total of reactance components divided by the arithmetic total of resistance components will produce an acceptable  $X/R$  ratio for use with the total short-circuit current. Simplifying estimates tending toward a higher  $X/R$  ratio will be on the safe side in the medium-voltage circuit breaker applications.

In some cases circuit breakers with adequate interrupting capacity may have inadequate close and latch ratings. ANSI/IEEE C37.010-1979 [5] discusses this case. In essence, the calculated first-cycle short-circuit symmetrical rms current should be multiplied by a factor of 1.6 to obtain an asymmetrical rms current value to be compared with the close and latch rating of the circuit breaker expressed in asymmetrical rms amperes. If the circuit breaker close and latch rating is inadequate, a second evaluation can be made by reducing the induction motor short-circuit contribution, as shown in Table 13.

### 2.3.5 Calculating Short-Circuit Currents Through Impedances

After the short-circuit currents produced by the various sources throughout the system have been determined, short-circuit values at various locations can be calculated. This involves considering the impedance of each circuit segment (from start at one bus to finish at another bus) until every pertinent bus or eschelon of the system has been considered. The procedure is detailed in the following Figs 13–16. Note that since resistance, reactance, and impedance values are very small they are usually expressed in milliohms and a factor of 1000 appears in the ohms law equations.

### 2.3.6 Current-Limiting Protective Devices

In industrial and commercial power systems, it is common practice to use current-limiting devices to protect other devices against high values of short-circuit current, which exceed their short-circuit ratings. Short-circuit calculations should be made without considering the effects of current-limiting devices to determine the [prospective] short-circuit current, or that which would flow if no current-limiting device were present. This [prospective] short-circuit current is used in applying the devices. The manufacturer of the device to be protected should be consulted to determine the suitability of the application for the level of short-circuit current available at the line-side terminals of the protected device. At this time the best practice is to determine the suitability of various applications by performance testing in accordance with recognized test procedures of qualifying organizations, such as Underwriters Laboratories. No general agreement has yet been reached on how to use the  $I^2t$  and peak current let-through values of a current-limiting device to establish its capability to protect another device.

It should be noted that a current-limiting device cannot be used to protect another current-limiting device. Also, current-limiting devices in series do not work together to compound the current-limiting effect. The faster acting of the two, which is usually the one to be protected, will try to interrupt the full short-circuit current before the other device is able to operate.

### 2.3.7 Short-Circuit Current Tables and Curves

These are often found in application literature as a quick means for determining short-circuit values. However, these should be used with caution. They usually apply to a very limited portion of a power system and are based on assumptions that may not be representative of the actual system being analyzed. The tables and curves usually refer to a transformer supplying a feeder and short-circuit current values are presented for various feeder lengths. To enable this simplicity, assumptions are made for supply system capacity, transformer impedance and  $X/R$  ratio, motor short-circuit contribution, and feeder cable electrical parameters. Error can be very significant if the assumptions, particularly the transformer impedance, do not represent the actual conditions. In view of this, the reader may find it more reliable to perform the few calculations described here using the actual data pertinent to his/her system or by making and appraising his/her own assumptions.

## 2.4 Example of Direct Method Short-Circuit Current Calculations

The direct method is used in a brief short-circuit study of a power system. Figure 17 is a one-line diagram representing a comprehensive medium voltage and low voltage power system. Data from this diagram are used to illustrate the calculation techniques. Locations in the system where a short-circuit current value is desired are designated with bus numbers. The direct method is used to determine the short-circuit current at fourteen bus locations. (In 2.6 the per-unit method is used to determine the short-circuit current at three of these bus locations. The results from the two methods are essentially the same.)

The general procedure involves three steps. First, the total motor and generator first-cycle short-circuit contribution flowing toward the source at each bus is calculated working from the loads up to the service point. Second, the total first-cycle symmetrical short-circuit current is calculated at the start and finish of each circuit segment (from one bus to another) by working from the service point down to the loads. Third, any necessary medium-voltage circuit breaker interrupting and close and latch short-circuit current values are calculated by refiguring the various source contributions.

Much of the direct method of short-circuit calculation is condensed into a short-circuit calculation worksheet, which is used in this example (Figs 18, 19, 20). This worksheet offers a concise procedure and a convenient way of storing the data for future reference. Filling in the columns from top to bottom indicates what data should be obtained and how they are to be used. When calculations are necessary the equations are shown. Reactance and resistance values are used for accurate vector addition of impedances as well as  $X/R$  ratios. The relation of reactance, resistance, and impedance is conveniently handled with the single trigonometric expression “sin arctan  $X/R$  ratio” (sine of the angle whose tangent is the  $X/R$  ratio). This is easily calculated with even very inexpensive readily available calculators.

A blank copy of this worksheet is included, which the reader may find useful (Fig 18). Also the format and sequence of calculation may be a helpful guide to those who would like to develop a simple computer program for short-circuit calculations.

### 2.4.1 First-Cycle Motor and Generator Short-Circuit Contributions

The total motor and generator short-circuit contribution flowing toward the source must be determined first. The actual calculations for each bus are shown.

- 1) Busses 14 and 15. No motor contribution.
- 2) Bus 13. 100 kVA for 100 hp induction motor at 80% power factor.

$$\begin{aligned}
 SCA_M &= 5 \cdot I_{FL} \\
 &= 5 \cdot \frac{100 \text{ kVA}}{\sqrt{3} \cdot 0.46 \text{ kV}} \\
 &= 5 \cdot 125.5 \text{ A} \\
 &= 628 \text{ SCA}
 \end{aligned}
 \tag{see Fig 9}$$

- 3) Busses 11 and 12.  
 $SCA_M = 2 \cdot 628 \text{ A} = 1256 \text{ SCA}$
- 4) Bus 10.

$$\begin{aligned}
 \text{transformer primary amperes} &= \frac{750 \text{ kVA}}{\sqrt{3} \cdot 4.16} \\
 &= 104.09 \text{ A}
 \end{aligned}$$

$$\begin{aligned}
 \text{transformer rated secondary amperes} &= \frac{750 \text{ kVA}}{\sqrt{3} \cdot 0.480} \\
 &= 902.11 \text{ A}
 \end{aligned}$$

$$\begin{aligned}
 SCA_M &= \frac{104.09 \text{ A}}{\frac{5.5\%}{100\%} + \frac{902.11 \text{ A}}{1256 \text{ A}}} \\
 &= 135 \text{ SCA}
 \end{aligned}
 \tag{see Fig 11}$$

- 5) Bus 9. No motor contribution.
- 6) Busses 7 and 8. Generator contribution.

$$\begin{aligned}
 \text{generator rated amperes} &= \frac{625 \text{ kVA}}{\sqrt{3} \cdot 4.16 \text{ kV}} \\
 &= 86.74 \text{ A}
 \end{aligned}$$

$$\begin{aligned}
 SCA_G &= \frac{86.74 \text{ A} \cdot 100\%}{9\%} \\
 &= 964 \text{ SCA}
 \end{aligned}
 \tag{see Fig 7}$$

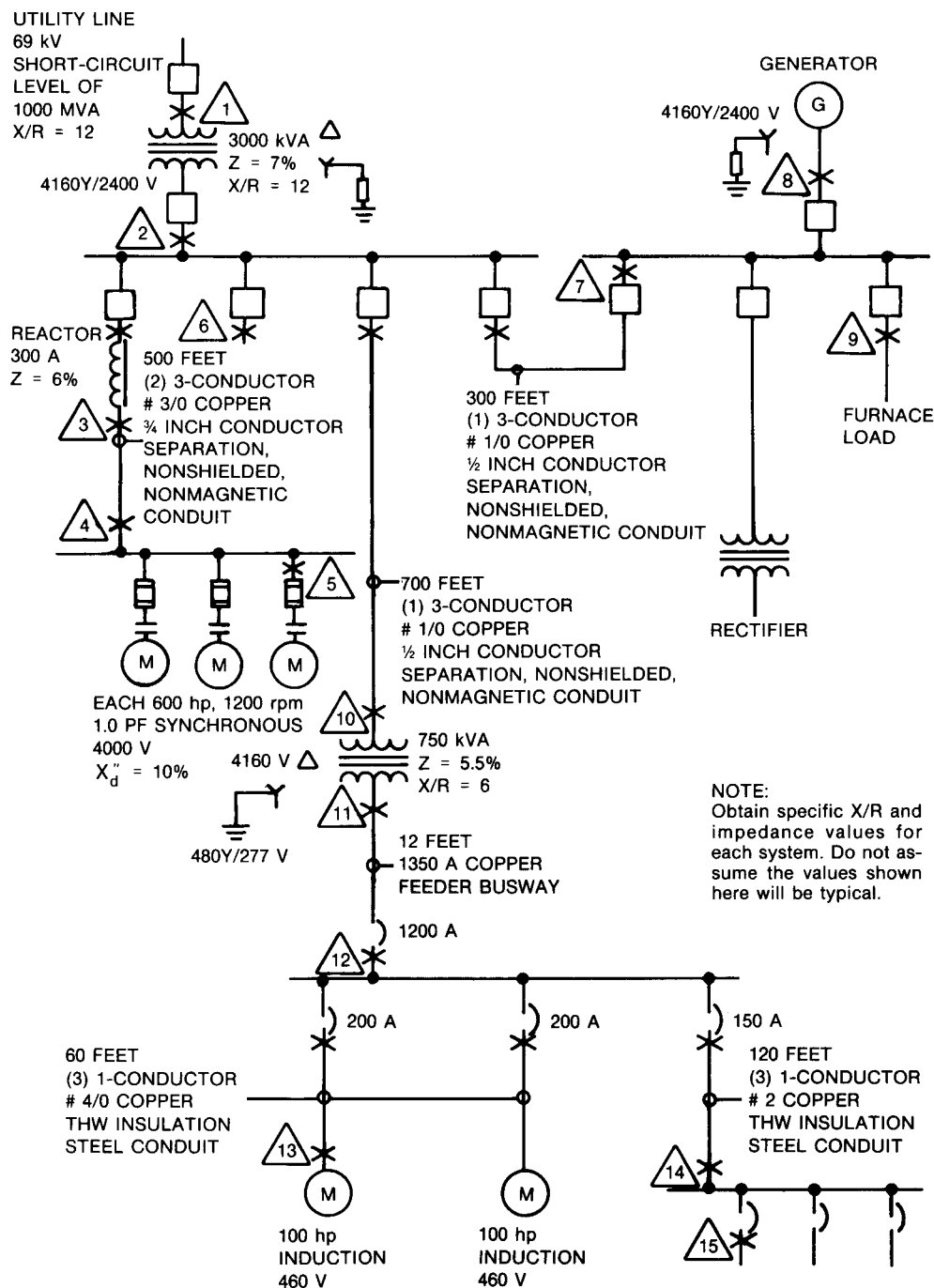


Figure 17—One-Line Diagram for Typical Industrial Distribution System