Application Information

Short-Circuit Current Calculations

For
Industrial
And
Commercial
Power
Systems

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The calculation of ac short-circuit currents, essential to the selection of adequately rated protective devices and equipment in industrial and commercial power systems, is becoming increasingly important to the system designer. Today, power systems carry larger blocks of power, are more important to the operation of the plant and building, and have greater safety and reliability requirements. Meeting these requirements necessitates the fulfillment of certain criteria, including the use of adequately rated equipment.

The system designer, who is usually a consulting engineer or plant electrical engineer, is responsible for the design of the power system and the selection of equipment and will generally have the task of calculating system short-circuit currents. Procedures and techniques for these calculations are not generally available in one place but are scattered among many publications, reports, and papers.

The purpose of this publication is to provide the system designer with information and procedures necessary to calculate short-circuit currents in industrial and commercial power systems. The intent has been to make it easier for the system designer to make short-circuit calculations by providing the necessary information in one place and oriented in a meaningful manner. The most frequently asked questions by system designers on this subject have been answered in this text.

CONTENTS

The contents of the various sections of this publication are briefly described below.

Section I describes the nature of ac short-circuit currents and discusses calculation procedures. Also included are equipment ratings and the criteria used for the selection of equipment. It provides a basis for understanding short-circuit calculating procedures.

Section II actually details short-circuit calculations, including the formulation of one-line and impedance diagrams, representation of specific system components, and step-by-step calculation procedures. It shows how to make the necessary calculations.

Section III contains examples of short-circuit calculations for both industrial and commercial building systems. A time-sharing computer example and tables for estimating short-circuit duty are illustrated.

The Appendix contains estimating data required to make short-circuit calculations. It includes tables for estimating short-circuit currents,impedance data for system components, and short-circuit ratings of standard devices and equipment. In addition, details of the per-unit system and computational techniques are included. The estimating impedance data and equipment short-circuit ratings are included for completeness; but it must be recognized that new equipment is continually becoming available, so that in actual practice the official rating and impedance data should be obtained from the appropriate, up-to-date equipment literature.

HOW TO USE

This publication is designed to be both instructional and procedural, a text book and a reference book. As seen from the contents it is arranged to provide the theory and definitions in Section I, the actual calculating procedures in Section II, examples in Section III, and estimating data in the Appendix. One who is unfamiliar with short-circuit calculations may want to use the publication as a text book and review the entire contents. For someone familiar with calculating procedures, the publication can be used as a reference for various questions which may arise.

Section I— The Nature of Ac Short-circuit Currents

INTRODUCTION

Electric power systems in industrial plants, commercial and institutional buildings are designed to serve loads in a safe and reliable manner. One of the major considerations in the design of a power system is adequate control of short-circuits. Uncontrolled short-circuits can cause service outages with accompanying production downtime and associated inconvenience, interruption of essential facilities or vital services, extensive equipment damage, personnel injury or fatality, and possible fire damage.

Electric power systems are designed to be as free of short-circuits as possible through careful system and equipment design, as well as proper installation and maintenance. However, even with these precautions, short-circuits do occur. Some causes are: presence of vermin or rodents in equipment; loose connections; voltage surges; deterioration of insulation; accumulation of moisture, dust, concrete juice and contaminants; the intrusion of metallic or conducting objects such as fish tape, tools, jack hammers or payloaders, and a large assortment of "undetermined phenomena."

When a short-circuit occurs on a power system, several things happen—all of them bad:

1. At the short-circuit location, arcing and burning can occur.
2. Short-circuit current flows from the various sources to the short circuit location.
3. All components carrying the short-circuit currents are subject to thermal and mechanical stress. This stress varies as a function of the current squared (I^2) and the duration of current flow.
4. System voltage drops in proportion to the magnitude of the short-circuit current. Maximum voltage drop occurs at the fault location (to zero for maximum fault) but all parts of the power system will be subject to some degree of voltage drop.

Clearly, the short-circuit must be quickly removed from the power system, and this is the job of the circuit protective devices—circuit breakers and fuses. In order to accomplish this, the protective device must have the ability to interrupt the maximum short-circuit current which can flow for a short circuit at the device location. The maximum value of short-circuit current is frequently referred to as the "available" short-circuit current.

The maximum value of short-circuit current is directly related to the size and capacity of the power source and is independent of the load current of the circuit protected by the protective device. The larger the capacity of the power source, the greater the short-circuit current will be.

For a simple example, consider Fig. 1 (top). The impedance which determines the flow of load current is the 20 ohms impedance of the motor. If a short circuit occurs at "F," the only impedance limiting the flow of short-circuit current is the transformer impedance (0.1 ohm compared with 20 ohms for the motor); therefore, the short-circuit current is 1000 amperes or 200 times as great as the load current. Consequently, circuit breaker "A" must have the ability to interrupt 1000 amperes.

If the load grows and a larger transformer, one rated at 1000 amperes, is substituted for the 100-ampere unit, then the short circuit at "F_1" (bottom of Fig. 1) becomes limited by 0.01 ohm, the impedance of the larger transformer. Although the load current is still five amperes, the short-circuit current increases to 10,000 amperes. Circuit breaker "A" must be able to interrupt that amount.

SOURCES OF SHORT-CIRCUIT CURRENTS

When determining the magnitude of short-circuit currents, it is extremely important that all sources of short circuit be considered and that

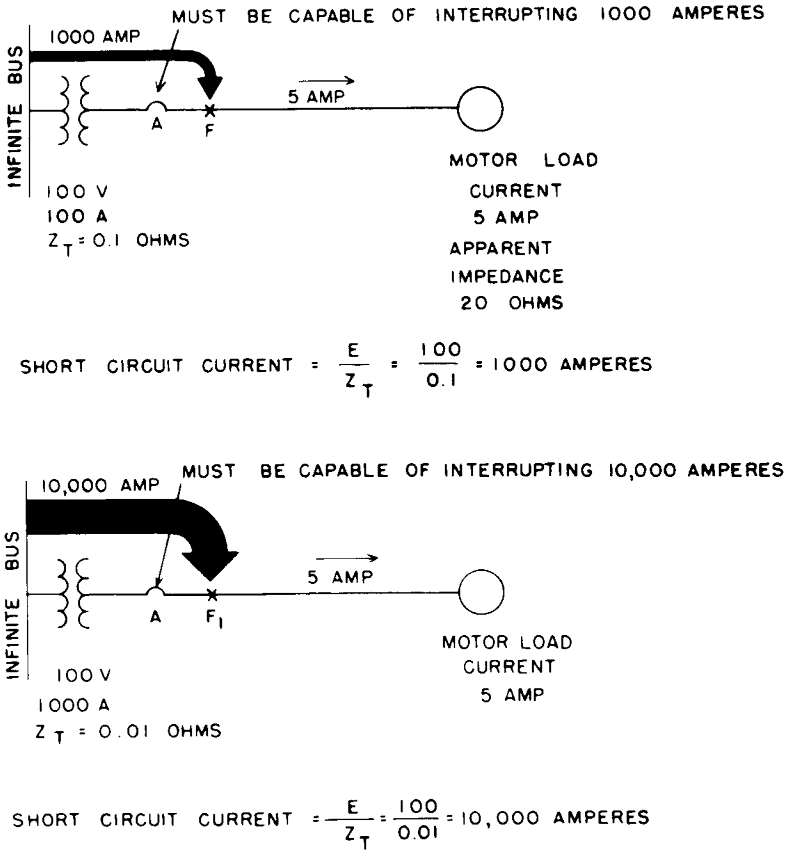

Fig. 1. **Note: These values have been chosen to simplify illustrations rather than to represent actual system values**

Section I— The Nature of Ac Short-circuit Currents

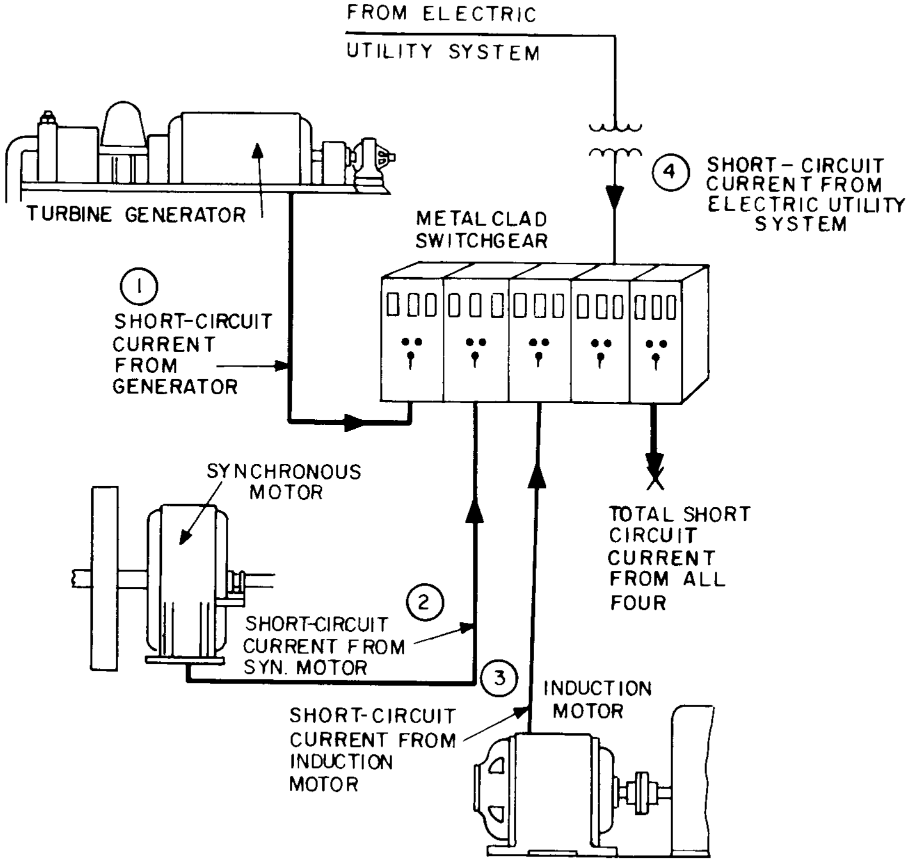

Fig. 2. Total short-circuit current equals sum of sources

the impedance characteristics of these sources be known:

There are four basic sources of short-circuit current:

1. Generators
2. Synchronous Motors
3. Induction Motors
4. Electric Utility Systems

All these can feed short-circuit current into a short circuit (Fig. 2).

Generators

Generators are driven by turbines, diesel engines, water wheels, or other types of prime movers. When a short circuit occurs on the circuit fed by a generator, the generator continues to produce voltage because the field excitation is maintained and the prime mover drives the generator at normal speed. The generated voltage produces a short-circuit current of a large magnitude that flows from the generator (or generators) to the short circuit. This flow of short-circuit current is limited only by the impedance of the generator and of the circuit between the generator and the short circuit. For a short circuit at the terminals of the generator, the current from the generator is limited only by its own impedance.

Synchronous Motors

Synchronous motors are constructed much like generators; that is, they have a field excited by direct current and a stator winding in which alternating current flows. Normally, synchronous motors draw ac power from the line and convert electric energy to mechanical energy.

During a system short-circuit, the voltage on the system is reduced to a very low value. Consequently, the motor stops delivering energy to the mechanical load and starts slowing down. However, just as the prime mover drives a generator, the inertia of the load and motor rotor drives the synchronous motor. The synchronous motor then becomes a generator and delivers short-circuit current for many cycles after the short circuit has occurred. The amount of short-circuit current produced by the motor depends upon the impedance of the synchronous motor and impedance of the system to the point of short circuit.

Induction Motors

The inertia of the load and rotor of an induction motor has the same effect on an induction motor as on a synchronous motor; that is, it drives the motor after the system short circuit occurs. There is one major difference. The induction motor has no dc field winding, but there is a flux in the induction motor during normal operation. This acts like flux produced by the dc field winding in the synchronous motor.

The field of the induction motor is produced by induction from the stator rather than from the dc winding. The rotor flux remains normal as long as voltage is applied to the stator from an external source. However, if the external source of voltage were suddenly removed, as it is when a short-circuit occurs on the system, the flux in the rotor cannot change instantly. Because the rotor flux cannot decay instantly and because the inertia of the rotating parts drives the induction motor, a voltage is generated in the stator winding. This causes a short-circuit current to flow to the short circuit until the rotor flux decays to zero. The short-circuit current vanishes almost completely in about four cycles, since there is no sustained field current in the rotor to provide flux, as in the case of a synchronous machine.

The flux does last long enough to produce enough short-circuit current to affect the momentary duty on circuit breakers and the interrupting duty on devices that open within one or two cycles after a short circuit. Hence, the short-circuit current produced by induction motors must be considered in certain calculations. The magnitude of a short-circuit current produced by the induction motor depends upon the impedance of the motor and the impedance of the system to the point of short circuit. The machine impedance, effective at the time of short circuit corresponds closely to the impedance at standstill. Consequently, the initial value of short-circuit current is approximately equal to the locked-rotor starting current of the motor.

Electric Utility Systems (Supply Transformers)

The electric utility system or the supply transformer from the electric utility system are often considered a source of short-circuit current. Strictly speaking, this is not correct because the utility system or supply transformer merely delivers the short-circuit current from the utility system generators. Transformers merely change the system voltage and magnitude of current but generate neither. The short-circuit current delivered by a transformer is determined by its secondary voltage rating and impedance, the impedance of the generators and system to the terminals of the transformer and the impedance of the circuit from the transformer to the short circuit.

Rotating Machine Reactance

The impedance of a rotating machine consists primarily of reactance and is not one simple value as it is for a transformer or a piece of cable, but is complex and variable with time. For example, if a short-circuit is applied to the terminals of a generator, the short-circuit current behaves as shown in Fig. 3. The current starts out at a high value and decays to a steady-state value after some time has elapsed from the inception of the short-circuit. Since the field excitation voltage and speed have remained relatively constant within the short interval of time considered, the reactance of the machine may be assumed — to explain the change in the current value — to have changed with time after the short-circuit was initiated.

Expression of such a variable reactance at any instant requires a complicated formula involving time as one of the variables. Therefore, for the sake of simplification, three values of reactance are assigned to generators and motors for the purpose of calculating short-circuit current at specific times. These values are called the subtransient reactance, transient reactance, and synchronous reactance and are described as follows:

1. Subtransient reactance (X''_d) is the apparent reactance of the stator winding at the instant short circuit occurs, and it determines the current flow during the first few cycles after short circuit.
2. Transient reactance (X'_d) determines the current following the period when subtransient reactance is the controlling value. Transient reactance is effective up to one-half second or longer, depending upon the design of the machine.
3. Synchronous reactance (X_d) is the reactance that determines the current flow when a steady state condition is reached. It is not effective until several seconds after the short circuit occurs; consequently, it is not generally used in short-circuit calculations.

A sychronous motor has the same kind of reactance as a generator, but it is of a different value. Induction motors have no field coils, but the rotor bars act like the amortisseur winding in a generator; therefore, induction motors are said to have subtransient reactance only.

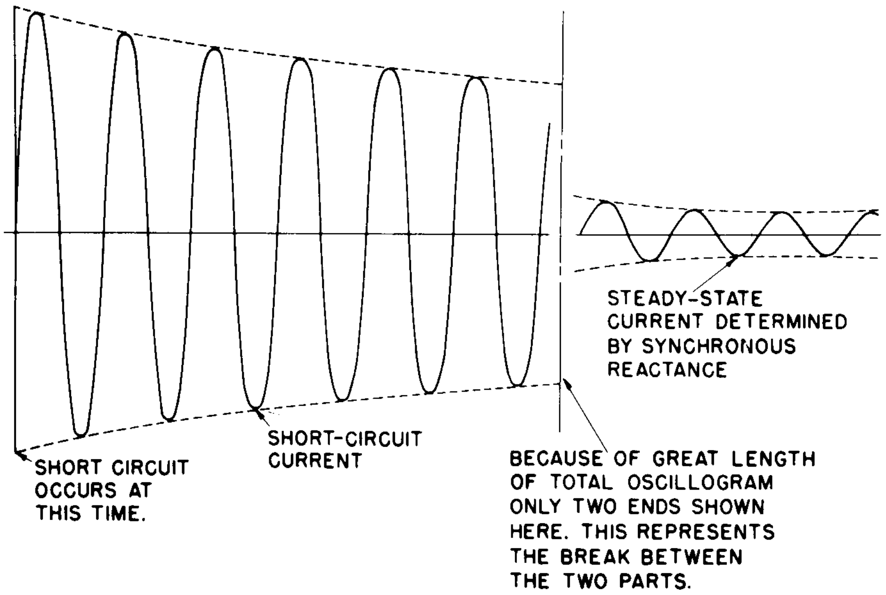

Fig. 3. Oscillogram of a symmetrical short-circuit current produced by a generator

SYMMETRICAL AND ASYMMETRICAL CURRENTS

The words "symmetrical" and "asymmetrical" describe the shape of the ac waves about the zero axis. If the envelopes of the peaks of the current waves are symmetrical around the zero axis, they are called "symmetrical current" envelopes (Fig. 4). If the envelopes are not symmetrical around the zero axis, they are called "asymmetrical current" envelopes (Fig. 5). The envelope is a line drawn through the peaks of the waves.

Most short-circuit currents are nearly always asymmetrical during the first few cycles after the short circuit occurs. The asymmetrical current is at a maximum during the first cycle after the short circuit occurs

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and in a few cycles gradually becomes symmetrical. An oscillogram of a typical short-circuit current is shown in Fig. 6.

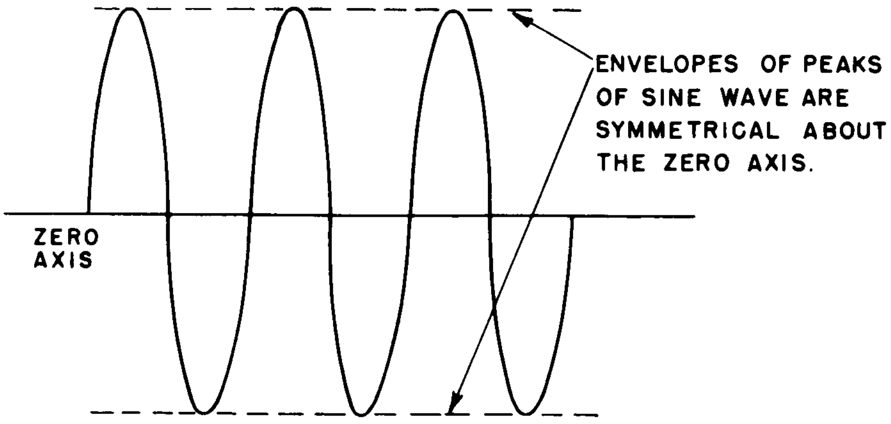

Fig. 4. Symmetrical ac wave

Why Short-circuit Currents Are Asymmetrical

In ordinary power systems, the applied or generated voltages are of sine-wave form. When a short circuit occurs, substantial sine-wave short-circuit currents result. The following discussion assumes sine-wave voltages and currents.

The power factor of a short circuit is determined by the series resistance and reactance of the circuit (from the point of short circuit back to and including the source or sources of the short circuit). For example, in Fig. 7, the reactance equals 19%, the resistance equals 1.4%, and the short-circuit power factor equals 7.4%, determined by using the formula,

Power Factor in percent

$$= R/Z\ (100)$$

$$= \left(\frac{R}{\sqrt{R^2+X^2}}\right)100$$

The relationship of the resistance and reactance of a circuit is sometimes expressed in terms of the X/R ratio. For example, the X/R ratio of the circuit shown in Fig 7 is 13.6.

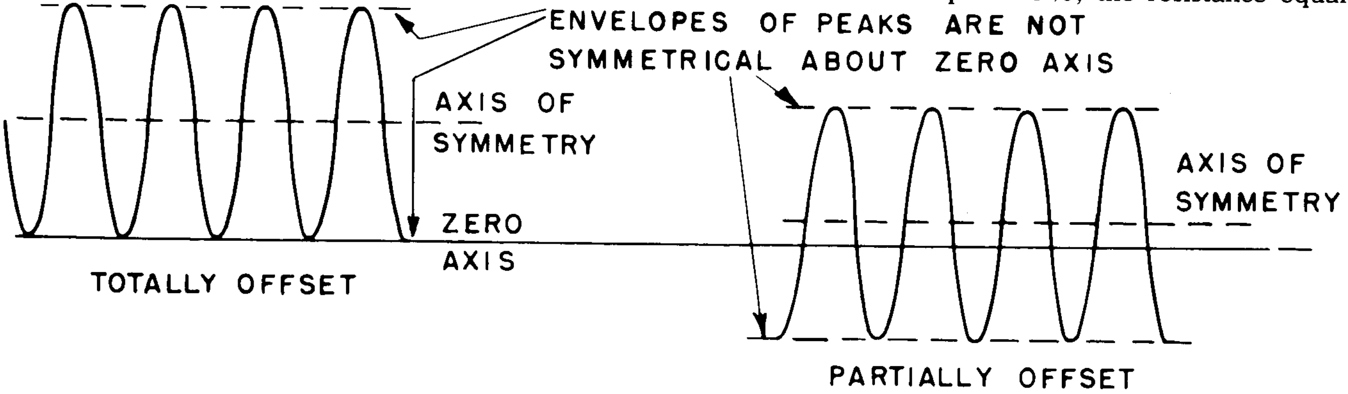

Fig. 5. Asymmetrical ac waves

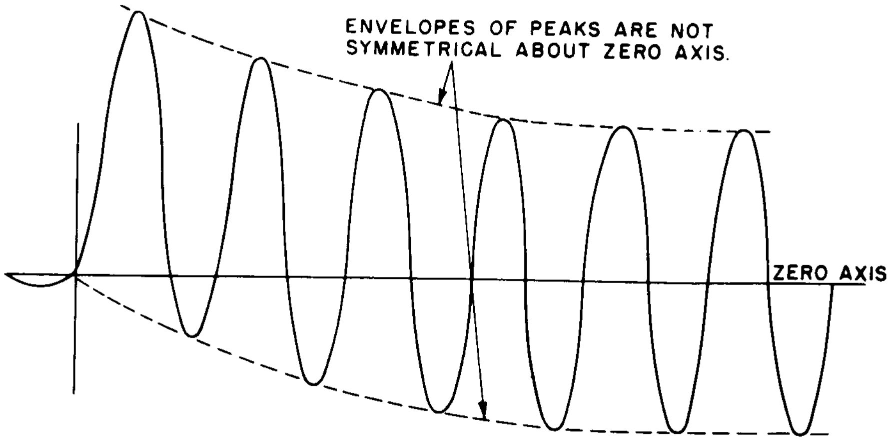

Fig. 6. Oscillogram of a typical short circuit

In high-voltage power circuits, the resistance of the circuit back to and including the power source is low compared with the reactance of the circuit. Therefore, the short-circuit current lags the source voltage by approximately 90 degrees (see Fig. 7). Low-voltage power circuits (below 600-volts) tend to have a larger percentage of resistance and the current

Section I — The Nature of as Short-circuit Currents

will lag behind the voltage by less than 90 degrees.

If a short-circuit occurs at the peak of the voltage wave in a circuit containing only reactance, the short-circuit current will start at zero and trace a sine wave which will be symmetrical about the zero axis (Fig. 8). If a short-circuit occurs at the zero point of the voltage wave, the current will start at zero but cannot follow a sine wave symmetrically about the zero axis because the current must lag behind the voltage by 90 degrees. This can happen only if the current is displaced from the zero axis as shown in Fig. 9.

The two cases shown in Figs. 8 and 9 are extremes. One shows a totally symmetrical current and the other a completely asymmetrical current. If the short circuit occurs at any point between zero voltage and peak voltage, the current will be asymmetrical to a degree dependent upon the point at which the short-circuit occurs on the voltage wave.

In a circuit containing resistance and reactance, the degree of asymmetry can vary between the same limits as a circuit containing only reactance. However, the point on the voltage wave at which the short-circuit must occur to produce maximum asymmetry depends on the ratio of resistance to reactance of the circuit.

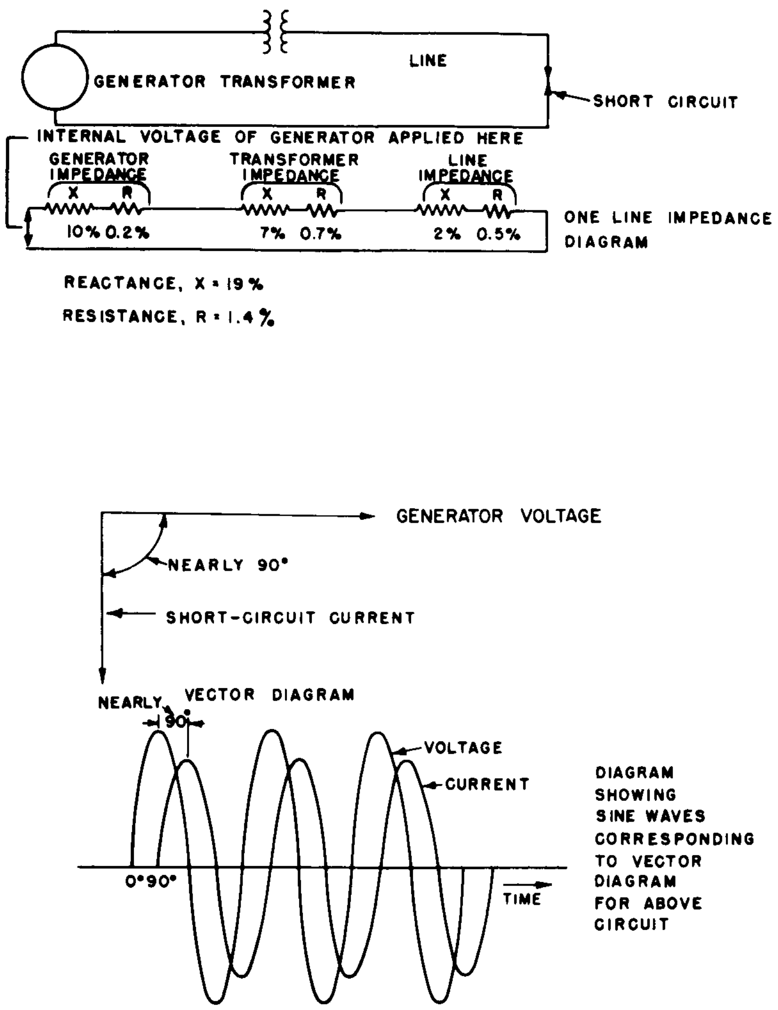

Fig. 7. Diagrams illustrating the phase relations of voltage and short-circuit currents

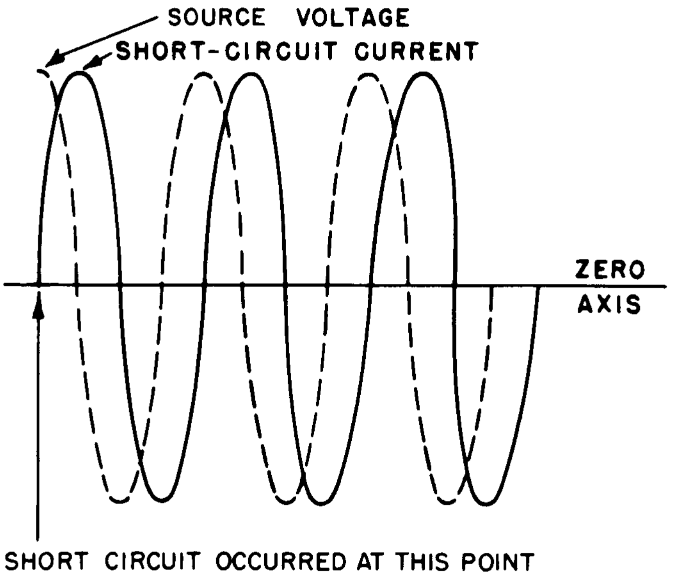

Fig. 8. Symmetrical current and voltage in a zero power-factor circuit

The Dc Component of Asymmetrical Short-circuit Currents

Asymmetrical currents are analyzed in terms of two components, a symmetrical current and a dc component as shown in Fig. 10. As previously discussed, the symmetrical component is at a maximum at the inception of the short circuit and decays to a steady state value due to the apparent change in machine reactance. In all practical circuits, that is, those containing resistance, the dc component will also decay (to zero) as the energy represented by the dc component is dissipated as I^2R loss in the resistance of the circuit. Fig. 11 illustrates the decay of the dc component.

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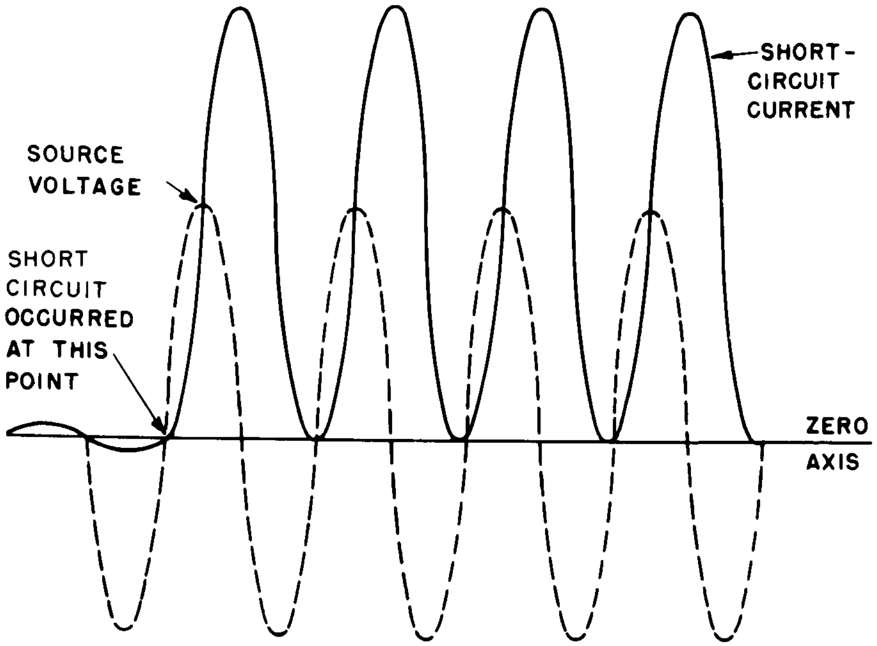

Fig. 9. Asymmetrical current and voltage in a zero power-factor circuit.

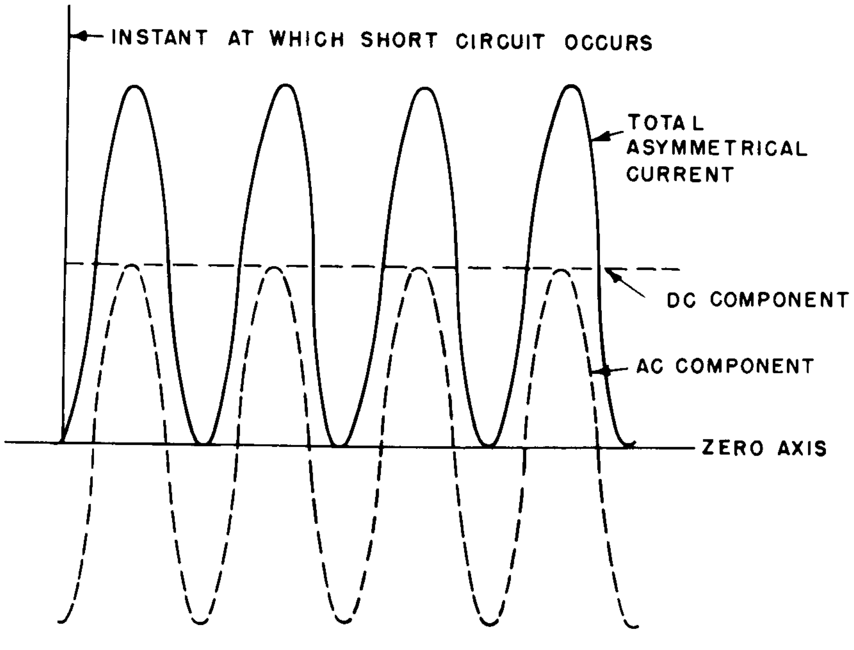

Fig. 10. Components of current shown in Fig. 9

The rate of decay of the dc component is a function of the resistance and reactance of the circuit. In practical circuits, the dc component decays to zero in from one to six cycles.

Total Short-circuit Current

The total symmetrical short-circuit current usually has several sources as illustrated in Fig. 12. The first includes generators either in the plant or in the utility system or both. The second source comprises synchronous motors. Induction motors, the third source, are located in every plant and building. Because these currents decay with time due to reduction of flux in the machine after short circuit, the total short-circuit current decays with time (bottom, Fig. 12). So even if only the symmetrical part of the short-circuit current is considered, the magnitude of current is highest at the first half cycle after short circuit and is of lower value a few cycles later. Note that the induction motor component disappears entirely after one or two cycles.

The magnitude during the first few cycles is further increased by the dc component (Fig. 13). This component also decays with time, accentuating the difference in magnitude of a short-circuit current at the first cycle after short circuit and a few cycles later.

SHORT-CIRCUIT CURRENT CALCULATIONS

The calculation of the precise value of an asymmetrical current at a given time after the inception of a short circuit is a rather complex computation. Consequently, simplified methods have been developed which yield short-circuit currents required to match the assigned ratings of various system protective devices and equipment.

The value of the symmetrical or a.c. component of the short-circuit current is determined through the use of the proper impedance in the basic equation: $I = E/Z$
where E is the system driving voltage and Z (or X) is the proper system impedance (or reactance) of the power system from the point of short circuit back to and including the source or sources of a short-circuit current. The value of the proper impedance is determined with regard to the basis of rating for the device or equipment under consideration.

The Basis of Device and Equipment Rating

It has been stated previously that a circuit protective device must have the ability to interrupt the

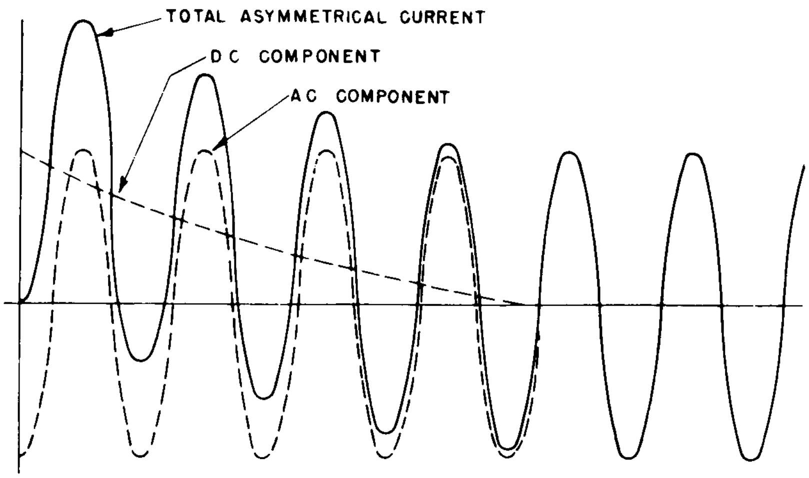

Fig. 11. Oscillogram showing decay of dc component and effect of asymmetry of current

maximum short-circuit current which can flow for a short circuit at a device location. This maximum current is called the "available" short-circuit current. But this is not entirely correct. For a short circuit on the load side of the device, the actual current that the device is required to interrupt may be less than the available current due to the impedance of the device, the impedance of the arc on contact parting, and the ability of the device to current-limit as in the case of a current limiting protector. The basic concept is that the device must have the ability, when applied at a location with a given available short-circuit current, to satisfactorily interrupt a fault at its load terminals. On this basis, the device short-circuit rating is stated in terms of the available short-circuit current.

The same concept applies to the short-circuit rating of busway and bus structures within switchgear, switch boards and panelboards in that the rating refers to the available short-circuit current at the locations where the equipment is to be connected.

Low-voltage Protective Devices and Equipment (below 600 volts)

Low-voltage protective devices and equipment, including low-voltage power circuit breakers; molded-case circuit breakers; motor control centers; motor controllers; low-voltage fuses, and busway are rated on the basis of available symmetrical amperes (a.c. component). Since these protective devices are fast operating (contact parting within the first cycle or two), their short-circuit ratings are based on maximum a.c. component current during the first cycle. Therefore, the subtransient reactance X" is used for all sources of short-circuit current in the basic equation I = E/Z.

Although rated on a symmetrical current basis, these devices and equipment are tested on the basis of typical circuit asymmetrical (a.c. plus d.c. components) conditions as covered by the applicable standards.

If these devices are used where the power factor of the circuit at the point of application of the device is equal to or greater than the power factor used for testing and rating the devices, then no further calculations are necessary. If the power factor is less, then the asymmetrical current may be greater than the device will withstand and the device should be derated in accordance with applicable standards. (See Appendix.)

High-voltage Circuit Breakers (above 600 volts)

To apply high-voltage circuit breakers, the short-circuit duties during the first cycle (momentary) and at contact parting time (interrupting) must be compared with the circuit breaker's short-circuit capability to close and latch during the first cycle and to interrupt at some time later.

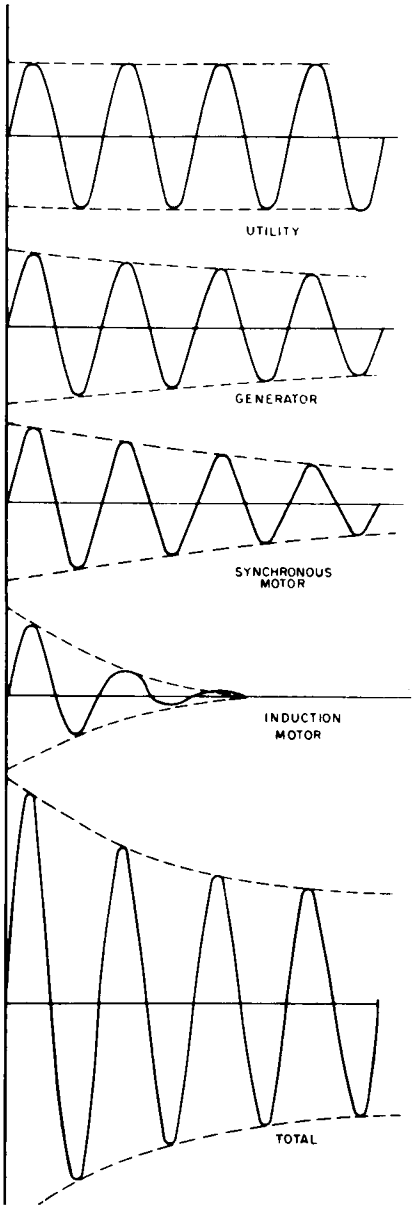

Fig. 12. Symmetrical short-circuit currents from four sources combined into total

Prior to 1964, high-voltage circuit breakers were rated on a total current (asymmetrical) basis. ANSI Standard C37.5-1979* should be used for the calculation of short circuit currents for these circuit breakers. Since 1964, high-voltage circuit breakers have been rated on a symmetrical current basis. ANSI Standard C37.010-1979 should be used for the calculation of short circuit current and the application of these circuit breakers. Both of these

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*Standard has been updated to reflect latest calculating procedures.

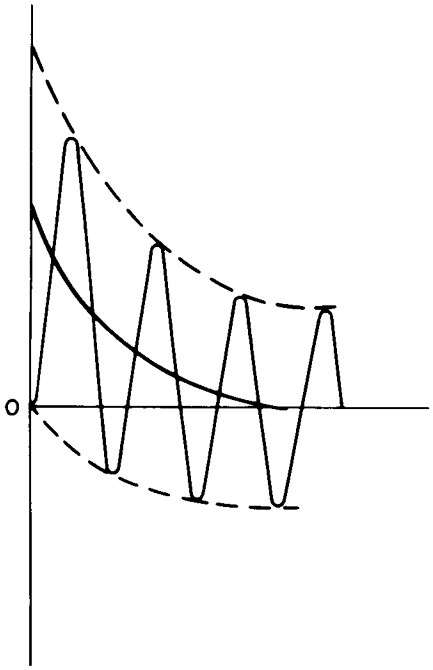

Fig. 13. Asymmetrical short-circuit currents plus the dc component from all sources

standards use calculating procedures which differ from those used prior to 1964. The differences are intended to account more accurately for contributions to high-voltage interrupting duty from large induction motors, for the exponential decay of the direct current component of short-circuit current, and for the alternating current decay of contributions from nearby generators.

Symmetrical Current Basis of Rating

A. Interrupting Rating

ANSI Standard C37.06-1979 lists the schedules of preferred ratings for high-voltage circuit breakers rated on a symmetrical basis.

The symmetrical current value of rated short-circuit current applies at rated maximum voltage. The short-circuit capability at a lower voltage (down to the maximum rated voltage ÷k, the voltage range factor) will be higher and is found by applying the voltage ratio to the rated short-circuit current. The circuit breaker must have a calculated interrupting duty (contact parting) equal to or greater than this current.

In most cases of short-circuit calculation, a simple E/X computation (E/X for three-phase faults or

$$\frac{3E}{2X_1 + X_0}$$

for single line-to-ground faults) will provide adequate accuracy. This is true if the X/R ratio is 15 or less or if E/X does not exceed 80 percent of the symmetrical interrupting capability of the breaker. If these conditions are not met then the more exact method of calculation described in Section 5.3.2 of ANSI Standard 37.010-1979 should be used. The more exact method should also be used if single line-to-ground fault supplied predominantly by generators, at generator voltage, exceeds 70 percent of the circuit breaker symmetrical interrupting capability.

The interrupting duty is calculated using the rotating-machine reactance multipliers in TABLE 1.

B. Momentary Rating

The first cycle duty (momentary) rating is calculated by reducing the equivalent network system to a single X or Z. Determine the preshort circuit operating voltage E. Divide E by X or Z and multiply by 1.6 to find the first cycle duty short-circuit current total per unit current. Then multiply by base current.

$$I_{\text{sc mom}} = \left(\frac{E_{\text{pu}}}{X_{\text{pu}}}\right) 1.6\ I_{\text{base}}$$

The rotating machine reactance multipliers shown in TABLE 1 are used.

For a more detailed description of high-voltage circuit breaker ratings and short-circuit calculation, the following references are recommended:

1. American National Standards
   C37.04-1979—Rating structure for ac high-voltage circuits rated on a symmetrical basis.
   C37.06-1979—Schedule of preferred ratings and related required capabilities for ac high-voltage circuit breakers rated on a symmetrical basis.
   C37.010-1979—Application guide for ac high-voltage circuit breakers rated on a symmetrical basis.
2. "Interpretation of New American National Standards for Power Circuit Breaker Application" by Walter C. Huening, Jr.
   IEEE Transactions on Industry and General Applications Vol IGA-5, No. 5 Sept/Oct 1969 (GER-2660)
3. "Electric Power Distribution For Industrial Plants"—IEEE Publication 141 (Red Book) dated 1976 or later revisions.

High-voltage Fuses (above 600 volts)

High-voltage fuses are rated in terms of symmetrical current but are designed to withstand full asymmetrical current based on an X/R ratio of 15. The machine reactances for calculating short-circuit currents are identical to those used for calculating momentary duty for high-voltage circuit breakers described above. If the X/R ratio is greater than 15, then the asymmetrical current may be greater than the fuses will withstand and it may be necessary to derate the fuse in accordance with applicable standards.

Distribution cutouts are rated on total current. Subtransient reactances should be used to calculate short-circuit currents. At 15,000 volts or below, when the fuse is located remote from the generating stations or primary substations (that is, X/R is less than 4) multiply symmetrical cur-

TABLE 1—Rotating-machine Reactance Multipliers*

Type of Rotating Machine	Momentary first cycle	Interrupting H.V. brk.
All turbine generators; all hydrogenerators with amortisseur windings, all condensers	$1.00\ X''_d$	$1.00\ X''_d$
Hydrogenerators with amortisseur windings	$0.75\ X'_d$	$0.75\ X'_d$
All synchronous motors	$1.00\ X''_d$	$1.50\ X''_d$
Induction motors		
Above 1000 horsepower at 1800 r/min. or less	$1.00\ X''_d$	$1.50\ X''_d$
Above 250 horsepower at 3600 r/min.	$1.00\ X''_d$	$1.50\ X''_d$
All others, 50 horsepower and above	$1.20\ X''_d$	$3.00\ X''_d$
All smaller than 50 horsepower	Neglect	Neglect

*From ANSI/IEEE C.37.5-1979

rent by 1.2 to obtain asymmetrical current. In all other cases multiply by 1.55.

Machine reactance and multiplying factor for application of high-voltage fuses (above 600 volts) is shown in TABLE 2.

TYPES OF POWER SYSTEM SHORT CIRCUITS

Short-circuits can occur on a three-phase power system in several ways. The protective device or equipment must have the ability to interrupt or withstand any type of short circuits which can occur. The basic type of short circuits will be described, but it should be noted that the basic short circuits calculation for the selection of equipment is the three-phase bolted short-circuit.

Three-phase Bolted Short Circuit

A three-phase bolted short-circuit describes the condition where the three conductors are physically held together with zero impedance between them just as if they were bolted together.

While this type of short circuit condition is not the most frequent in occurrence, it generally results in maximum short-circuit values and for this reason is the *basic short circuit calculation* in commercial and industrial power systems.

Line-to-line Bolted Short Circuits

In most three-phase power systems, the levels of line-to-line bolted short circuits currents are approximately 87% of three-phase bolted short circuits currents, but this calculation is seldom required because it is not the maximum value.

Line-to-ground Bolted Short Circuit

In solidly grounded systems, line-to-ground bolted short circuit current is usually equal to, or less than a three-phase bolted short circuit current. Sometimes it is significantly lower than the three-phase bolted short circuit current due to the high impedance of the ground-return circuit (that is, conduit, busway enclosure, grounding conductor, and building steel). Line-to-ground short circuit calculations are seldom necessary in solidly grounded, low-voltage industrial and commercial power systems.

When required, symmetrical component techniques are used to analyze line-to-ground short circuit where the line-to-ground current can be expressed as:

$$I_{sc} = \frac{3E_{L\text{-}N}}{Z_1 + Z_2 + Z_0 + 3Z_g}$$

Where $E_{L\text{-}N}$ = line-to-neutral voltage
Z_1 = positive-sequence impedance
Z_2 = negative-sequence impedance
Z_0 = zero-sequence impedance
Z_g = ground return impedance including resistance of neutral grounding resistor if any

In resistance-grounded, medium-voltage systems (2.4-13.8 kV) the resistor is generally selected to limit ground fault current to a value ranging between 400 and 2000 amperes. Line-to-ground fault magnitudes on these systems are determined primarily by the resistor itself and a line-to-ground short-circuit calculation is generally not required.

TABLE 2—Machine Reactance Multipliers*

	Multiplying Factor	Synchronous Generators and Condensers	Synchronous Motors	Induction Motors
A. Power Fuses at Station—All Current-limiting Fuses				
With symmetrical ratings.	1.00	Subtransient	Subtransient	Subtransient
With asymmetrical ratings	1.55			
B. Distribution Fuse Cutouts				
1. At 15,000 volts, or below, when the fuse is located remote from generating stations and when the X/R is less than 4.	1.20	Subtransient	Subtransient	Subtransient
2. All other cases.	1.55			

Arcing Short Circuit

Many power system short circuits, particularly in low-voltage systems, tend to be arcing in nature.

Arcing faults can display a much lower level of short-circuit current than a bolted short circuit at the same location, particularly in low-voltage systems. These lower levels of current are due in part to the impedance of the arc inserted into the circuit.

The low levels of arcing short circuit current in low-voltage systems become important in designing adequate system protection. Due to its complex nature, arcing short circuit is a subject all to itself and is treated as such in GET-6533.

Selection of Equipment

In order to provide for personal safety and to minimize equipment damage, it is absolutely essential to use equipment with short-circuit ratings equal to or greater than the available short-circuit current that can occur at the equipment location.

The 1987 National Electrical Code states:

> Article 110-9
> "Interrupting Capacity. Devices intended to break current shall have an interrupting capacity sufficient for the voltage employed and for the current which is available at the line terminals of the equipment."

For any given location, there may be several types of protective devices which have an adequate short-circuit rating. Selection of a specific device would then depend on other factors such as economics; users preference; protection characteristics; maintainability, and so on.

There is, however, one instance when low voltage equipment can be applied to a location where the available short-circuit current is higher than the short-circuit rating of the device. This arrangement utilizes an upstream protector which can furnish short-circuit protection for down-stream equipment, defined as coordinated rating.

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*From ANSI C37.41-1981

Coordinated Ratings

The cascade operation of low-voltage power circuit breakers (GE TYPE AKR) is no longer recognized by NEMA with the publication of SG-3-1965. This application procedure previously allowed a feeder breaker to be applied on a system where the available short-circuit current was in excess of the breaker's short-circuit rating, provided the feeder breaker was backed up by an adequately rated main breaker. In addition, the NEMA standards specified certain other requirements for this application.

In recent years, cascaded arrangements have been infrequently used in industrial and commercial power systems mostly because of the increased recognition of the importance of service continuity. In cascade operation, when a short circuit occurs on a feeder circuit, both the main and feeder breaker would probably trip.

Since 1971 the National Electrical Code has permitted systems ratings. The Underwriters Laboratories has developed procedures for testing devices in series as a system and assigning a "coordinated rating" to the system that is equal to the upstream device but in excess of the downstream device rating when used alone. For successful operation in a system using coordinated ratings, the upstream device must operate and clear simultaneously with the downstream device which prohibits selectivity between devices and increases system maintenance.

Coordinated ratings are based on two protective devices operating in series with all short-circuit current flowing through the upstream device. If any current bypasses the upstream device (such as motor contribution fed in on load side of upstream device) a fully rated system, not a coordinated rated system, should be used.

It should be emphasized that coordinated ratings are assigned by U.L. only when verified by actual U.L. witnessed test in a short circuit laboratory.

Section II— The Details of Short-circuit Calculations

INTRODUCTION

In Section I the general nature of ac short-circuits, including the calculation of short-circuit currents, was discussed. It was determined that the basic equation for the calculation of short-circuit current is $I = E/Z$ where E is the system driving voltage and Z (or X) is the proper system impedance (or reactance) of the power system back to and including the source(s) of short-circuit current. Furthermore, the proper value of impedance depends on the basis of short-circuit rating for the device or equipment under consideration.

In this section the details of short-circuit calculations will be presented. Much of the detail of a short-circuit calculation or study involves the representation of the proper system impedances from the point of short-circuit back to and including the source(s) of short-circuit current. After this representation is accomplished, the actual short-circuit computation is very simple. Step-by-step procedures will be presented for making short-circuit calculations.

These step-by-step procedures will provide a basis for making short-circuit calculations for most types of industrial and commercial power systems from an extensive industrial system where the primary service may be 115 kV with distribution and utilization voltage at 13.8 kV, 2.4 kV, 480Y/277 volts and 208Y/120 volts, including in-plant generation, to a commercial building system where the service and utilization voltage is 208Y/120 volts. The industrial system would require an extensive representation and many procedural steps while the building system may require minimal representation with just a few steps. Sometimes, a short-circuit calculation is required for only a part of the system—for instance, to determine the required short-circuit ratings for equipment to be served from a new feeder to an existing building service equipment, or for low-voltage systems where the only sources of short-circuit current are a supply transformer (or a utility system) and induction motors. Examples are included which show simple and direct solutions for the cases.

STEP-BY-STEP PROCEDURES

The following steps identify the basic considerations in making short-circuit calculations. In the simpler systems, several steps may be combined—for example, the use of a combined one-line and impedance diagram.

1. Prepare System One-Line Diagram. Include all significant system components.
2. Decide on short-circuit locations and type of short-circuit current calculations required, based on type of equipment being applied. Consider the variation of system operating conditions required to display the most severe duties. Assign bus numbers or suitable identification to the short-circuit locations.
3. Prepare an impedance diagram. For systems above 600 volts, two diagrams are usually required to calculate interrupting and momentary duty for high-voltage circuit breakers. Refer to Section I for determining the type of short-circuit rating required for various kinds of equipment as well as the machine reactances to use in the impedance diagram. Select suitable kVA and voltage bases for the study when the per-unit system is being used.
4. For the designated short-circuit locations and system conditions, resolve the impedance network and calculate the required symmetrical currents (E/Z or E/X). When calculations are being made on a computer, submit impedance data in proper form as required by the specific program. For high-voltage equipment apply appropriate multipliers from SECTION 1 to calculated symmetrical values so that the short-circuit currents will be in terms of equipment rating.

A System One-line Diagram

The system one-line diagram is fundamental to short-circuit analysis. It should include all significant equipment and components and show their interconnections. Fig. 14 illustrates a typical system one-line diagram.

Type and Location of Faults Required

All buses should be numbered or otherwise identified. The location where short circuits are required should be selected. In many studies, all buses are faulted. The type of short-circuit currents required is based on the short-circuit rating of the equipment located at the faulted bus.

System Conditions for Most Severe Duty

It is sometimes quite difficult to predict which of the intended or possible system conditions should be investigated to reveal the most severe duties for various components. Severe duties are those that are most likely to tax the capabilities of components.

Future growth and change in the system can modify short-circuit currents. For example, the initial utility available short-circuit duty for an in-building system being investigated may be 150 mVA. But future growth plans may call for an increase in available duty to 750 mVA several years hence. This increase could substantially raise the short-circuit duties on the in-building equipment. Therefore, the increase must be factored in the present calculations so that adequate in-building equipment can be selected. In a similar manner, future in-plant or in-building expansions very often will raise short-circuit duties in various parts of the power system so that future expansions must also be considered initially.

The most severe duty usually occurs when the maximum concentration of machinery is in operation and all interconnections are closed. The conditions most likely to influence the critical duty include:

1. Which machines and circuits are to be considered in actual operation?
2. Which switching units are to be open or closed?

3. What future expansions or system changes will affect in-plant or in-building short-circuit currents?

PREPARING IMPEDANCE DIAGRAMS

The impedance diagram displays the interconnected circuit impedances that control the magnitude of short-circuit currents. The diagram is derived from the system one-line diagram, showing an impedance for every system component that exerts a significant effect on short-circuit current magnitude. Not only must the impedances be interconnected to reproduce actual circuit conditions, but it will be helpful to preserve the same arrangement pattern used in the one-line diagram. See Fig. 15.

Component Impedance Values

Component impedance values are expressed in terms of any of the following units:

1. Ohms-per-phase
2. Percent on rated kVA or a reference kVA base
3. Per-unit on a reference kVA

In formulating the impedance diagram, all impedance values must be expressed in the same units; either in *Ohms-per-phase* or *per-unit on a reference kVA base* (percent is a form of per-unit).

Use of Per-unit or Ohms

Short-circuit calculations can be made with impedances represented in per-unit or ohms. Both representations will yield identical results. Which should be used?

In general, if the system being studied has several different voltage levels or is a high-voltage system (above 600 volts), per-unit impedance representation will provide the easier, more straightforward calculation. The per-unit system is ideal for studying multi-voltage systems. Also, most of the components included in high-voltage networks, (machines, transformers, and utility systems) are given in per-unit or percent values and further conversion is not required.

On the other hand, where few or no voltage transformations are involved and for low-voltage systems where many conductors are included in the impedance network, representation of system elements in ohms may provide the easier, more straightforward calculation.

Neglecting Resistance

All system components have an impedance (Z) consisting of resistance (R) and inductive reactance (X) where:

$$Z = \sqrt{R^2 + X^2}$$

Many system components such as rotating machines, transformers, and reactors have high values of reactance compared to resistance. When the system impedance consists mainly of such components, the magnitude of a short-circuit current as derived by the basic equation $I = E/Z$ is primarily determined by the reactance so the resistance can practically be neglected in the calculation. This allows a much simpler calculation because then $I = E/X$.

Conductors (cables, buses, and open-wire lines), however, have a significant resistance compared to their reactance so that when the system impedance contains considerable conductor impedance, the resistance may have an effect on the magnitude of the short-circuit current and should be included in the calculation.

The result is the appearance of using Z or X interchangeably. The proper concept is that whenever the resistance does not significantly affect the calculated short-circuit current, a network of reactances alone can be used to represent the system impedance. When the ratio of the reactance to the resistance (X/R ratio) of the system impedance is greater than 4, negligible errors (less than 3%) will result from neglecting resistance. Neglecting R introduces some error but always increases the calculated current.

On systems above 600 volts, circuit X/R ratios usually are greater than 4 and resistance can generally be neglected in short-circuit calculations.

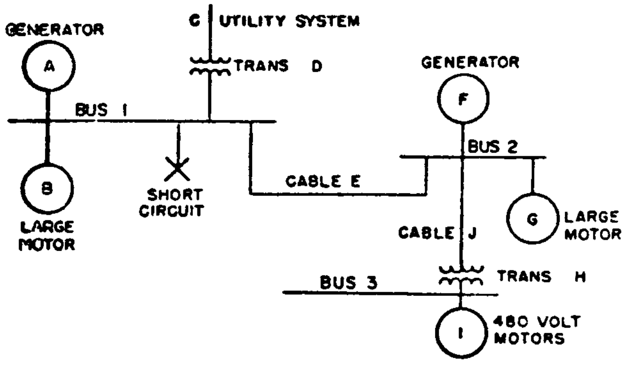


Fig. 14. A typical system one-line diagram

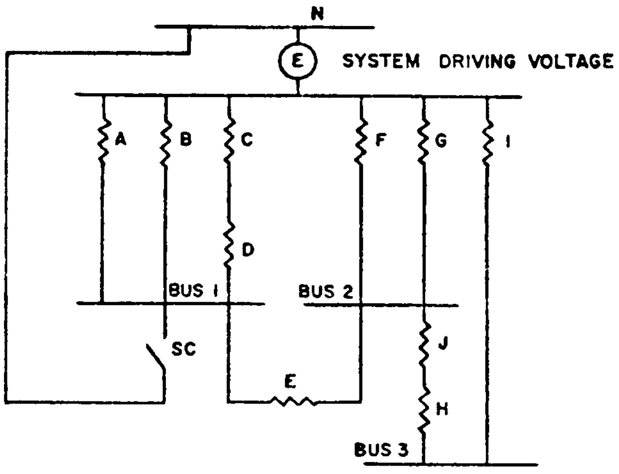


Fig. 15. An equivalent impedance diagram for the system represented in Fig. 14

Section II— The Details of Short-circuit Calculations

However, on systems below 600 volts, the circuit X/R ratio at locations remote from the supply transformer can be low and the resistance of circuit conductors should be included in the short-circuit calculation. Because of their high X/R ratio, rotating machines, transformers, and reactors are generally represented by reactance only, regardless of the system voltage, an exception being transformers with impedances less than 4%. Fig 16 summarizes the locations in a system where resistance is generally used in the short-circuit calculation.

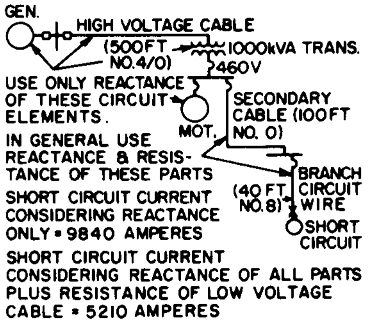


Fig. 16. Locations in system where reactance and resistance are generally used for short-circuit calculations

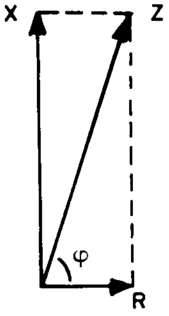
Combining of Impedances

An impedance (Z) containing resistance (R) and reactance (X) is a complex quantity or vector. It is frequently expressed in the form R + j X, and is illustrated in Fig. 17.

When combining impedances in series, impedances (Z) cannot be added directly. The resistance (R) and reactance (X) values must be added together separately, and then Z can be computed, $Z = \sqrt{R^2+X^2}$. Figure 18 illustrates the addition of impedances in series. Further details of complex quantity manipulation are included in the Appendix.

Per-Unit Representations

In the per-unit system, there are four base quantities: base kVA, base volts, base ohms, and base amperes. When any two of the four are assigned values, the other two values can be derived. It is common practice to assign study base values to kVA and voltage. Base amperes and base ohms are then derived for each of the voltage levels in the system. For example, refer to TABLE 3 in Section III. The kVA base assigned may be the kVA rating of one of the predominant pieces of system equipment such as a generator or transformer, but more conveniently a number such as 10,000 is selected as base kVA. The latter selection has some advantage of commonality when many studies are made while the former choice means that the impedance or reactance of at least one significant component will not have to be converted to a new base.



$$Z = R + jX$$

where: R = 2 and X = 6,

$$Z = \sqrt{R^2 + X^2}$$

$$= \sqrt{(2)^2 + (6)^2}$$

$$= 6.324$$

or

$$\tan \varphi = X/R = 6/2 = 3$$

$$\varphi = 71.565°$$

$$Z = \frac{R}{\cos \varphi} = \frac{X}{\sin \varphi} = \frac{2}{0.316} = \frac{6}{0.949}$$

$$= 6.324$$

Fig. 17. Impedance vectors

The nominal line-to-line system voltages are normally used as the base voltages. Conversion of impedances to per-unit on an assigned study kVA base will be illustrated for various equipment components. A summary of frequently used per-unit relationships follows. The Appendix contains a more detailed discussion of the per-unit system.

Basic per-unit relationship

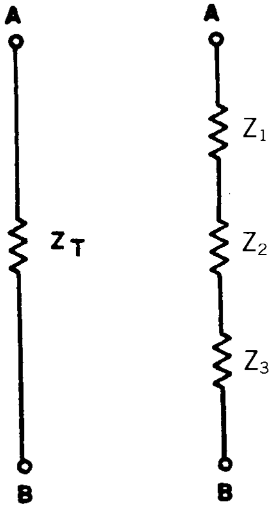
$$\text{Per-unit volts} = \frac{\text{Actual volts}}{\text{Base volts}}$$

$$\text{Per-unit amperes} = \frac{\text{Actual amperes}}{\text{Base amperes}}$$

$$\text{Per-unit ohms} = \frac{\text{Actual ohms}}{\text{Base ohms}}$$

For three-phase systems

Assigned Values:
Base Volt = line-to-line volts
Base kVA = three-phase kVA



$$Z_1 = R_1 + jX_1 = 2 + j6$$

$$Z_2 = R_2 + jX_2 = 1 + j8$$

$$Z_3 = R_3 + jX_3 = 7 + j7$$

$$Z_T = (R_1 + R_2 + R_3) + j(X_1 + X_2 + X_3)$$

$$Z_T = (2 + 1 + 7) + j(6 + 8 + 7)$$

$$Z_T = R_T + jX_T = 10 + j21$$

$$Z_T = \sqrt{R_T^2 + X_T^2} = \sqrt{(10)^2 + (21)^2}$$

$$Z_T = 23.26$$

Fig. 18. How impedances are added

Section II— The Details of Short-circuit Calculations

Derived Values:

$$\text{Base amperes} = \frac{\text{Base kVA}\,(1000)}{\sqrt{3}\,(\text{Base volts})}$$

or

$$= \frac{\text{Base kVA}}{\sqrt{3}\,\text{Base kV}}$$

$$\text{Base ohms} = \frac{\text{Base Volts}}{\sqrt{3}\,(\text{base amperes})}$$

$$\text{Base ohms} = \frac{\text{Base kV}^2\,(1000)}{\text{Base kVA}}$$

Changing from perunit on an old base to per-unit on a new base

$$\text{new } X_{pu} = \text{old } X_{pu}\left(\frac{\text{new base KVA}}{\text{old base KVA}}\right)$$

The Electric Utility System

The electric utility system is usually represented by a single equivalent reactance referred to the user's point of connection which is equivalent to the available short-circuit current from the utility. This value is obtained from the utility and may be expressed in several ways.

1. Three-phase short-circuit kVA available.
2. Three-phase short-circuit amperes available at a given voltage.
3. Percent or per-unit reactance on a specified kVA base.
4. Reactance in ohms-per-phase (sometimes R+JX) at a given voltage.

The X/R ratio of a utility source varies greatly. Sources near generating plants have higher X/R ratios (15-30) while short-circuit levels of long open-wire lines have lower X/R ratios (2-15). Typically, the X/R value of a utility source is from 5 to 12. As explained previously, R may be neglected with small error (less than 3 percent) when X/R ratio is greater than 4. However, it is always more accurate to include R. If the X/R ratio is known or estimated, then R may be determined by dividing X by the value of X/R ratio.

If X/R = 10 and X = 0.0037 ohms per phase (see examples following for calculation) then

$$R = \frac{X}{10} = \frac{0.0037}{10}$$

= 0.00037 ohms per phase.

EXAMPLES:

Conversion to per-unit on a 10,000 kVA base (kVA_b)

1. Available 3ϕ short-circuit kVA = 500,000kVA (500MVA)

$$X_{pu} = \frac{kVA_b}{kVA_{sc}} = \frac{10{,}000}{500{,}000} = 0.02$$

2. Available 3ϕ short-circuit amperes = 20,940 at 13.8 kV

$$X_{pu} = \frac{kVA_b}{\sqrt{3}\,(I_{sc})\,(kV)}$$

$$= \frac{10{,}000}{\sqrt{3}\,(20{,}940)\,(13.8)} = 0.02$$

3. Equivalent utility reactance = 0.2 per-unit on a 100,000 kVA base

$$X_{pu} = X_{pu_{Old}}\left(\frac{kVA_b}{kVA_{Old}}\right)$$

$$= 0.2\left(\frac{10{,}000}{100{,}000}\right) = 0.02$$

4. Equivalent utility reactance = 0.38 ohms-per-phase at 13.8 kV

$$X_{pu} = X\left(\frac{kVA_b}{1000\,kV^2}\right)$$

$$X_{pu} = 0.38\left(\frac{10{,}000}{1000\,(13.8)^2}\right) = 0.02$$

Conversion to ohms-per-phase at 480 volts

1. Available 3ϕ short-circuit kVA = 62,270

$$X = \frac{kV^2\,(1000)}{kVA} = \frac{(0.48)^2\,1000}{62{,}270}$$

= 0.0037 ohms-per-phase at 480 volts

2. Available 3ϕ short-circuit amperes = 75,000 at 480 volts

$$X = \frac{\text{Volts L-N}}{I_{sc}} = \frac{277}{75{,}000}$$

= 0.0037 ohms-per-phase at 480 volts

3. Equivalent utility reactance = 0.1605 per-unit on a 10,000 kVA base

$$X = X_{pu}\left(\frac{kV^2\,(1000)}{kVA}\right)$$

$$= 0.1605\left(\frac{(0.48)^2\,1000)}{10{,}000}\right)$$

= 0.0037 ohms-per-phase at 480 volts

Transformers

Transformer reactance (impedance) will most commonly be expressed as a percent value ($\%X_T$ or $\%Z_T$) on the transformer rated kVA. (Impedance values are usually expressed on the self-cooled kVA rating.)

EXAMPLES:

A 500 kVA transformer with an impedance of 5% on its kVA rating (assume impedance is all reactance)

Conversion to per-unit on a 10,000 kVA base (kVA_b)

$$X_{pu} = \frac{\%X_T}{100}\left(\frac{kVA_b}{\text{Transf. kVA}}\right)$$

$$= \frac{5}{100}\left(\frac{10{,}000}{500}\right) = 1.0$$

Conversion to ohms-per-phase at 480 volts

$$X = \frac{\%X_T}{100}\left(\frac{kV^2\,1000}{\text{Transf. kVA}}\right)$$

$$= \frac{5}{100}\left(\frac{(0.48)^2 1000}{500}\right)$$

= 0.023 ohms-per-phase at 480 volts

Busways, Cables, Conductors

The resistance and reactance of busway, cables, and conductors will most frequently be available in terms of ohms-per-phase per unit length (see Appendix).

Section II— The Details of Short-circuit Calculations

EXAMPLES:

250 ft. of a three conductor copper 500 mcm cable (600 volt) installed in steel conduit on a 480-volt system.

Conversion to per-unit on a 10,000 kVA base (kVA_b)

$R = 0.0287$ ohms/1000 ft.,
$R = 0.00718$ ohms/250 ft.
$X = 0.0301$ ohms/1000 ft.,
$X = 0.00753$ ohms/250 ft.

$$R_{pu} = R\left(\frac{kVA_b}{1000\ kV^2}\right)$$
$$= 0.00718\left(\frac{10{,}000}{1000\ (0.48)^2}\right)$$
$$= 0.312$$
$$X_{pu} = X\left(\frac{kVA_b}{1000\ kV^2}\right)$$
$$= 0.00753\left(\frac{10{,}000}{1000\ (0.48)^2}\right)$$
$$= 0.327$$

For high-voltage cables (above 600 volts) the resistance of cables can generally be omitted; in fact, for short high-voltage cable runs (less than 1000 feet) the entire impedance of the cable can be omitted with negligible error.

Rotating Machines

Machine reactances are usually expressed in terms of per-cent reactance ($\%X_m$) or per-unit reactance (X_{pu}) on the normal rated kVA of the machine (see Appendix). Either the subtransient reactance (X'') or the transient reactance (X') should be selected, depending on the type of short-circuit calculation required (refer to Section I). Motor rated kVA can be estimated, given motor horsepower as follows:

Type Motors	Rated kVA =
All (exact)	$\frac{(V\ rated)\ (I\ rated)}{1000}$
Induction (approximate)	
100 hp or less	Rated hp
>100, <1000 hp	0.95 rated hp
≥ 1000 hp	0.9 rated hp
Synchronous (approximate)	
0.8 p.F	Rated hp
1.0 p.F	0.8 rated hp

Motors Rated Above 600 Volts

Motors rated above 600 volts are generally high in horsepower rating and will have a significant bearing on short-circuit current magnitudes. Very large motors of several thousand horsepower should be considered individually and their reactances should be accurately determined before starting the short-circuit study. However, in large plants where there are numerous motors of several hundred horsepower, each located at one bus, it is often desirable to group such motors and represent them as a single equivalent motor with one reactance in the impedance diagram.

Motors Rated 600 Volts or Less

In systems of 600 volts or less, the large motors (that is, motors of several hundred horsepower) are usually few in number and represent only a small portion of the total connected horsepower. These large motors can be represented individually, or they can be lumped in with the smaller motors, representing the complete group as one equivalent motor in the impedance diagram. Small motors are turned off and on frequently, so it is practically impossible to predict which ones will be on the line when short circuit occurs. Therefore, small motors are generally lumped together and assumed to be running.

Where more accurate data are not available, the following procedures may be used in representing the combined reactance of a group of miscellaneous motors:

1. In systems rated 600 or 480 volts, assume that the running motors are grouped at the transformer secondary bus and have a reactance of *25%* on a kVA rating equal to *100%* of the transformer rating.
2. In all 208-volt systems and 240-volt systems, a substantial portion of the load consists of lighting, so assume that the running motors are grouped at the transformer secondary bus and have a reactance of *25%* on a kVA rating equal to *50%* of the transformer rating.
3. Groups of small induction motors as served by a motor control center can be represented by considering the group to have a reactance of 25% on a kVA rating equal to the *connected motor horsepower.*

EXAMPLES:

Conversion to per-unit on a 10,000 kVA base (kVA_b)

A 500 hp, 0.8 PF, synchronous motor has a subtransient reactance (X''_d) of 15%.

$$X''_{pu} = \frac{\%X''_d}{100}\left(\frac{kVA_b}{Motor\ kVA}\right)$$
$$= \frac{15}{100}\left(\frac{10{,}000}{500}\right) = 3.0$$

Conversion to ohms-per-phase at 480 volts

A motor control center has induction motors with a connected horsepower totaling 420 horsepower. Assume group of motors to have a reactance of 25% on a kVA rating of 420.

$$X = \frac{\%X_m}{100}\left(\frac{kV^2\ 1000}{Motor\ kVA}\right)$$
$$= \frac{25}{100}\left(\frac{(0.48)^2\ 1000}{420}\right)$$

$= 0.137$ ohms-per-phase at 480 volts

MULTI-VOLTAGE SYSTEMS

The recommended practice based on ANSI standards and IEEE for representing rotating machine in short-circuit calculations for multi-voltage systems are as follows:

TYPE OF ROTATING MACHINE	FIRST CYCLE (a)	1.5–4 CYCLES (b)
All turbine generators, all hydrogenerators with amortisseur windings, all condensers	1.00 X''_d	1.00 X''_d
Hydrogenerators with amortisseur windings	0.75 X'_d	0.75 X'_d
All synchronous motors	1.00 X''_d	1.50 X''_d
Induction motors		
above 1000 horsepower at 1800 rpm or less	1.00 X''_d	1.50 X''_d
above 250 horsepower at 3600 rpm	1.00 X''_d	1.50 X''_d
all others 50 horsepower and above	1.20 X''_d	3.00 X''_d
all smaller than 50 horsepower	1.67 X''_d	neglect

Typical subtransient reactance (X''_d) values and X/R ratios are listed in part II of the appendix.

(a) for comparison with medium voltage circuit breaker closing and latch (momentary), medium and low voltage fuse interrupting, and low voltage circuit breaker interrupting capabilities.

(b) for comparison with medium voltage circuit breaker interrupting capabilities.

Other Circuit Impedances

There are other circuit impedances such as those associated with circuit breakers, current transformers, bus structures and connections which for ease of calculation are usually neglected in short-circuit calculations. Accuracy of the calculation is not generally affected because the effects of the impedances are small and omitting them provides conservative (higher) short-circuit currents. However, on low-voltage systems and particularly at 208 volts, there are cases where their inclusion in the calculation can result in a lower short-circuit current and allow the use of lower-rated circuit components. The system designer may want to include these impedances in such cases.

Shunt-connected Impedances

In addition to the components already mentioned, every system includes other components or loads that would be represented in a diagram as shunt-connected impedances. Examples are lights, welders, ovens, furnaces and capacitors. A technically accurate solution requires that these impedances be included in the equivalent circuit used in calculating a short-circuit current, but practical considerations allow the general practice of omitting them. Such impedances are relatively high values and their omission will not significantly affect the calculated results.

System-driving Voltage (E)

The system-driving voltage (E) in the basic equation can be represented by the use of a single over-all driving voltage as illustrated in Fig. 15, rather than the array of individual, unequal generated voltages acting within individual rotating machines. This single-driving voltage is equal to the prefault voltage at the point of fault connection. The equivalent circuit is a valid transformation accomplished by Thevenin's Theorem and permits an accurate determination of short-circuit current for the assigned values of system impedance. The prefault voltage referred to is ordinarily taken as *system nominal voltage* at the point of fault as this calculation leads to the full value of short-circuit current that may be produced by the probable maximum operating voltage.

In making a short-circuit calculation on three-phase balanced systems, a single-phase representation of a three-phase system is utilized so that all impedances are expressed in ohms-per-phase, and the system-driving voltage (E) is expressed in line-to-neutral volts. Line-to-neutral voltage is equal to line-to-line voltage divided by the $\sqrt{3}$.

When using the per-unit system, if the system per-unit impedances are established on voltage bases equal to system nominal voltages, the per-unit driving voltage is equal to 1.0. In the per-unit system, both line-to-line voltage and line-to-neutral voltage have equal values; that is, both would have values of 1.0.

When system impedance values are expressed in ohms-per-phase rather than per-unit, the system-driving voltage would be equal to system line-to-neutral voltage; that is, 277 volts for a 480-volt system.

DETERMINATION OF SHORT-CIRCUIT CURRENTS

After the impedance diagram is prepared, the short-circuit currents can be determined. This can be accomplished by longhand calculation, network analyzer or digital computer techniques.

In general, the presence of closed loops in the impedance network, such as might be found in a large industrial plant high-voltage system, and the need for short-circuit duties at many system locations will favor using a network analyzer or digital computer from an economic and time-saving standpoint. Simple radial systems, such as those used in most low-voltage systems, can be easily resolved by longhand calculations though digital computers can yield significant time savings particularly when short-circuit duties at many system locations are required and when resistance is being included in the calculation.

A longhand solution requires the combining of impedances in series and parallel from the source driving voltage and Z (or X) is the single equivalent network impedance. single equivalent network impedance. The calculation to derive the symmetrical short-circuit current is $I = E/Z$ where E is the system-driving voltage and (or X) is the single equivalent network impedance.

When calculations are made in per-unit, the following formulas apply:

Sym. 3ϕ short-circuit current in per-unit $\quad I_{pu} = \dfrac{E_{pu}}{Z_{pu}}$

Sym. 3ϕ short-circuit current in amperes $\quad I = \dfrac{I_b}{Z_{pu}}$

Sym. 3ϕ short-circuit kVA $\quad kVA = \dfrac{kVA_b}{Z_{pu}}$

where:

I_{pu} = per-unit amperes,
Z_{pu} = equivalent network per-unit impedance,
E_{pu} = per-unit volts,
I_b = Base amperes,
kVA_b = Base kVA_b

When calculations are made in ohms:

Sym. 3ϕ short circuit in amperes $\quad I = \dfrac{E_{l\text{-}n}}{Z}$

where $E_{l\text{-}n}$ = line-to-neutral voltage and Z = equivalent network impedance in ohms-per-phase.

A new combination of impedances to determine the single equivalent network impedance is required for each fault location.

For a radial system, the longhand solution is fairly simple. For systems containing loops, simultaneous equations may be necessary though delta-wye network transformations can usually be used to combine impedances. Methods of combining impedances are included in the Appendix. Some of the newer electronic calculators can be excellent timesavers in making longhand calculations. Examples of longhand calculations are included in a later section.

Network Analyzers and Digital Computer Solutions

Network analyzers have been used for many years to make power system short-circuit studies. Quite simply, a network analyzer is a model using interconnected driving voltages and impedances to simulate a power system. Faults are actually applied to the system model and actual currents and voltages recorded. With the advent of the digital computer, however, few power system studies are still made on the network analyzer.

Digital computer solutions require the input of system data into the computer program in a manner dictated by the program being used. This may take the form of punched cards or paper tape for batch processing with the master program stored on magnetic tape. A new development in computers is the time-sharing concept where data can be submitted at a remote teletypewriter by the person making the short-circuit study. With time-sharing systems, it is not unusual to submit the required input data and receive the answers within a period of 10 to 20 minutes at a very low cost for the computer time.

Computer solutions have more than just economic benefits. Accuracy is extremely high. Calculations are practically error-free. In addition, input and output data are printed in a systematic form, providing a complete record of the study and thereby eliminating the need for further data transcription with its possibility of further error. Examples of computer solutions will be shown in Section III.

Use of Estimating Tables and Curves

There are many times when a short-circuit duty is required at the secondary of a transformer or at the end of a low-voltage conductor. Curves and tables, which give the estimated short-circuit duty, are available for commonly used transformers and for various conductor configurations. Use of these tables may eliminate the need for a formal short-circuit study and can be used where appropriate. Estimating tables and curves are included in the Appendix, and their use is illustrated in Section III.

MEANS FOR REDUCING SHORT-CIRCUIT CURRENT

There is a natural reduction of short-circuit duty due to the impedance of the conductors from the power source to the loads. For example, the short-circuit duty at the terminals of a 1500 kVA, 480-volt transformer may be 37,000 amperes, while at the end of a 600-amp cable run, the duty may be 13,000 amperes. But beyond this natural reduction in short-circuit duty, it is sometimes desired or necessary to insert additional impedance in the form of reactance to achieve a lower required duty for application of some specific equipment. This can be done with current-limiting reactors (all voltages) or current-limiting busways (600 volts and below).

For instance, the available short-circuit duty from a utility service supplying a plant or building may be 850 mVA at 13.8 kV. This would require 1000 mVA circuit breakers for the in-plant or in-building system. A more economical approach might be to apply current-limiting reactors on the incoming line to reduce the available duty to less than 500 mVA so that lower cost 500-mVA circuit breakers can be applied.

Example Two in Section III illustrates the use of a current-limiting busway to reduce the available short-circuit duty from a 480-volt spot network.

The general procedure is to determine the additional reactance required to reduce the short-circuit duty to the desired level as follows:

$$X = \frac{E}{I_{\text{desired}}} - \frac{E}{I_{\text{available}}}$$

Section III— Examples of Ac Short-circuit Calculations

INTRODUCTION

The following example illustrate how short-circuit a.c. component currents are calculated by several of the procedures described in Sections I and II. It is understood, however, that the selection of the method of calculation must be coordinated with the particular system components requirements as discussed in the previous sections.

Step A—The System One-Line Diagram

Figure 19 contains the basic information that identifies the various electric components of the system and how they are interconnected. The diagram also includes the necessary data that is:

1. The voltage, short-circuit available and X/R ratio from the utility system.
2. The KVA, voltage, connection, impedance and X/R ratio for transformers T1, T2 and T3.
3. The type, hp, rpm, reactance and X/R ratios for motors M1, M2, M3 and motor summation designated as M4.
4. The type, length and impedance of the cables.

Step B—Type and Location of Short-Circuits

Protective devices are located at buses 2, 5, 7 and 8 and these are the locations where available system short-circuits are to be calculated. That is at short-circuit locations F1, F2, F3 and F4. High-voltage power circuit breakers and associated equipments are located at bus 2 and 5, therefore, both first cycle fault current and 1.5 to 4 cycle fault current will be calculated to determine breaker momentary and interrupting rating requirements. Low voltage circuit breakers and associated equipments are located at buses 7 and 8, therefore, first cycle fault current will be calculated to determine breaker interrupting rating requirements at these buses.

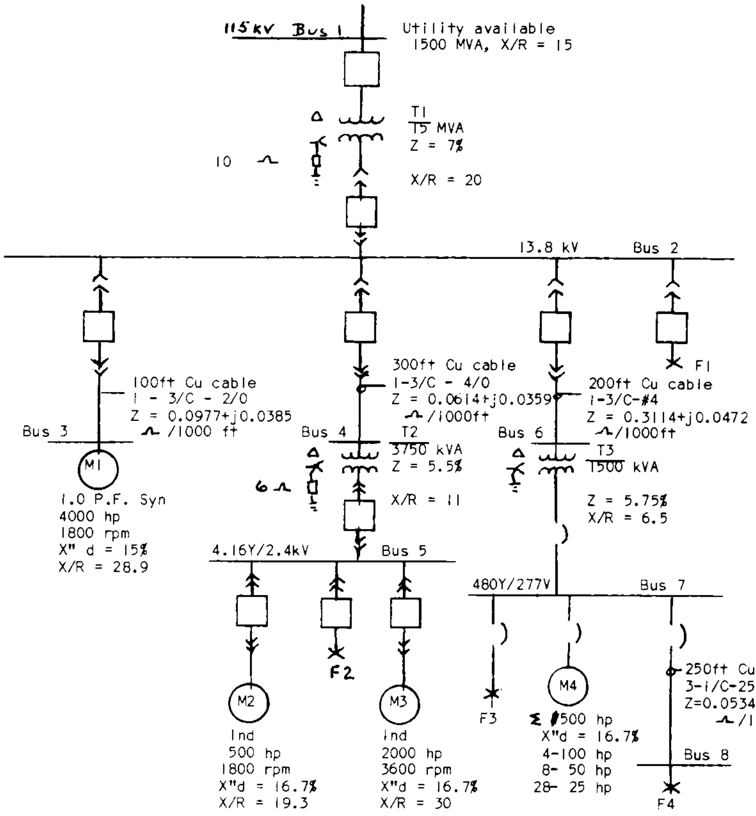


Fig. 19. A one-line diagram of an industrial power system.

Maximum short-circuit currents are needed for device selection, therefore, three-phase bolted short-circuit will be calculated since line-to-ground fault calculations are limited by the grounding resistors. Furthermore the most severe duty will occur when all breakers are closed, utility is connected and motors are operating.

Step C—System Impedance Diagrams

The one or more impedance diagrams should be patterned after the one-line diagram. The arrangement of elements should assist easy identification of any given component in the two types of diagrams (one-line vs. impedance) even through identification of components and significant points in the circuits may become impossible as the network is resolved into a single-value impedance.

The per-unit system lends itself to a analysis of this system because of the several voltage levels. A base kVA of 15,000 is chosen. The assigned base voltages will be the nominal system voltages of 13,800, 4,160 and 480 volts. Base amperes and base ohms for each of the voltage levels can then be derived as shown in Table 3.

TABLE 3—Three-phase Values for Example

Assigned Values		Derived Values	
kVA_B	kV_B	I_B	Z_B
15,000	13.8	628	12.7
15,000	4.16	2,084	1.1539
15,000	0.48	18,064	0.0153

Figures 20 and 21 are the impedance diagrams for the Figure 19 one-line diagram. The assigned impedance values are based on the ANSI and IEEE recommended rotating machine modified subtransient (X''_d) values for multi-voltage systems as outlined in Section II.

Section III — Examples of Ac Short-circuit Calculations

Figure 20 represents first-cycle impedance representation and figure 21 represents 1.5 to 4 cycle impedance representation from time of short-circuit. The per-unit values for all components impedances in figures 20 and 21 are derived and listed as follows:

	First Cycle R + j X	1.5-4 Cycles R + j X
Utility- $Z = \frac{15,000}{1,500,000} = 0.01$ pu		
$X/R = 15$, $\tan^{-1} 15 = 86.19°$		
$R = (\cos 86.19)(.01)$, $X = (\sin 86.19)(01)$	$= 0.0007 + j0.01$	$0.0007 + j0.01$
Transf. T1 - $Z = \frac{7\ (15,000)}{100\ (15,000)} = 0.07$ pu		
$X/R = 20$, $\tan^{-1} 20 = 87.14°$		
$R = (\cos 87.14)(0.07)$, $X = (\sin 87.14)(0.07)$	$= 0.0035 + j0.0699$	$0.0035 + j0.0699$
C1 (Mot. M1 cable) $= 0.0977 + j0.0385\ \Omega/1000$ ft		
$Z = \frac{100}{1000}(0.0977 + j0.0385)\frac{15}{(13.8)^2}$	$= 0.0008 + j0.0003$	$0.0008 + j0.0003$
Mot. M1 $X = \frac{15\ (15000)}{100\ (4000)\ (0.8)} = 0.703$		
$X/R = 28$, $R = X/28 = 0.0251$		
$1\ (R + jX)$	$= 0.0251 + j0.703$	
$1.5\ (R + jX)$	$=$	$0.0377 + j\ 1.0545$
C2 (Transf. T2 cable) $= 0.0614 + j0.0359\ \Omega/1000$ ft		
$Z = \frac{300}{1000}(0.0614 + J0.0359)\frac{(15)}{(13.8)}\ 2$	$=0.0014 +0.0008$	$0.0014 +j0.0008$
Transf. T2 - $Z = \frac{5.5\ (15000)}{100\ (3750)} = 0.22$		
$X/R = 11$, $\tan^{-1} 11 = 84.80°$		
$R = (\cos 84.80)(0.22)$, $X = (\sin 84.80)(0.22)$	$= 0.0199 + j0.2191$	$0.0199 + j0.2191$
Mot. M2 $X = \frac{16.7\ (15000)}{100\ (500)\ (.95)} = 5.2737$		
$X/R = 19$, $R = X/19 = 0.2776$		
$1.2\ (R + jX)$	$= 0.3331 + j6.3284$	
$3.0\ (R + jX)$	$=$	$0.8328 + j15.8211$

	First Cycle R + j X	1.5-4 Cycles R + j X
Mot. M3 $X = \frac{16.7\ (15000)}{100\ (2000)\ (.9)} = 1.3917$		
$X/R = 31$, $R = X/31 = 0.0449$		
$1.0\ (R + jX)$	$= 0.0449 + j1.3917$	
$1.5\ (R + jX)$	$=$	$0.0674 + j2.0875$
C3 (Transf. T3 Cable) $= 0.3114 + j0.0472\ \Omega/1000$ ft.		
$Z = \frac{200}{1000}(0.3114 + j0.0472)\frac{(15)}{(13.8)}\ 2$	$= 0.0049 + j0.0007$	$j0.0049 + j0.0007$
Transf. T3 $Z = \frac{5.75\ (15000)}{100\ (1500)} = 0.575$		
$X/R = 6.5$, $\tan^{-1} 6.5 = 81.25°$		
$R = (\cos 81.25)(0.575)$, $X = (\sin 81.25)(0.575)$	$= 0.0874 + 0.5683$	$0.0874 + j0.5683$
Mot. M4 Σ 1500Hp		
Assumed 25% 100 Hp = 4-100 Hp		
35% 50 Hp = 8- 50 Hp		
remainder 25 Hp = 28- 25 Hp		
100 Hp $X = \frac{16.7\ (15000)}{100(4)(100)} = 6.2625$		
$X/R = 8.3$, $R = X/8.3 = 0.75457$		
$1.2\ (R + j\ X)$	$= 0.9054 + j7.515$	
$3.0\ (R + j\ X)$	$=$	$2.2635 + j18.7875$
50 Hp $X = \frac{16.7\ (15000)}{100\ (8)(50)} = 6.2625$		
$X/R = 5.5$, $R = X/5.5 = 1.1386$		
$1.20\ (R + j\ X)$	$= 1.3664 + j7.515$	
$3.00\ (R + jX)$	$=$	$3.4158 + j18.7875$
25 Hp $X = \frac{16.7\ (15000)}{100\ (28)(25)} = 3.5786$		
$X/R = 3.8$, $R = X/3.8 = 0.9417$		
$1.67\ (R + jX)$	$= 1.5727+ j5.9763$	
C4 (Cable-Bus 7 to Bus 8)		
$Z = 0.0534 + j0.0428\ \Omega/1000$ ft		
$= \frac{250}{(1000)}(0.0534 + j0.0428)\frac{(15)}{(.48)}\ 2$	$= 0.8691 + j0.6966$	

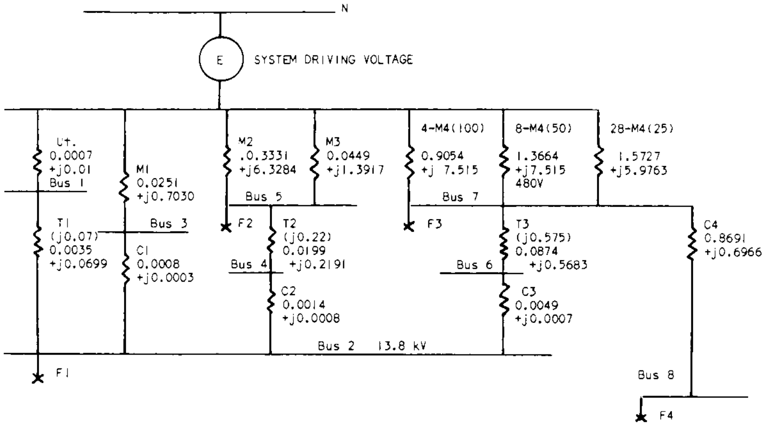


Fig. 20. An impedance diagram for calculating first cycle a.c. component short-circuit current for system one-line diagram shown in Figure 19.

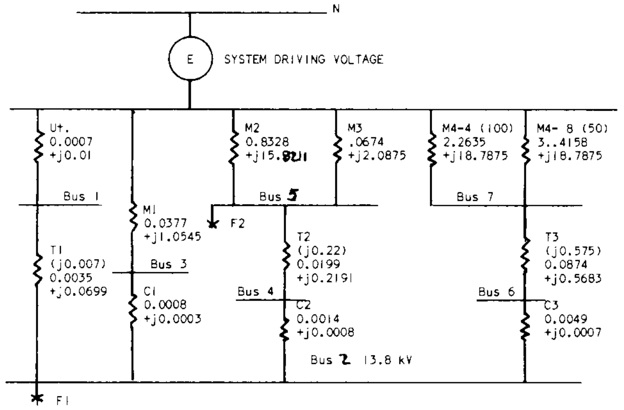


Fig. 21. An impedance diagram for calculating 1.5 to 4 cycle a.c. component short-circuit current for system one-line diagram shown in Figure 19.

Step D—Calculation of Short-circuit (a.c. component) Current

The results attained is dependent on the method used to resolve the impedance network. If the network resolution is treated as a complex quantity accurate results will be attained. If the network is treated as separate R and X networks the result will provide slightly higher short-circuit currents. However, if the system impedance has a large resistance component compared to the reactive component then the resultant current calculation will increase. A separate R and X calculation is still performed to determine the short-circuit X/R ratios in accordance with ANSI standards.

The base voltages were assigned values, as listed in Table 3, equal to the nominal system voltages which are equivalent to the pre-short circuit or operating voltage. This means that the system per-unit driving voltage (E) equals 1.0.

A total of two cases will be systematically presented by:

1. Indicating an applicable network
2. Indicating network resolution to be applied
3. Solving the network to a single-value impedance
4. Calculating a symmetrical current
5. Application

Case One—First Cycle a.c. Component Short-circuit Current

The impedances of Figure 20 are to be resolved into a single impedance value that limits the current for a three-phase short-circuit at F1, F2, F3 and F4. The resolution methods to be applied are:

Method A: Neglect resistive component except for low voltage cables and resistive and reactive component for high voltage cables. Justification being that the neglected components are negligible compared to reactive components being considered.

Method B: Consider all components, resistive and reactive, however, resolve each independently. Justification to provide a more accurate result but simplify the mathematics compared to Method C. This method is required however to determine system X/R ratios.

Method C: Consider all components, resistive and reactive, and resolve the network as a complex quantity. Justification provides an accurate result but requires more complex mathematics.

Case One—Short Circuit at F1

Method A—Network resolution

Branch	X	1/X	
Ut. + T1	0.01 + 0.07		12.5
M1	0.703		1.4225
M2	6.3284	0.1580	
M3	1.3917	0.7185	
M2 + M3	1.1409	← 0.8765	
T2 + (M2 + M3)	0.22 + 1.1409		0.7348
M4 (4–100 hp)	7.515	0.1331	
M4 (8–50 hp)	7.515	0.1331	
M4 (28–25 hp)	5.9763	0.1673	
ΣM4	2.3068	← 0.4335	
T3 + ΣM4	0.575 + 2.3068		0.3470
Net X	0.0666	←	15.0043

Equivalent Z = 0 + j0.0666 per unit

Method B—Network resolution

Branch	R	1/R	
Ut. + T1	0.0007 + 0.0035		238.0952
M1 + C1	0.0251 + 0.0008		38.61
M2	0.3331	3.0021	
M3	0.0449	22.2717	
M1 + M3	0.0396	← 25.2738	
C2 + T2 + (M1 + M3)	0.0014 + 0.0199 + 0.0396		16.4294
M4 (4–100 hp)	0.9054	1.1045	
M4 (8–50 hp)	1.3664	0.7319	
M4 (28–25 hp)	1.5727	0.6359	
ΣM4	0.4045	← 2.4722	
C3 + T3 + ΣM4	0.0049 + 0.0874 + 0.4045		2.0128
Net R	0.0034	←	295.1474

Branch	X	1/X	
Ut + T1	0.01 + 0.0699		12.5156
M1 + C1	0.703 + 0.0003		1.4219
M2	6.3284	0.1580	
M3	1.3917	0.7185	
M2 + M3	1.1409	← 0.8765	
C2 + T2 + (M2 + M3)	0.0008 + 0.2191 + 1.1409		0.7349
M4 (4–100 hp)	7.515	0.1331	
M4 (8–50 hp)	7.515	0.1663	
M4 (28–25 hp)	5.9763	0.1673	
ΣM4	2.3068	← 0.4335	
C3 + T3 + ΣM4	0.0007 + 0.5683 + 2.3068		0.3477
Net X	0.0666	←	15.0201

Equivalent Z = 0.0034 + j0.0666, per unit
X/R ratio = 0.0666/0.0034 = 19.6

Method C—Network resolution. Note: refer to appendix analytical techniques for complex quantity mathematics.

Branch

$$\begin{aligned}
\text{Ut + T1} &= (0.0007+j0.01)+(0.0035+j0.0699)\\
&= 0.0042+j0.0799\\
\text{M1 + C1} &= (0.0251+j0.703)+(0.0008+j0.0003)\\
&= 0.0259+j0.7033\\
\text{(Ut+T1)+(M1+C1)} &= \frac{(0.0042+j0.0799)(0.0259+j0.7033)}{(0.0042+j0.0799)+(0.0259+j0.7033)}\\
&= 0.0036+j0.0718\\
\text{M2 + M3} &= \frac{(0.3331+j6.3284)(0.0449+j1.3917)}{(0.3331+j6.3284)+(0.0449+j1.3917)}\\
&= 0.0410+j1.1409\\
\text{(M2+M3)+T2+C2} &= (0.0410+0.0199+0.0014)+j(1.1409+0.2191+0.0008)\\
&= 0.0623+j1.3608
\end{aligned}$$

$$\begin{aligned}
\text{(Ut+T1)+(M1+C1)]+(M2+M3+T2+C2)} &= \frac{(0.0036+j0.0718)(0.0623+j1.3608}{(0.0036+j0.0718)+(0.0623+j1.3608)}\\
&= 0.0034+j0.0682
\end{aligned}$$

$$\begin{aligned}
\text{M4 (4-100hp)} &= 0.9054+j7.515\\
\text{M4 (8-50hp)} &= 1.3664+j7.515\\
\text{M4 (28-25hp)} &= 1.5727+5.9763\\
\Sigma\ \text{M4} &= \frac{(0.9054+j7.515)+(1.3664+j7.515}{(0.9054+j7.515)+(1.3664+j7.515)}\\
&= 0.5674+3.761\\
&= \frac{(0.5674+j3.761)(1.5727+j5.9763)}{(0.5674+j3.761)+(1.5727jJ5.9763}\\
&= 0.4469+j2.3149\\
\Sigma\ \text{M4+T3+C3} &= (0.4469+0.0874+0.0049)+j(2.3149+0.5683+0.0007)\\
&= 0.5392+j2.8839
\end{aligned}$$

$$\begin{aligned}
\text{Net Z} &= \text{(Ut+T1+M1+C1+M2+M3+T2+C2)+(}\Sigma\text{M4+T3+C3)}\\
&= \frac{(0.0034+j0.0682)(0.5392+j2.8839)}{(0.0034+j0.0682)+(0.5392+j2.8839)}\\
&= 0.0035+j0.0666 \text{ per unit}
\end{aligned}$$

The symmetrical short-circuit current at F1 is $I = I_b$ (I per unit) $= I_b$ (E/Z net) = 628 ($^{1.0}/$Z net) = 628/Z net

Method	Z net Per Unit	I Amperes rms Symmetrical
A	0+j0.0666	9429
B	0.0034+j0.0666	9417
C	0.0035+j0.0666	9415

Note: The fault currents calculated per method A, B, or C differ by only 0.15 per cent which continues to justify neglecting high voltage resistance as well as cable reactance thus simplifying calculations.

The power circuit breaker applied at the 13.8 kV bus should have a momentary or close and latch rating equal to or greater than 1.6 (9429) = 15086 amperes rms asymmetrical. If other protectors such as fuses are to be applied the short-circuit rating capability may have to be derated due to the system X/R ratio = 19.6 per ANSI C37.41 1981 standard.

Case One—Short-circuit at F2

Method A—Network resolution

Branch	X	1/X	
Ut + T1	0.01 + 0.07	12.5	
M1	0.703	1.4225	
ΣM4 + T3	2.3068 + 0.575	0.3470	
(Ut + T1) + (M1) + (ΣM4 + T3)	0.0701 ←	14.2695	
(Ut + T1 + M1 + M4 + T3) + (T2)	0.0701 + 0.22		3.4473
M2	6.3284		0.1580
M3	1.3917		0.7185
Net X	0.2313 ←		4.3238

Equivalent Z = 0 + j0.2313 per unit

Method B—Network resolution

Branch	R	1/R	
Ut + T1	0.0007 + 0.0035	238.0952	
M1 + C1	0.0251 + 0.0008	38.61	
ΣM4 + T3 + C3	0.4045 + 0.0874 + 0.0049	2.0129	
(UT + T1) + (M1 + C1) + (ΣM4 + T3 + C3)	0.0036 ←	278.7181	
(Ut + T1 + M1 + C1 + ΣM4 + T3 + C3) + C2 + T2)	0.0036 + 0.0014 + 0.0199		40.1626
M2	0.3331		3.0021
M3	0.0449		22.2717
Net R	0.0153 ←		65.4364

Branch	X	1/X	
Ut + T1	0.01 + 0.0699	12.5156	
M1 + C1	0.7030 + 0.0003	1.4219	
ΣM4 + T3 + C3	2.3068 + 0.5683 + 0.0007	0.3477	
(Ut + T1) + (M1 + C1) + (ΣM4 + T3 + C3)	0.070 ←	14.2852	
(Ut + T1 + M1 + C1 + ΣM4 + T3 + C3) + (C2 + T2)	0.070 + 0.0008 + 0.2191		3.4495
M2	6.3284		0.1580
M3	1.3917		0.7185
Net X	0.2312 ←		4.3260

Equivalent Z = Net R + Net X = 0.0153 + j0.2312 per unit

X/R ratio = 0.2312/0.0153 = 15.11

Method C—Network resolution

From F1 solution: $Ut+T1+M1+C1 = 0.0036+j0.0718$

$M4+T3+C3 = 0.5392+j2.8839$

$M2+M3 = 0.0410+j1.1409$

$(Ut+T1+M1+C1)+(\Sigma M4+T3+C3)$

$$= \frac{(0.0036+j0.0718)(0.5392+j2.8839)}{(0.0036+j0.0718)+(0.5392+j2.8839)}$$

$$= 0.0037+j0.0701$$

$(Ut+T1+M1+C1+\Sigma M4+T3+C3) + (C2) + (T2)$

$$= (0.0037+0.0014+0.0199)+j(0.0701+0.0008+0.2191)$$

$$= 0.0250+j0.2900$$

$$\text{Net } Z = (Ut+T1+M1+C1+\Sigma M4+T3+C3+C2+T2)+(M2+M3)$$

$$= \frac{(0.0250+j0.2900)(0.0410+j1.1409)}{(0.0250+j0.2900)+(0.0410+j1.1409)}$$

$$= 0.0175+j0.2313 \text{ per unit}$$

The symmetrical short-circuit current at F2 is $I=I_b$ (I per unit) $= I_b$ (E/Z net) = 2084 (1.0/Z net) = 2084/Z net

Method	Z Net Per Unit	I Amperes rms Symmetrical
A	0+j0.2313	9010
B	0.0153+j0.2312	8994
C	0.0175+j0.2313	8984

Note the fault currents calculated per method A, B or C differ by only 0.30 percent which justifies neglected high voltage resistance as well as cable reactance thus simplifying calculations.

The power circuit breaker applied at the 4.16Kv bus should have a momentary or close and latch rating equal to or greater than 1.6 (9010) = 14,416 amperes rms asymmetrical.

Section III— Examples of Ac Short-circuit Calculations

Case One—Short-circuit at F3

Method A—Network resolution

Branch	X	1/X	
Ut+T1	0.01+0.07	12.5	
M1	0.703	1.4225	
Ut+T1+M1	0.0718 ←	13.9225	
M2	6.3284		0.1580
M3	1.3917		0.7185
M2+M3	1.1409 ←		0.8765
(M2+M3+T2)	1.1409+0.22	0.7348	
(Ut+T1+M1)+(M2+M3+T2)	.0682 ←	14.6573	
(Ut+T1+M1+M2+M3+T2)+(T3)	.0682+0.575		1.5547
ΣM4	2.3068		0.4335
Net X	0.503 ←		1.9882

Equivalent $Z = 0 + j0.503$ per unit

Method B—Network resolution

Branch	R	1/R	
Ut+T1	0.0007+0.0035	238.0952	
M1+C1	0.0251+0.0008	38.61	
Ut+T1+M1+C1	0.0036 ←	276.7052	
M2	0.3331		3.0021
M3	0.0449		22.2717
M2+M3	0.0396 ←		25.2738
M2+M3+T2+C2	0.0396+0.0199+0.0014	16.4294	
(Ut+T1+M1+C1)+(M2+M3+T2+C2)	0.0034 ←	293.1346	
(Ut+T1+M1+C1+M2+M3+T2+C2) + (C3+T3)	0.0034+0.0049+0.0874		10.4493
ΣM4	0.4045		2.4722
Net R	0.0774 ←		12.9215

Branch	X	1/X	
Ut+T1	0.01+0.0699	12.5156	
M1+C1	0.703+0.0003	1.4219	
Ut+T1+M1+C1	0.0717 ←	13.9375	
M2	6.3284		0.1580
M3	1.3917		0.7185
M2+M3	1.1409 ←		0.8765
M2+M3+T2+C2	1.1409+0.2191+0.0008	0.7349	
(Ut+T1+M1+C1)+(M2+M3+T2+C2)	0.0682 ←	14.6724	
(Ut+T1+M1+C1+M2+M3+T2+C2) + (C3+T3)	0.0682+0.0007+0.5683		1.5694
M4	2.3068		0.4335
Net X	0.4993 ←		2.0029

Equivalent $Z = R + jX = 0.0774 + j0.4993$ per unit
X/R ratio $= 0.4993/0.0774 = 6.45$

Method C—Network resolution

From F1 Solution:

Ut+T1+M1+C1+M2+M3+T2+C2 = 0.0034 + j0.0682
Σ M4 = 0.4469 + j2.3149
(Ut+T1+M1+C1+M2+M3+T2+C2) + (C3) + (T3)
= (0.0034+0.0049+0.0874)+j(0.0682+0.0007+0.5683)
= 0.0957+j0.6372
Net Z = (Ut+T1+M1+C1+M2+M3+T2+C2+C3+T3) + (ΣM4)

$$= \frac{(0.0957+j0.6372)\ (0.4469+j2.3149)}{(0.0957+j0.6372) + (0.4469+j2.3149)}$$

= 0.0796 + j0.5000 per unit

The symmetrical short circuit current @ F3 is $I = I_b$ (I per unit) $= I_b$ (E/Znet) = 18064 (1.0/Znet) = 18064/Znet

Method	Z net Per Unit	I Amperes rms Symmetrical
A	0+j0.503	35912
B	0.0774+j0.4993	35751
C	0.0796+j0.5000	35679

Note: the fault currents calculated per method A, B, or C differ by only 0.65% which continues to justify neglecting high voltage resistance as well as cable reactance thus simplifying calculations.

The low voltage breakers applied at the 480V bus should have a momentary or interrupting rating equal to or greater than 35912 amperes rms symmetrical. Note computed X/R ratio at this bus is 6.45 thus low voltage molded case or insulated case breakers if applied at this bus would require derating per applicable standards since they are tested at a lower X/R ratio.

Case One—Short-circuit at F4

Method A - Network Resolution

Net Z = X net @ F3 + C4
= (0+j0.503) + (0.8691+j0.6966)
= 0.8691+j1.1996 per unit

Method B - Network resolution

Net R = R net @ F3 + RC4
= 0.0774+0.8691
= 0.9465
Net X = X net @ F3 + XC4
= 0.4993+0.6966
= 1.1959
Net Z = R+JX = 0.9465+j1.1959 per unit
X/R ratio = 1.1959/0.9465 = 1.26

Method C - Network resolution

Net Z = Znet @ F3 + C4
= (0.0796+j0.5000) + (0.8691+j0.6966)
= 0.9487+j1.1966 per unit

The symmetrical short circuit current @ F4 is I = I_b (I per unit) = I_b (E/Znet) = 18064 (1.0/Znet) = 18064/Znet

Method	Z net Per Unit	I Amperes rms Symmetrical
A	0.8691+j1.1996	12194
B	0.9465+j1.1959	11844
C	0.9487+j1.1966	11829

Note: the fault currents calculated per method A, B or C difference is increasing. This increase is mostly due to neglecting the low voltage motor resistance in method A. Method B and C results remain relatively close justifying Method B approach thus reducing the computation to one method since method B is required to determine system X/R ratios.

Case Two—A.C. Component Short-circuit Current—1.5 to 4 Cycle After Fault

The impedances of figure 21 are to be resolved into a single impedance value that limits the current for a three-phase short-circuit at F1 and F2. The resolution methods to be applied are identical to method A, B and C defined previously for case one.

Case Two—Short-circuit at F1

Method A—Network Resolution

Branch	X	1/X		
Ut+T1	0.01+0.07			12.5
M1	1.0545			0.9483
M2	15.8211	0.0632		
M3	2.0875	0.4790		
M2+M3	1.8442 ←	0.5422		
(M2+M3)+(T2)	1.8442+0.22			0.4845
M4 (4–100 hp)	18.7875		0.0532	
M4 (8–50 hp)	18.7875		0.0532	
ΣM4	9.3985 ←		0.1064	
(ΣM4)+(T3)	9.3985+0.575			0.1003
Net X	0.0713 ←			14.0331

Net X = 0j0.0713 per unit

Method B—Network Resolution

Branch	R	1/R		
Ut+T1	0.0007+0.0035			238.0952
M1+C1	0.0377+0.0008			25.9740
M2	0.8328	1.2008		
M3	0.0674	14.8368		
M2+M3	0.0624 ←	16.0376		
(M2+M3)+(T2)+(C2)	0.0624+0.0199+0.0014			11.9541
M4 (4–100 hp)	2.2635		0.4418	
M4 (8–50 hp)	3.4158		0.2928	
ΣM4	1.3614 ←		0.7346	
(ΣM4)+(T3)+(C3)	1.3614+0.0874+0.0049			0.6879
Net R	0.0036 ←			276.7112

Branch	X	1/X		
Ut+T1	0.01+0.0699			12.5156
M1+C1	1.0545+0.0003			0.9480
M2	15.8211	0.0632		
M3	2.0875	0.4790		
M2+M3	1.8442 ←	0.5422		
(M22+M3)+(T2)+(C2)	1.8442+0.2191+0.0008			0.4845
M4 (4–100 hp)	18.7875		0.0532	
M4 (8–50 hp)	18.7875		0.1064	
ΣM4	9.3985 ←		0.1064	
(ΣM4)+(T3)+(C3)	9.3985+0.5683+0.0007			0.1003
Net X	0.0712 ←			14.0484

Net Z = 0.0036 + j0.0712 per unit
X/R ratio = 0.0712/0.0036 = 19.8

Method C—Network resolution

$$\begin{aligned}
\mathrm{Ut{+}T1} &= (0.0007+0.0035)+(0.01+0.0699)\\
&= 0.0042+j0.0799\\
\mathrm{M1{+}C1} &= (0.0377+.0008)+j(1.0545+0.0003)\\
&= 0.0385+j1.0548\\
\mathrm{Ut{+}T1{+}M1{+}C1} &= \frac{(0.0042+j0.0799)(0.0385+j1.0548)}{(0.0042+j0.0799)+(0.0385+j1.0548)}\\
\Sigma\ \mathrm{M4} &= \frac{(2.2635+j18.7875)(3.415+j18.7875)}{(2.2635+j18.7875)+(3.4158+j18.7875)}\\
&= 1.4185+j9.4024\\
\Sigma\ \mathrm{M4{+}T3{+}C3} &= (1.4185+0.0874+0.0049)+j(9.4024+0.5683+0.0007)\\
&= 1.5108+j9.9714
\end{aligned}$$

$$\begin{aligned}
&(\mathrm{Ut{+}T1{+}M1{+}C1})+(\Sigma\ \mathrm{M4{+}T3{+}C3})\\
&\quad= \frac{(0.0038+j0.0743)\ (1.5108+9.9714)}{(0.0038+j0.0743)+(1.5108+j9.9714}\\
&\quad= 0.0038+j0.0738\\
\mathrm{M2{+}M3} &= \frac{(0.8328+j15.8211)(0.0674+j2.0875)}{(0.8328+j15.8211)+(0.0674+j2.0875}\\
&= 0.0639+j1.8442\\
\mathrm{M2{+}M3{+}T2{+}C2} &= (0.0639+0.0199+0.0014)+j(1.8442+0.219+0.0008)\\
&= 0.0852+j2.0641
\end{aligned}$$

$$\begin{aligned}
&(\mathrm{Ut{+}T1{+}M1{+}C1{+}\Sigma M4{+}T3{+}C3})+(\mathrm{M2{+}M3{+}T2{+}C2})\\
&\quad= \frac{(0.0038+j0.0738)(0.0852+j2.0641)}{(0.0038+j0.0738)+(0.0852+j2.0641)}\\
\text{Net Z} &= 0.0036+j0.0712\ \text{per unit}
\end{aligned}$$

The Symmetrical short-circuit current 1.5 to 4 cycle after fault at F1 is I = I_b (I per unit) = I_b (E/Z net) = 628 (1.0/Z net) = 628/Z net

Method	Z net Per Unit	I Amperes rms Symmetrical
A	0+j0.0713	8808
B	0.0036+j0.0712	8808
C	0.0036+j0.0712	8808

The power circuit breaker applied at the 13.8 kV bus should have an interrupting rating of 1.2 (8808) = 10.569 amperes rms symmetrical or greater. If not then a more exact method of calculation described in Section 5.3.2 of ANSI Standard 37.010–1979 should be used. Refer to Section 1.

Case Two—Short-circuit at F2

Method A—Network resolution

Branch	X	1/X
Ut + T1	0.01 + 0.0.07	12.5
M1	1.05 + 5	0.9483
M4 (4–100 hp)	18.7875	0.0532
M4 (8–50 hp)	18.7875	0.0532
ΣM4	9.3985 ←	0.1064
(ΣM4) + (T3)	9.3985 + 0.575	0.1003
(Ut + T1) + (M1) + (M4 + T3)	0.0738 ←	13.5486
(Ut + T1 + M1 + M4 + T3) + (T2)	0.0738 + 0.22	3.4037
M2	15.8211	0.0632
M3	2.0875	0.4790
Net X	0.2534 ←	3.9459

Net X = 0 + j0.2534 per unit

Method B—Network Resolution

Branch	R	1/R
Ut + T1	0.0007 + 0.0035	238.0952
M1 + C1	0.0377 + 0.0008	25.9740
M4 (4–100 hp)	2.2635	0.4418
M4 (8–50 hp)	3.4158	0.2928
ΣM4	1.3614 ←	0.7346
(ΣM4) + (T3) + (C3)	1.3614 + 0.0874 + 0.0049	0.6879
(Ut + T1) + (M1 + C1) + (ΣM4 + T3 + C3)	0.0038 ←	264.7571
(Ut + T1 + M1 + C1 + ΣM4 + T3 + C3) + (T2 + C2)	0.0038 + 0.0199 + 0.0014	39.8406
M2	0.8328	1.2008
M3	0.0674	14.8368
Net R	0.0179 ←	55.8782

Branch	X	1/X
Ut + T1	0.01 + 0.0699	12.5156
M1 + C1	0.7030 + 0.0003	0.9480
M4 (4–100 hp)	18.7875	0.0532
M4 (8–50 hp)	18.7875	0.0532
ΣM4	9.3985 ←	0.1064
(ΣM4) + (T3) + (C3)	9.385 + 0.5683 + 0.0007	0.1003
(Ut + T1) + (M1 + C1) + (ΣM4 + T3 + C3)	0.0737 ←	13.5639
(Ut + T1 + M1 + C1 + ΣM4 + T3 + C3) + (T2 + C2)	0.0737 + 0.2191 + 0.0008	3.4057
M2	15.8211	0.0632
M3	2.0875	0.4790
Net X	0.2533 ←	3.9479

Net Z = 0.0179 + j0.2533 per unit
X/R ratio = 0.2533/0.0179 = 14.2

Method C—Network Resolution

From previous calculations for fault at F1

$$\begin{aligned} Ut+T1=M1+C1+\Sigma M4+T3+C3 &= 0.0038+j0.0738 \\ M2+M3 &= 0.0639+j1.8442 \end{aligned}$$

$$\begin{aligned} &(Ut+T1+M1+C1+\Sigma M4+T3+C3)+(T2)+(C2) \\ &\quad = (0.0038+0.0199+0.0014)+j(0.0738+0.2191+0.0008) \\ &\quad = 0.0251+j0.2937 \end{aligned}$$

$$\begin{aligned} &(Ut+T1+M1+C1+\Sigma M4+T3+C3+T2+C2)+(M2+M3) \\ &\quad = \frac{(0.0251+j0.2937)(0.0639+j1.8442)}{(0.0251+j0.2937)+(0.0639+j1.8442)} \end{aligned}$$

$$\text{Net } Z = 0.0199+j0.2534 \text{ per unit}$$

The symmetrical short-circuit current 1.5 to 4 cycle after fault at F2 is
$I = I_b$ (I per unit) = I_b (E/Z net) = 2084(1.0/Z net) = 2084/Z net

Method	Z net Per Unit	I Amperes rms Symmetrical
A	0 + j0.2534	8224
B	0.0179+j0.2533	8207
C	0.0199+j0.2534	8199

The power circuit breaker applied at the 4.16 kV bus should have an interrupting rating of 8224 amperes rms symmetrical since, as noted in Section 1, the X/R ratio is less than 15 at the 4.16 kV bus.

Computer Solution

Many computer programs have been written for the calculation of short-circuit currents. The system designer who knows how to use these programs benefits from the computer's well known accuracy and speed. A typical computer solution for the example previously solved will be illustrated.

A separate data reduction computer program is used to convert the impedance values of the system components into per unit values all on a common kVA or Mva base. These per unit values are used as an input to the computer program for calculating short-circuit currents. Not only does the computer calculate faster and more accurately but the necessity of making an impedance diagram is eliminated.

The results for the system shown in the one-line-diagram figure 19 are as follows:

Impedance Data Reduction
GE Industrial Power Systems Engineering—Schenectady, NY
Data Reduction program—Version 1.40
15 MVA Base—60 Hertz

Impedance Data Reduction

```
Utility Source Impedance on a 15 MVA Base

Bus        MVA      X/R     P.U.R.        P.U.X.
 1         1500     15.0    0.00067       0.00998


Element Impedance on a 15 MVA Base

Ident      kVA      %Z      X/R     P.U.R.        P.U.X.     Bus   Bus
T1        15000     7.00    20.0    0.00350       0.06991     1     2
T2         3750     5.50    11.0    0.01992       0.21910     4     5
T3         1500     5.75     6.5    0.08743      0.56831     6     7


Cable Impedance on a 15 MVA Base at 60 Hz-Res. at 75C

Cable    Conductor        Conduit  Len.   Volts   P.U.R.    P.U.X.   Bus  Bus
C1     1-3C-2/0AWG CU     N'Mag   100ft   13800  0.00077   0.00030   2    3
C2     1-3C-4/0AWG CU     N'Mag   300ft   13800  0.00145   0.00085    2    4
C3     1-3C-4AWG  CU      N'Mag   200ft   13800  0.00491   0.00074    2    6
C4     3-1C-250MCM CU      Mag    250ft     480  0.86974   0.69640    7    8


P.U. Motor X"  d or Locked Rotor Impedances on 15 MVA Base

Bus  Hp    Motor   kVA    RPM    PF   QUAN   $X     X/R   P.U.R.  P.U.X.  CODE
3   4000   SYN    3200   1800   1.0   1.00  15.00   27.6  .02547  .70313   3
5    500   IND     475   1800    -    1.00  16.70   19.3  .27299  5.2736   5
5   2000   IND    1800   3600    -    1.00  16.70   31.0  .04495  1.3916   4
7    100   IND     100   1800    -    4.00  16.70    8.3  .75452  6.2625   5
7     50   IND      50   1800    -    8.00  16.70    5.5  1.1386  6.2625   5
7     25   IND      25   1800    -   28.00  16.70    3.8   .94174 3.5785   6
```

Section III— Examples of Ac Short-circuit Calculations

Short-circuit currents using impedance per unit values based on ANSI and IEEE recommended rotating machine modified subtransient values for multi-voltage systems as outlined in Section II.

GE Industrial Power Systems Engineering—Schenectady, NY

Three Phase Short-Circuit Program—Version 1.40

First Cycle Calc. For Breaker Duties Per ANSI C37.13–1981

Tot. Current & Flows From Complex Network, X/R From Separate R & X

08/24/87 15 MVA Base 60 Hertz

Case: 1—First Cycle Multi-voltage

```
Input Data
   BUS TO BUS                  R P.U.          X P.U.          CODE
    0     1                    0.00067         0.00998          1
    1     2                    0.00350         0.06991          0
    4     5                    0.01992         0.21910          0
    6     7                    0.08743         0.56831          0
    2     3                    0.00077         0.00030          0
    2     4                    0.00145         0.00085          0
    2     6                    0.00491         0.00074          0
    7     8                    0.86974         0.69640          0
    0     3                    0.02547         0.70313          3
    0     5                    0.04495         1.39167          4
    0     5                    0.32759         6.32842          5
    0     7                    0.54457         3.75752          5
    0     7                    1.57271         5.97624          6
* Bus 2        E/Z = 9.409 kA (224.89 MVA) AT-86.94 DEG., X/R = 19.73, 13.800 kV
               Z = 0.003558 + J  0.066603
               1.6 * ISYM = 15.05   IASYM based on X/R = 14.74

Contributions in kA

  BUS TO BUS          MAG          ANG          BUS TO BUS      MAG        ANG
   1     2           7.845        -87.02          3     2       0.892     -87.866
   4     2           0.461        -87.378         6     2       0.214     -79.577

* Bus 5        E/Z = 8.974 kA (64.66MVA) AT-85.64 DEG., X/R = 15.12, 4.160 kV
               Z =  0.017655 +J   0.231308
               1.6*ISYM = 14.36    IASYM based on X/R = 13.67

Contributions in kA

  BUS TO BUS          MAG          ANG          BUS TO BUS      MAG        ANG
   4     5           7.152        -85.045       INDMOT   5      1.495     -88.149
 INDMOT  5           0.329        -87.035

* Bus 7        E/Z = 35.656 kA (29.64 MVA) AT -80.99 DEG., X/R = 6.45, 0.480 kV
               Z = 0.079281 + J 0.499760
               Max. Low Voltage Power Circuit Breaker Duty Level = 35.66

Contributions in kA

  BUS TO BUS          MAG          ANG          BUS TO BUS      MAG        ANG
   6     7          28.000        -81.452         8     7      -0.000     -119.670
 INDMOT  7           4.752        -81.752       INDMOT   7      2.920      -75.255

*Bus 8         E/Z = 11.816 kA (9.82 MVA) AT -51.57 DEG., X/R = 1.26, 0.480 kV
               Z = 0.949021 + J 1.196160
               Max. Low Voltage Power Circuit Breaker Duty Level =  11.82

Contributions in kA

  BUS TO BUS          MAG          ANG
   7     8          11.816        -51.572
```

Short-circuit currents using impedance per unit values based on ANSI and IEEE recommended rotating machine modified subtransient values for high voltage systems as outlined in Section II.

GE Industrial Power Systems Engineering—Schenectady, NY

Three Phase Short Circuit Program—Version 1.40

First Cycle Calc. For Bkr Duties Per ANSI C37.010–1979, C37.5–1979

Tot. Current & Flows From Complex Network, X/R From Separate R & X

08/24/87 15 MVA Base 60 Hertz

Case: 2—First Cycle High Voltage

```
Input Data
   BUS TO BUS                  R P.U.          X P.U.          CODE
    0     1                    0.00067         0.00998          1
    1     2                    0.00350         0.06991          0
    4     5                    0.01992         0.21910          0
    6     7                    0.08743         0.56831          0
    2     3                    0.00077         0.00030          0
    2     4                    0.00145         0.00085          0
    2     6                    0.00491         0.00074          0
    7     8                    0.86974         0.69640          0
    0     3                    0.02547         0.70313          3
    0     5                    0.04495         1.39167          4
    0     5                    0.32759         6.32842          5
    0     7                    0.54457         3.75752          5
* Bus 2        E/Z = 9.340 kA ( 223.3 MVA) AT -87.03 DEG., X/R = 19.85, 13.800 Kv
               Z = 0.003483 +J  0.067103
               1.6 *ISYM = 14.94    IASYM based on X/R = 14.64

Contribution in kA

  BUS TO BUS          MAG          ANG          BUS TO BUS      MAG        ANG
   1     2           7.845        -87.012         3     2       0.892     -87.867
   4     2           0.461        -87.381         6     2       0.144     -81.624

*Bus 5         E/Z = 8.961 kA (  64.56 MVA) AT-85.66 DEG., X/R = 15.14, 4.160 kV
               Z =  0.017595 + J 0.231658
               1.6*ISYM = 14.34     IASYM based on X/R = 13.65

Contribution in kA


  BUS TO BUS          MAG          ANG          BUS TO BUS      MAG        ANG
   4     5           7.139        -85.071       INDMOT   5      1.495     -88.149
 INDMOT  5           0.329        -87.035
```

Section III— Examples of Ac Short-circuit Calculations

Short-circuit currents using impedance per unit values based on ANSI and IEEE recommended rotating machine modified subtransient values for high voltage breaker interrupting duty requirement as outlined in Section II.

GE Industrial Power Systems Engineering—Schenectady, NY

Three Phase Short Circuit Program—Version 1.40

Interrupting Calc. For Bkr Duties Per ANSI C37.010–1979, C37.5–1979

Tot. Current & Flows From Complex Network, X/R From Separate R & X

08/24/87 15 MVA Base 60 Hertz

Case: 3—1.5 to 4 Cycle High Voltage

```
Input Data
  BUS TO BUS              R P.U.         X P.U.        CODE
  0       1               0.00067        0.00998        1
  1       2               0.00350        0.06991        0
  4       5               0.01992        0.21910        0
  6       7               0.08743        0.56831        0
  2       3               0.00077        0.00030        0
  2       4               0.00145        0.00085        0
  2       6               0.00491        0.00074        0
  7       8               0.86974        0.69640        0
  0       3               0.03820        1.05470        3
  0       5               0.06742        2.08750        4
  0       5               0.81897       15.82104        5
  0       7               1.36143        9.39381        5

* Bus 2    E/Z = 8.805 kA ( 210.45 MVA) AT -87.05 DEG., X/R = 19.79, 13.800 Kv
           Z = 0.003662 +J  0.071180

       Circuit Breaker Type        8Tot, SYM     5SYM       5Tot       3SYM
       Max. Duty Level                  9.38     9.05       9.95       9.12
       Mult. Factor                    1.066    1.027      1.130      1.036

Contribution in kA

   BUS TO BUS        MAG         ANG        BUS TO BUS     MAG       ANG
    1     2          7.845      -87.012      3     2       0.594    -87.885
    4     2          0.304      -87.633      6     2       0.062    -81.693

   SOURCE          TYPE       CONTRIBUTIONS AT FAULT BUS      P.U. GEN
    BUS           SOURCE          LOCAL      REMOTE       TOTAL      VOLTS
     1            REMOTE           0.00       7.84         7.84       0.875
REMOTE/TOTAL = 0.891     SUM       0.00       7.84        7.84

*Bus 5     E/Z = 8.190 kA (  59.01 MVA) AT-85.50 DEG., X/R = 14.15, 4.160 kV
           Z =  0.019945 + J 0.253411

       Circuit Breaker Type        8Tot, SYM     5SYM       5Tot       3SYM
       Max. Duty Level                  8.19     8.19       8.65       8.19
       Mult. Factor                    1.000    1.000      1.056      1.000

Contributions in kA

   BUS TO BUS        MAG         ANG        BUS TO BUS     MAG       ANG
    4     5          7.063      -85.097    INDMOT   5      0.997    -88.149
  INDMOT  5          0.131      -87.035

   SOURCE          TYPE       CONTRIBUTIONS AT FAULT BUS      P.U. GEN
    BUS           SOURCE          LOCAL      REMOTE       TOTAL      VOLTS
     1            REMOTE           0.00       6.52         6.52       0.969
REMOTE/TOTAL = 0.796     SUM       0.00       6.52        6.52
```

Comparison Results: Amperes rms symmetrical First Cycle Multi-voltage and 1.5–4 cycle Using complex Impedance Values for Short-circuit calculations

Location	Calculated			Computer		
	Case One 1st Cycle	Case Two 1.5–4 Cycle	X/R	Case One 1 Cycle	Case Three 1.5–4 Cycle	X/R
F1—bus 2	9,415		19.6	9,409		19.73
		8,808	19.8		8,805	19.79
F2—bus 5	8,984		15.11	8.974		15.12
		8,199	14.2		8,190	14.15
F3—bus 7	35,679		6.45	35,656		6.45
F4—bus 8	11,829		1.26	11,816		1.26

Note the computer produces more accurate results since the calculations were based on impedance values rounded to the four decimal place.

Estimating Short-circuits

Tables and curves can be very useful in estimating short-circuit duty. For example, consider the 1500 kVA transformer T3 Figure 19. The primary available short-circuit duty as calculated for a fault at F1 is 224.89 MVA or 225 MVA (Bus 2 Case 1 computer output). Referring to table 4 for a 1500 kVA, 480 volt, 5.75% transformer with 250 MVA primary available and 100% motor contribution, we note the secondary short-circuit current is 35600 amperes rms symmetrical. This compares with the 35,656 amperes calculated per computer for a fault at F3 bus 7. Also the short-circuit current at F4 at the end of the 250 ft. 250 MCM cable can be estimated from Figure 25–27 to be 12,000 amperes rms symmetrical which compares with the computer calculated value of 11,816 amperes (Case 1 bus 8).

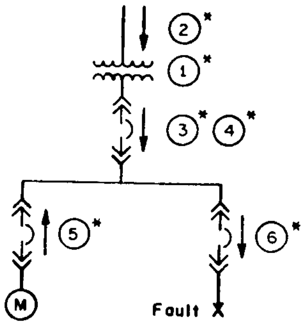
Appendix

INTRODUCTION

The tables and supplementary information contained in this Appendix provide systems designers with reference for the equipment parameters necessary for a short-circuit study. Parts I, II, and III are concerned with specific equipment short-circuit ratings and impedance data. Part IV illustrates the mathematical techniques involved with short-circuit calculations.

PART I—Estimated Short-circuit Duties

Frequently it is convenient to use tables to estimate the short-circuit duties on the secondary side of a transformer or at the end of a cable served from a transformer. The estimated short-circuit duty is based on the component impedance values listed with each table.



* Numbers refer to columns in table.

A. Secondary Unit Substation Transformers

TABLE 4—Three-phase Secondary Unit Substation Transformers

Transformer Rating 3-phase kVA and Impedance Percent	Maximum Short-circuit mVA Available From Primary System	Normal-load Continuous Current Amp	Short-circuit Current RMS Symmetrical Amp		
			Transformer Alone	50% Motor Load	Combined
1	2	3	4	5	6
208 VOLTS, THREE PHASE					
300 †4.5%	50	834	16300	1700	18000
	100		17300		19000
	150		17770		19400
	250		18000		19700
	500		18300		20000
	750		18400		20100
	Unlimited		18500		20200
500 †4.5%	50	1388	25300	2800	28000
	100		27800		29600
	150		28700		31500
	250		29500		32300
	500		30200		33000
	750		30400		33200
	Unlimited		30800		33600
750 5.75%	50	2080	28700	4200	32900
	100		32000		36200
	150		33300		37500
	250		34400		38600
	500		35200		39400
	750		35600		39800
	Unlimited		36200		40400
1000 5.75%	50	2780	35800	5600	41400
	100		41100		46700
	150		43200		48800
	250		45100		50700
	500		46600		52200
	750		47300		52900
	Unlimited		48200		53800
1500 5.75%	50	4160	47600	8300	55900
	100		57500		65800
	150		61700		70000
	250		65600		73900
	500		68800		77100
	750		69900		78200
	Unlimited		72400		80700
240 VOLTS, THREE PHASE					
300 †4.5%	50	722	14200	2900	17100
	100		15000		17900
	150		15400		18300
	250		15600		18500
	500		15800		18700
	750		15900		18800
	Unlimited		16000		18900

Transformer Rating 3-phase kVA and Impedance Percent	Maximum Short-circuit Mva Available From Primary System	Normal-load Continuous Current Amp	Short-circuit Current RMS Symmetrical Amp		
			Transformer Alone	100% Motor Load	Combined
1	2	3	4	5	6
240 VOLTS, THREE PHASE (Cont'd)					
500 †4.5%	50	1203	21900	4800	26700
	100		24000		28800
	150		24900		29700
	250		25600		30400
	500		26100		30900
	750		26300		31100
	Unlimited		26700		31500
750 5.75%	50	1804	24900	7200	32100
	100		27800		35000
	150		28900		36100
	250		29800		37000
	500		30600		37800
	750		30800		38000
	Unlimited		31400		38600
1000 5.75%	50	2406	31100	9600	40700
	100		35700		45300
	150		37500		47100
	250		39100		48700
	500		40500		50100
	750		41000		50600
	Unlimited		41900		51500
1500 5.75%	50	3609	41300	14400	55700
	100		49800		64200
	150		53500		67900
	250		56900		71300
	500		59700		74100
	750		60600		75000
	Unlimited		62800		77200
480 VOLTS, THREE PHASE					
300 ‡4.5%	50	360	7100	1400	8500
	100		7500		8900
	150		7700		9100
	250		7800		9200
	500		7900		9300
	750		7900		9300
	Unlimited		8000		9400
500 †4.5%	50	601	10900	2400	13300
	100		12000		14400
	150		12400		14800
	250		12800		15200
	500		13100		15500
	750		13200		15600
	Unlimited		13400		15800
750 5.75%	50	902	12500	3600	16100
	100		13900		17500
	150		14400		18000
	250		14900		18500
	500		15300		18900
	750		15400		19000
	Unlimited		15700		19300
480 VOLT, THREE PHASE (Cont'd)					
1000 5.75%	50	1203	15500	4800	20300
	100		17800		22600
	150		18800		23600
	250		19600		24400
	500		20200		25000
	750		20500		25300
	Unlimited		20900		25700
1500 5.75%	50	1804	20600	7200	27800
	100		24900		32100
	150		26700		33900
	250		28400		35600
	500		29800		37000
	750		30300		37500
	Unlimited		31400		38600
2000 5.75%	50	2406	24700	9600	34300
	100		31100		40700
	150		34000		43600
	250		36700		46300
	500		39100		48700
	750		40000		49600
	Unlimited		41900		51500
2500 5.75%	50	3008	28000	12000	40000
	100		36400		48400
	150		40500		52500
	250		44500		56500
	500		48100		60100
	750		49500		61500
	Unlimited		52300		64300
3000 5.75%	50	3607	30700	14400	45100
	100		41200		55600
	150		46500		60900
	250		51900		66300
	500		56800		71200
	750		58700		73100
	Unlimited		62700		77100

‡ Minimum impedance.

TABLE 4 (Cont'd)

Transformer Rating 3-phase kVA and Impedance Percent	Maximum Short-circuit Mva Available From Primary System	Normal-load Continuous Current Amp	Short-circuit Current RMS Symmetrical Amp		
			Transformer Alone	10% Motor Load	Combined
1	2	3	4	5	6
600 VOLTS, THREE PHASE					
300 †4.5%	50	289	5700	1200	6900
	100		6000		7200
	150		6100		7300
	250		6200		7400
	500		6300		7500
	750		6400		7600
	Unlimited		6400		7600
500 †4.5%	50	481	8700		10600
	100		9600		11500
	150			10000	11900
	250		10200	1900	12100
	500		10500		12400
	750		10500		12400
	Unlimited		10700		12600
750 5.75%	50	722	9900	2900	12800
	100		11100		14000
	150		11500		14400
	250		11900		14800
	500		12200		15100
	750		12300		15200
	Unlimited		12500		15400
1000 5.75%	50	962	12500	3800	16300
	100		14300		18100
	150		15000		18800
	250		15700		19500
	500		16200		20000
	750		16400		20200
	Unlimited		16800		20600
1500 5.75%	50	1444	16500	5800	22300
	100		19900		25700
	150		21400		27200
	250		22700		28500
	500		23800		29600
	750		24200		30000
	Unlimited		25100		30900
2000 5.75%	50	1924	19700	7700	27400
	100		24800		32500
	150		27200		34900
	250		29400		37100
	500		31200		38900
	750		32000		39700
	Unlimited		33500		41200
2500 5.75%	50	2406	22400	9600	32000
	100		29200		38800
	150		32400		42000
	250		35700		45300
	500		38500		48100
	750		39600		49200
	Unlimited		41900		51500
3000 5.75%	50	2786	23700	11100	34800
	100		31800		42900
	150		35900		47000
	250		40100		51200
	500		43900		55000
	750		45300		56400
	Unlimited		48500		59600

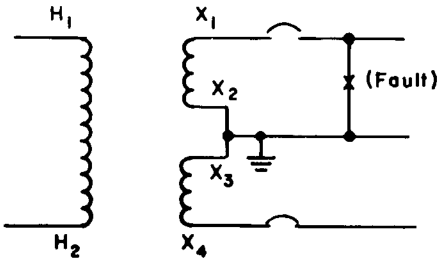
† Minimum impedance.

Application Tables are based on the following:

1. A three-phase bolted fault at the low-voltage terminals of the substation;
2. Transformer impedances listed in table;
3. Only source of power to the secondary is the substation transformer;
4. Total connected motor kVA does not exceed 50 percent of transformer rating at 208Y/120 volts and 100 percent of transformer rating at 240, 480, and 600 volts.
5. The motor contribution is taken as 2.0 times the normal current of the transformer at 208Y/120 volts and 4.0 times normal at 240, 480, and 600 volts;
6. Tabulated values of short circuit current are in terms of RMS **symmetrical amperes** per NEMA Standard SG-3.

B. Single-phase, Three-wire, Distribution Transformers

A line-to-neutral fault involving one of the secondary half-windings (terminals x_1 to x_2 or x_3 to x_4 in the illustration below) of these single-phase three-wire transformers allows approximately twice as much short-circuit current to flow as does a line-to-line fault involving the full secondary winding (terminals x_1 to x_4).



Consequently breaker selections for three-wire service must be based on the faulted half-winding value of short-circuit current.

Basis of Table 5 values:

1. A half-winding solid fault exists at at the transformer low-voltage terminals.
2. The transformer primary was assumed to have the more common line-to-line connected to the three-phase system.
3. The generally permissible assumption of equal positive and negative-sequence reactances in the three-phase system was made.
4. Because of assumptions 2 and 3 above, the supply stiffness is defined as a single-phase short-circuit mVA just one-half the three-phase short-circuit mVA.
5. The transformer half-winding reactance was taken from typical transformer designs at 1.2 times the full-winding reactance, while the half-winding resistance was taken at 1.44 times the full-winding resistance, and both values were on the full kVA base.
6. It was assumed that the 120/240-volt unit substation would supply lighting loads only, i.e., no motor contribution.
7. It was assumed that the only source of power for the secondary bus was one transformer of the rating indicated.

TABLE 5—Estimated Secondary Short-circuit For Single-phase, Three-wire Secondary Distribution Transformers

(7200/12,470Y—120/240-VOLT TRANSFORMER)

MAXIMUM SYMMETRICAL SHORT-CIRCUIT CURRENT FOR STANDASRD 120/240-VOLTS, 3-WIRE, SINGLE-PHASE DISTRIBUTION TRANSFORMER (LINE-TO-NEUTRAL FAULT AT TRANSFORMER TERMINALS)

Available Primary 3 phase Short-circuit MVA	Transformer kVA Rating, Single Phase					
	25	37.5	50	75	100	167
	Normal-load Continuous Current—Amperes at 240 Volts					
	104	156	208	313	417	696
	Short-circuit Symmetrical Current at 120 Volts					
25	5997	7765	12664	18782	22971	34758
50	6128	8007	13347	20425	25633	41603
100	6195	8133	13710	21342	27191	45037
150	6217	8175	13835	21663	27749	46513
250	6235	8210	13936	21926	28211	47754
500	6248	8235	14012	22127	28567	48722
750	6253	8244	14038	22194	28688	49052
Unlimited	6262	8261	14089	22331	28931	49723

TRANSFOMER FULL-WINDING IMPEDANCE ON RATED kVA, (7200/12,470Y—120/240-VOLT TRANSFORMER)

% IR	1.6	1.6	1.2	1.0	0.8	1.0
% IX	2.0	2.5	2.0	2.0	2.2	2.0

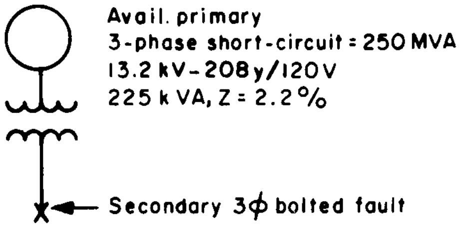
Appendix

C. Three-phase Padmount Distribution Transformers

TABLE 6—Estimated Secondary Short-circuit Currents for GE Three-phase Padmount Distribution Transformer Single-voltage Primary.

LINE-TO-LINE PRIMARY VOLTAGE 25 kV WYE—18 kV DELTA

Available Primary 3-phase Short-circuit mVA	Secondary Voltage Rating		Transformer kVA Rating					
			75	112.5	150	225	300	500
			Transformer Impedance—%					
	(1) 480Y/277V	%IR	1.7	1.8	1.7	1.4	1.4	1.2
		%IX	2.0	3.5	3.8	3.7	4.5	4.2
	(2) 208Y/120V	%IR	1.8	1.8	1.6	1.5	1.4	1.2
		%IX	2.2	3.5	4.0	3.8	4.4	4.7
			Maximum Short-circuit Symmetrical rms Amperes					
100	(1)		3363	3353	4196	6494	7217	12398
	(2)		7176	7737	9361	14540	16980	26008
250	(1)		3407	3403	4278	6698	7475	13187
	(2)		2764	7854	9541	14980	17598	27511
500	(1)		3422	3421	4306	6769	7565	13471
	(2)		7294	7894	9602	15132	17814	28050



Solve for the Secondary Fault using the per-unit method.

Select 225 kVA as the study base

$$X \text{ Utility Source} = \frac{225 \text{ kVA}}{250{,}000 \text{ kVA}} = 0.0009 \text{ pu}$$

$$X \text{ Trans} = \left(0.038\right)\left(\frac{225 \text{ kVA}}{225 \text{ kVA}}\right) = 0.038 \text{ pu}$$

$$X = X \text{ trans} + X \text{ utility} = 0.0389$$

$$R \text{ Trans} = \left(0.015\right)\left(\frac{225 \text{ kVA}}{225 \text{ kVA}}\right) = 0.015 \text{ pu}$$

$$\begin{aligned} Z &= \sqrt{R^2 + X^2} \\ &= \sqrt{(0.015)^2 + (0.0389)^2} \\ &= 0.0417 \end{aligned}$$

$$I_{sc} = \frac{\text{kVA}_h}{\sqrt{3}\,(\text{kV})\,(Z \text{ pu})} = \frac{225}{\sqrt{3}(0.208)\,(0.0477)}$$

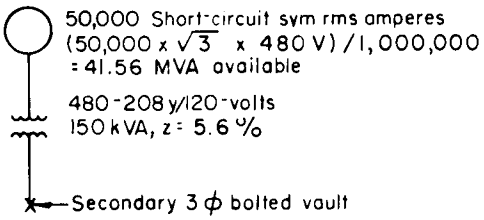
$= 14{,}977$ 3ϕ Short-circuit Symmetrical rms Amperes at Transformer Terminals.

D. "QHT" Dry-type Three-phase Transformers

TABLE 7—Estimated Secondary Short-circuit Currents for GE Type "QHT" Dry-type 3-phase Transformers

PRIMARY RATING 600 VOLTS AND BELOW, SECONDARY RATING 480Y/277V and 208/120V

Available Short-circuit Symmetrical rms Amperes	Transformer kVA Rating											
		6	9	15	30	45	75	112.5	150	225	300	500
	Transformer Impedance											
	%IR	2.72	2.31	2.1	3.8	2.52	2.27	2.43	2.35	1.15	1.8	1.6
	%IX	1.72	1.16	1.80	1.37	1.73	1.91	3.87	5.0	5.5	4.5	5.9
	Short-circuit Symmetrical rms Amperes											
	Secondary Voltage											
25,000	480	225	415	640	885	1,700	2,810	2,690	2,925	4,050	5,800	7,100
	208	515	960	1,475	2,035	3,925	6,500	6,200	6,750	9,350	13,400	16,400
50,000	480	225	420	645	890	1,740	2,925	2,820	3,085	4,400	6,550	8,260
	208	520	965	1,485	2,050	4,005	6,750	6,500	7,125	10,151	15,100	19,160
200,000	480	225	420	650	845	1,760	3,010	2,925	....	4,700	7,200	9,400
	208	520	970	1,495	2,060	4,065	7,010	6,750	7,450	10,860	16,600	21,700



Solve for the Secondary Fault using the per-unit method.

Select 150 kVA as the study base.

$$X \text{ available} = \frac{150 \text{ kVA}}{41{,}570 \text{ kVA}} = 0.0036 \text{ pu}$$

$$X \text{ trans} = (0.050)\,\frac{150 \text{ kVA}}{150 \text{ kVA}} = 0.050 \text{ pu}$$

$$X = X \text{ available} + \text{Trans} = 0.0036 + 0.050 = 0.0536 \text{ pu}$$

$$R \text{ Trans} = \left(.0235\right)\left(\frac{150 \text{ kVA}}{150 \text{ kVA}}\right) = 0.0235 \text{ pu}$$

$$\begin{aligned} Z &= \sqrt{R^2 + X^2} \\ &= \sqrt{(0.0235)^2 + (0.0536)^2} \\ &= 0.0585 \end{aligned}$$

$$I_{sc} = \frac{\text{kVA}_b}{\sqrt{3}\,(\text{kV})\,(Z)} = \frac{150}{\sqrt{3}\,(0.208)\,(0.0585)}$$

$I_{sc} = 7{,}117$ 3ϕ Short-circuit sym. rms amperes at transformer terminals

E. Estimated Short-circuit at End of Low-voltage Feeder (See Figs. 25-1 thru 25-30)

Power-system maximum estimated short-circuit currents, as functions of distance along feeder conductors fed from standard three-phase radial secondary unit substations, can be read directly in rms symmetrical amperes from a series of curves, Fig. 25-1 through 25-30. The one-line diagram shows the typical radial circuit investigated.

The conditions on which the curves are based were as follows:

1. The fault was a bolted three-phase short circuit.
2. The primary three-phase short-circuit duty was 500 MVA (60 cycles) for all curves. A typical supply-system X/R at the low-voltage bus was used in calculating the curves for each case.
3. Motor contributions through the bus to the point of short circuit were included in the calculations on the basis of 100-percent contribution for the 240-, 480-, and 600-volt systems and 50-percent contributions for the 208-volt systems.
4. The feeder-conductor impedance values used in the calculations are indicated for various conductor sizes.

These curves can also be used to select feeder conductor sizes and lengths needed to reduce short-circuit duties to desired smaller values. Note that conductors thus selected must be further checked to assure adequate load and short-circuit capabilities and acceptable voltage drop.

Coordinated ratings are based on two protective devices operating in series with all short-circuit current flowing through the upstream device. If any current bypasses the upstream device (such as motor contribution fed in on load side of upstream device) a fully rated system, not coordinated rated system, should be used.

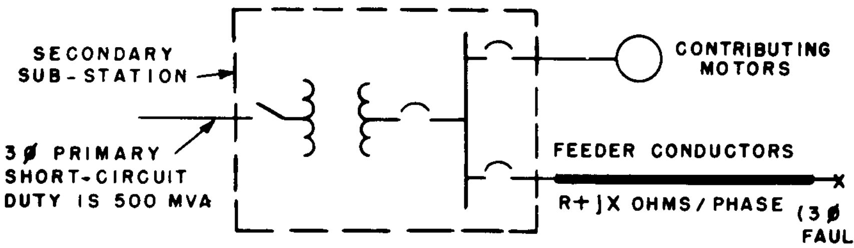


Fig. 24. Typical circuit investigated to show effect on short-circuit duty as point of fault is moved away from the low-voltage bus along the feeder conductors.

Feeder Impedance Values Used in Investigation

Feeder Conductor Size/Phase	Resistance (R) Ohms/Phase/1000 ft.	60-Cycle Inductance/Reactance (X) Ohms/Phase/1000 ft.
#4	0.3114	0.0492
#1/0	0.1231	0.0457
500 MCM	0.0288	0.0402
2-500 MCM	0.0144	0.0201
2-750 MCM	0.0103	0.0198
4-750 MCM	0.0053	0.0099

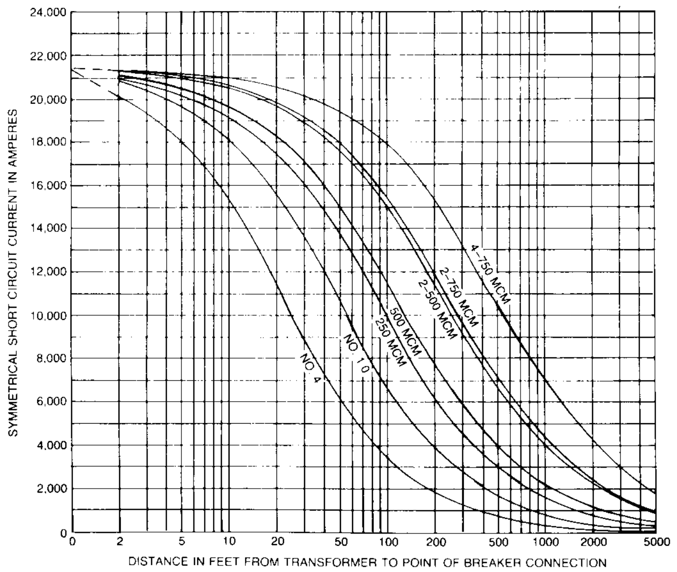


Fig. 25–1 Transf: 150 kVA, 208V, 2.0%Z

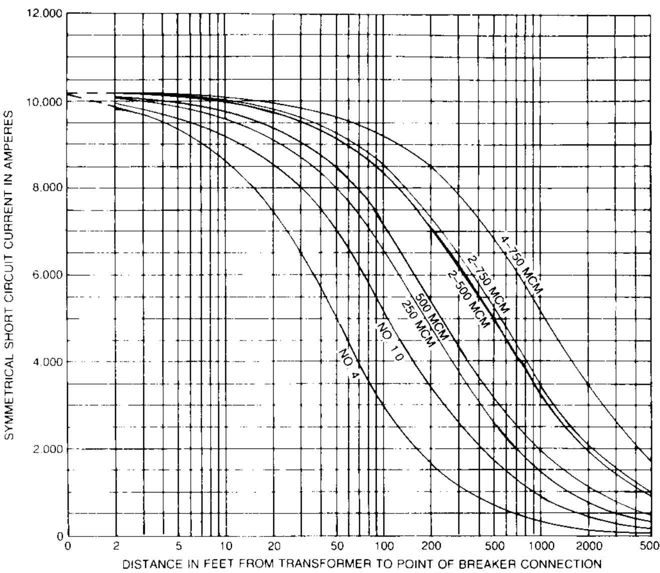


Fig. 25–2 Transf: 150 kVA, 208V, 4.5%Z

Appendix

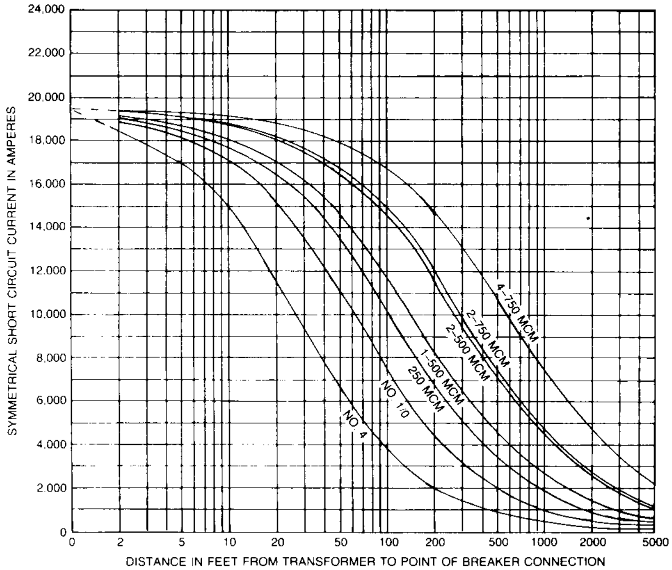


Fig. 25-3 Transf: 150 kVA, 240V, 2.0%Z

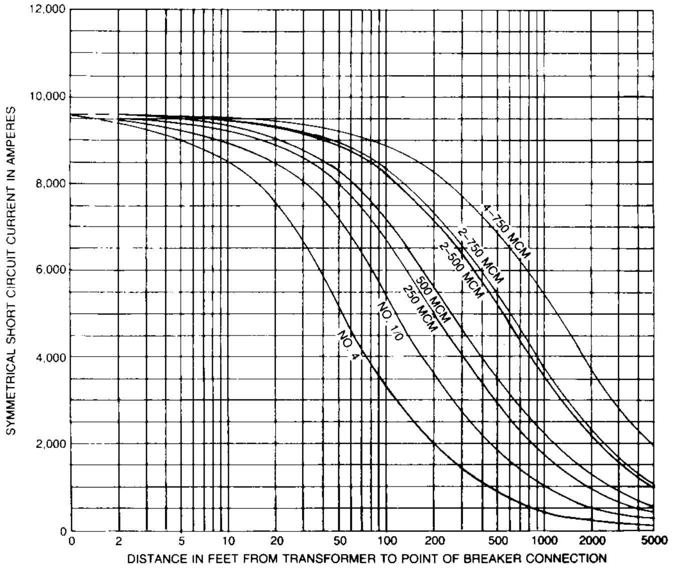


Fig. 25-4 Transf: 150 kVA, 240V, 4.5%Z

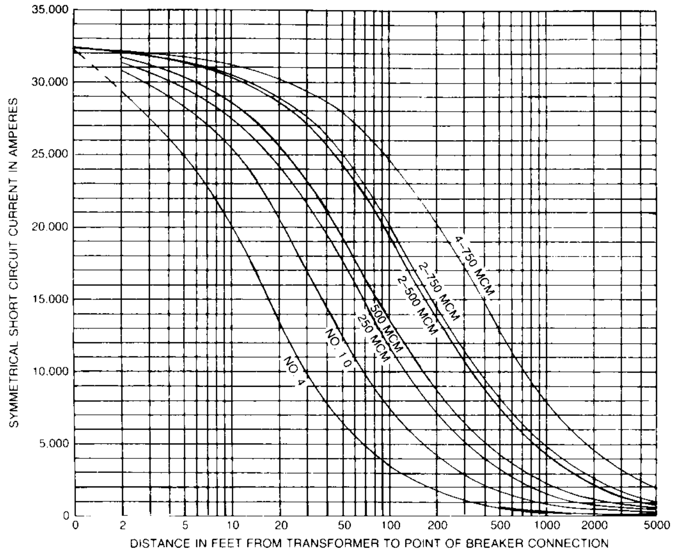


Fig. 25-5 Transf: 225 kVA, 208V, 2.0%Z

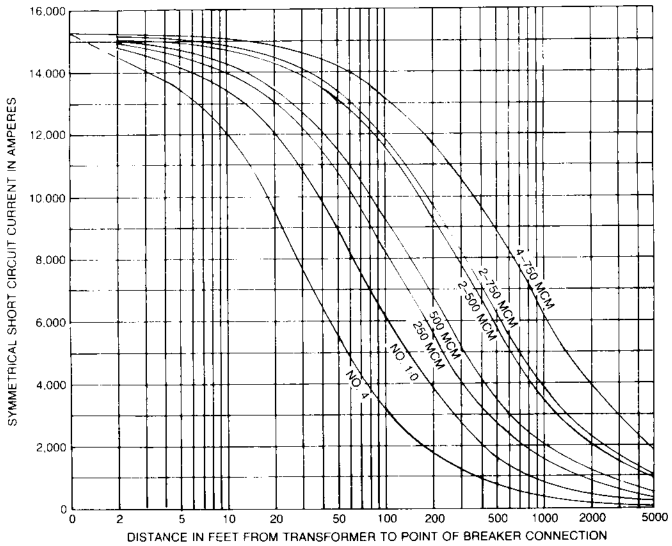
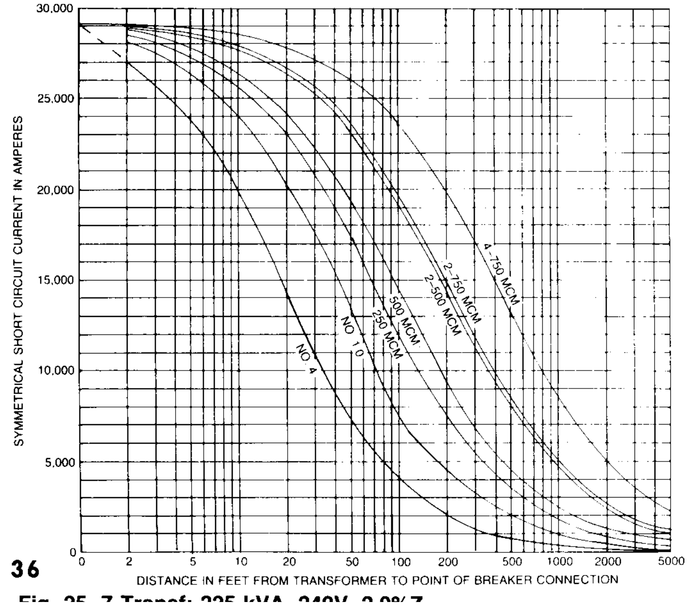


Fig. 25-6 Transf: 225 kVA, 208V, 4.5%Z



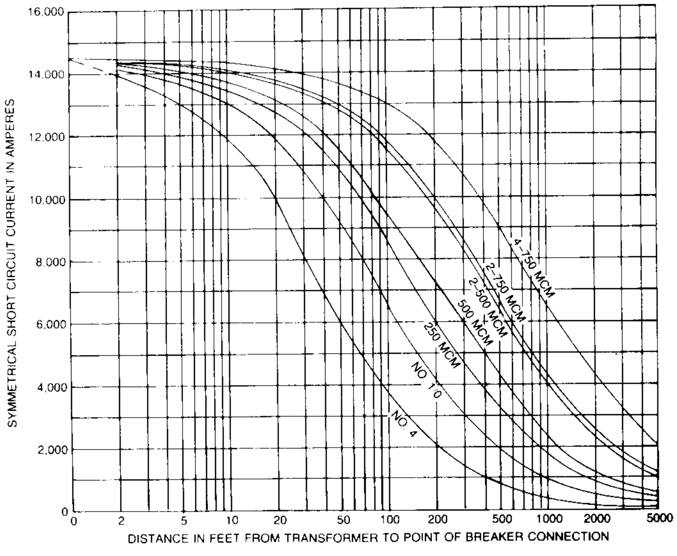


Fig. 25-8 Transf: 225 kVA, 240V, 4.5%Z

Fig. 25-7 Transf: 225 kVA, 240V, 2.0%Z

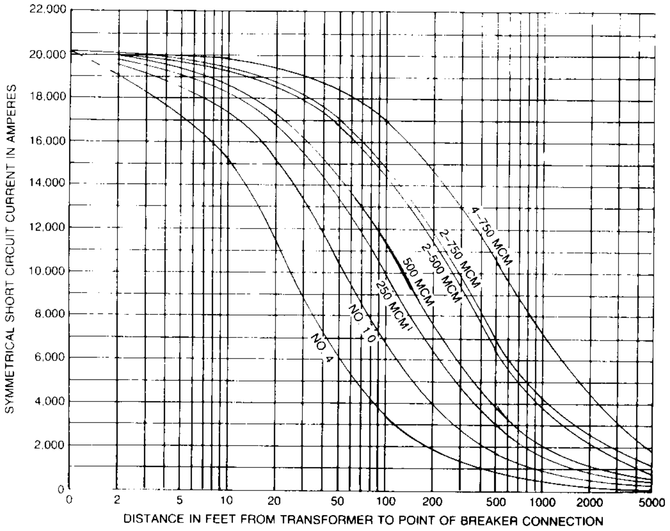


Fig. 25-9 Transf: 300 kVA, 208V, 4.5%Z

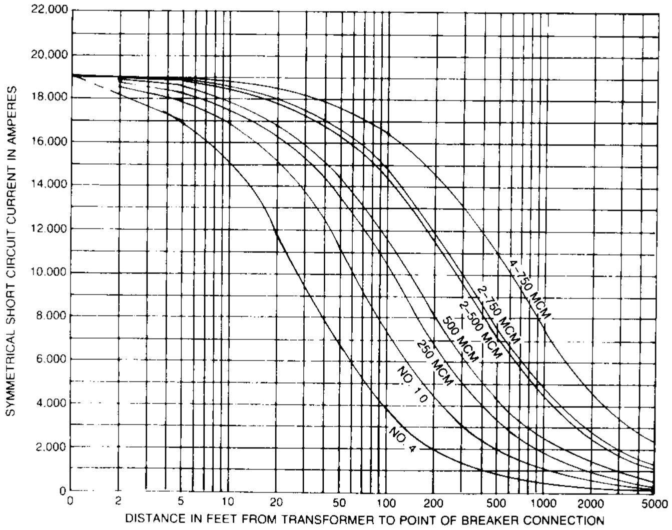


Fig. 25-10 Transf: 300 kVA, 240V, 4.5%Z

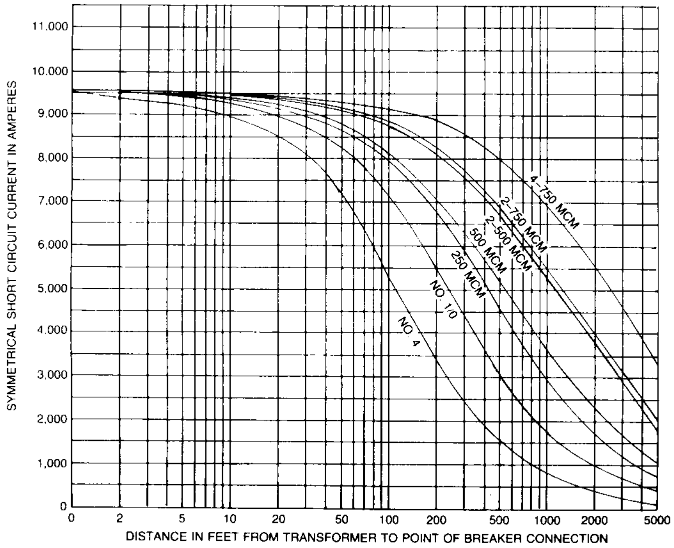


Fig. 25-11 Transf: 300 kVA, 480V, 4.5%Z

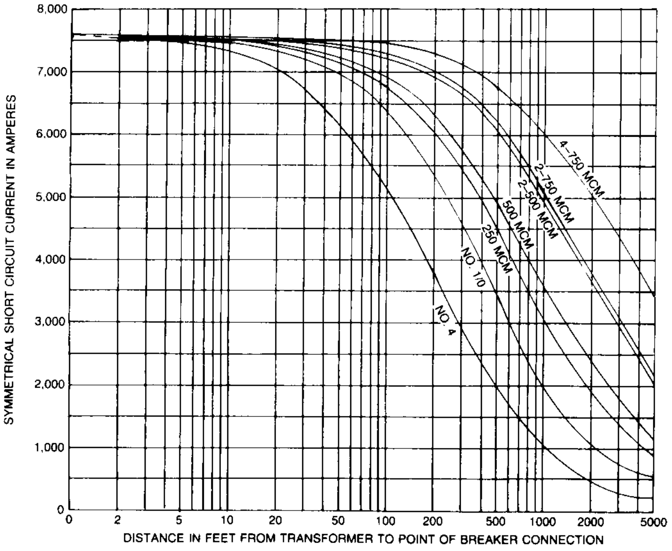


Fig. 25-12 Transf: 300 kVA, 600V, 4.5%Z

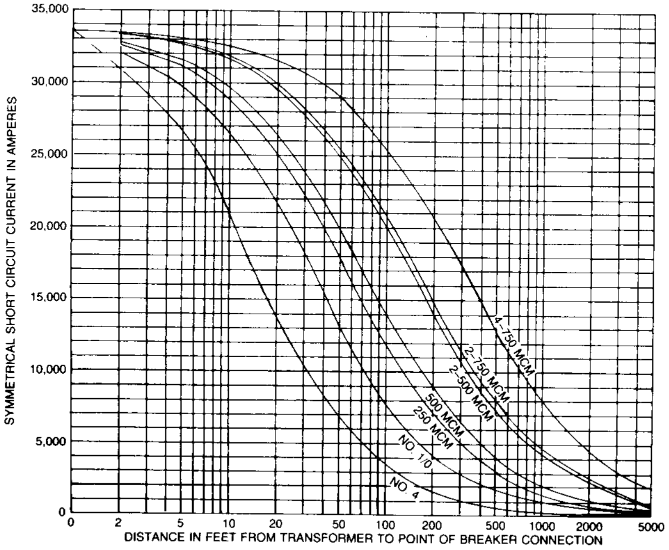


Fig. 25-13 Transf: 500 kVA, 208V, 4.5%Z

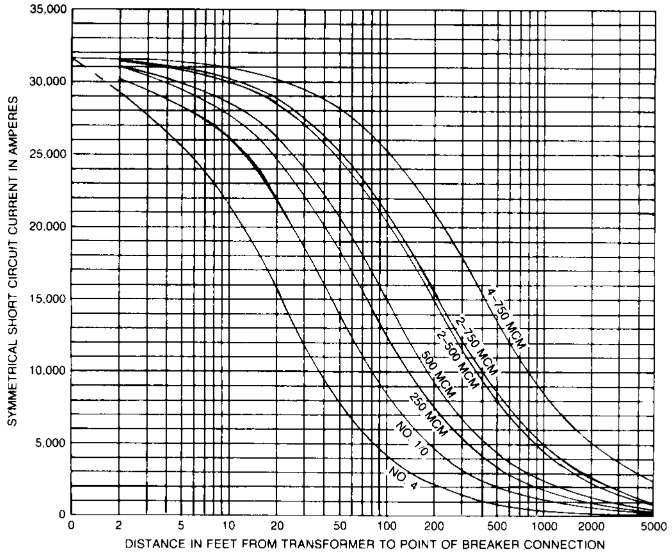


Fig. 25-14 Transf: 500 kVA, 240V, 4.5%Z

Appendix

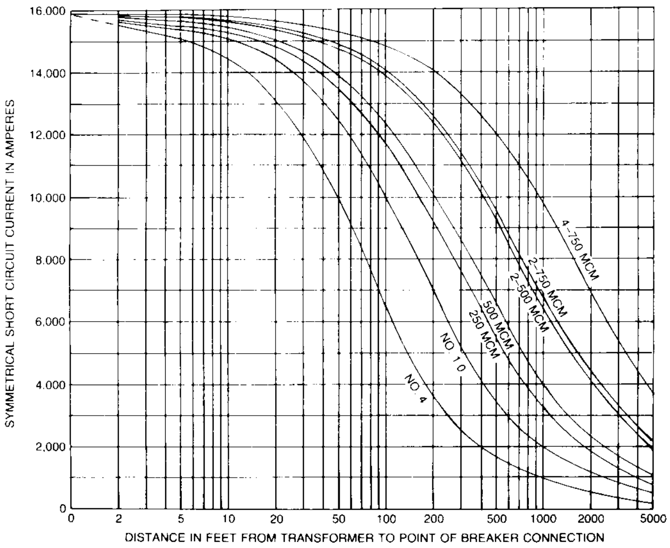


Fig. 25-15 Transf: 500 kVA, 480V, 4.5%Z

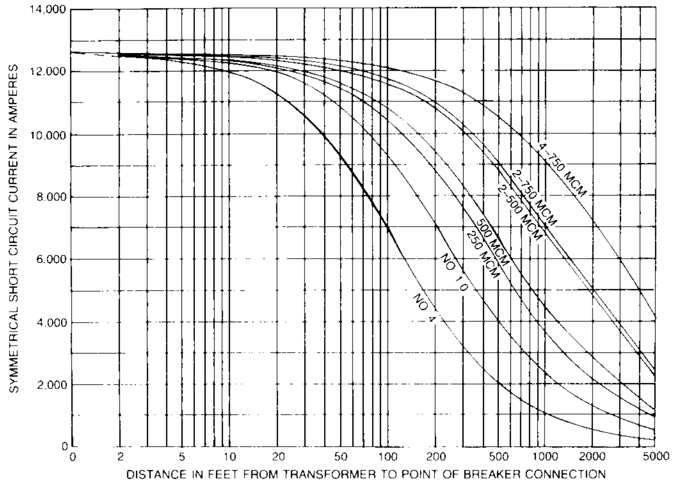


Fig. 25-16 Transf: 500 kVA, 600V, 4.5%Z

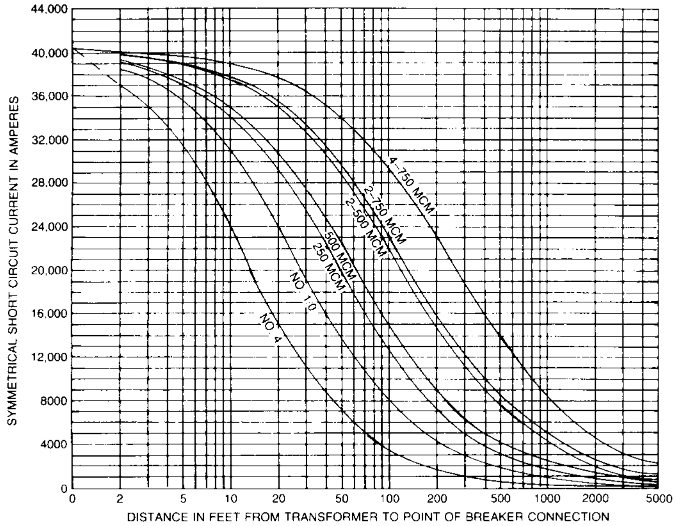


Fig. 25-17 Transf: 750 kVA, 208V, 5.75%Z

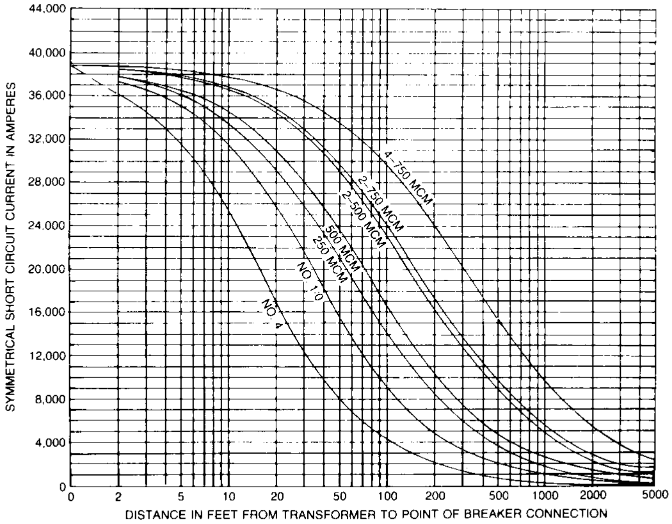


Fig. 25-18 Transf: 750 kVA, 240V, 5.75%Z

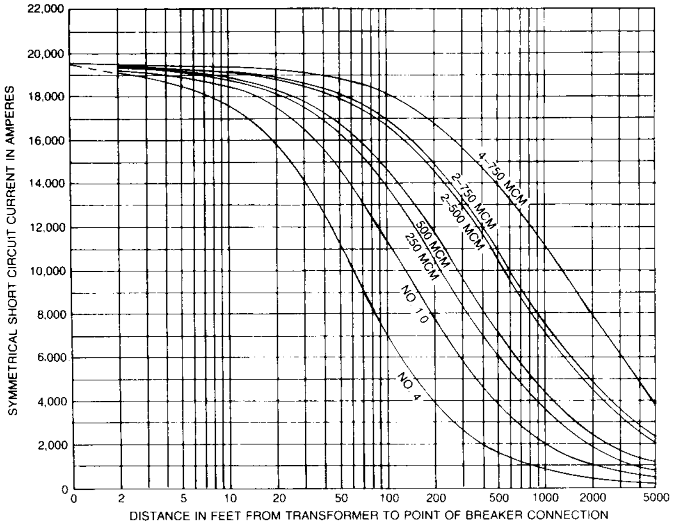


Fig. 25-19 Transf: 750 kVA, 480V, 5.75%Z

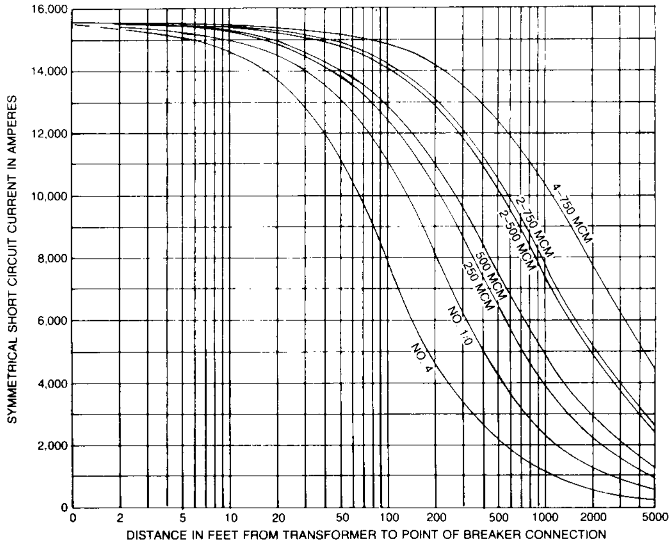


Fig. 25-20 Transf: 750 kVA, 600V, 5.75%Z

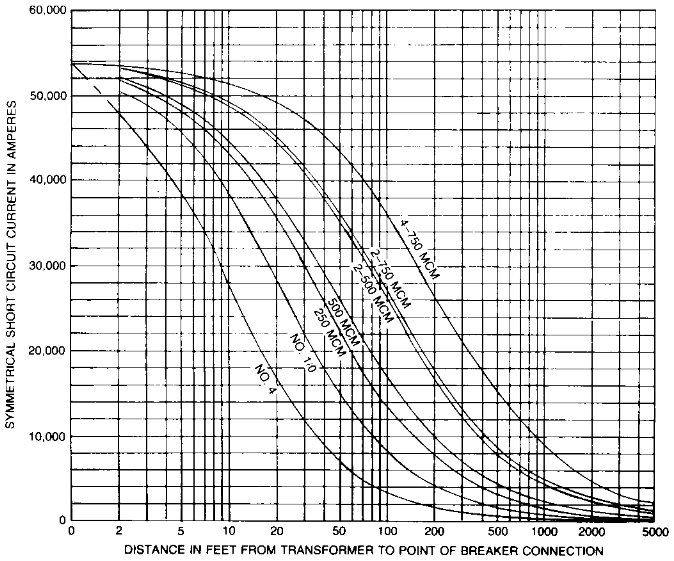


Fig. 25-21 Transf: 1000 kVA, 208V, 5.75%Z

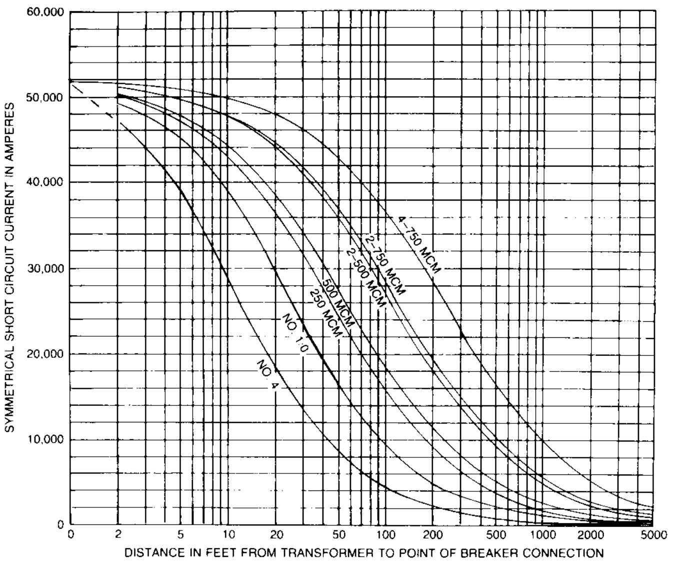


Fig. 25-22 Transf: 1000 kVA, 240V, 5.75%Z

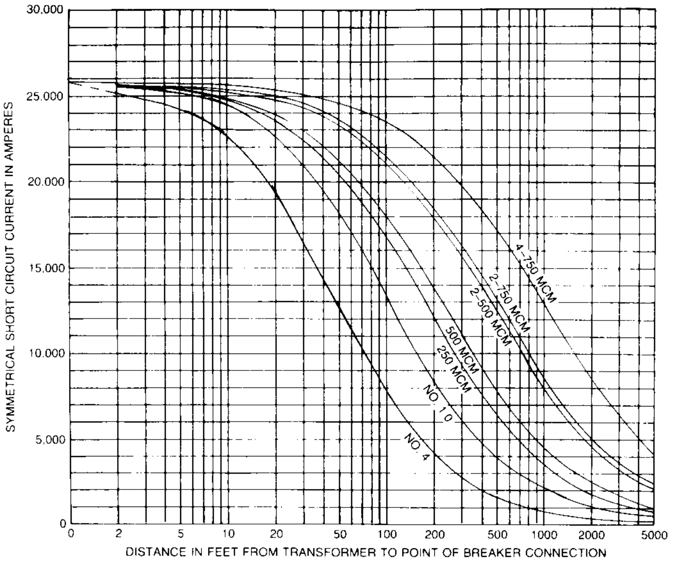


Fig. 25-23 Transf: 1000 kVA, 480V, 5.75%Z

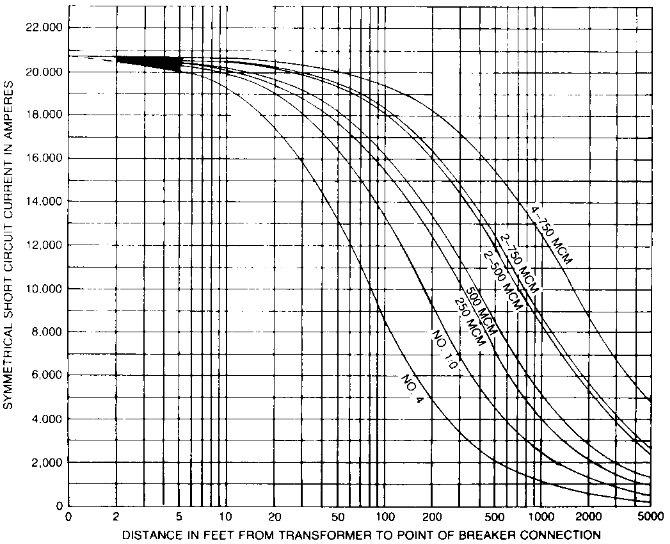


Fig. 25-24 Transf: 1000 kVA, 600V, 5.75%Z

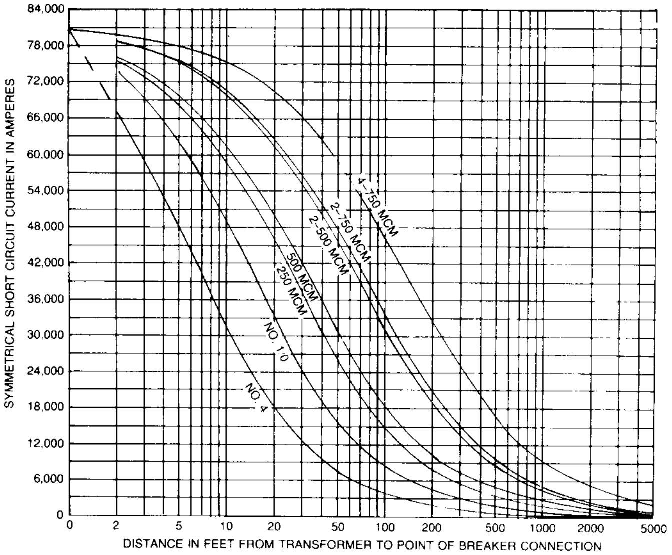


Fig. 25-25 Transf: 1500 kVA, 208V, 5.75%Z

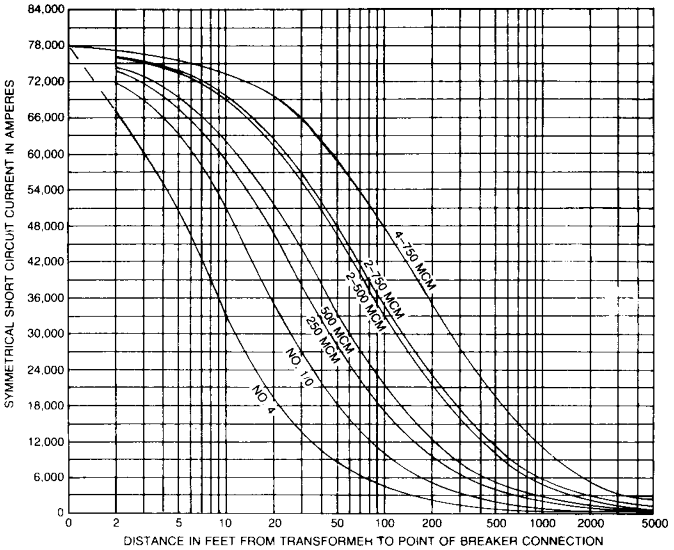


Fig. 25-26 Transf: 1500 kVA, 240V, 5.75%Z

Appendix

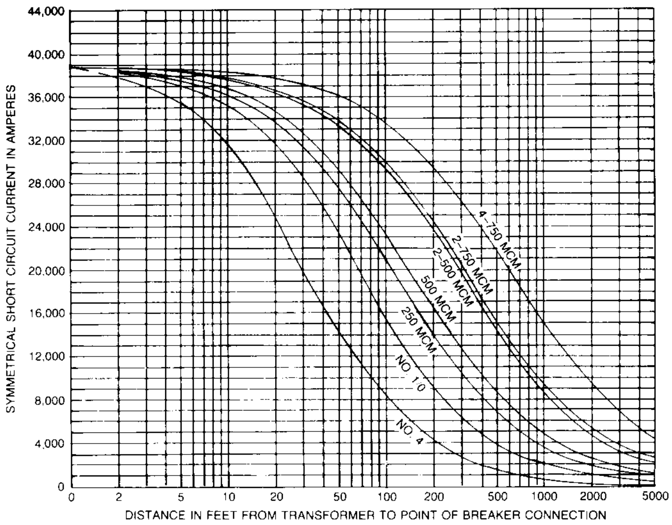


Fig. 26–27 Transf: 1500 kVA, 480V, 5.75%Z

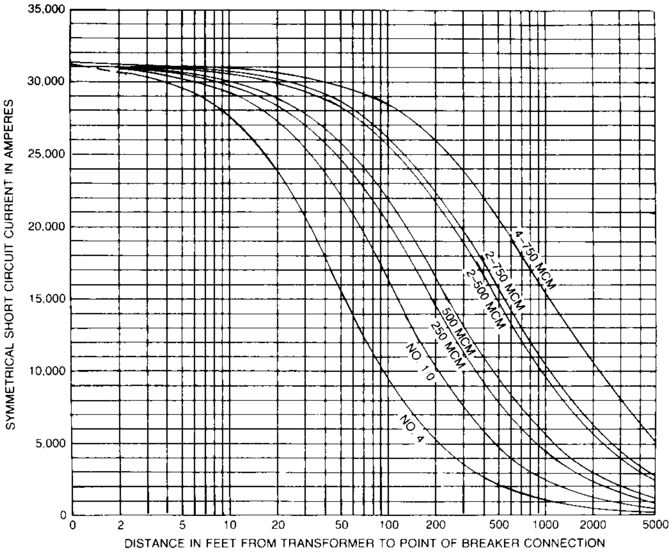


Fig. 25–28 Transf: 1500 kVA, 600V, 5.75%Z

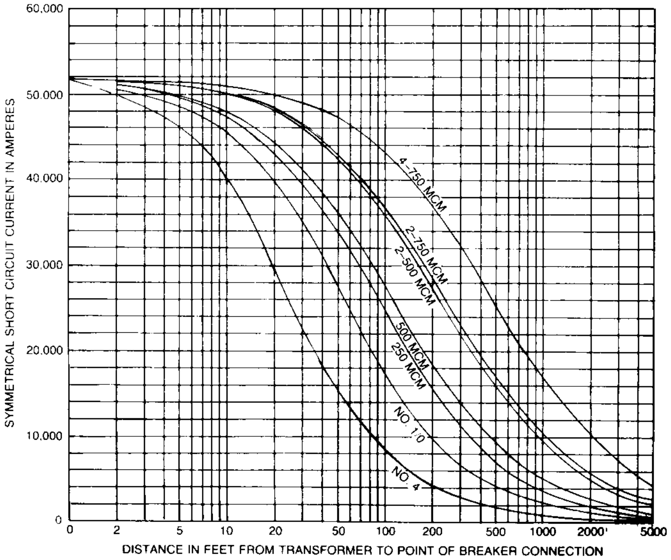


Fig. 25–29 Transf: 2000 kVA, 480V, 5.75%Z

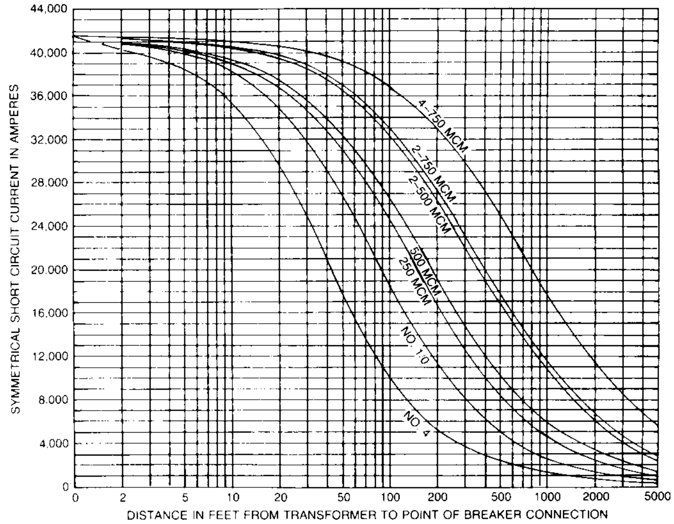
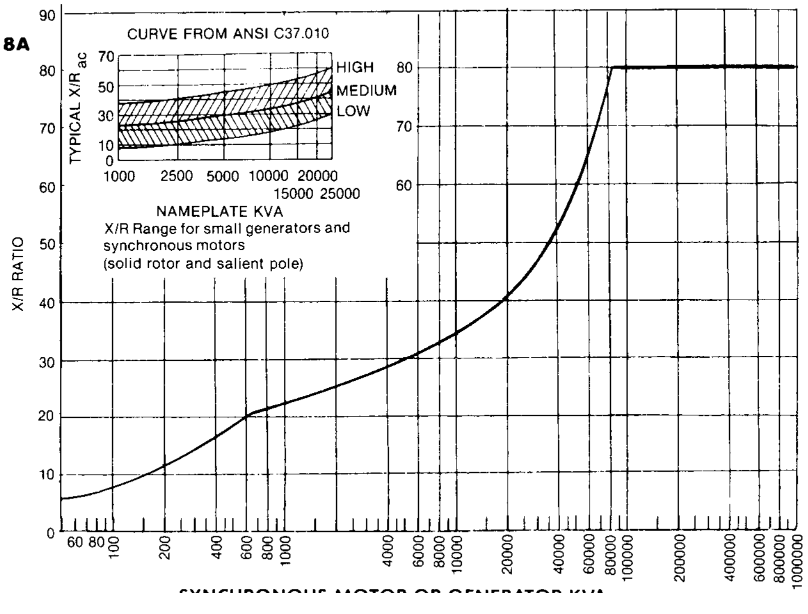


Fig. 25–30 Transf: 2000 kVA, 600V, 5.75%Z

PART II— Impedance Data

The approximate impedance data listed in these tables are representative of standard equipment in current production. The impedance values of this equipment change from time to time so that the up-to-date validity of the impedance values should be verified.

TABLE 8A



X/R Ratios

Typical values for generators, synchronous motors, power transformers, induction motors, utility sources, and reactors. (From ANSI Standard C37.010)

A. Large generators and hydrogen-cooled sychronous condensers

Range	Typical
40-120	80

B. Generators and synchronous motors (See TABLE 8A)

C. Power transformer (See TABLE 8B)

D. Induction motors (See TABLE 8C)

E. Utility source

1. Near generating plant
   Range: 15-30
2. Long open-wire line
   Range: 2-16
3. Typical
   Range: 5-12

F. Reactors

Range	Typical
40-120	80

TABLE 9—Primary Substation Transformers (501-5000 kVA 1ϕ, 501—10,000 kVA 3ϕ) 65C rise ANSI C57.12.00

STANDARD IMPEDANCES

High-voltage Winding BIL kV	Low-voltage Winding BIL kV	Percent Impedance*
110	45	5.75
	60-110	5.5
150	45	5.75
	60-110	5.
200	45	7.25
	60-150	7.0
250	45	7.75
	60-200	7.5
350	60-250	8.0
450	60-350	8.5
550	60-450	9.0
650	60-550	9.5

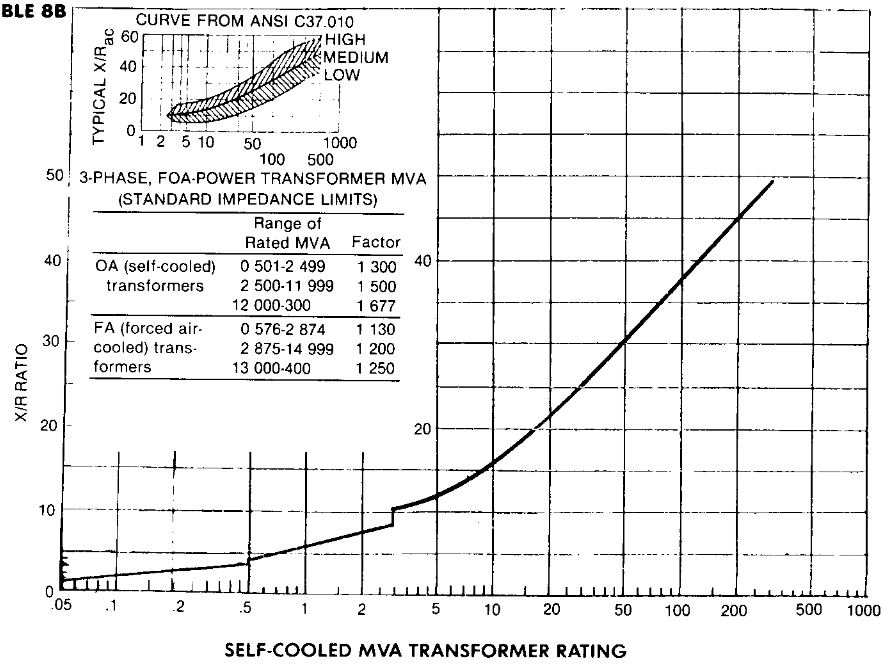
* For load tap changing (LTC) transformers, add 0.5 to values listed.

TABLE 10—Network Transformers Three-phase (Low Voltages 216Y/125 or 480Y/277 volts)

STANDARD IMPEDANCES

kVA	Percent Impedance
1000 kVA and Below	5.0
Above 1000 kVA	7.0

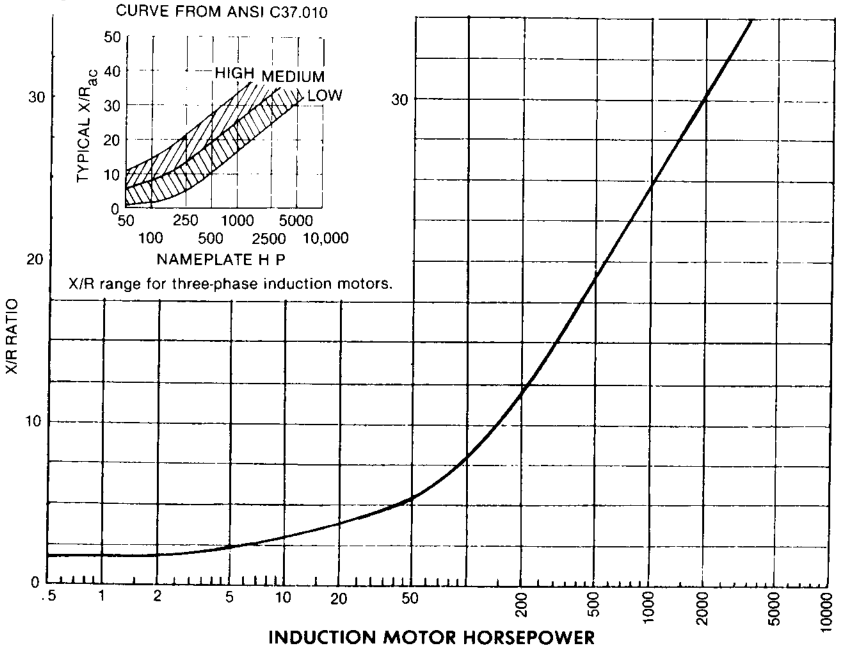
TABLE 8B



(STANDARD IMPEDANCE LIMITS)

	Range of Rated MVA	Factor
OA (self-cooled) transformers	0 501-2 499	1 300
	2 500-11 999	1 500
	12 000-300	1 677
FA (forced air-cooled) transformers	0 576-2 874	1 130
	2 875-14 999	1 200
	13 000-400	1 250

TABLE 8C



X/R range for three-phase induction motors.

Appendix

TABLE 11—Distribution Transformers—Single-phase

kVA	Low Voltage	%IR	%IX	%IZ
HIGH VOLTAGE 2400/4160Y				
10	**120/240**	2.4	0.9	2.6
15		2.2	1.4	2.6
25		1.6	1.9	2.5
37½		1.6	2.3	2.8
50		1.6	1.9	2.2
75		1.0	2.1	2.3
100		0.8	2.1	2.3
167		1.0	1.9	2.1
10	**240/480**	2.4	0.8	2.5
15		2.2	1.3	2.5
25		1.6	1.8	2.4
37½		0.9	1.5	1.8
50		1.2	1.6	2.0
75		0.9	1.9	2.1
100		0.7	1.9	2.0
167		0.9	1.6	1.8
HIGH VOLTAGE 4160/7200Y				
10	**120/240**	2.4	0.8	2.5
15		2.1	1.4	2.5
25		1.6	1.9	2.4
37½		1.6	2.3	2.8
50		1.1	1.8	2.1
75		1.0	1.9	2.2
100		0.8	2.1	2.2
10	**240/480**	2.4	0.8	2.5
15		2.1	1.2	2.5
25		1.4	2.0	2.4
37½		0.9	1.5	1.8
50		1.1	1.6	1.9
75		0.9	1.7	1.9
100		0.7	1.7	1.8
HIGH VOLTAGE 4800/8320Y				
10	**120/240**	2.4	0.8	2.5
15		2.0	1.5	2.5
25		1.6	1.8	2.4
37½		1.6	2.2	2.7
50		1.1	1.9	2.2
75		1.0	1.9	2.2
100		0.8	2.2	2.3
167		1.0	1.9	2.1
10	**240/480**	2.4	0.8	2.5
15		2.1	1.3	2.4
25		1.4	2.0	2.5
37½		1.0	1.3	1.7
50		1.2	1.6	2.0
75		0.9	1.7	1.9
100		0.7	1.8	1.9
167		0.9	1.6	1.8
HIGH VOLTAGE 7200/12470 or 12470GRDY/7200				
10	**120/240**	2.5	0.9	2.6
15		2.1	1.6	2.6
25		1.6	2.0	2.6
37½		1.6	2.5	3.0
50		1.2	2.0	2.3
75		1.0	2.0	2.3
100		0.8	2.2	2.3
167		1.0	2.0	2.2
10	**240/480**	2.5	0.8	2.6
15		2.1	1.5	2.6
25		1.6	1.9	2.5
37½		1.0	1.5	1.8
50		1.1	1.8	2.1
75		0.9	1.8	2.0
100		0.7	1.8	2.0
167		0.9	1.7	1.9
HIGH VOLTAGE 7620/13200Y OR 13200GRDY/7620				
10	**120/240**	2.5	0.9	2.6
15		2.1	1.6	2.6
25		1.6	2.0	2.6
37½		1.6	2.5	3.0
50		1.2	2.0	2.3
75		1.0	2.0	2.3
100		0.8	2.2	2.3
167		1.0	2.0	2.2
10	**240/480**	2.5	0.8	2.6
15		2.1	1.5	2.6
25		1.6	1.9	2.5
37½		1.0	1.5	1.8
50		1.1	1.6	2.1
75		0.9	1.8	2.0
100		0.7	1.8	2.0
167		0.9	1.7	1.9
HIGH VOLTAGE 14400/24940GRDY OR 24940GRDY/14400				
10	**120/240**	1.9	1.3	2.3
15		2.2	1.6	2.7
25		1.6	2.1	2.6
37½		1.7	2.3	2.9
50		1.2	1.9	2.2
75		1.0	2.1	2.3
100		0.8	2.1	2.3
10	**240/480**	2.0	1.1	2.3
15		1.2	1.5	2.7
25		1.6	2.0	2.5
37½		1.0	1.7	1.9
50		1.1	1.8	2.1
75		0.9	1.8	2.0
100		0.7	1.8	2.0

TABLE 12—Distribution Transformers—Three-phase Padmount—Single-voltage Primary Maximum Line-to-Line Primary Voltage—25 kV Wye—18 kV Delta

kVA	Low Voltage					
	208Y/120			480Y/277		
	%IZ	%IR	%IX	%IZ	%IR	%IX
75	2.9	1.8	2.2	2.6	1.7	2.0
112.5	3.9	1.8	3.5	3.9	1.8	3.5
150	4.4	1.6	4.0	4.2	1.7	3.8
225	4.1	1.5	3.8	4.0	1.4	3.7
300	4.6	1.4	4.4	4.7	1.4	4.5
500	4.90	1.20	4.70	4.40	1.20	4.20
750	5.75	1.40	5.50	5.75	1.30	5.70
1000	5.75	1.30	5.70	5.75	1.20	5.70
1500	....	....	....	5.75	0.72	5.70
2000	....	....	....	5.75	0.68	5.71
2500	....	....	....	5.75	0.61	5.72

Appendix

Table 13—Transformers for secondary unit substation and Integral· Distribution Centers. Liquid filled (oil, silicone and vapor-tran*) and dry-type (including encapsulated coil).

	Dry-Type						Liquid-Filled	
	480V		2400–4800V		6900–15,000V		2400–15,000V	
kVA	%Z	X/R †	%Z	X/R †	%Z	X/R †	%Z	X/R †
75	3	0.83	6.2	2.15				
112.5	4.6	1.63	4.5	1.77	6.1	1.93		
150	5.5	2.08	4.2	1.95	5.3	2.33		
225	5.9	4.58	4.6	1.75	6.1	2.45	2.0‡	2.0
300	4.9	2.50	5.2	3.57	6.0	3.22	4.5‡	2.8
500	6.1	3.69	5.8	4.33	6.4	4.43	4.5‡	3.0
			2400–15,000V					
			%Z	Dry X/R	Cast Coil X/R			
500			5.75		6.0			
750	5.2	2.88	5.75	5.0	6.1		5.75	4.00
1000	4.7	3.46	5.75	5.7	6.2		5.75	4.10
1500			5.75	6.5	6.8		5.75	4.50
2000			5.75	7.2	7.00		5.75	5.00
2500			5.75	7.5	7.00		5.75	5.35

† Typical ratios based on several manufacturer's data

‡Minimum impedance

TABLE 14—Dry-type transformers—Type QHT, % Impedance, Reactance and Resistance ‡

kVA	Single-phase			Three-phase			
	%IX	%IR	%IZ	kVA	%IX	%IR	%IZ
5	1.68	2.94	3.4	6	1.72	2.72	3.2
7.5	1.84	2.42	3.0	9	1.16	2.31	2.6
10	1.92	2.04	2.75	15	1.82	2.1	2.8
15	2.02	1.60	2.6	30	1.37	3.8	4.0
25	2.3	1.4	2.7	45	1.73	2.52	3.1
37.5	2.7	3.6	4.5	75	1.91	2.27	3.0
50	2.8	3.1	4.2	112½	3.87	2.43	4.6
75	3.7	2.48	4.45	150	5.0	2.35	5.5
100	3.55	2.12	4.14	225	5.5	1.15	5.9
167	3.25	1.60	3.63	300	4.5	1.8	4.9
				500	5.9	1.6	6.1

‡Typical values based on data from several manufacturers.

TABLE 15—Standard Current Limiting Reactors

60 Volt Insulation Class			5 kV Insulation Class		15 kV Insulation Class	
Indoor Service 3φ			Single-phase and Three-phase		Single-phase and Three-phase	
Amperes	Fault△ Current 1 second Duration	OHMS per Phase	Continuous Current Amperes	OHMS per Phase	Continuous Current Amperes	OHMS per Phase
1000	23,000	0.015	200	0.25	30	0.50
1000	34,000	.010		.40		.63
						.80
800	12,000	.0285	300	.10		1.0
800	34,000	.010		.16		1.6
				.25		2.5
600	15,000	.0285				
600	15,000	.0230	400	.10	400	.40
600	20,000	.0170		.16		.50
600	25,000	.0130		.25		.63
600	25,000	.010				.80
600	25,000	.0046	600	.063		1.0
				.10		1.6
400	8,000	.0485		.16		
400	15,000	.0285		.25	600	.25
400	15,000	.0230				.40
400	20,000	.0170	1200	.04		.50
400	25,000	.0130		.063		.63
400	25,000	.010		.10		.80
400	25,000	.0046		.16		1.0
225	12,500	.0285				
			2000	.04	1200	.16
				.063		.25
				.10		.40
						.50
						.63
					2000	.10
						.16
						.25
						.40

△Maximum allowable sustained symmetrical rms amperes

TABLE 16—Approximate Machine Reactances

A. Induction Motors

The short-circuit reactance of an induction motor or induction generator in percent of its own kVA base, assuming rated voltage and frequency applied, may be taken as:

$$X''_d\% = \frac{100}{\text{Times normal stalled rotor current}}$$

The reactance will generally be approximately (in percent on own kVA base).

Reactance	Range	Average
Subtransient X''_d	15–25	16.7
Transient X'_d	∞	∞

B. Synchronous Machines

Percent Values on Machine kVA Rating

	X''d		X'd	
(A) Generators (1) Turbo Generators (distributed pole)	Range	Mean	Range	Mean
2 pole, 625-9375 kVA	6-13	9		
2 pole, 12,500 kVA-up	8-12	10		
4 pole, 12,500 kVA-up	10-17	14		
(2) Salient-pole Generators (without amortisseur)				
12 poles or less	15-35	25		
14 poles or more	25-45	35		
(3) Salient-pole Generators$^{\theta}$ (with amortisseur)				
12 poles or less	10-25	18		
14 poles or more	18-40	24		
(B) Synchronous Condensers	9-38	24		
(C) Synchronous Converters				
600 V dc	17-22	20		
250 V dc	28-38	33		
(D) Synchronous Motors				
2-6 pole	7-23	15	10-30	20
8-14 pole (incl.)	11-29	20	20-38	29

θNearly all salient-pole generators built by GE since 1935 have amortisseur windings.

C. Grouped Small Motors

In many short-circuit studies the number size and type of low-voltage motors (perhaps up to 250 hp, induction or synchronous) is not known precisely, but the short-circuit contributions from these motors must be estimated. In such cases, to account for a group of a large number of low voltage induction and synchronous motors in the first-cycle network, use a reactance of 25 percent based on the total rated kVA of the group. This first cycle estimated reactance is a combination of several X″ times multiplying factor values, see text page 18.

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* Trademark of General Electric Company.

Appendix

TABLE 17—Cables

Approximate 60-cycle resistance and reactance of copper and aluminum cable, 75 C conductor temperature. 600 volts, 5 kV and 15 kV. Magnetic and nonmagnetic conduit ohms/1000 ft l-n*.

Cable Size	Copper Conductor								Aluminum Conductor							
	Cable in Magnetic Conduit				Cable in Nonmagnetic Conduit				Cable in Magnetic Conduit				Cable in Nonmagnetic Conduit			
	I/C Conductor		3/C Conductor		1/C Conductor		3/C Conductor		I/C Conductor		3/C Conductor		1/C Conductor		3/C Conductor	
	R	X	R	X	R	X	R	X	R	X	R	X	R	X	R	X
600 Volts																
8 AWG	0.7873	0.0514	0.7873	0.0394	0.7873	0.0411	0.7873	0.0343	1.2911	0.0514	1.2911	0.0394	1.2911	0.0411	1.2911	0.0343
6 AWG	.4954	.0521	.4954	.0399	.4954	.0417	.4954	.0347	.8124	.0521	.8124	.0399	.8124	.0417	.8124	.0347
4 AWG	.3114	.0492	.3114	.0377	.3114	.0393	.3114	.0328	.5107	.0492	.5107	.0377	.5107	.0393	.5107	.0328
3 AWG	.247	.0479	.247	.0367	.247	.0383	.247	.0319	.4051	.0479	.4051	.0367	.4051	.0383	.4051	.0319
2 AWG	.1959	.0466	.1959	.0357	.1959	.0373	.1959	.0311	.3212	.0466	.3212	.0357	.3212	.0373	.3212	.0311
1 AWG	.1553	.0485	.1553	.0371	.1553	.0388	.1553	.0323	.2547	.0485	.2547	.0371	.2547	.0388	.2547	.0320
1/0 AWG	.1231	.0457	1231	.035	.1231	.0366	.1231	.0305	.2019	.0457	.2019	.035	.2019	.0366	.0219	.0305
2/0 AWG	.0977	.0446	.0977	.0341	.0977	.0356	.0977	.0297	.1602	.0446	.1602	.0341	.1602	.0356	.1602	.0297
3/0 AWG	.0775	.0435	.0775	.0333	.0775	.0348	.0775	.029	.127	.0435	.127	.0333	.127	.0348	.127	.029
4/0 AWG	.0614	.0425	.0614	.0326	.0614	.034	.0614	.0283	.1007	.0425	.1007	.0326	.1007	.034	.1007	.0283
250 MCM	.0534	.0428	.0534	.0328	.0529	.0342	.0529	.0285	.0868	.0428	.0868	.0328	.0854	.0342	.0854	.0285
300 MCM	.0452	.042	.452	.032	.0443	.0336	.0443	.028	.0727	.042	.0727	.032	.0713	.0336	.0713	.028
350 MCM	.0392	.0414	.0392	.0315	.0383	.0331	.0383	.0276	.0627	.0414	.0627	.0315	.0612	.0331	.0612	.0276
400 MCM	.0348	.0409	.0348	.0311	.0337	.0327	.0337	.0273	.0553	.0409	.0553	.0311	.0536	.0327	.0536	.0273
500 MCM	.0287	.0402	.0287	.0301	.0275	.0321	.0275	.0268	.0451	.0402	.0451	.0301	.0429	.0321	.0429	.0268
600 MCM	.0249	.0404	.0249	.0299	.0234	.0323	.0234	.0269	.0384	.0404	.0384	.0299	.0358	.0323	.0358	.0269
750 MCM	.0213	.0396	.0213	.0288	.0194	.0317	.0194	.0264	.0318	.0396	.0318	.0288	.0288	.0317	.0288	.0264
1000 MCM	.0179	.0388	.0179	.0276	.0155	.031	.0155	.0259	.0254	.0388	.0254	.0276	.0219	.031	.0219	.0259
1250 MCM	.0161	.0388	.0161	.0271	.0131	.031	.0131	.0258	.0215	.0388	.0215	.0271	.0178	.031	.0178	.0258
1500 MCM	.0149	.0383	.0149	.0265	.0115	.0306	.0115	.0255	.0189	.0383	.0189	.0265	.0151	.0306	.0151	.0255
1750 MCM	.0141	.0378	.0141	.026	.0104	.0302	.0104	.0252	.0171	.0378	.0171	.026	.0132	.0302	.0132	.0252
2000 MCM	.0135	.0375	.0135	.0257	.0096	.03	.0096	.025	.0157	.0375	.0157	.0257	.0118	.03	.0118	.025
5 kV																
8 AWG	0.7873	0.0733	0.7873	0.0479	0.7873	0.0586	0.07873	0.0417	1.2911	0.0733	1.2911	0.0479	1.2911	0.0586	1.2911	0.0417
6 AWG	.4954	.0681	.4954	.0447	.4954	.0545	.4954	.0389	.8124	.0681	.8124	.0447	.8124	.0545	.8124	.0389
4 AWG	.3114	.0633	.3114	.0418	.3114	.0507	.3114	.0364	.5107	.0633	.5107	.0418	.5107	.0507	.5107	.0364
3 AWG	.247	.0611	.247	.0405	.247	.0489	.247	.0353	.4051	.0611	.4051	.0405	.4051	.0489	.4051	.0353
2 AWG	.1959	.0591	.1959	.0393	.1959	.0472	.1959	.0342	.3212	.0591	.3212	.0393	.3212	.0472	.3212	.0342
1 AWG	.1553	.0571	.1553	.0382	.1553	.0457	.1553	.0332	.2547	.0571	.2547	.0382	.2547	.0457	.2547	.0332
1/0 AWG	.1231	.0537	.1231	.036	.1231	.043	.1231	.0313	.2019	.0537	.2019	.036	.2019	.043	.2019	.0313
2/0 AWG	.0977	.0539	.0977	.035	.0977	.0431	.0977	.0305	.1602	.0539	.1602	.035	.1602	.0431	.1602	.0305
3/0 AWG	.0775	.0521	.0775	.0341	.0775	.0417	.0775	.0297	.127	.0521	.127	.0341	.127	.0417	.127	.0297
4/0 AWG	.0614	.0505	.0614	.0333	.0614	.0404	.0614	.029	.1007	.0505	.1007	.0333	.1007	.0404	.1007	.029
250 MCM	.0531	.049	.0531	.0324	.0531	.0392	.0531	.0282	.0868	.049	.0868	.0324	.0854	.0392	.0854	.0282
300 MCM	.0462	.0478	.0462	.0317	.0446	.0383	.0446	.0277	.0727	.0478	.0727	.0317	.0713	.0383	.0713	.0277
350 MCM	.0405	.0469	.0405	.0312	.0386	.0375	.0386	.0274	.0627	.0469	.0627	.0312	.0612	.0375	.0612	.0274
400 MCM	.0359	.0461	.0359	.0308	.0341	.0369	.0341	.027	.0553	.0461	.0553	.0308	.0536	.0369	.0536	.027
500 MCM	.0294	.045	.0294	.0299	.0279	.036	.0279	.0265	.0451	.045	.0451	.0299	.0429	.036	.0429	.0265
600 MCM	.0252	.0439	.0252	.029	.0238	.0351	.0238	.0261	.0384	.0439	.0384	.029	.0358	.0351	.0358	.0261
750 MCM	.0214	.0434	.0214	.0284	.0199	.0347	.0199	.026	.0318	.0434	.0318	.0284	.0288	.0347	.0288	.026
1000 MCM	.0182	.0421	.0182	.0272	.0161	.0337	.0161	.0255	.0254	.0421	.0254	.0272	.0219	.0337	.0219	.0255
1250 MCM	.0167	.0438	.0167	.027	.0139	.0342	.0139	.0257	.0215	.0428	.0215	.027	.0178	.0342	.0178	.0257
1500 MCM	.016	.042	.016	.0264	.0125	.0336	.0125	.0254	.0189	.042	.0189	.0264	.0151	.0336	.0151	.0254
1750 MCM	.0156	.0413	.0156	.0259	.0115	.033	.0115	.0251	.0171	.0413	.0171	.0259	.0132	.033	.0132	.0251
2000 MCM	.0153	.0408	.0153	.0256	.0108	.0326	.0108	.0249	.0157	.0408	.0157	.0256	.0118	.0326	.0118	.0249
15 kV																
8 AWG	0.7873	0.0905	0.7873	0.0629	0.7873	0.0724	0.7873	0.0547	1.2911	0.0905	1.2911	0.0629	1.2911	0.0724	1.2911	0.0547
6 AWG	.4954	.0842	.4954	.0584	.4954	.0674	.4954	.0508	.8124	.0842	.8124	.0584	.8124	.0674	.8124	.0508
4 AWG	.3114	.0783	.3114	.0543	.3114	.0626	.3114	.0472	.5107	.0783	.5107	.0543	.5107	.0626	.5107	.0472
3 AWG	.247	.0755	.247	.0523	.247	.0604	.247	.0455	.4051	.0755	.4051	.0523	.4051	.0604	.4051	.0455
2 AWG	.1959	.0727	.1959	.0505	.1959	.0582	.1959	.0439	.3212	.0727	.3212	.0505	.3212	.0582	.3212	.0439
1 AWG	.1553	.0701	.1553	.0487	.1553	.0561	.1553	.0424	.2547	.0701	.2547	.0487	.2547	.0561	.2547	.0424
1/0 AWG	.1231	.0661	.1231	.0458	.1231	.0529	.1231	.0399	.2019	.0661	.2019	.0458	.2019	.0529	.2019	.0339
2/0 AWG	.0977	.0637	.0977	.0442	.0977	.051	.0977	.0385	.1602	.0637	.1602	.0442	.1602	.051	.1602	.0385
3/0 AWG	.0775	.0614	.0775	.0427	.0775	.0491	.0775	.0372	.127	.0614	.127	.0427	.127	.0491	.127	.0372
4/0 AWG	.0614	.0592	.0614	.0413	.0614	.0474	.0614	.0359	.1007	.0592	.1007	.0413	.1007	.0474	.1007	.0359
250 MCM	.0531	.0573	.0531	.04	.0531	.0458	.0531	.0348	.0868	.0573	.0868	.04	.0854	.0458	.0854	.0348
300 MCM	.0462	.0557	.0462	.0387	.0446	.0446	.0446	.0339	.0727	.0557	.0727	.0387	.0713	.0446	.0713	.0339
350 MCM	.0405	.0544	.0405	.0379	.0386	.0436	.0386	.0332	.0627	.0544	.0627	.0379	.0612	.0436	.0612	.0332
400 MCM	.0359	.0534	.0359	.0371	.0341	.0427	.0341	.0326	.0553	.0534	.0553	.0371	.0536	.0427	.0536	.0326
500 MCM	.0294	.0517	.0294	.0357	.0279	.0414	.0279	.0317	.0451	.0517	.0451	.0357	.0429	.0414	.0429	.0317
600 MCM	.0252	.0516	.0252	.0343	.0238	.0413	.0238	.0309	.0384	.0516	.0384	.0343	.0358	.0413	.0358	.0309
750 MCM	.0214	.05	.0214	.0328	.0199	.04	.0199	.0301	.0318	.05	.0318	.0328	.0288	.04	.0288	.0301
1000 MCM	.0182	.0482	.0182	.0311	.0161	.0385	.0161	.0291	.0254	.0482	.0254	.0311	.0219	.0385	.0219	.0291
1250 MCM	.0167	.0467	.0167	.0298	.0139	.0374	.0139	.0284	.0215	.0467	.0215	.0298	.0178	.0374	.0178	.0284
1500 MCM	.016	.0457	.016	.029	.0125	.0366	.0125	.0279	.0189	.0457	.0189	.029	.0151	.0366	.0151	.0279
1750 MCM	.0156	.0448	.0156	.0283	.0115	.0358	.0115	.0274	.0171	.0448	.0171	.0283	.0132	.0358	.0132	.0274
2000 MCM	.0153	.0441	.0153	.0279	.0108	.0353	.0108	.0271	.0157	.0441	.0157	.0279	.0118	.0353	.0118	.0271

*These values are from IEEE Standard 141 and differ slightly from values used in earlier publications of this bulletin.

TABLE 18—GE Busway Impedances

Busway Type	Ampere Rating	Ohms Per 100 Feet, Line-To-Neutral		
		60-HZ Alternating Current		
		Resistance(R)	Reactance(X)	Impedance(Z)
LVD Feeder With Aluminum Bus Bars	600	0.00331	0.00228	0.00402
	800	.00210	.00081	.00226
	1000	.00163	.00079	.00181
	1350	.00143	.00052	.00153
	1600	.00108	.00051	.00119
	2000	.00081	.00037	.00089
	2500	.00064	.00030	.00071
	3000	.00054	.00024	.00059
	4000	.00041	.00018	.00045
	5000	.00032	.00013	.00035
LVD Feeder With Copper Bus Bars	800	0.00200	0.00228	0.00304
	1000	.00132	.00081	.00156
	1350	.00099	.00079	.00126
	1600	.00088	.00052	.00102
	2000	.00066	.00051	.00083
	2500	.00059	.00037	.00062
	3000	.00040	.00030	.00050
	4000	.00034	.00024	.00042
	5000	.00025	.00018	.00031
LVDP Plug-in With Aluminum Bus Bars	800	0.00210	0.00114	0.00238
	1000	.00163	.00110	.00197
	1350	.00143	.00069	.00159
	1600	.00108	.00066	.00127
	2000	.00081	.00044	.00092
	2500	.00064	.00035	.00073
	3000	.00054	.00028	.00061
	4000	.00041	.00021	.00046
	5000	.00032	.00016	.00036
LVDP Plug-in With Copper Bus Bars	800	0.00200	0.00460	0.00500
	1000	.00132	.00114	.00174
	1350	.00099	.00110	.00148
	1600	.00088	.00069	.00112
	2000	.00066	.00066	.00093
	2500	.00050	.00044	.00067
	3000	.00040	.00035	.00053
	4000	.00034	.00028	.00044
	5000	.00025	.00021	.00032
CL With Aluminum Bus Bars	1000	0.00220	0.0069	0.0072
	1350	.00200	.0064	.0067
	1600	.00148	.0064	.0066
	2000	.00112	.0058	.0059
	2500	.00090	.0054	.0055
	3000	.00077	.0050	.0051
	4000	.00059	.0042	.0042
CL With Copper Bus Bars	1000	0.00177	0.0069	0.0071
	1350	.00134	.0069	.0070
	1600	.00121	.0064	.0065
	2000	.00090	.0064	.0065
	2500	.00070	.0058	.0058
	3000	.00058	.0054	.0054
	4000	.00041	.0046	.0046
FVK With Copper Bus Bars	225	0.0052	0.0064	0.0082
	400	.0038	.0064	.0075
	600	.0021	.0048	.0052
	800	.0014	.0034	.0037
	1000	.0011	.0032	.0034

TABLE 18—Busway Impedances (Cont'd)

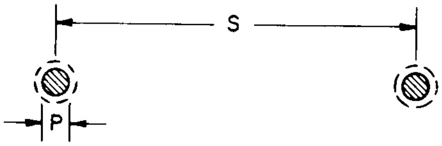
Busway Type	Ampere Rating	Ohms Per 100 Feet, Line-To-Neutral		
		60-HZ Alternating Current		
		Resistance(R)	Reactance(X)	Impedance(Z)
FVA With Aluminum Bus Bars	225	0.0074	0.0064	0.0098
	400	.0038	.0048	.0061
	600	.0022	.0034	.0041
	800	.0018	.0032	.0037
DH CU	100	0.0290	0.0050	0.0294
AL	100	0.0450	0.0050	0.0187
LTG	50	0.053	0.014	0.055
LW	30	0.093	0.003	0.093
	60	.051	.003	.051
ARMOR-CLAD Feeder Aluminum	600	0.00333	0.00135	0.00359
	800	.00221	.00097	.00241
	1000	.00166	.00065	.00178
	1200	.00133	.00053	.00143
	1350	.00110	.00045	.00119
	1600	.00102	.00045	.00112
	2000	.00078	.00031	.00084
	2500	.00055	.00023	.00059
	3000	.00049	.00020	.00053
	4000	.00036	.00015	.00039
ARMOR-CLAD Feeder Copper	600	0.00268	0.00168	0.00316
	800	.00206	.00135	.00246
	1000	.00135	.00097	.00166
	1200	.00100	.00065	.00119
	1350	.00096	.00061	.00114
	1600	.00083	.00053	.00099
	2000	.00068	.00049	.00084
	2500	.00051	.00032	.00060
	3000	.00041	.00027	.00049
	4000	.00030	.00020	.00036
	5000	.00023	.00015	.00027
ARMOR-CLAD Plug-in Aluminum	225	0.00951	0.00394	0.01029
	400	.00378	.00433	.00575
	600	.00358	.00380	.00522
	800	.00240	.00252	.00348
	1000	.00159	.00159	.00225
	1200	.00120	.00122	.00171
	1350	.00104	.00106	.00149
	1600	.00110	.00124	.00166
	2000	.00080	.00086	.00118
	2500	.00051	.00057	.00077
	3000	.00043	.00048	.00068
	4000	.00036	.00019	.00041
ARMOR-CLAD Plug-in Copper	225	0.00524	0.00394	0.00656
	400	.00273	.00276	.00388
	600	.00226	.00433	.00488
	800	.00210	.00380	.00434
	1000	.00142	.00252	.00289
	1200	.00109	.00182	.00212
	1350	.00088	.00144	.00169
	1600	.00072	.00117	.00137
	2000	.00066	.00124	.00141
	2500	.00049	.00086	.00099
	3000	.00037	.00066	.00076
	4000	.00027	.00048	.00055

Overhead Lines

Practical transmission lines are often assumed to have a 60-cps positive- or negative-sequence reactance as high as 0.8 ohms/mile (or 0.15 ohms/1000 feet) line-to-neutral. Closer values can be obtained from Fig. 26-1 (page 44) if the conductor spacing is known. The values in Fig. 26-1 were calculated from the equation

$$X_L = 10^{-6}{}_{w}\left(15.2+140.4\log\frac{2S}{d}\right)$$

with dimensions according to the following illustration where S and d are in the same units:



For an unsymmetrical arrangement of three conductors, an equivalent value of S can be derived from the relation

$$S = \sqrt[3]{(S_1)(S_2)(S_3)}.$$

There is a considerable amount of variation in the spacing of conductors of overhead lines. Fig. 26-2 gives representative values for current practice on an equivalent-delta basis.

Bus

Site-assembled bus will have 60-cycle inductive reactance (positive- or negative-sequence) varying with conductor spacing according to Fig. 26-3 through 26-5.

The zero-sequence reactance of site-assembled bus, with respect to nearby grounded enclosures or material, will be indefinite because the spacings are not definite. Ratios of Z_0/Z_1 tend to be very large.

Appendix

Conductor Constants

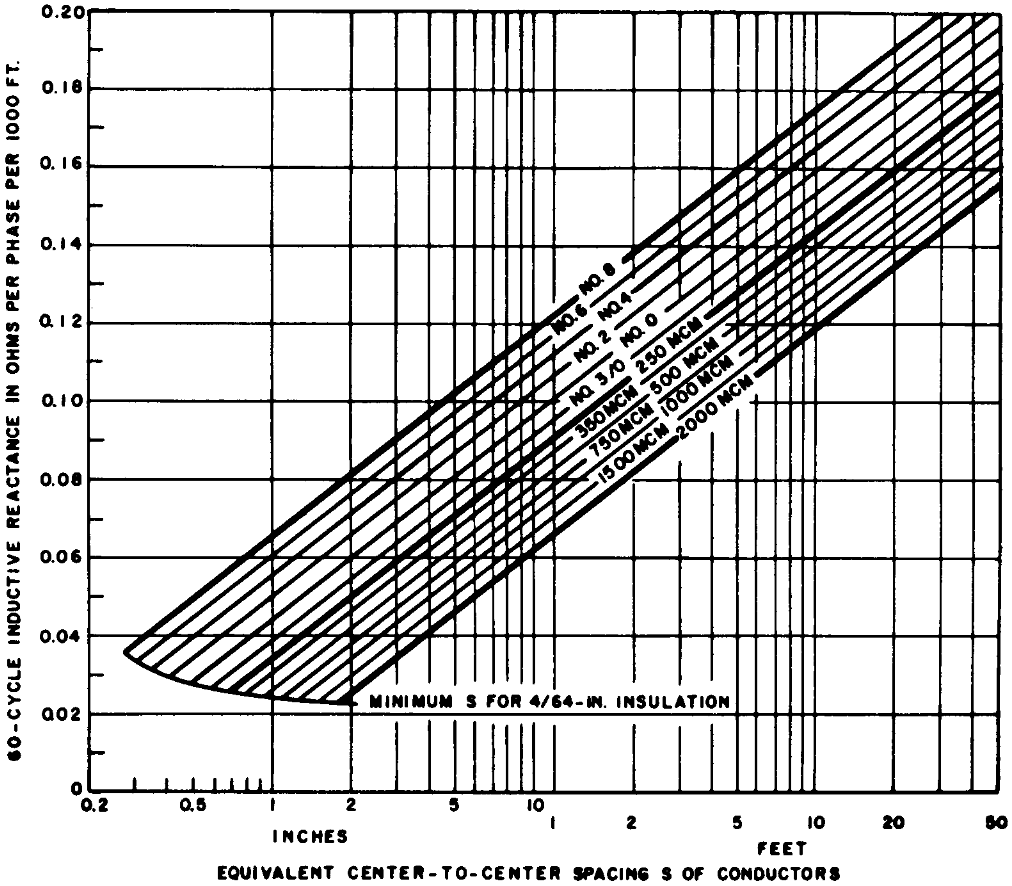


Fig. 26-1. Calculated inductive reactance for parallel conductors with standard stranding where valves are per conductor for two-wire, single-phase circuits and line-to-neutral for three-phase circuits

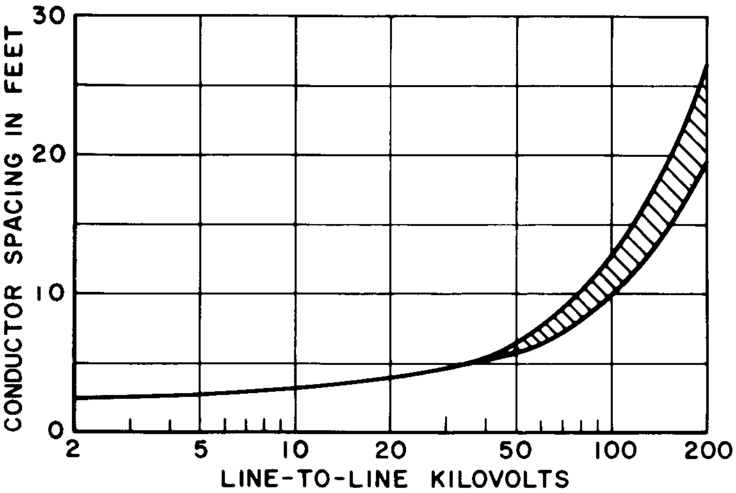
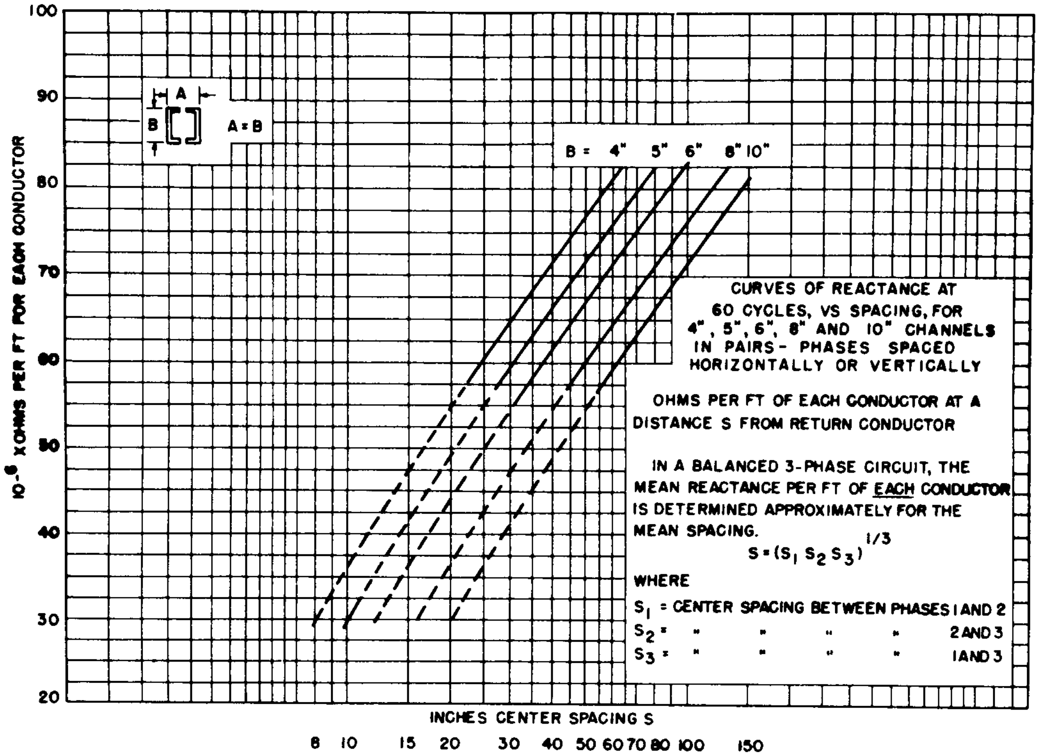


Fig. 26-2. Typical equivalent-delta spacing used for three-wire overhead transmission lines

Conductor Constants (Cont'd)



CURVES OF REACTANCE AT 60 CYCLES, VS SPACING, FOR 4", 5", 6", 8" AND 10" CHANNELS IN PAIRS - PHASES SPACED HORIZONTALLY OR VERTICALLY

OHMS PER FT OF EACH CONDUCTOR AT A DISTANCE S FROM RETURN CONDUCTOR

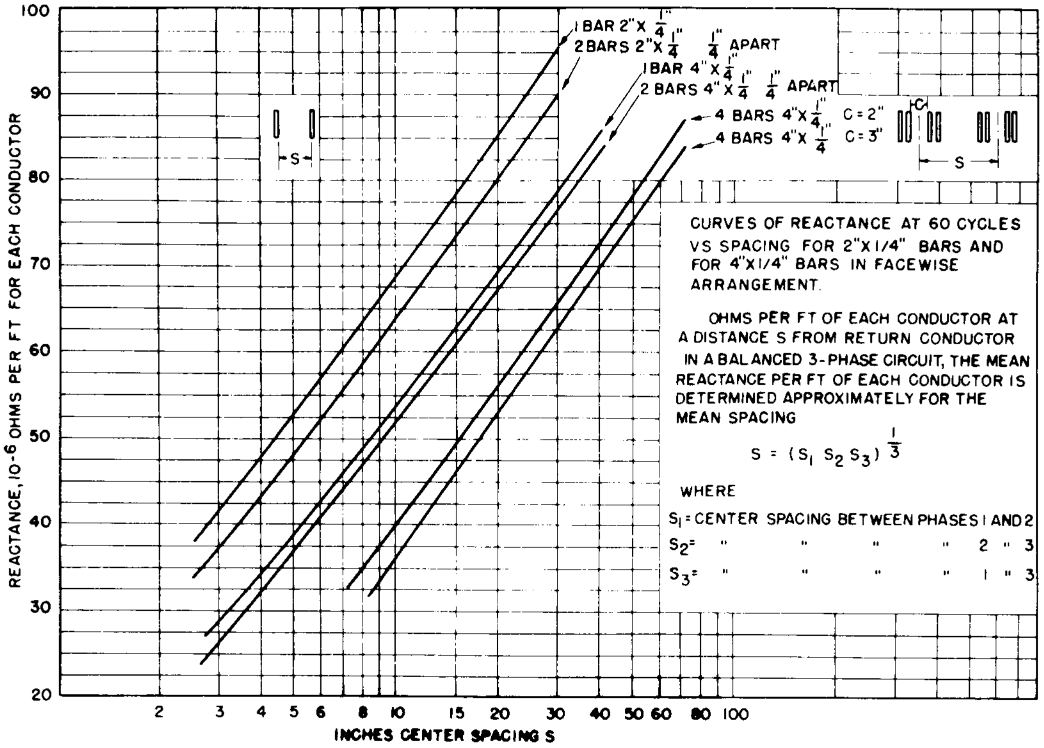
IN A BALANCED 3-PHASE CIRCUIT, THE MEAN REACTANCE PER FT OF EACH CONDUCTOR IS DETERMINED APPROXIMATELY FOR THE MEAN SPACING.

$$S = (S_1\, S_2\, S_3)^{1/3}$$

WHERE

S_1 = CENTER SPACING BETWEEN PHASES 1 AND 2
S_2 = " " " " 2 AND 3
S_3 = " " " " 1 AND 3

Fig. 26-3



CURVES OF REACTANCE AT 60 CYCLES VS SPACING FOR 2"X1/4" BARS AND FOR 4"X1/4" BARS IN FACEWISE ARRANGEMENT.

OHMS PER FT OF EACH CONDUCTOR AT A DISTANCE S FROM RETURN CONDUCTOR

IN A BALANCED 3-PHASE CIRCUIT, THE MEAN REACTANCE PER FT OF EACH CONDUCTOR IS DETERMINED APPROXIMATELY FOR THE MEAN SPACING

$$S = (S_1\, S_2\, S_3)^{\frac{1}{3}}$$

WHERE

S_1 = CENTER SPACING BETWEEN PHASES 1 AND 2
S_2 = " " " " 2 " 3
S_3 = " " " " 1 " 3

Fig. 26-4

Appendix

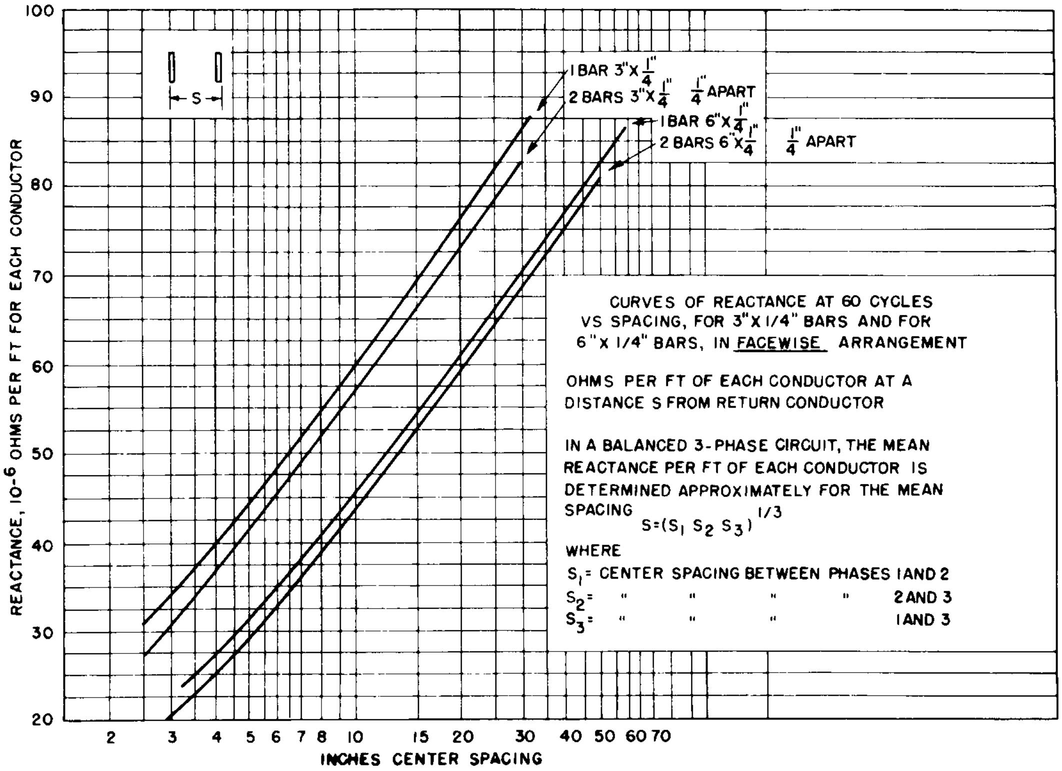


Fig. 26-5

Part III Short-circuit Ratings of a.c. Components and Equipments

The short-circuit ratings listed in the following tables are representative of standard components or equipment in current production. The short-circuit ratings may change from time to time and in addition new components or equipments are continually becoming available so it is suggested that up-to-date short-circuit ratings be verified by consulting the appropriate product bulletin.

TABLE 19—Low Voltage Circuit Breakers

COMPONENT	BULLETIN NUMBER
Molded Case Circuit Breakers	GET-2779
Insulated Case Circuit Breakers	GET-6211
Low voltage Power Circuit Breaker	GET-6218
Coordinated Ratings	GIZ-2691-26

TABLE 20—Low-Voltage Safety and Disconnect Switches

TYPE	MAXIMUM VOLTAGE AC	CONTINUOUS CURRENT RMS AMPERES	INTERRUPTING RATINGS RMS SYMMETRICAL KILO-AMPERES				
			NO FUSE kA	FUSED UNIT FUSE CLASS			
				H	R	J	L
TG	240	30	0.18	10	—	—	—
		60	0.36	10	—	—	—
		100	0.6	10	—	—	—
		200	1.2	10	—	—	—
		400	2.4	10	—	—	—
		600	3.6	10	—	—	—
TH	600	30	0.36	10	200	200	—
		60 or 100	1.2	10	200	200	—
		200	3.40	10	200	200	—
		400 or 600	10.0	10	200	200	—
		800	4.8	—	—	—	100
		1200	7.2	—	—	—	100
QMR	600	30	0.42	10	200	200	—
		60	0.9	10	200	200	—
		100	1.7	10	200	200	—
		200	3.4	10	200	200	—
		400	10.0	10	200	200	—
		600	10.0	10	200	200	—
QMW	600	30	0.95	10	200	200	—
		60	1.7	10	200	200	—
		100	1.8	10	200	200	—
		200	3.6	10	200	200	—
HPC	600	800–1600	19.2	—	—	—	200
		2000–4000	42	—	—	—	200

Appendix

TABLE 21—Low-voltage Individually Mounted Combination Motor Starters

PROTECTOR TYPE	NEMA		THREE-PHASE SHORT-CIRCUIT RATING RMS SYMMETRICAL KILOAMPERES		
	SIZE	ENCLOSURE	240 Volt	480 Volt	600 Volt
Circuit Breaker TEB	0,1,2,3,	ALL	5	—	—
Motor Circuit Breaker TEC	0,1,2,3	All	25	25	5
	4	Except 7/9	25	25	5
	4	7/9	25	25	10
Motor Circuit Breaker TEC with TECL Limiter	0,1,2,3	All	100	100	100
	4	Except 7/9	100	100	100
	4	7/9	100	100	100
Circuit Breaker TED	0	7/9	18	14	5
(15–30A)	0	Except 7/9	5	5	5
(35–70A)	1	All	25	25	25
(35–70A)	1	Except 7/9	5	5	5
(15–50A)	1	7/9	18	14	5
(60–100A)	2	All	25	25	5
(25–100A)	2	All	5	5	5
(110–150A)	3	All	25	25	5
	3	All	5	5	5
Circuit Breaker THED	0	All	65	14	5
(15–50A)	1	All	65	25	25
(60–70A)	1	Except 7/9	65	14	5
(15–70A)	1	7/9	65	14	5
(15–50A)	2	Except 7/9	65	25	25
(60–100A)	2	Except 7/9	65	25	5
(15–100A)	2	7/9	65	25	25
(25–100A)	3	All	65	25	25
(110–150A)	3	All	42	25	5
Circuit Breaker TFJ & TFK	4	All	22	22	22
Circuit Breaker THFK	4	All	25	25	10
Circuit Breaker TJJ & TJK	5	Except 7/9	10	10	10
Circuit Bkr TJK4 (200–400A)	5	7/9	30	30	22
TJK6 (250–600A)	5	7/9	10	10	10
Circuit Bkr THJK (225–400A)	5	All	35	35	25
(450–600A)	5	All	10	10	10
Fusible Class R or J	0,1,2,3, 4,5	Except 7/9	100	100	100

Short-circuit ratings apply to NEMA type 1, 3R, 4, 4X 7/9 and 12 enclosures. Combination starters with circuit breakers or fuses listed are adequate for installation in motor branch circuits where the available short-circuit current at the incoming line terminals of the circuit breaker or fusible disconnect switch does not exceed the values indicated in Table 21. After a fault maintenance and replacement of some components or devices may be required.

TABLE 22—Current-limiting Fuses

Class	Voltage A.C.	Available Continuous Current rms Amperes	Interrupting Rating—rms Symmetrical Amperes
RK-1	600	3–600	200,000
RK-5	600	3–600	200,000
T	600	3–800	200,000
J	600	3–600	200,000
L	600	601–4000	200,000

TABLE 23—Busway Short-circuit Ratings

BUSWAY		3-PHASE SHORT-CIRCUIT RATING RMS SYMMETRICAL KILO AMPERES	
Type	Continuous Current RMS Amperes	Aluminum Bus Bars	Copper Bus Bars
LW	30 & 60		5
LTG	50	5	
DH	100	5*	
FVA	225	14	14
(Alum Bus)	400	22	22
FVK	600	22	22
(Copper Bus)	800	22	22
	1000	—	22
LVD	600	35	—
and	800	60	35
LVDP	1000	70	65
	1350	85	70
	1600	105	85
	2000	140	105
	2500	175	140
	3000	175	175
	4000	175	175
	5000	175	175

* 14 kA when protected by 100A max. GE Type TED or TQ circuit breakers
50 kA when protected by 100A max. Class RK5 fuses
200 kA when protected by 100A max Class J or T Fuses

Appendix

Table 23A—Busway Short-Circuit Ratings[+]

BUSWAY		3-PHASE SHORT-CIRCUIT RATING RMS SYMMETRICAL KILOAMPERES							
		Aluminum Bus Bars				Copper Bus Bars			
		3 Ph 4 Wire			Internal Ground Bar	3 Ph 4 Wire			Internal Ground Bar
Type	Continuous Current rms Amperes	Full Neutral or 3ph3W		Half Neutral		Full Neutral or 3ph3W		Half Neutral	
Armor-Clad Feeder	600	85		85	85	75		75	75
	800	100		100	100	75		75	75
	1000	100		85	100	85		85	85
	1200	100		75	100	100		75	100
	1350	125		75	100	100		75	100
	1600	200		150	200	100		75	100
	2000	200		150	200	150		150	150
	2500	200		150	200	200		150	200
	3000	200		200	200	200		150	200
	4000	200		200	200	200		200	200
	5000	200		200	200	200		200	200
		STD	HIGH			STD	HIGH		
Armor-Clad Plug-in	225	25	—		—	25	—		—
	400	65	100		65	30	50		50
	600	65	100		65	65	100		65
	800	65	100		100	65	100		100
	1000	65	100		100	65	100		100
	1200	75	100		100	65	100		100
	1350	75	125		125	65	100		100
	1600	125	150		150	75	100		100
	2000	125	150		150	125	150		150
	2500	150	200		200	125	150		150
	3000	200	200		200	125	150		150
	4000	200	200		200	200	200		200
	5000	—	—		—	200	200		200

[+] Short-circuit ratings have been assigned to all General Electric busway based on tests performed in accordance with UL 857 busway standard. These UL short-circuit ratings apply to all busway and associated fittings such as straight lengths, elbows, T's, tap boxes power take-offs and plugs which are necessary for a busway installation. The short-circuit ratings cover all types of busway three-pole, three-phase four wire with half and full neutral all with and without internal ground bar. Ratings without a ground bar are established by tests which require the housing and housing joints to provide a satisfactory ground return.

The short-circuit rating of fittings with protective devices which are part of the busway such as power take-offs and reducers is equal to the lower of the short-circuit rating of the protective device or the busway with which the fitting is used. The short-circuit rating of busway plugs is equal to the short-circuit rating of the circuit breaker or fuses used in the plug.

TABLE 24—Maximum Fuse Rating for Busway Short-circuit Protection

BUSWAY			MAXIMUM CLF FUSE RATING (CLASS R, J, T OR L)		
			AVAILABLE RMS SYMMETRICAL SHORT-CIRCUIT CURRENT		
Type	Continuous Current RMS Amperes	Std S.C. Rating kA	50 kA	100 kA	200 kA
Armor-Clad Feeder Al	400	75		R600, J600, T800, L1600	R600, J600, T800, L800
	600	85		R600, J600, T800, L2000	R600, J600, T800, L1200
	800	100			T800, L2000
	1000	100			L2500
	1200	100			L2500
	1350	125			L3000
Armor-Clad Feeder Cu	600	75		R600, J600, T800, L2000	R600, J600, T800, L1200
	800	75		T800, L2000	T800, L1200
	1000	85		L2000	L1600
	1200	100			L2500
	1350	100			L2500
	1600	100			L2500
	2000	150			L4000
Armor-Clad Plug-in Al	225	25	R200, J600, T600	R200, J400, T400	J200, T200
	400	65			
	600	65		R600, J600, T800, L1600	R600, J600, T800, L800
	800	65		T800, L1600	T800, L800
	1000	65		L2000	L1200
	1200	75		L2000	L1200
	1350	75		L2000	L1200
	1600	125			L3000
	2000	125			L3000
	2500	150			L4000
Armor-Clad Plug-in Cu	225	25	R200, J600, T600	R200, J600, T600	J400, T400
	400	30	R400, J600, T800	J600, T800	J400, T400
	600	65		R600, J600, T800, L1600	R600, J600, T800, L800
	800	65		T800, L1600	T800, L800
	1000	65		L1600	L800
	1200	65		L2000	L1200
	1350	65		L2000	L1200
	1600	75		L2000	L1200
	2000	125			L3000
	2500	125			L3000
	3000	125			L4000

Table 25—Motor Control Centers 600 Volt Maximum

MOTOR CONTROL CENTER SHORT-CIRCUIT RATINGS	GET-6728

Standard bus bracing for motor control centers is 25,000 rms symmetrical amperes. 42,000; 65,000 and 100,000 rms symmetrical ampere bracing is available.

TABLE 26—Limitamp Motor Starters—2400, 4800, and 7200 Volts

Type	Voltage RMS Volts	Continuous Current RMS Amperes	MAXIMUM MOTOR HORSEPOWER* Induction Wound Rotor Synchronous 0.8.P.F.	MAXIMUM MOTOR HORSEPOWER* Synchronous 1.O.P.F.	Interrupting Rating MVA Symmetrical Three-phase Class E1 Unfused	Interrupting Rating MVA Symmetrical Three-phase Class E2 Fused
Mech. Contactor	2400	400	1500	1700	50	200
		700	2500	2750	50	260
	4800	400	2500	3000	50	400
		700	4500	5000	50	520
	7200	300	4000	5000	30	600
Vacuum Contactor	2400	200	800	1000	25	200
		400	1600	2000	29	200
		800	3200	4000	37	200
	4800	400	3350	4200	50	400
		800	6700	8400	75	400
	7200	400	4800	6000	75	600

*Horsepower ratings are for one-high NEMA 1 vented enclosures in 40°C Max. ambient.

TABLE 27— Magne-blast Circuit Breaker Characteristics (Symmetrical Rating Basis ANSI C37.06)

Identification			Rated Values								Related Required Capabilities			
ANSI Line Number	Nominal Voltage Class kV, rms	Nominal 3-phase mVA Class	Voltage: Rated Maximum Voltage kV, rms *	Voltage: Rated Voltage Range K Factor, †	Insulation Level, Rated Withstand Test Voltage: Low Frequency kV, rms	Insulation Level, Rated Withstand Test Voltage: kV Crest Impulse	Current: Rated Con-tinuous Current at 60 Hz amp, rms	Current: Rated Short-circuit Current (at Rated Max kV) kA, rms ‡ §	Rated Inter-rupting Time Cycles	Rated Per-missible Tripping Delay, Y Sec	Rated Maximum Voltage Divided by K kV, rms	Current Values: K Times Rated Short-circuit Current: Maximum Symmet-rical Inter-rupting Capability ¶ kA, rms	Current Values: K Times Rated Short-circuit Current: 3 Sec Short-time Current Carrying Capability kA, rms	Closing and Latching Capability 1.6 K Times Rated Short-circuit Current kA, rms
3Λ	4.16	250	4.76	1.24	19	60	1200	29	5	2	3.85	36	36	58
4	4.16	250	4.76	1.24	19	60	2000	29	5	2	3.85	36	36	58
5	4.16	350	4.76	1.19	19	60	1200	41	5	2	4.0	49	49	78
5a	4.16	350	4.76	1.19	19	60	2000	41	5	2	4.0	49	49	78
6	4.16	350	4.76	1.19	19	60	3000	41	5	2	4.0	49	49	78
8	7.2	500	8.25	1.25	36	95	1200	33	5	2	6.6	41	41	66
9	7.2	500	8.25	1.25	36	95	2000	33	5	2	6.6	41	41	66
11	13.8	500	15	1.30	36	95	1200	18	5	2	11.5	23	23	37
12	13.8	500	15	1.30	36	95	2000	18	5	2	11.5	23	23	37
13	13.8	750	15	1.30	36	95	1200	28	5	2	11.5	36	36	58
14	13.8	750	15	1.30	36	95	2000	28	5	2	11.5	36	36	58
15	13.8	1000	15	1.30	36	95	1200	37	5	2	11.5	48	48	77
15a	13.8	1000	15	1.30	36	95	2000	37	5	2	11.5	48	48	77
16	13.8	1000	15	1.30	36	95	3000	37	5	2	11.5	48	48	77
HIGH CLOSE AND LATCH CAPABILITY CIRCUIT BREAKERS. (These ratings exceed ANSI C37.06)														
	4.16	250	4.76	1.24	19	60	1200 2000	29	5	2	3.85	36	36	78
	13.8	500	15	1.30	36	95	1200 2000	18	5	2	11.5	23	23	58
	13.8	750	15	1.30	36	95	1200 2000	28	5	2	11.5	36	36	77

* Maximum voltage for which the breaker is designed and the upper limit for operation.

†K is the ratio of rated maximum voltage to the lower limit of the range of operating voltage in which the required symmetrical and asymmetrical interrupting capabilities vary in inverse proportion to the operating voltage.

‡To obtain the required symmetrical interrupting capability of a circuit breaker at an operating voltage between 1/K times rated maximum voltage and rated maximum voltage, the following formula shall be used:

$$\text{Required Symmetrical Interrupting Capability} = \text{Rated Short-circuit Current} \times \frac{(\text{Rated Max. voltage})}{(\text{Operating voltage})}$$

For operating voltages below 1/K times rated maximum voltage, the required symmetrical interrupting capability of the circuit breaker shall be equal to K times rated short-circuit current.

§With the limitation stated in 0.4-4.5 of ANSI C37.04, all values apply for polyphase and line-to-line faults. For single phase-to-ground faults, the specific conditions stated in 0.4-4.5.2.3 of ANSI C37.04 apply.

¶Current values in this column are not to be exceeded even for operating voltages below 1/K times rated maximum voltage. For voltages between rated maximum voltage and 1/K times rated maximum voltage, follow ‡ above.

ANSI-C37.06 symmetrical rating basis is supplementary to ANSI-C37.6 (total current rating basis) and does not replace it. When a changeover from the total current basis of rating to the symmetrical basis of rating is effected the older standards will be withdrawn.

In accordance with ANSI-C37.06, users should confer with the manufacturer on the status of the various circuit breaker ratings.

ΛGeneral Electric Magne-blast circuit breakers are designated as Type AM-"kV"-"mVA". For example, this breaker is Type AM-4.16-2.50

Appendix

TABLE 28—POWER/VAC Circuit Breaker Characteristics
(Symmetrical Rating Basis ANSI C37.06–1979

Identification (6 & 7)*		Rated Values								Related Required Capabilities			
		Voltage		Insulation Level		Current					Current Values		
				Rated Withstand Test Voltage							Maximum Symmetrical Inter-Capability (5)	3 Sec. Short-time Current Carrying Capability	
Nominal rms Voltage Class (kV)	Nominal 3-phase Class (MVA)	Rated Maximum rms Voltage (kV) (1)	Rated Voltage Range Factor K (2)	Low Frequency rms Voltage (kV)	Crest Impulse Voltage (kV)	Continuous rms Current Rating at 60 Hz (amperes)	Short Circuit rms Current (at Rated Max kV) (kA) (3) (4)	Rated Interrupting Time (Cycles)	Rated Permissible Tripping Delay, Y (Seconds)	Rated Maximum rms Voltage Divided by K (kA)	K Times Rated Short-circuit rms Current		Closing and Latching rms Current (kA)
											(kA)	(kA)	
4.16	250	4.76	1.24	19	60	1200	29	5	2	3.85	36	36	58
4.16	250	4.76	1.24	19	60	2000	29	5	2	3.85	36	36	58
4.16	250	4.76	1.24	19	60	3000	29	5	2	3.85	36	36	58
4.16	350	4.76	1.19	19	60	1200	41	5	2	4.0	49	49	78
4.16	350	4.76	1.19	19	60	2000	41	5	2	4.0	49	49	78
4.16	350	4.76	1.19	19	60	3000	41	5	2	4.0	49	49	78
7.2	500	8.25	1.25	36	95	1200	33	5	2	6.6	41	41	66
7.2	500	8.25	1.25	36	95	2000	33	5	2	6.6	41	41	66
7.2	500	8.25	1.25	36	95	3000	33	5	2	6.6	41	41	66
13.8	500	15	1.30	36	95	1200	18	5	2	11.5	23	23	37
13.8	500	15	1.30	36	95	2000	18	5	2	11.5	23	23	37
13.8	500	15	1.30	36	95	3000	18	5	2	11.5	23	23	37
13.8	750	15	1.30	36	95	1200	28	5	2	11.5	36	36	58
13.8	750	15	1.30	36	95	2000	28	5	2	11.5	36	36	58
13.8	750	15	1.30	36	95	3000	28	5	2	11.5	36	36	58
13.8	1000	15	1.30	36	95	1200	37	5	2	11.5	48	48	77
13.8	1000	15	1.30	36	95	2000	37	5	2	11.5	48	48	77
13.8	1000	15	1.30	36	95	3000	37	5	2	11.5	48	48	77

Non-standard Breakers—High Close and Latch Capability

4.16	250	4.76	1.24	19	60	1200 2000	29	5	2	3.85	36	36	78
13.8	500	15	1.30	36	95	1200 2000	18	5	2	11.5	23	23	58
13.8	750	15	1.30	36	95	1200 2000	28	5	2	11.5	36	36	77

1 Maximum voltage for which the breaker is designed and the upper limit for operation.

2 K is the ratio of rated maximum voltage to the lower limit of the range of operating voltage in which the required symmetrical and asymmetrical interrupting capabilities vary in inverse proportion to the operating voltage.

3 To obtain the required symmetrical interrupting capability of a circuit breaker at an operating voltage between 1/K times rated maximum voltage and rated maximum voltage, the following formula shall be used:

$$\text{Required Symmetrical Interrupting Capability} = \text{Rated Short-circuit Current} \times \frac{(\text{Rated Max. voltage})}{(\text{Operating voltage})}$$

For operating voltages below 1/K times rated maximum voltage, the required symmetrical interrupting capability of the circuit breaker shall be equal to K times rated short-circuit current.

4 With the limitation stated in 5.10 of ANSI C37.04-1979, all values apply for poly-phase and line-to-line faults. For single phase-to-ground faults, the specific conditions stated in 5.10-2.3 of ANSI C37.04 apply.

5 Current values in this column are not to be exceeded even for operating voltages below 1/K times rated maximum voltage. For voltages between rated maximum voltage and 1/K times rated maximum voltage, follow 3 above.

TABLE 29—Vacuum Breakers—Type PVDB-1

Breaker Type	Rated Values									Related Required Capabilities			
	Voltage		Insulation Level		Current					Current Values			
			Withstand Test Voltage										
	Max. kV, rms	Range Factor K	Low Frequency kV, rms	Impulse kV, Crest	Continuous Current at 60 Hz	Short Circuit Current (at rated Max. kV) kA, rms	Inter-rupting Time Cycles	Rated Permissible Tripping Delay Y-Seconds	Max. kV Divided by K kV, rms	Maximum Symmetrical Interrupting Capability	3-Sec. Short-time Current-Carrying Capability	Closing and Latching Capability 1.6K Times Times Rated Short-circuit Current	Ship-ping Wt. in lb
										K Times Rated Short-circuit Current			
										kA, rms	kA, rms		
PVDB1–15.5–12000	15.5	1.0	50	110	600	12	5	2	15.5	12	12	20	2000
PVDB1–15.5–16000	15.5	1.0	50	110	800	16	5	2	15.5	16	16	26	2000
PVDB1–15.5–16000	15.5	1.0	50	110	1200	16	5	2	15.5	16	16	26	2000
PVDB1–15.5–20000	15.5	1.0	50	110	1200	20	5	2	15.5	20	20	32	2000
PVDB1–15.5–25000	15.5	1.0	50	110	1200	25	5	2	15.5	25	25	40	2000
PVDB1–15.5–20000	15.5	1.0	50	110	2000	20	5	2	15.5	20	20	32	2300
PVDB1–15.5–25000	15.5	1.0	50	110	2000	25	5	2	15.5	25	25	40	2300

Appendix

TABLE 30 —Summary of Ratings of Current-limiting Power Fuses, Types EJ-1 and EJO-1

Voltage Ratings kV*△		Continuous Current Ratings Amperes§		Interrupting Ratings 60 Hertz*	
Nominal	Max	EJ-1 (Indoor)	EJO-1 (Outdoor)	Total Rms Amp (Asymm)‡	Max 3φMVA (Symm)†
0.6	0.625	3E-10E	—	100,000	—
2.4	2.75	1E-200E	—	60,000	155
2.4	2.75	—	1E-200E	80,000	210
2.4/4.16	2.75/4.76	250E-450	—	80,000	210/360
4.8	5.5	—	0.5E-10E	80,000	415
4.8	5.5	—	15E-200E	80,000	415
4.8	5.5	0.5E-10E	—	100,000	515
4.8	5.5	15E-25E	—	100,000	515
4.8	5.5	0.5E-3E	—	80,000	410
7.2	8.25	0.5E-3E	0.5E-10E	80,000	620
7.2	8.25	—	15E-200E	80,000	620
14.4	15.5	0.5E-3E	0.5E-3E	190,000	2950
14.4	15.5	—	5E-10E	130,000	2020
14.4	15.5	—	15E-100E	60,000	935
14.4	15.0	125	—	60,000	925
14.4	15.0	150-175	—	50,000	700
23.0	25.8	—	0.5E-10E	70,000	1740
23.0	25.8	—	15E-100E	40,000	1000
34.5	38.0	—	0.5E-10E	70,000	2600
34.5	38.0	—	15E-80E	20,000	750

△May be applied at 50 Hertz without derating. For frequency less than 50 Hertz, consult the Company.

*The line-to-line circuit operating voltage should be between 100 percent and 70 percent of the fuse-unit voltage rating. Exceptions: Fuse units rated 600 volts may be applied on circuits rated 220 to 600 volts. High current fuse units rated 2400/4160 volts may be used at either voltage.

§All current ratings are the continuous 100-percent ratings, in accordance with NEMA Standards.

1. "E" rated fuses conform to NEMA Standards.
2. Continuous ratings without the "E" are 100-percent ratings. However, these fuses may not necessarily meet other NEMA requirements such as a 65-degree rise on the ferrule. All material in Type EJ fuses is capable of withstanding the temperatures encountered.

‡These asymmetrical current values for fuses correspond to momentary current ratings for power circuit breakers. Note, however, that the system duty calculated for the purpose of selecting current-limiting power fuses is 1.6 times the calculated symmetrical value of available current during the first cycle.

†The three-phase mVA interrupting ability for power fuses is based on the maximum symmetrical value of available rms amperes to which a set of fuses shall be subjected in interrupting a three-phase short circuit. The values in these columns are derived as follows:

Three-phase mVA =

$$\sqrt{3}\left(\frac{\text{Fused rated kV}}{1000}\right)\left(\frac{\text{Fuse rated interrupting amp}}{1.6}\right)$$

Notes: When lightning arresters are required in the same circuit as current limiting fuses.

1. Use distribution surge arresters (Form 28 or magne-valve), or full-rated station or intermediate surge arresters on either the source or the load side of the fuse.
2. Use reduced-rated station or intermediate surge arresters on load side of fuse only.
3. If reduced-rated station or intermediate surge arresters are required on the source side of the fuse, refer to Company for recommendations.

Low Voltage Equipments Circuit-breaker Panelboards

The short-circuit rating of a panelboard is the interrupting rating of the lowest rated device.

The interrupting rating of individual devices, fusible switches with fuses, molded case circuit breakers, etc. is not altered when the device is mounted in a panelboard. Bus bars are braced to withstand forces exerted by the let-through current. Ratings are based on circuit power factors corresponding to those used to rate devices.

Switchboards, AV-LINE and POWER BREAK—600 Volts Ac Maximum

Switchboard bus bars are braced for 50,000 symmetrical rms amperes as standard. 65,000, 100,000 150,000, and 200,000 ampere bracing is available.

TABLE 31—Low Voltage Equipments

EQUIPMENT	BULLETIN NUMBER
Panelboards	GET-6592
Switchboards AV-Line®	GET-6212
Switchboards Power Break®	GEA-10258
Switchgear Type AKD-8	GET-6937

Switchgear, Type AKD-8—600 Volts Ac Maximum

Switchgear bus bars are braced for 50,000 symmetrical rms amperes as standard. 100,000, 150,000 and 200,000 amperes bracing is available.

Part IV—Analytical Techniques

Simplification in the calculation of short-circuit currents is obtained for various configurations of power systems by the use of the per-unit system complex numbers, and other practices as well—some of which are described below.

Per-Unit System

A per-unit system is a means of expressing numbers for ease in comparing them.

A per-unit value is a ratio:

$$\text{Per-unit} = \frac{\text{A Number}}{\text{Base Number}}$$

The base number is also called unit value since in the per-unit system it has a value of one or unity. Thus, base voltage is also called unit voltage.

We may select any convenient number for the base number. For example, for the columns below, a base of 560 is used:

Number	Per-unit Value with 560 as a Base
95	0.17
123	0.22
560	1.00
2053	3.66

Each number in the second column is a per-unit part of the base number. In the first column, in order to compare the numbers, we must first mentally determine the ratio of one to the other. In the second column this is already accomplished for us.

We can aid the comparison by selection of the base number which will illustrate the comparison best. In the above example, if we wanted to show how much larger each number is when compared with the smallest number, we might have selected 95 as our base. We would then obtain:

Number	Per-unit Value with 95 as a Base
95	1.00
123	1.30
560	5.90
2053	21.60

The value of a per-unit system is particularly useful when we want to compare numbers that are similarly related to two different base numbers. For example:

	Case A	Case B
Normal volts	2300	460
Volts during motor starting	2020	420

The above figures in themselves have little significance until we mentally compare each with its normal condition as follows:

Volts during starting in per-unit of normal	0.88	0.91

Percent Values

Obviously percent and per-unit systems are similar. The percent system is obtained by multiplying the per-unit value arbitrarily by 100 in order to keep many frequently used per-unit values expressed as whole integers. By definition—

$$\text{Percent} = \frac{\text{A Number}}{\text{Base Number}} (100)$$

Thus to change percent to per-unit we divide by 100. For example, a transformer which has an impedance of six percent has an impedance of 0.06 per unit.

The percent system is somewhat more difficult to work with and more subject to possible error since we must always remember that the numbers have been arbitrarily multiplied by 100. For a simple example, money may draw interest at the rate of four percent per year. We learned in our early arithmetic to determine the interest by multiplying the principal by 0.04. We thus had to remember to convert to the per-unit value before using the figure. In a complex calculation this repeated conversion may invite errors. In effect it is safer and more convenient to say that interest is at the rate of 0.04 per unit.

Impedances of electric apparatus are usually given in percent. It is usually convenient to convert these figures immediately to per unit by dividing by 100 and thereafter do all calculating in terms of per unit rather than attempt to remember always during the calculations whether a number should or should not be multiplied or divided by 100 to obtain the true value.

Base-Value Relations

In a per-unit system as used for expressing electrical quantities of voltage, current, and impedance, we may arbitrarily select numbers for the following:

Base Volts
Base Amperes

Then we may not in addition arbitrarily select base ohms since it has already been fixed by the first two selections because of Ohm's Law:

$$Z = \frac{E}{I}, \text{ or}$$

$$\text{Base Ohms} = \frac{\text{Base Volts}}{\text{Base Amps}}$$

Using our selected base values, we may express all parts of an electric circuit or system in per-unit terms as follows:

$$\text{Per-unit Volts} = \frac{\text{Volts}}{\text{Base Volts}}$$

$$\text{Per-unit Amps} = \frac{\text{Amps}}{\text{Base Amps}}$$

$$\text{Per-unit Ohms} = \frac{\text{Ohms}}{\text{Base Ohms}}$$

In practice we find it more convenient to select:

Base Volts
Base kVA

The base values of other quantities are thus automatically fixed. Hence, for a single-phase system:

$$\text{Base Amps} = \frac{\text{Base kVA (1000)}}{\text{Base volts}}$$

$$\text{Base Ohms} = \frac{\text{Base Volts}}{\text{Base Amps}}$$

Similarly for a three-phase system:

$$\text{Base Amps} = \frac{\text{Base kVA (1000)}}{\sqrt{3}\,\text{(Base Volts)}}$$

$$\text{Base Ohms} = \frac{\text{Base Volts}}{\sqrt{3}\,\text{(Base Amps)}}$$

Where Base kVA is three-phase kVA

Base Volts is line-to-line
Base Ohms is line-to-neutral.

Per-Unit Ohms

In practice it is convenient to convert directly from ohms to per-unit ohms, without first determining base ohms according to the following easily derived expression:

$$\text{Per-unit Ohms} = \frac{\text{Ohms (Base kVA)}}{(\text{Base kV})^2 \text{x } 1000}$$

The expression above is valid for single-phase circuits where

Base kVA is a single-phase value,
Base kV is a line-to-line value.

The same expression is valid for three-phase circuits where

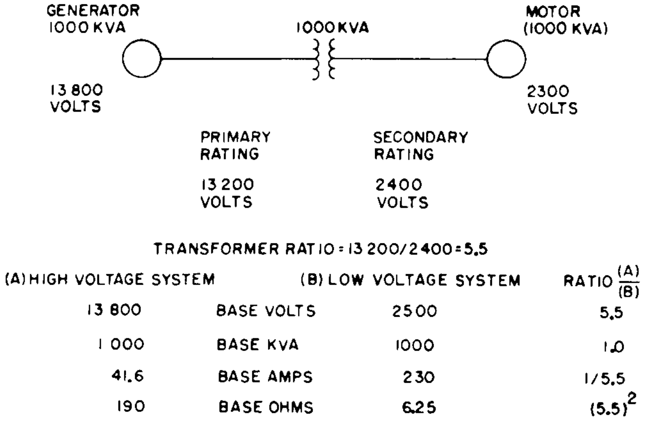
Ohms are line-to-neutral,
Base kVA is a three-phase value,
Base kV is a line-to-line value.

Preferred Base Values

In system studies, base voltage is usually selected as the nominal system voltage, or the voltage rating of the generators and supply transformers. Base kVA will usually be selected as the kVA rating of one of the machines or transformers in the system, or a convenient round number such as 1000 or 10,000 or 100,000 kVA.

Where two systems of differing voltage are interconnected through a transformer, we may select a common kVA base for both systems and the rated voltage of each system as its own base voltage. (These base voltages must have the same ratio to each other as the turns ratio of the transformer connecting the two systems.) Base ohms and base amps for the two systems will thus be correspondingly different. Fig. 27 shows a typical example.

Once the system values are expressed as per-unit values we may treat the two interconnected systems as a single system and carry out any calculations necessary. Only in reconverting the per-unit values of the results to actual voltage and current values do we need to remember that two different voltages actually existed in the system.



TRANSFORMER RATIO = 13 200/2400 = 5.5

(A) HIGH VOLTAGE SYSTEM		(B) LOW VOLTAGE SYSTEM	RATIO $\frac{(A)}{(B)}$
13 800	BASE VOLTS	2500	5.5
1 000	BASE KVA	1000	1.0
41.6	BASE AMPS	230	1/5.5
190	BASE OHMS	6.25	$(5.5)^2$

(Photo A129287)

Fig. 27

Change To A New Base

Frequently the impedance of a circuit element expressed in terms of a particular base kVA must be expressed in terms of a different base kVA. For example, suppose a 500-kVA transformer having 0.05 pu reactance and a 1000-kVA transformer having 0.06 pu reactance (both expressed on their rated kVA as a base) are used in the same system. If calculations are to be made from an impedance diagram including both of those transformers they must be converted to a common kVA base.

Inasmuch as per-unit ohms is directly proportional to base kVA,

$$\left(\frac{\text{Per-unit ohms on new base kVA}}{\text{Per-unit ohms on old base kVA}}\right) = \frac{\text{New base kVA}}{\text{Old base kVA}}$$

and

Per-unit ohms on new base =

$$\left(\begin{matrix}\text{Per-unit ohms}\\ \text{on old base}\end{matrix}\right)\left(\frac{\text{New base kVA}}{\text{Old base kVA}}\right)$$

Likewise a machine rated at one voltage may actually be used in a circuit at a different voltage. If this latter voltage is selected as the base voltage, the per-unit impedance of the machine must then be changed to the new base voltage.

Inasmuch as per-unit ohms is inversely proportional to the square of base volts,

$$\frac{\text{Per-unit ohms on new base volts}}{\text{Per-unit ohms on old base volts}} = \frac{(\text{old base volts})^2}{(\text{new base volts})^2}$$

and

Per-unit ohms on new base volts =

$$\left(\begin{matrix}\text{Per-unit ohms}\\ \text{on old base volts}\end{matrix}\right)\left(\frac{(\text{old base volts})^2}{(\text{new base volts})^2}\right)$$

MANIPULATION OF COMPLEX QUANTITIES IN RECTANGULAR FORM

The rectangular form of complex quantities is the most widely used, although it does not lead to the simplest computations in all types of problems. A generalized notation in the rectangular form is $\pm A \pm jB$ where $j = \sqrt{-1}$. The basic quantities in most electrical problems are vector voltages such as $E = E_1+jE_2$, vector currents such as $I = I_1+jI_2$, and impedance operators such as $Z = R+jX$.

A very common type of problem requires long-hand resolution of a more-or-less complicated network of impedances into a single impedance quantity.

Whenever several impedances appear in the same example, they will have the following identifying notation:

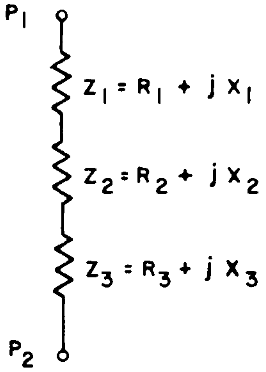
$$Z_1 = R_1+jX_1$$
$$Z_2 = R_2+jX_2$$
$$Z_3 = R_3+jX_3$$

The real part of a complex quantity will often be so small compared to the quadrature part that it can be ignored with little effect on a computed result. In such cases, resolved expressions and computation can be greatly simplified. Some of the examples to follow will include special cases of this type to indicate the extent of simplification.

Sums (or Differences)

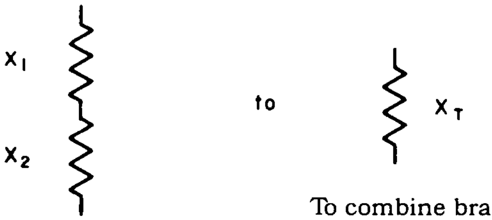
The sum of complex quantities is obtained by adding the real parts together to get the total real part, and adding the quadrature parts together to get the total quadrature part.

For example, the sum total impedance of series-connected impedances Z_1, Z_2, and Z_3 is determined by addition as follows:



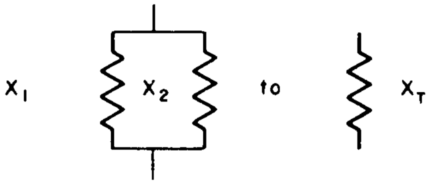
$$Z_1 = R_1+jX_1$$
$$Z_2 = R_2+jX_2$$
$$\underline{Z_3 = R_3+jX_3}$$
$$Z_t = (R_1+R_2+R_3)+j(X_1+X_2+X_3)$$
$$=R_t+jX_t$$

Methods for Combining Reactances



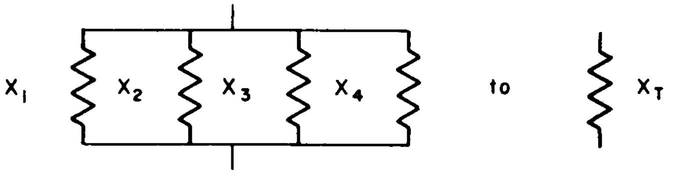
$X_T = X_1 + X_2$

To combine branches in series



$$X_T = \frac{X_1\,X_2}{X_1+X_2}$$

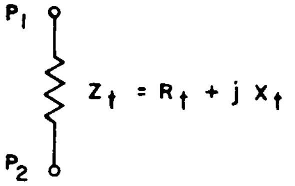
To combine branches in parallel
for two branches only



$$X_T = \frac{1}{\frac{1}{X_1}+\frac{1}{X_2}+\frac{1}{X_3}+\frac{1}{X_4}}$$

To combine branches in parallel
for more than two branches

The resulting equivalent diagram is:



Subtraction is accomplished as in algebra by first reversing all signs in the subtrahend, and then adding.

Products

Multiplication follows the fundamental rules of multiplying binomials. For example, the product:

$$Z_1Z_2 = (R_1+jX_1)\,(R_2+jX_2)$$
$$= (R_1\,R_2-X_1\,X_2)+j\,(R_1\,X_2+R_2\,X_1)$$
$$= R_{eq}+jX_{eq}$$

Special case where Resistance = 0:

$$Z_1Z_2 = (+jX_1)\,(+jX_2)$$
$$=-X_1\,X_2$$

Quotients

To resolve an expressed quotient requires applying the rationalization process just described. The resolution is repeated on the next page with respect to two impedances:

$$\frac{Z_1}{Z_2} = \frac{R_1+jX_1}{R_2+jX_2}$$
$$= \frac{R_1+jX_1}{R_2+jX_2}\left(\frac{R_2-jX_2}{R_2-jX_2}\right)$$
$$= \frac{(R_1R_2+X_1X_2)+j\,(R_2X_1-R_1X_2)}{R_2^2+X_2^2}$$
$$=\left(\frac{R_1R_2+X_1X_2}{R_2^2+X_2^2}\right)+j\left(\frac{R_2X_1-R_1X_2}{R_2^2+X_2^2}\right)$$
$$= R_{eq}+jX_{eq}$$

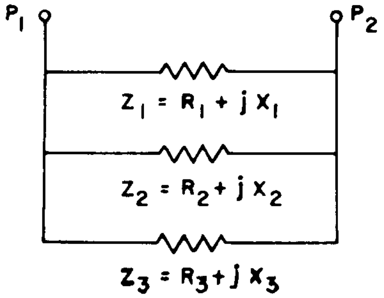
Special case where Resistance = 0:

$$\frac{Z_1}{Z_2} = \frac{+jX_1}{+jX_2} = \frac{X_1}{X_2}$$

Appendix—Analytical Techniques

Paralleled Impedances

To evaluate a multiplicity of impedances in parallel: (1) determine the admittance (1/Z) of each branch; (2) add the admittances of the several branches; and (3) convert the sum total admittance to an impedance by taking the reciprocal. This process is illustrated by the following example:



The resolution process is readily guided in routine work by the tabular form shown as TABLE 36 in which the parts of the several complex impedances are entered and manipulated as indicated.

Note that a plus sign is proper in all five columns, if the branch impedance is of the more common inductive character (R+jX). If any reactance is capacitive (−jX), the entry in the corresponding "B" column should be assigned a minus sign. In the rare event that a negative resistance (−R) is encountered, the entry in the corresponding "G" column should be assigned a minus sign.

TABLE 36—Form for Coverting Parallel Impedances to Single Admittance

	Impedances		$Z^2 = R^2+X^2$	Admittances	
	R	X		$G = R/\lvert Z\rvert^2$	$B = X/\lvert Z\rvert^2$
Branch 1	( )	( )	( )	( )	( )
Branch 2	( )	( )	( )	( )	( )
Branch 3	( )	( )	( )	( )	( )
				G_t	B_t

The tabulation process yields a total admittance $Y_t = G_t - jB_t$, and $|Y_t|^2 = G_t^2 + B_t^2$. Then the resulting impedance P_1 to P_2 becomes:

$$Z_{eq} = \frac{1}{Y_t} = \frac{G_t}{|Y_t|^2} + j\frac{B_t}{|Y_t|^2}$$

Special case where Resistance = 0:

$$Z_{eq} = +j\left(\frac{1}{\frac{1}{X_1} + \frac{1}{X_2} + \frac{1}{X_3}}\right);$$

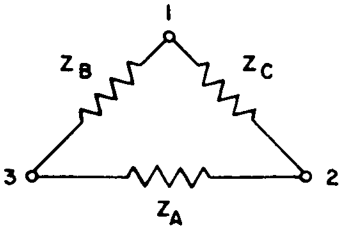
or for two reactances only, rearrangement yields the following valid expression:

$$Z_{eq} = +j\left(\frac{X_1X_2}{X_1+X_2}\right)$$

DELTA-Y AND Y-DELTA IMPEDANCE CONVERSIONS

In a three-terminal three-branch network limited to fixed-frequency operation, a delta impedance pattern can be converted to a Y pattern and vice versa. These can be very useful tools in the long-hand solution of network problems.

The diagrams here provide notation for internal impedances which are to be related in conversion formulas so that the two diagrams are equivalent when viewed from their terminals.

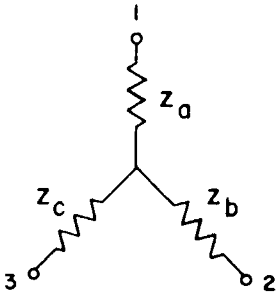


Case 1: With delta-connected impedances Z_A, Z_B, and Z_C known,

$$Z_a = \frac{Z_B Z_C}{Z_A+Z_B+Z_C}$$

$$Z_b = \frac{Z_C Z_A}{Z_A+Z_B+Z_C}$$

$$Z_c = \frac{Z_A+Z_B}{Z_A+Z_B+Z_C}$$



Case 2: With Y-connected impedances Z_a, Z_b, and Z_c known,

$$Z_A = Z_b + Z_c + \frac{Z_bZ_c}{Z_a}$$

$$Z_B = Z_a + Z_c + \frac{Z_aZ_c}{Z_b}$$

$$Z_C = Z_a + Z_b + \frac{Z_aZ_b}{Z_c}$$

Notes

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