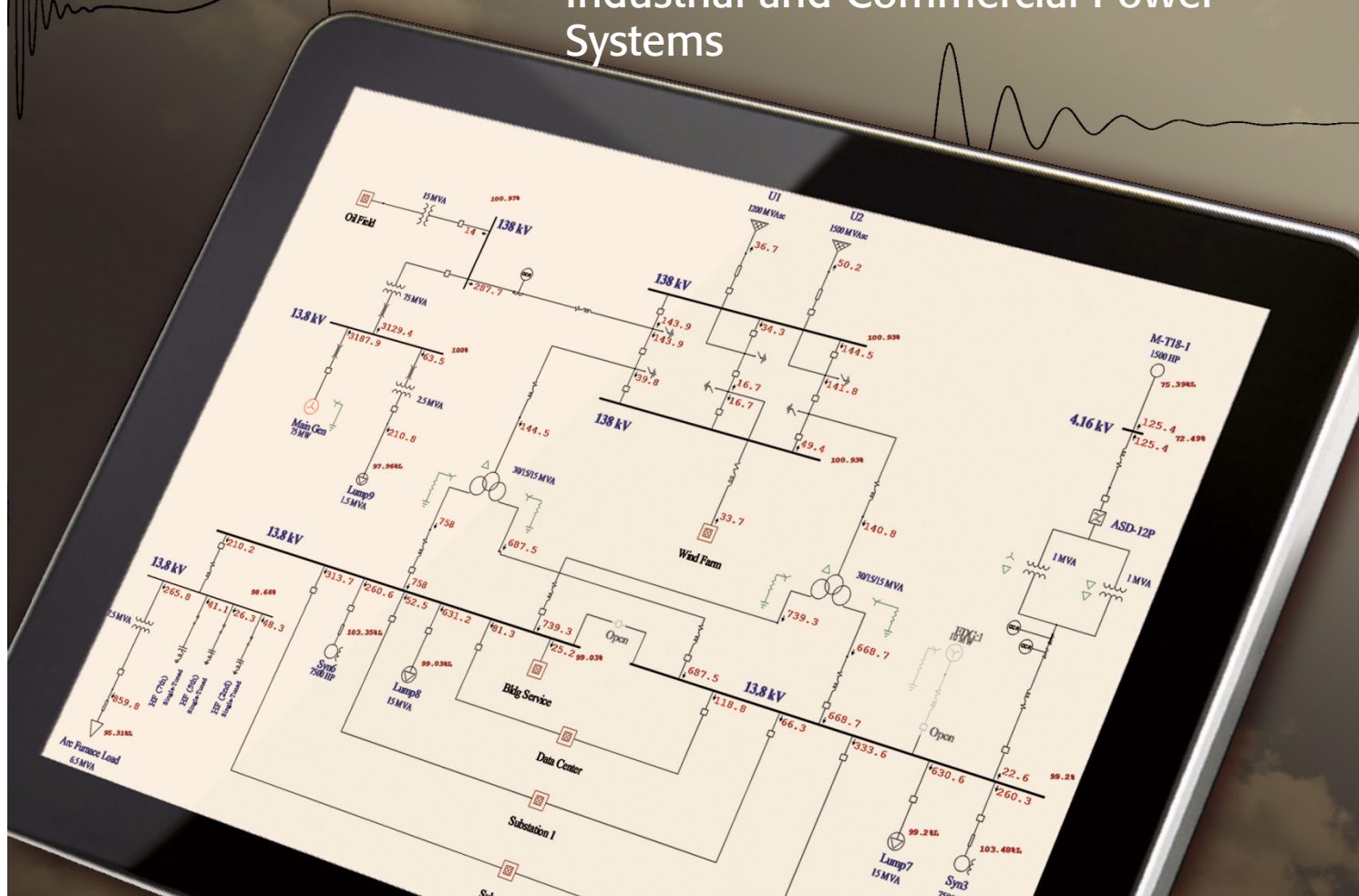


IEEE Std 3002.3™-2018

Recommended Practice for Conducting
Short-Circuit Studies and Analysis of
Industrial and Commercial Power
Systems



IEEE Recommended Practice for Conducting Short-Circuit Studies and Analysis of Industrial and Commercial Power Systems

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Abstract: Activities related to short-circuit analysis, including design considerations for new systems, analytical studies for existing systems, as well as operational and model validation considerations for industrial and commercial power systems are addressed. Fault current calculation and device duty evaluation is included in short-circuit analysis. Accuracy of calculation results primarily relies on system modeling assumptions and methods used. The use of computer-aided analysis software with a list of desirable capabilities recommended to conduct a modern short-circuit study is emphasized. Examples of system data requirements and result analysis techniques are presented.

Keywords: ac decrement, asymmetrical fault current, available fault current, bolted fault, breaking capacity, breaking duty, data collection, dc component, dc decrement, dc offset, device duty calculation, fault calculation, fault duty, IEEE 3002.3, interrupting capacity, interrupting duty, making capacity, making duty, momentary capacity, momentary duty, short-circuit analysis, short-circuit current, short-circuit studies, short-circuit withstand, symmetrical component, symmetrical fault current, system modeling, system validation, X/R ratio

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This introduction is not part of IEEE Std 3002.3-2018, IEEE Recommended Practice for Conducting Short-Circuit Studies and Analysis of Industrial and Commercial Power Systems.

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When this project is completed, the technical material included in the 13 IEEE Color Books will be included in a series of new standards—the most significant of which will be a new standard, IEEE Std 3000™, IEEE Recommended Practice for the Engineering of Industrial and Commercial Power Systems. The new standard will cover the fundamentals of planning, design, analysis, construction, installation, startup, operation, and maintenance of electrical systems in industrial and commercial facilities. Approximately 60 additional dot standards, organized into the following categories, will provide in-depth treatment of many of the topics introduced by IEEE Std 3000™:

- Power Systems Design (3001 series)
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IEEE Std 3002.3™

The material in this recommended practice partially comes from IEEE Std 551™, IEEE Recommended Practice for Calculating AC Short-Circuit Currents in Industrial and Power Systems (*IEEE Violet Book™*) and IEEE Std 399™, IEEE Recommended Practice for Industrial and Commercial Power System Analysis.^{1, 2}

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IEEE Recommended Practice for Conducting Short-Circuit Studies and Analysis of Industrial and Commercial Power Systems

1. Scope

This recommended practice describes how to conduct short-circuit studies and analysis of industrial and commercial power systems. It is likely to be of greatest value to the power-oriented engineer with limited experience in this area.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

ANSI/IEEE Std C37.5™, IEEE Guide for Calculation of Fault Currents for Application of AC High-Voltage Circuit Breakers Rated on a Total Current Basis.¹

IEC 60909, Short-circuit currents in three-phase a.c. systems.²

IEC 61363-1:1998, Electrical installations of ships and mobile and fixed offshore units—Part 1: Procedures for calculating short-circuit currents in three-phase a.c.

IEEE Std 141™, IEEE Recommended Practice for Electric Power Distribution for Industrial Plants (*IEEE Red Book™*).^{3, 4}

IEEE Std 241™, IEEE Recommended Practice for Electric Power Systems in Commercial Buildings (*IEEE Gray Book™*).

IEEE Std 242™, IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems (*IEEE Buff Book™*).

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IEEE Std 551TM-2006, IEEE Recommended Practice for Calculating AC Short-Circuit Currents in Industrial and Commercial Power Systems (*IEEE Violet Book*TM).

IEEE Std C37.010TM, IEEE Application Guide for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis.

IEEE Std C37.13TM, IEEE Standard for Low-Voltage AC Power Circuit Breakers Used in Enclosures.

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.⁵

arcing time: The interval of time between the instant of the first initiation of the arc and the instant of final arc extinction in all poles.

armature: The main current carrying winding of a machine, usually the stator.

armature resistance: R_a —The direct current armature resistance. This is determined from a dc resistance measurement. The approximate effective ac resistance is $1.2 R_a$.

effective resistance: The applicable ac resistance of rotating machines for the purpose of short-circuit calculations.

NOTE—For induction machines, the approximate effective resistance is 1.2 times the armature resistance, R_a . For synchronous machines, the effective resistance is given as follows:⁶

$$\text{Effective resistance} = \frac{X_{2v}}{(2\pi f T_{a3})}$$

where X_{2v} is the rated voltage negative sequence reactance and T_{a3} is the rated voltage generator armature time constant(s). (See footnote of IEEE Std C37.010TM-1999, Table 8.)

asymmetrical current: The combination of the symmetrical component and the direct current component of the current.

available current: The current that would flow if each pole of the breaking device under consideration were replaced by a link of negligible impedance without any change of the circuit or the supply.

breaking current: The current in a pole of a switching device at the instant of the arc initiation. Better known as *interrupting current*.

circuit breaker: A switching device capable of making, carrying, and breaking currents under normal circuit conditions and also making, carrying for a specified time, and breaking currents under specified abnormal conditions, such as those of short-circuit.

⁵ *IEEE Standards Dictionary Online* subscription is available at: <http://dictionary.ieee.org>.

⁶ Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

clearing time: The total time between the beginning of specified overcurrent and the final interruption of the circuit at rated voltage. In regard to fuses, it is the sum of the minimum melting time of a fuse, plus tolerance and the arcing time. In regard for circuit breakers, depending on types and operating mechanism, the clearing time may be made up of some or all of the following: sensing time (relay tripping time), algorithm execution time, electromechanical actuation time, mechanism operating time, and additional arcing time. Sometimes referred to as *total clearing time* or *interrupting time*.

close and latch: The capability of a switching device to close (allow current flow) and immediately thereafter latch (remain closed) and conduct a specified current through the device under specified conditions.

close and latch duty: The maximum rms value of calculated short-circuit current for medium- and high-voltage circuit breakers during the first cycle with any applicable multipliers for fault current X/R ratio. Often the close and latching duty calculation is simplified by applying a 1.6 factor to the calculated circuit breaker first-cycle symmetrical ac rms short-circuit current. Also called *first-cycle duty* (formerly, *momentary duty*).

close and latch rating: The maximum current capability of a medium or high-voltage circuit breaker to close and immediately thereafter latch closed for normal-frequency making current. The close and latch rating is 1.6 times the circuit breaker rated maximum symmetrical interrupting current in ac rms amperes, or a peak current is 2.7 times ac rms rated maximum symmetrical interrupting current. Also called *first-cycle rating* (formerly, *momentary rating*).

contact parting time: The interval between the time when the actuating quantity in the release circuit reaches the value causing actuation of the release and the instant when the primary arcing contacts have parted in all poles. Contact parting time is the numerical sum of release delay and opening time.

crest current: The highest instantaneous current during a period. *Syn:* **peak current**.

direct axis: The machine axis that represents a plane of symmetry in line with the no-load field winding.

direct-axis saturated subtransient reactance: X''_{dv} (rated voltage) is the apparent reactance of the stator winding at the instant short-circuit occurs with the machine at rated voltage, no load. This reactance determines the current flow during the first few cycles after short-circuit.

direct-axis unsaturated subtransient reactance: X''_{di} (rated current) is the reactance that is determined from the ratio of an initial reduced voltage open circuit condition and the currents from a three-phase fault at the machine terminals at rated frequency. The initial open-circuit voltage is adjusted so that rated current is obtained. The impedance is determined from the currents during the first few cycles.

direct-axis saturated transient reactance: X'_{dv} (rated voltage) is the apparent reactance of the stator winding several cycles after initiation of the fault with the machine at rated voltage, no load. The time period for which the reactance may be considered X'_{dv} can be up to a half second or longer, depending upon the design of the machine and is determined by the machine direct-axis transient time constant.

direct-axis unsaturated transient reactance: X'_{di} (rated current) is the reactance that is determined from the ratio of an initial reduced voltage open circuit condition and the currents from a three-phase fault at the machine terminals at rated frequency. The initial open-circuit voltage is adjusted so that rated current is obtained. The initial high decrement currents during the first few cycles are neglected.

fault: A current that flows from one conductor to ground or to another conductor owing to an abnormal connection (including an arc) between the two. *Syn:* **short-circuit**.

fault point angle: The calculated fault point angle ($\tan^{-1}[X/R \text{ ratio}]$) using complex ($R + jX$) reactance and resistance networks for the X/R ratio.

fault point X/R : The calculated fault point X/R ratio using separate reactance and resistance networks.

field: The exciting or magnetizing winding of a machine.

first-cycle duty: The maximum value of calculated short-circuit current for the first cycle with any applicable multipliers for fault current X/R ratio.

first-cycle rating: The maximum current capability of a piece of equipment during the first cycle of a fault.

frequency: The rated frequency of a circuit.

fuse: A device that protects a circuit by melting open its current-carrying element when an overcurrent or short-circuit current passes through it.

high voltage: Circuit voltages over nominal 34.5 kV.

NOTE—ANSI standards are not unanimous in establishing the threshold of “high voltage.”

impedance: The vector sum of resistance and reactance in an ac circuit.

interrupting current: The current in a pole of a switching device at the instant of the arc initiation. Sometime referred to as *breaking current*.

interrupting time: The interval between the time when the actuating device “sees” or responds to a operating value, the opening time and arcing time. Sometimes referred to as *total break time* or *clearing time*.

low voltage: Circuit voltage under 1000 V.

maximum rated voltage: The upper operating voltage limit for a device.

medium voltage: Circuit voltage greater than 1000 V up to and including 34.5 kV.

NOTE—ANSI standards are not unanimous in establishing the threshold of medium voltage.

minimum rated voltage: The lower operating voltage limit for a device where the rated interrupting current is a maximum. Operating circuit breakers at voltages lower than minimum rated voltage restricts the interrupting current to maximum rated interrupting current.

momentary current rating: The maximum rms current measured at the major peak of the first cycle, which the device or assembly is required to carry. Momentary rating was used on medium- and high-voltage circuit breakers manufactured before 1965. See presently used terminology of **close and latch rating**.

momentary current duty: See presently used terminology of **close and latch duty**. Used for medium- and high-voltage circuit breaker duty calculations for circuit breakers manufactured before 1965.

negative sequence: A set of symmetrical components that have the angular phase lag from the first member of the set to the second and every other member of the set equal to the characteristic angular phase difference and rotating in the reverse direction of the original vectors. For a three-phase system, the angular different is 120° . *See also: symmetrical components.*

negative sequence reactance: X_{2v} (saturated, rated voltage). The rated current value of negative sequence reactance is the value obtained from a test with a fundamental negative sequence current equal to rated armature current (of the machine). The rated voltage value of negative sequence reactance is the value obtained from a line-to-line short-circuit test at two terminals of the machine at rated speed, applied from no load at rated voltage, the resulting value being corrected when necessary for the effect of harmonic components in the current.

offset current: A current waveform whose baseline is offset from the ac symmetrical current zero axis.

opening time: The time interval between the time when the actuating quantity of the release circuit reaches the operating value, and the instant when the primary arcing contacts have parted. The opening time includes the operating time of an auxiliary relay in the release circuit when such a relay is required and supplied as part of the switching device.

peak current: The highest instantaneous current during a period.

positive sequence: A set of symmetrical components that have the angular phase lag from the first member of the set to the second and every other member of the set equal to the characteristic angular phase difference and rotating in the same phase sequence of the original vectors. For a three-phase system, the angular difference is 120° . *See also:* **symmetrical components**.

positive sequence machine resistance: R_1 is that value of rated frequency armature resistance that, when multiplied by the square of the rated positive sequence armature current and by the number of phases, is equal to the sum of the copper loss in the armature and the load loss resulting from the flow of that current. This is **NOT** the resistance to be used for the machine in short-circuit calculations.

quadrature axis: The machine axis that represents a plane of symmetry in the field that produces no magnetization. This axis is 90° ahead of the direct axis.

quadrature-axis saturated subtransient reactance: X''_{qv} (rated voltage) same as X''_{dv} except in quadrature axis.

quadrature-axis unsaturated subtransient reactance: X''_{qi} (rated current) same as X''_{di} except in quadrature axis.

quadrature-axis unsaturated transient reactance: X_q (rated current) is the ratio of reactive armature voltage to quadrature-axis armature current at rated frequency and voltage.

quadrature-axis saturated transient reactance: X'_{qv} (rated voltage) same as X'_{dv} except in quadrature axis.

quadrature-axis unsaturated transient reactance: X'_{qi} (rated voltage) same as X'_{di} except in quadrature axis.

rating: The designated limit(s) of the operating characteristic(s) of a device. These data are usually on the device nameplate.

rms: The square root of the average value of the square of the voltage or current taken throughout one period. In this text, rms will be considered total rms unless otherwise noted.

rms ac: The square root of the average value of the square of the ac voltage or current taken throughout one period.

rms, single cycle: *See:* **single-cycle rms**.

rms, total: *See:* **total rms**.

rotor: The rotating member of a machine.

short-circuit: An abnormal connection (including arc) of relative low impedance, whether made accidentally or intentionally, between two points of different potentials. *Syn:* **fault**.

short-circuit duty: The maximum value of calculated short-circuit current for either first-cycle current or interrupting current with any applicable multipliers for fault current X/R ratio or decrement.

single-cycle rms: The square root of the average value of the square of the ac voltage or current taken throughout one ac cycle.

stator: The stationary member of a machine.

symmetrical: That portion of the total current that, when viewed as a waveform, has equal positive and negative values over time, such as the form exhibited by a pure, single frequency sinusoidal waveform.

symmetrical components: A symmetrical set of three vectors used to mathematically represent an unsymmetrical set of three-phase voltages or currents. In a three-phase system, one set of three equal magnitude vectors displaced from each other by 120° in the same sequence as the original set of unsymmetrical vectors. This set of vectors is called the positive sequence component. A second set of three equal magnitude vectors displaced from each other by 120° in the reverse sequence as the original set of unsymmetrical vectors. This set of vectors is called the negative sequence component. A third set of three equal magnitude vectors displaced from each other by 0° . This set of vectors is called the *zero sequence component*.

synchronous reactance: Direct axis X_d (unsaturated, rated current) is the self-reactance of the armature winding to the steady-state balanced three-phase positive sequence current at rated frequency and voltage in the direct axis. It is determined from an initial open-circuit voltage and a sustained short-circuit on the synchronous machine terminals.

time constant, rated voltage three-phase short-circuit armature (T_{a3}): T_{a3} is the time constant representing the decay of the machine currents to a suddenly applied three-phase short-circuit to the terminals of a machine initially at rated voltage, rated speed, and no load.

total break time: The interval between the time when the actuating quantity of the release circuit reaches the operating value, the switching device being in a closed position, and the instant of arc extinction on the primary arcing contacts. Total break time is equal to the sum of the opening time and arcing time. Better known as **interrupting time**.

total clearing time: *See:* **clearing time** or **interrupting time**.

total rms: The square root of the average value of the square of the ac and dc voltage or current taken throughout one period.

voltage, high: *See:* **high voltage**.

voltage, low: *See:* **low voltage**.

voltage, medium: *See:* **medium voltage**.

voltage range factor: The voltage range factor, K , is the range of voltage to which the circuit breaker can be applied where EI equals a constant. K equals the maximum rated operating voltage divided by the minimum rated operating voltage.

X/R ratio: The ratio of rated frequency reactance and effective resistance to be used for short-circuit calculations. Approximately equal to $\frac{X_{2v}}{1.2R_a}$ or $2\pi fT_{a3}$.

zero sequence: A set of symmetrical components that have the angular phase lag from the first member of the set to the second and every other member of the set equal to 0° and rotating in the same direction as the original vectors. *See also:* **symmetrical components**.

30-cycle time: A time 30 cycles after the actuating quantity of the release circuit reaches the operating value. After this time period, the ac decaying component of a fault current is considered to be negligible.

3.2 Acronyms and abbreviations

The following are the symbols and their definitions that are used in this standard.

a	symmetrical component operator = 120°
e	instantaneous voltage
e_o	initial voltage
E	rms voltage
$E_{\max}$	peak or crest voltage
E_{LN}	rms line-to-neutral voltage
E_{LL}	rms line-to-line voltage
f	frequency in Hertz
i	instantaneous current
i_{dc}	instantaneous dc current
i_{ac}	instantaneous ac current
I	rms current
$I_{\max}$	peak or crest current
$I_{\max,s}$	symmetrical peak current
$I_{\max,ds}$	decaying symmetrical peak current
I'	rms transient current
I''	rms subtransient current

I'_{dd}	interrupting duty current
I''_{dd}	first-cycle duty current
I_{ss}	rms steady-state current
j	90° rotative operator, imaginary unit
L	inductance
Q	electric charge
R	resistance
R_a	armature resistance
t	time
T_{a3}	three-phase short-circuit armature time constant
X	reactance
X'_d	transient direct-axis reactance
X''_d	subtransient direct-axis reactance
X'_q	transient quadrature-axis reactance
X''_q	subtransient quadrature-axis reactance
X_{2v}	negative sequence reactance
Z	impedance: $Z = R + jX$
α	$\tan^{-1}(\omega L/R) = \tan^{-1}(X/R)$
ϕ	phase angle
ω	angular frequency: $\omega = 2\pi f$
τ	intermediate time
θ	phase angle difference

4. Introduction

4.1 Overview

Conducting thorough and detailed short-circuit studies and analysis of industrial and commercial power systems is of critical importance. Electric power systems in industrial plants and 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 or *faults* as they are commonly called. Uncontrolled short-circuits can cause service outage 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.

Short-circuits are caused by faults in the insulation of a circuit, and in many cases an arc ensues at the point of the fault. Such an arc may be destructive and may constitute a personnel arc-flash hazard or a structure fire hazard. Prolonged duration of arcs, in addition to the heat released, may result in transient overvoltages that may endanger the insulation of equipment in other parts of the system. Faults can also be caused by accidental contact or too small a separation between live conductors or between live conductors and ground. Arcing faults, specifically at low voltage, may be significantly lower in magnitude than calculated maximum bolted faults. Clearly, the fault must be quickly removed from the power system, and this is the job of the circuit protective devices—the circuit breakers and fusible switches.

A short-circuit current generates heat that is proportional to the square of the current magnitude, I^2R . The large amount of heat generated by a short-circuit current may damage the insulation of rotating machinery and apparatus which is connected in the faulted system, including cables, transformers, switches, and circuit breakers. The most immediate danger involved in the heat generated by short-circuit currents is permanent destruction of insulation. This may be followed by actual fusion of the conducting circuit, with resultant additional arcing faults.

The heat that is generated by high short-circuit currents tends not only to impair insulating materials to the point of permanent destruction, but also exerts harmful effects upon the contact members in interrupting devices.

The small area common between two contact members that are in engagement depends mainly upon the hardness of the contact material and upon the amount of pressure by which they are kept in engagement. Owing to the concentration of the flow of current at the points of contact engagement, the temperatures of these points reached at the times of peak current are very high. As a result of these high-spot temperatures, the material of which the contact members are made may soften. If, however, the contact material is caused to melt by excessive I^2R losses, there is an imminent danger of welding the contacts together, rendering it impossible to separate the contact members when the switch or circuit breaker is called upon to open the circuit. Since it requires very little time to establish thermal equilibrium at the small points of contact engagement, the temperature at these points depends more upon the peak current than upon the rms current. If the peak current is sufficient to cause the contact material to melt, solidification may occur immediately upon decrease of the current from its peak value.

Other important effects of short-circuit currents are the strong electromagnetic forces of attraction and repulsion to which the conductors are subjected when short-circuit currents are present. These forces are proportional to the square of the current and may subject any rotating machinery, transmission, and switching equipment to severe mechanical stresses and strains. The strong electromagnetic forces that high short-circuit currents exert upon equipment can cause deformation in rotational machines, transformer windings, and equipment bus bars, which may fail at a future time. Deformation in circuit breakers and switches will cause alignment and interruption difficulties.

Modern interconnected systems involve the operation in parallel of large numbers of synchronous machines, and the stability of such an interconnected system may be greatly impaired if a short-circuit in

any part of the system is allowed to prevail. The stability of a system requires short fault-clearing times and can be more limiting than the longer time considerations imposed by thermal or mechanical effects on the equipment.

4.2 Objectives for short-circuit analysis

Due to the severe impact that a short-circuit can cause to power system operation and safety of equipment and personnel, a fault in a system must be automatically detected and removed from the system as soon as possible. This requires extensive studies of system conditions under a fault. The system behavior under a short-circuit can be studied by short-circuit analysis or dynamic simulation. A dynamic simulation solves a set of algebraic and differential equations representing dynamic characteristics of rotating machines and their control systems. The dynamic simulation requires detailed modeling of system equipment, especially synchronous generators including governor and exciter, etc. It provides detailed short-circuit current waveforms. However, the equipment data required to perform dynamic simulation of short-circuit is often not readily available and therefore this type of study is not commonly used. The dynamic simulation of short-circuit is beyond the scope of this standard.

The short-circuit analysis is quasi-static study. It determines the total fault current and fault current contributions throughout the system, including contribution sources, such as power grid, synchronous generator, synchronous motor, and induction motors. In the short-circuit analysis, contributing sources are represented by approximate models to calculate the maximum possible fault current values for protection device evaluation or selection. Minimum fault current, arcing fault current, and fault current under other conditions can also be determined in short-circuit analysis. The calculation results are used in determining protective device settings and arc flash incident energy.

The results from a short-circuit analysis are required in the design of new systems and in analysis of existing systems. In the design of a new system, they are used to size equipment ratings, such as bus bars, cables, transformers, and protective devices. For an existing system, the short-circuit analysis results are used to verify acceptable equipment ratings. The following are objectives for short-circuit analysis:

- a) Verify the protective device closing and latching capability.
- b) Verify the protective device interrupting capability.
- c) Verify the equipment's ability to withstand large mechanical forces caused by the maximum short-circuit capacity.
- d) Verify the equipment's ability to withstand thermal stress based on I^2t values.
- e) Determine branch fault currents under various conditions as required to determine protective relay settings and associated equipment ratings.
- f) Determine short-circuit currents necessary for the calculation of arc fault incident energy (IEEE Std 1584™-2002 [B46]).

4.3 Methodology and standards

There are a number of standards for short-circuit analysis adopted by different organizations in the world, such as ANSI/IEEE standards, IEC standards, Russian standards (GOST), Chinese standards (GB), etc. The basic methods for short-circuit calculations are very similar, but with differences in modeling of various types of equipment and considerations of system prefault operating conditions. This standard will provide a detailed description based on the ANSI/IEEE and IEC standards, primarily due to their most eminent influence in the world. Clause 2 lists several IEEE and IEC standards that are indispensable for the application of this document.

5. Description of short-circuit current

5.1 Introduction

Electric power systems are designed to be as fault-free as possible through careful system and equipment design, proper equipment installation, and periodic equipment maintenance. However, even when these practices are followed, faults do occur. Some of the causes of faults are:

- a) Presence of animals, such as birds and insects, in equipment
- b) Loose connections causing equipment overheating
- c) Voltage surges
- d) Deterioration of insulation due to age
- e) Voltage or mechanical stresses applied to the equipment
- f) Accumulation of moisture or other contaminants
- g) The intrusion of metallic or conducting objects into the equipment, such as grounding clamps, fish tape, tools, jackhammers, or pay-loaders
- h) A large assortment of “undetermined causes”
- i) Over-dutied equipment
- j) Human error during installation or maintenance work
- k) Inadequate cooling
- l) Natural disasters (heavy rain or wind storms, floods, etc.)

When a short-circuit occurs in an electric power distribution system, several things can happen, such as:

- The short-circuit currents may be very high, introducing a significant amount of energy into the fault.
- At the fault location, arcing and burning can occur damaging adjacent equipment and also possibly presenting an arc flash hazard to personnel working on the equipment.
- Short-circuit current may flow from the various rotating machines in the electrical distribution system to the fault location.
- All components carrying the short-circuit currents will be subjected to thermal and mechanical stresses due to current flow. This stress varies as a function of the magnitude of the current squared and the duration of the current flow (I^2t) and may damage these components.
- System voltage levels drop in proportion to the magnitude of the short-circuit currents flowing through the system elements. Maximum voltage drop occurs at the fault location (down to zero for a bolted fault), but all parts of the power system will be subject to a voltage drop to some degree.

5.2 Available short-circuit current

The *available* short-circuit current is defined as the maximum possible value of short-circuit current that may occur at a particular location in the distribution system assuming that no fault-related influences, such as fault arc impedances, are acting to reduce the fault current. The available short-circuit current is directly related to the size and capacity of the power sources (utility, generators, and motors) supplying the system and is typically independent of the load current of the circuit. The larger the capacity of the power sources supplying the system, the greater the available short-circuit current (generally). The main factors

determining the magnitude and duration of the short-circuit currents are the type of fault, fault current sources present, and the impedances between the sources and the point of the short-circuit. The characteristics, locations, and sizes of the fault current sources connected to the distribution system at the time the short-circuit occurs have an influence on both the initial magnitude and the wave shape of the fault current.

Alternating current (ac) synchronous and induction motors, generators, and utility ties are the predominant sources of short-circuit currents. At the time of the short-circuit, synchronous and induction motors will act as generators and will supply current to the short-circuit based on the amount of stored electrical energy in them. In an industrial plant, motors often contribute a significant share of the total available short-circuit current.

5.3 Symmetrical and asymmetrical currents

The terms *symmetrical* current and *asymmetrical* current describe the shape of the ac current waveforms about the zero axis. If the envelopes of the positive and negative peaks of the current waveform are symmetrical around the zero axis, they are called *symmetrical current envelopes* (Figure 1). The envelope is a line drawn through the peaks or crests of the waves.

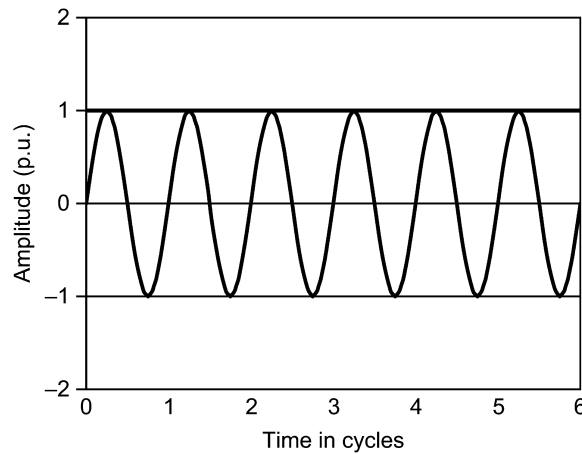


Figure 1—Symmetrical ac waveform

If the envelopes of positive and negative peaks are not symmetrical around the zero axis, they are called *asymmetrical current envelopes*. Figure 2 shows a fully offset (non-decaying) fault current waveform. The amount of offset that will occur in a fault current waveform depends on the time at which the fault occurs on the ac voltage waveform and the network resistances and reactances. The current in a purely reactive network could have any offset from none to fully offset, depending on the time of its inception, and the offset would be sustained (not decaying). A fault occurring in a purely resistive system would have no offset in the current waveform. A network containing both resistances and reactances will generally begin with some offset in the current (up to peak ac value) and gradually the current will become symmetrical (because of the decay of the offset) around the zero axis.

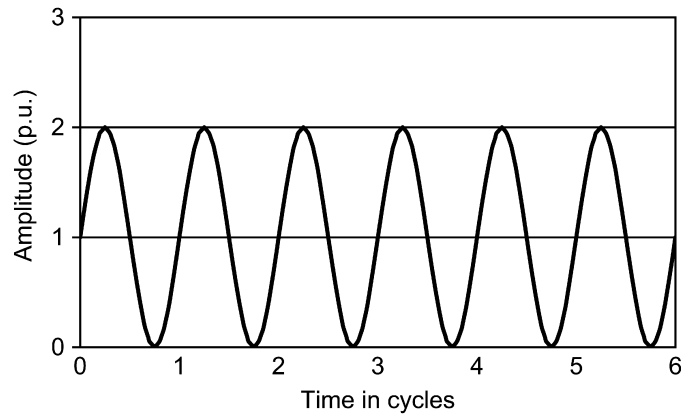


Figure 2—Totally offset ac waveform

As stated previously, induction and synchronous machines connected to the system supply current to the fault and, because of the limited amount of stored electrical energy in them, their currents decay with time. Figure 3 shows the symmetrical portion of a decaying fault current waveform typical for such equipment.

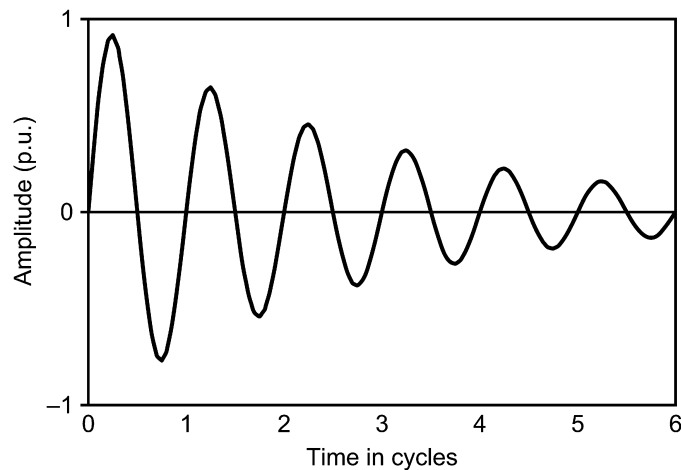


Figure 3—Decaying symmetrical ac waveform

Short-circuit currents are nearly always asymmetrical during the first few cycles after the short-circuit occurs and contain both dc and ac components. The dc component is shown in Figure 4. The asymmetrical current component (dc) is always at a maximum during the first cycle after the short-circuit occurs. This dc component gradually decays to zero. A typical asymmetrical short-circuit current waveform is shown in Figure 5.

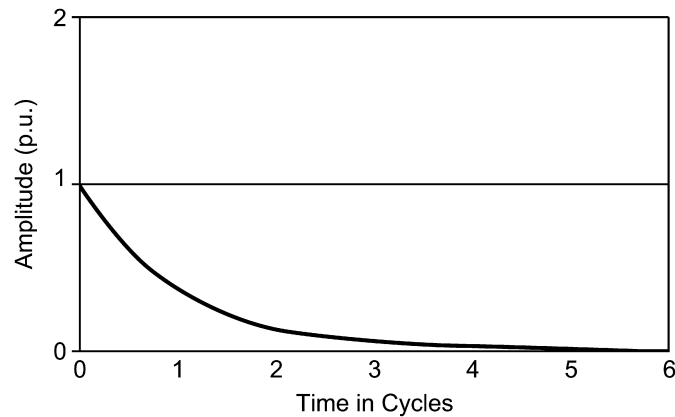


Figure 4—Decaying dc waveform

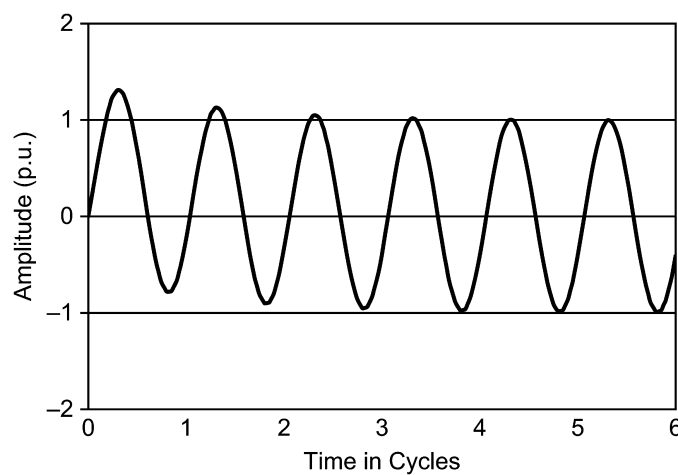


Figure 5—Asymmetrical fault current ac waveform

5.4 Short-circuit calculations

The calculation of the precise magnitude of a short-circuit current at a given time after the inception of a fault is a rather complex computation. Consequently, simplified methods have been developed that yield conservative calculated short-circuit currents that may be compared with the assigned (tested) fault current ratings of various system overcurrent protective devices. Figure 6 provides a means of understanding the shape of the fault current waveform, and consequently the fault current magnitude at any point in time. The circuit consists of an ideal sinusoidal voltage source and a series combination of a resistance, an inductance, and a switch. The fault is initiated by the closing of the switch. The value of the rms symmetrical short-circuit current, I , is determined through the use of the proper impedance in Equation (1):

$$I = \frac{E}{Z} \quad (1)$$

where

E is the rms driving voltage

Z (or X) is the Thevenin equivalent system impedance (or reactance) from the fault point back to and including the source or sources of short-circuit currents for the distribution system

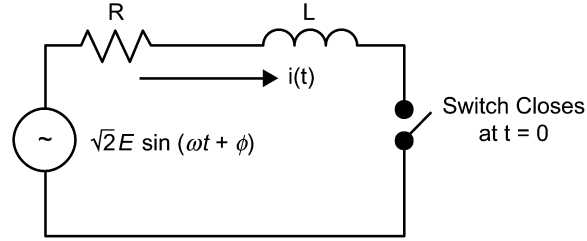


Figure 6—Circuit model for asymmetry

One simplification that is made is that all machine internal voltages are the same. In reality, the equivalent driving voltages used are the internal voltages of the electrical machines where each machine has a different voltage based on loading and impedance. During a fault, the machine's magnetic energy or its internal voltage is reduced faster than it can be replaced by energy supplied by the machine's field. This results in a decay (gradual reduction) of driving voltage over time. The rate of decay differs for each source. The resistance and reactance of machines is a fixed value based on the physical design of the equipment. Solving a multi-element system with many varying voltage sources becomes cumbersome. The same current can be determined by holding the voltage fixed and varying the machine impedance with time. This interchange helps to simplify the mathematics. The value of the impedance that must be used in these calculations is determined with regard to the basis of rating for the protective device or equipment under consideration. Different types of protective devices or equipment require different machine impedances to determine the fault current duty. Equipment evaluated on a first-cycle criteria would use a lower machine impedance and hence a higher current than equipment evaluated on an interrupting-time basis (1.5 to 8 cycles), which uses a higher impedance.

The determination of how the fault current behaves as a function of time involves expansion of Equation (1) and the solution of Equation (2) for current i :

$$Ri + L \frac{di}{dt} = \sqrt{2}E \sin(\omega t + \alpha) \quad (2)$$

where

- E is the rms magnitude of the sinusoidal voltage source
- i is the instantaneous current in the circuit at any time after the switch is closed
- R is the circuit resistance in ohms
- L is the circuit inductance in Henries (equal to the circuit reactance divided by ω)
- t is time in seconds
- α is the angle of the applied voltage in radians when the fault occurs
- ω is $2\pi f$ where f is the system frequency in hertz (Hz)

The details of the solution of Equation (2) are well-covered in electric power textbooks, so only the solution of the equation will be stated here. Assuming the prefault current through the circuit to be zero (i.e., load current = 0), then the instantaneous current solution to Equation (2) is

$$i = -\frac{\sqrt{2}E}{Z} \sin(\alpha - \phi) e^{-\frac{\omega t R}{X}} + \frac{\sqrt{2}E}{Z} \sin(\omega t + \alpha - \phi) \quad (3)$$

$$i = -i_{dc} \sin(\alpha - \phi) e^{-\frac{\omega t R}{X}} + \sqrt{2}I_{ac,rms} \sin(\omega t + \alpha - \phi) \quad (4)$$

where

$$\phi = \tan^{-1} \left(\frac{\omega L}{R} \right) = \tan^{-1} \left(\frac{X}{R} \right)$$

$$X = \omega L$$

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

If time t is expressed in cycles, Equation (4) becomes

$$i = -i_{dc} \sin(\alpha - \phi) e^{-\frac{2\pi R t}{X}} + \sqrt{2} I_{ac,rms} \sin(2\pi t + \alpha - \phi) \quad (5)$$

The first term in Equation (3) represents the transient dc component of the solution. The initial magnitude $\sqrt{2} E/Z \times \sin(\alpha - \phi)$ decays in accordance with the exponential expression. This dc component eventually disappears. The second term represents the steady-state ac component of the solution. The second term is a sinusoidal function of time whose crest value is simply the maximum peak value of the supply voltage divided by the magnitude of the Thevenin equivalent system impedance ($\sqrt{2} E/Z$) as viewed from the fault. The difference between the initial fault current magnitude and the final steady-state fault current magnitude depends only on the X/R ratio of the circuit impedance and the phase angle α of the supply voltage when the fault occurs. Note that at time zero the dc component of fault current is exactly equal in magnitude to the value of the ac fault current component, but opposite in sign. This condition must exist due to the fact that the initial current in the circuit is zero and the fact that current cannot change instantaneously in the inductive circuit of Figure 6.

The significance of the transient and steady-state components of the fault current is best illustrated by considering an actual example. Figure 5 shows the response of a specific circuit with an X/R ratio of 7.5. The circuit is supplied by a 60 Hertz source ($\omega = 377$), with the fault occurring (switch closes) when the voltage is at $\alpha = 58^\circ$. The plot of the current is obtained from the general solution of Equation (3).

5.5 Total short-circuit current

The total short-circuit current available in a distribution system is usually supplied from a number of sources, which can be grouped into three main categories. The first is the utility transmission system supplying the facility, which acts like a large, remote generator. The second includes “local” generators, either in the plant or nearby in the utility. The third source category is synchronous and induction motors, which are located in many plants and facilities. All these are rotating machines; those of the second and third categories have machine currents that decay significantly with time due to reduction of flux in the machine during a short-circuit. For a short-circuit at its terminals, the induction motor symmetrical current disappears entirely after one to twelve cycles, while the current of a synchronous motor is maintained at a lower initial value by its energized field. Networks having a greater proportion of induction motors to synchronous motors will have quicker decays of ac short-circuit current components. The fault current magnitude during the first few cycles is further increased by the dc fault current component (Figure 4). This component also decays with time, increasing the difference in short-circuit current magnitude between the first cycle after the short-circuit occurs and a few cycles later.

The total short-circuit current that has steady-state ac, decaying ac, and decaying dc current components can be expressed as shown in Equation (6). Figure 7 shows the circuit diagram and Figure 8 shows the response curve corresponding to Equation (6). Although decaying sources are not usually shown in equivalent circuits, a separate decaying source has been shown in Figure 7 to assist the reader with understanding the interactions that occur in real world applications.

$$i = i_{dc\ decay} + i_{ac\ steady\ state} + i_{ac\ decay} \quad (6)$$

with

$$i_{dc\ decay} = (I_{ac\ steady\ state}) \sin(\alpha - \phi) e^{-\frac{R\omega t}{X}}$$

$$i_{ac\ steady\ state} = \sqrt{2} I_s \sin(\omega t + \alpha - \phi)$$

$$i_{ac\ decay} = \sqrt{2} I_{ds} \sin(\omega t + \alpha - \phi) e^{-kt}$$

where

- I_s is the symmetrical steady-state rms current magnitude
- I_{ds} is the decaying symmetrical rms current magnitude
- k is a variable depending upon the mix and size of rotational loads
- t is in seconds

The magnitude and duration of the asymmetrical current depends upon the following two parameters:

- The X/R ratio of the faulted circuit
- The phase angle of the voltage waveform at the time the short-circuit occurs

The greater the fault point X/R ratio, the longer the asymmetrical fault current decay time. For a specific X/R ratio, the angle of the applied voltage at the time of short-circuit initiation determines the degree of fault current asymmetry that will exist for that X/R ratio.

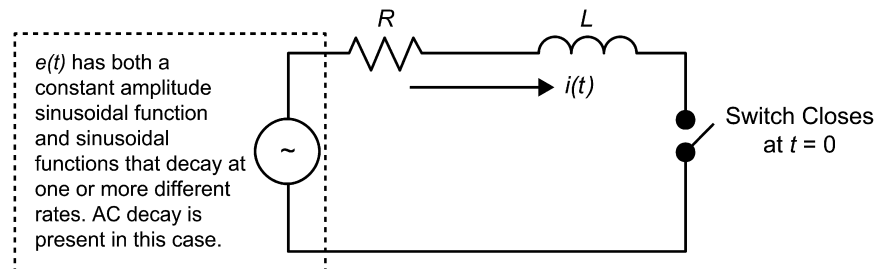


Figure 7—Circuit model with steady-state and decaying ac current sources

In a purely inductive circuit, the maximum dc current component is produced when the short-circuit is initiated at the instant the applied voltage is zero ($\alpha = 0^\circ$ or 180° when using sine functions). The current will then be fully offset in either the positive or negative direction. Maximum asymmetry for any circuit X/R ratio often occurs when the short-circuit is initiated near voltage zero. The initial dc fault current component is independent of whether the ac component remains constant or decays from its initial value.

For any circuit X/R ratio, the voltage and current waveforms will be out of phase from each other by an angle corresponding to the amount of reactance in the circuit compared to the amount of resistance in the circuit. This angle is equal to $\tan^{-1}(2\pi f \times L/R)$. For a purely inductive circuit, the current waveform will be displaced from the voltage waveform by 90° (lagging). As resistance is added to the circuit this angular displacement will decrease to zero. In a purely resistive circuit, the voltage and current will be completely in-phase and without an offset.

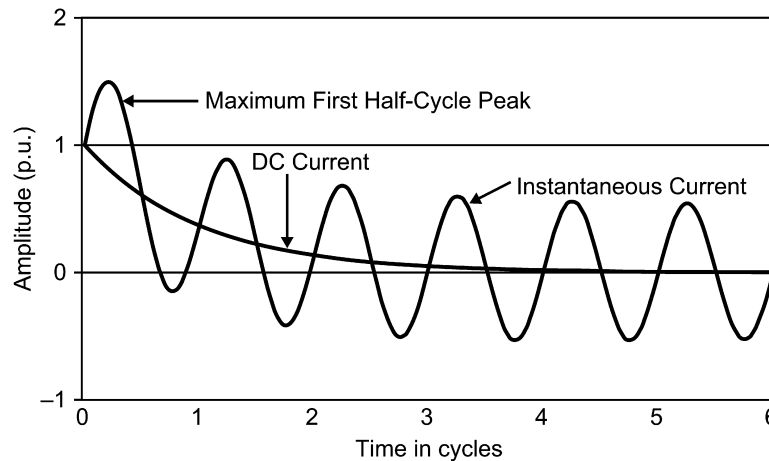


Figure 8—Asymmetrical ac short-circuit current made up of dc, decaying ac, and symmetrical ac current

5.6 Why short-circuit currents are asymmetrical

If a short-circuit occurs at the peak of the voltage waveform in a circuit containing only reactance, the short-circuit current will start at zero and trace a sine wave that will be symmetrical about the zero axis (Figure 1). If a short-circuit occurs at a voltage zero, the current will start at zero, but cannot follow a sine wave symmetrically about the zero axis because in an inductive circuit the current must lag the applied voltage by 90° . This can happen only if the current is displaced from the zero axis as shown in Figure 2. The two cases shown in Figure 1 and Figure 2 represent the extremes. One represents a totally symmetrical fault current; the other represents a completely asymmetrical current. If the fault occurs at any point between a voltage zero and a voltage crest, the current will be asymmetrical to some degree depending upon the point at which the short-circuit occurs on the applied voltage waveform. In a circuit containing both resistance and reactance, the degree of asymmetry can vary between zero and the same fully offset limits as a circuit containing only reactance. However, the point on the applied voltage waveform at which the short-circuit must occur to produce maximum fault current asymmetry depends upon the ratio of circuit reactance to circuit resistance.

5.7 DC component of short-circuit currents

Short-circuit currents are analyzed in terms of two components—a symmetrical current component and the total current that includes a dc component as shown in Figure 1 and Figure 4, respectively. As previously discussed, the asymmetrical fault current component is at a maximum during the first cycle of the short-circuit and decays to a steady-state value due to the corresponding changes of the magnetic flux fields in the machine. In all practical circuits containing resistance and reactance, the dc component will also decay to zero as the energy represented by the dc component is dissipated as I^2R heating losses in the circuit. 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 one to 30 cycles.

5.8 Significance of current asymmetry

Current asymmetry is significant for two important reasons. First is the electromagnetic force exerted on equipment parts carrying the current, and second is the thermal energy content of the fault current. The peak characteristics of both the magnetic forces and the thermal heating are a function of the square of the

current, i^2 . In Figure 8 the first peak of the asymmetrical fault current waveform has a magnitude that is approximately 1.5 times the crest value of the steady-state waveform. At the first current peak, the magnetic forces exerted on current-carrying equipment by the asymmetrical fault current are about 2.25 times the peak forces that would be caused by symmetrical fault current during the first cycle. In addition, these large values do not immediately vanish. Consequently, the i^2t (thermal or heating effect) content of the current is also much greater. Magnetic forces and heating affect the design and application of the protective equipment used on a power system.

This is where the significance of current asymmetry lies. In designing and applying devices that will be exposed to fault currents, the transient (asymmetrical) as well as the steady-state fault currents magnitudes must be considered, because both the mechanical forces and the thermal effects placed on protective equipment can be greatly magnified in the initial fault current period.

5.9 The application of current asymmetry information

In the previous discussion, a single-phase current was examined to give an understanding of asymmetry. In a three-phase system with a bolted three-phase fault, the sum of the current at any point in time in the three phases must add to zero. Therefore, if one phase has a maximum offset, then the other two phases must have a negative offset to balance current. The decay time constant of all phases is the same.

The maximum magnetic force produced on a circuit element, such as a circuit breaker, occurs at the instant the fault current through the circuit element is at a maximum. From an equipment design and application viewpoint, the phase with the largest of the fault current peaks is of particular interest. This current value subjects the equipment to the most severe magnetic forces. The largest fault current peak typically occurs in the first current cycle when the initiation of the short-circuit current is near or coincident with the applied voltage passing through zero. This condition is called the *condition of maximum asymmetry*.

In the application of equipment that can carry fault current—such as circuit breakers, switches, transformers, and fuses—the total available short-circuit current must be determined. For correct equipment application, knowledge of the maximum test X/R ratio or minimum power factor of the applied fault current used in the acceptance test by ANSI, NEMA, UL, or other standard is also required. Peak fault current magnitudes are significant for some devices, such as low-voltage circuit breakers, while asymmetrical rms current magnitudes are equally significant for high-voltage circuit breakers. This leads to the need to develop an X/R ratio dependent short-circuit calculation for proper comparison to the equipment being applied. The fault current calculation needs to take into account the ac component and the transient dc component of the calculated fault current to determine the total maximum peak or rms current magnitude that can occur in a circuit. When the calculated fault X/R ratio is greater than the equipment test X/R ratio, the higher total fault current associated with the higher X/R ratio must be taken into account when evaluating the application of the equipment.

The references (Alm [B1], Close [B9], Guillemin [B13], Reichenstein and Gomez [B56], Stevenson [B60], and Wagner [B63]) show that the effects of the peak fault current magnitude and the energy content of the first current cycle are much greater than the effect of the rms value. For the condition of maximum asymmetry, the rms value of the first-cycle fault current theoretically can be as great as 1.732 times the steady-state rms symmetrical fault current component. However, the peak first-cycle current for the same condition can be up to two times the peak of the steady-state current component, and the magnetic forces can be four times that of the rms symmetrical ac component. From the equipment design viewpoint, these peak currents and energy comparisons are the maximum that the equipment must withstand. For ANSI rated equipment, the maximum asymmetrical rms current provides this measure of maximum capability.

It is important to know the terms defining the characteristic short-circuit current waveforms. The test short-circuit currents used for circuit breaker and fuse interrupting ratings have different test procedures and power factor (X/R ratios) requirements. For example, high-voltage power circuit breakers use rms current interrupting tests at a power factor of 6.7% ($X/R = 15$), while low-voltage circuit breakers use peak currents

at a power factor of 15% ($X/R = 6.59$). Molded case and insulated case circuit breakers have different (from 6.7% and 15%) test power factors that must be considered. If the calculated fault point X/R ratio is greater than the test X/R ratio of the interrupting device, then the calculation of equipment duty current is affected. The duty current calculation is covered in Clause 9.

5.10 Maximum peak current

After a bolted three-phase fault is initiated, the maximum peak current occurs in one phase during the first half-cycle, and is often assumed, usually erroneously, to occur when the symmetrical ac current component is at its peak. The familiar first half-cycle current assumption suggests that the highest first-cycle peak current also occurs at the first half-cycle in the phase that has the maximum initial dc component. This is also erroneous, except for faults that occur on purely inductive circuits, where the resistance is zero. For circuits with resistance, the absolute maximum fault current peak occurs before the symmetrical current peak and before one half-cycle as shown on Figure 9. Figure 9 is drawn for fault in a circuit with a relatively low X/R ratio of 2 to emphasize these important characteristics. This analysis assumes fundamental 60 Hertz voltage, linear impedances, no ac decaying sources, and no prefault load currents. The largest of these fault current peaks can be found mathematically by differentiating the current expression in Equation (3) with respect to its two independent variables t and α . The other variables E , R , X , and ω are fixed for any given circuit. Differentiating the expression shows the largest fault current peak occurs for zero voltage angle α . In this situation, the largest peak occurs in the first current cycle, so the current waveform resembles that shown in Figure 9.

Important characteristics shown in Figure 9 are as follows:

- a) The short-circuit starts at zero voltage.
- b) The initial asymmetrical current is zero, due to the assumption of no prefault load current and item c) below.
- c) At the instant of fault initiation, the dc fault current value is equal in magnitude of the ac fault current value but opposite in sign.
- d) The maximum fault current peak occurs before the first positive symmetrical fault current peak.

The maximum peak current is obtained by Equation (3) using an iterative approach and results in maximum peak and maximum rms currents multipliers as shown in Table 1 and Table 2. The values listed under the column headed *Exact* of Table 1 and Table 2 have been calculated from the equation and are theoretically exact.

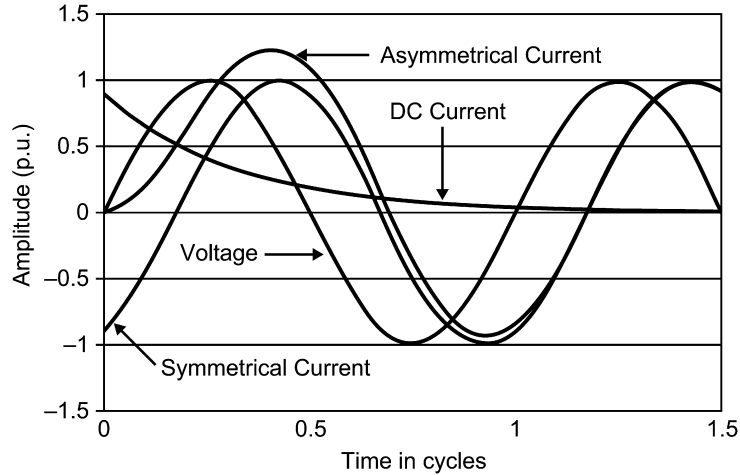


Figure 9—Maximum peak asymmetrical short-circuit current

For circuit X/R ratios between 0.5 and 1000, the second column in Table 1 and Table 2 shows the time in cycles at which the maximum peak and maximum rms currents occur. Note that the rms value of a function is based on an average, over one period, of the function squared. Strictly speaking, a non-periodic function does not have an rms value, because no period exists over which to determine an average. When the function consists of a sinusoidal component and an exponentially-decaying dc term as is commonly found in power systems, it is common practice to use the dc value at the half-cycle point in calculations of the total rms current. It should be noted that this half-cycle value does not necessarily correspond to the peak value of the total asymmetrical current. The use of the dc value evaluated at half-cycle is, however, very widely accepted and is the basis for numerous standards relating to short-circuits and protective equipment.

Because the current is lagging the applied voltage by the angle of $\tan^{-1}(X/R)$, the peak current occurs before one half-cycle. Only in a pure reactance circuit (X/R equals infinity) does the peak occur at the one half-cycle. Figure 9 illustrates a typical circuit where the peak occurs before the first half-cycle. The figure represents a circuit having a fault point X/R equal to 2.0 with the peak current occurring at approximately 0.40 cycles and a magnitude equal to 1.242 times the ac symmetrical peak current.

Calculating the peak current at a time of one half-cycle on a 60 Hertz base by using Equation (7) yields a non-conservative (lower than Exact) value for the peak current. The peak current multipliers for the one half-cycle calculations are given in Table 1 and Table 2 under the columns labeled *Half cycle* and are shown to be less than the multipliers given under the column labeled *Exact*. The half-cycle equation is as follows:

$$I_{peak} = I_{ac\ peak} + I_{dc} = \sqrt{2}I_{ac\ rms} \left(1 + e^{-\frac{2\pi\tau}{X/R}} \right) \quad (7)$$

where

$$t = 0.5 \text{ cycles}$$

The IEC calculating procedure for short-circuit currents includes the empirical formula shown in Equation (8) for estimating the absolute maximum peak current value, knowing the circuit fault point X/R ratio. This expression provides a rather close approximation to the exact peak current values and is conservative for circuit fault point X/R ratios greater than 3. Determining peak currents for circuit X/R ratio less than 3 is rarely necessary. Because most types of protective equipment short-circuit ratings are based on fault point X/R ratios greater than 3 (power factor lower than 31.6%), a current correction or multiplying factor is not needed. The peak current multipliers at one half-cycle are given in Table 1 and Table 2 under the columns labeled *IEC*. The form of Equation (7) should not be used for the peak current when applying

equipment because it is non-conservative. The equation is given here for reference only. The IEC equation is shown in Equation (8):

$$I_{peak} = \sqrt{2}I_{ac,rms} \left(1.02 + 0.98e^{-\frac{3}{(X/R)}} \right) \quad (8)$$

From the IEC Equation (8), the dc component would be as shown in Equation (9):

$$I_{dc} = \sqrt{2}I_{ac,rms} \left(0.02 + 0.98e^{-\frac{3}{(X/R)}} \right) \quad (9)$$

An alternate equation is available that provides a closer approximation to the exact peak currents than either the half cycle or IEC methods. The expression has two parts. First, a fictitious time τ is calculated from Equation (10) and then substituted into Equation (7) for t . For convenience, Equation (7) is listed below Equation (10).

$$\tau = 0.49 - 0.1e^{-\frac{(X/R)}{3}} \quad (10)$$

$$I_{peak} = I_{ac\ peak} + I_{dc} = \sqrt{2}I_{ac,rms} \left(1 + e^{-\frac{2\pi\tau}{(X/R)}} \right)$$

The peak current calculations provided by the combination of these two equations yields a very close approximation to the exact peak current and is conservative for most values of circuit X/R ratios greater than 0.81. The non-conservative errors for circuit X/R ratios around 10 are negligible. If a conservative multiplier is required for these circuit X/R ratios, then 0.0001 can be added to the peak current multiplier. The peak current multipliers for this alternate approach for the maximum half-cycle values are given in Table 1 under the columns labeled *Conservative approx.*

Equation (11), Equation (12), and Equation (13) are used for peak current factors in Table 1.

$$Half-cycle_{peak} = I_{ac\ peak} \left(1 + e^{-\frac{\pi}{(X/R)}} \right) \quad (11)$$

$$IEC_{peak} = I_{ac\ peak} \left(1.02 + 0.98e^{-\frac{3}{(X/R)}} \right) \quad (12)$$

$$Conservative\ approx._{peak} = I_{ac\ peak} \left(1 + e^{-\frac{2\pi\tau}{(X/R)}} \right) \quad (13)$$

where

$$\tau = 0.49 - 0.1e^{-\frac{(X/R)}{3}} \quad (14)$$

Negative percent error occurs when the above equations predict a value less than the exact value for the first-cycle peak current. Therefore, the equations can be considered as non-conservative for any conditions that produce negative error.

A similar set of equations can be used for first-cycle rms current factors where:

$$I_{rms} = \sqrt{I_{ac,rms}^2 + I_{dc}^2} \quad IEC_{rms} = I_{ac,rms} \sqrt{1 + 2 \left(1.02 + 0.98e^{-\frac{3}{(X/R)}} \right)^2} \quad (15)$$

Recall the difficulty in determining the rms value of a non-periodic waveform. Equation (15) is valid only when I_{dc} is constant. In short-circuit currents, the dc term is a decaying exponential and is not constant; it is a very common practice to evaluate this term at half-cycle after fault initiation even though this point in time does not necessarily correspond to the maximum peak value of the asymmetrical fault current.

These equations are given as follows and used in Table 2.

$$IEC_{rms} = I_{ac,rms} \sqrt{1 + 2 \left(1.02 + 0.98e^{-\frac{3}{(X/R)}} \right)^2} \quad (16)$$

$$Half\ cycle_{rms} = I_{ac,rms} \sqrt{1 + 2 \left(e^{-\frac{\pi}{(X/R)}} \right)^2} \quad (17)$$

$$Conservative\ approx_{rms} = I_{ac,rms} \sqrt{1 + 2e^{-\frac{4\pi\tau}{(X/R)}}} \quad (18)$$

where

$$\tau = 0.49 - 0.1e^{-\frac{(X/R)}{3}}$$

As with the first-cycle peak current, any of the above equations that produce negative percent errors can be considered non-conservative under the specified conditions. Equation (17) has been given here for reference because it has been used in other texts. Use of this equation is not recommended in those instances where the first-cycle rms current value obtained is to be used for equipment application because the current value obtained is non-conservative.

Table 1—Differences in per-unit peak currents based on Equation (11), Equation (12), and Equation (13). One per unit equals ac peak.

Exact				IEC Equation (11)		Half-cycle Equation (12)		Conservative approx. Equation (13)	
X/R	Time to peak (CY)	DC	Maximum peak	Maximum peak	Percent error	Maximum peak	Percent error	Maximum peak	Percent error
0.5	0.3213	0.0078	1.0078	1.0224	1.45	1.0019	−0.59	1.0061	−0.16
1.0	0.3635	0.0694	1.0694	1.0688	−0.06	1.0432	−2.45	1.0722	0.26
1.5	0.3891	0.1571	1.1571	1.1526	−0.39	1.1231	−2.94	1.1656	0.73
2.0	0.3977	0.2418	1.2418	1.2387	−0.25	1.2079	−2.73	1.2521	0.83
2.5	0.4063	0.3157	1.3157	1.3152	−0.04	1.2846	−2.36	1.3255	0.75
3.0	0.4282	0.3786	1.3786	1.3805	0.14	1.3509	−2.01	1.3870	0.61
3.5	0.4357	0.4319	1.4319	1.4359	0.28	1.4075	−1.70	1.4388	0.48
4.0	0.4417	0.4774	1.4774	1.4829	0.37	1.4559	−1.45	1.4827	0.36
6.0	0.4575	0.6057	1.6057	1.6144	0.54	1.5924	−0.83	1.6072	0.09
8.0	0.4665	0.6842	1.6842	1.6935	0.56	1.6752	−0.53	1.6843	0.01
10.0	0.4735	0.7368	1.7368	1.7460	0.53	1.7304	−0.37	1.7367	−0.01
14.0	0.4795	0.8027	1.8027	1.8110	0.46	1.7990	−0.20	1.8029	0.01
20.0	0.4852	0.8566	1.8566	1.8635	0.37	1.8546	−0.11	1.8574	0.04
25.0	0.4880	0.8832	1.8832	1.8892	0.32	1.8819	−0.07	1.8841	0.05
30.0	0.4899	0.9015	1.9015	1.9067	0.27	1.9006	−0.05	1.9025	0.05
40.0	0.4923	0.9250	1.9250	1.9292	0.22	1.9245	−0.03	1.9259	0.05
50.0	0.4938	0.9395	1.9395	1.9429	0.18	1.9391	−0.02	1.9403	0.04
75.0	0.4958	0.9591	1.9591	1.9616	0.12	1.9590	−0.01	1.9598	0.03
100.0	0.4969	0.9692	1.9692	1.9710	0.09	1.9691	−0.00	1.9697	0.03
250.0	0.4987	0.9875	1.9875	1.9883	0.04	1.9875	−0.00	1.9878	0.01
500.0	0.4994	0.9937	1.9937	1.9941	0.02	1.9937	−0.00	1.9939	0.01
1000.	0.4997	0.9969	1.9969	1.9971	0.01	1.9969	−0.00	1.9969	0.00

Table 2—Per-unit rms currents at peak ac current based on Equation (16), Equation (17), and Equation (18). One per unit equals ac rms

Exact				IEC Equation (16)		Half-cycle Equation (17)		Conservative approx. Equation (18)	
X/R	Time to peak (CY)	DC	Maximum rms	Maximum rms	Percent error	Maximum rms	Percent error	Maximum rms	Percent error
0.5	0.3213	0.0110	1.0001	1.0005	0.04	1.0000	−0.01	1.0000	−0.00
1.0	0.3635	0.0981	1.0048	1.0047	−0.01	1.0019	−0.29	1.0052	0.04
1.5	0.3891	0.2222	1.0244	1.0230	−0.13	1.0151	−0.91	1.0270	0.26
2.0	0.3977	0.3419	1.0568	1.0554	−0.13	1.0423	−1.37	1.0616	0.45
2.5	0.4063	0.4464	1.0951	1.0948	−0.03	1.0780	−1.57	1.1009	0.53
3.0	0.4282	0.5354	1.1343	1.1356	0.11	1.1164	−1.58	1.1400	0.50
3.5	0.4357	0.6108	1.1718	1.1747	0.25	1.1542	−1.50	1.1769	0.43
4.0	0.4417	0.6751	1.2066	1.2110	0.36	1.1899	−1.38	1.2108	0.35
6.0	0.4575	0.8566	1.3167	1.3248	0.61	1.3045	−0.93	1.3181	0.10

8.0	0.4665	0.9676	1.3915	1.4007	0.66	1.3827	−0.63	1.3916	0.01
10.0	0.4735	1.0420	1.4442	1.4536	0.65	1.4377	−0.45	1.4441	−0.01
14.0	0.4795	1.1352	1.5128	1.5216	0.58	1.5089	−0.26	1.5131	0.02
20.0	0.4852	1.2114	1.5709	1.5784	0.48	1.5687	−0.14	1.5717	0.05
25.0	0.4880	1.2491	1.6001	1.6066	0.41	1.5986	−0.09	1.6011	0.06
30.0	0.4899	1.2750	1.6203	1.6261	0.36	1.6193	−0.07	1.6214	0.06
40.0	0.4923	1.3082	1.6466	1.6513	0.28	1.6460	−0.04	1.6476	0.06
50.0	0.4938	1.3286	1.6629	1.6668	0.24	1.6625	−0.02	1.6638	0.06
75.0	0.4958	1.3564	1.6852	1.6880	0.16	1.6850	−0.01	1.6859	0.04
100.0	0.4969	1.3706	1.6966	1.6988	0.13	1.6965	−0.01	1.6972	0.03
250.0	0.4987	1.3966	1.7177	1.7186	0.05	1.7177	−0.00	1.7179	0.02
500.0	0.4994	1.4054	1.7248	1.7253	0.03	1.7248	−0.00	1.7250	0.01
1000.	0.4997	1.4099	1.7285	1.7287	0.01	1.7284	−0.00	1.7285	0.00

5.11 Types of faults

In a three-phase power system, the type of faults that can occur are classified by the combination of conductors or buses that are faulted together. In addition, faults may be classified as either bolted faults or faults that occur through some impedance, such as an arc. Each of the basic types of faults will be described and shown in Figure 10, but it should be noted that in a majority of cases, the fault current calculation required for the selection of interrupting and withstand current capabilities of equipment is the three-phase bolted fault with zero impedance. Other fault impedances may be needed for other fault calculations for protection and arc flash tasks.

A three-phase bolted fault describes the condition where the three conductors are physically held together with zero impedance between them, just as if they were bolted together. For a balanced symmetrical system, the fault current magnitude is balanced equally within the three phases. While this type of fault does not occur frequently, its results are used for protective device selection, because this fault type generally yields the maximum short-circuit current values. Figure 10(a) provides a graphical representation of a bolted three-phase fault.

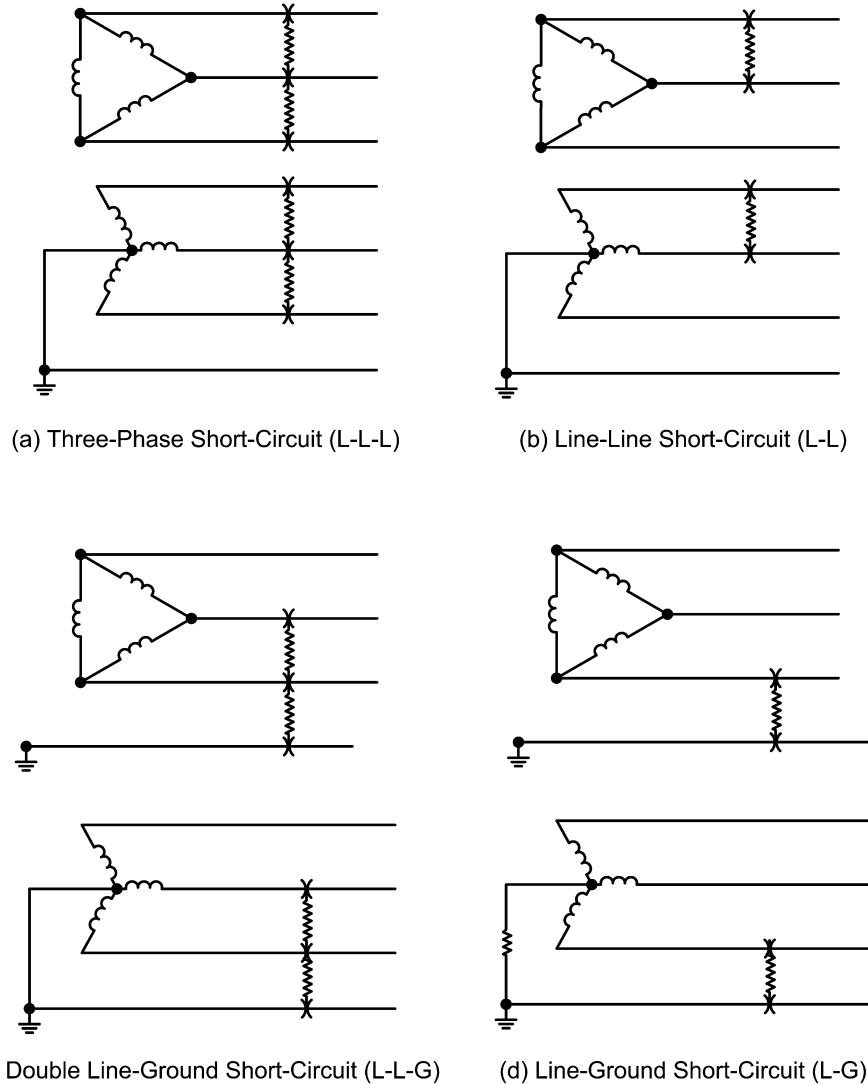


Figure 10—Designation of short-circuit categories

Bolted line-to-line faults, Figure 10(b), are more common than three-phase faults and have fault currents that are approximately 87% of the three-phase bolted fault current. This type of fault is not balanced within the three phases and its fault current is seldom calculated for equipment ratings because it does not provide the maximum fault current magnitude. The line-to-line current can be calculated by multiplying the three-phase value by 0.866, when the impedance $Z_1 = Z_2$. Special symmetrical component calculating techniques are not required for this condition.

Line-to-line-to-ground faults, Figure 10(c), are typically line-to-ground faults that have escalated to include a second-phase conductor. This is an unbalanced fault. The magnitudes of double line-to-ground fault currents are usually greater than those of line-to-line faults, but are less than those of three-phase faults. Calculation of double line-to-ground fault currents requires the use of symmetrical components analysis. The impedance of the ground return path will affect the result, and should be obtained if possible.

Line-to-ground faults, Figure 10(d), are the most common type of faults and are usually the least disturbing to the system. The current in the faulted phase can range from near zero to a value slightly greater than the bolted three-phase fault current. The line-to-ground fault current magnitude is determined by the system grounding method and the impedance of the ground return path of the fault current. Calculation of the exact

line-to-ground fault current magnitudes requires the special calculating techniques of symmetrical components. However, close approximations can be made knowing the method of system grounding used (refer to IEEE P3003.1 or IEEE Std 142™ for additional information regarding system grounding methods). On ungrounded distribution systems, the line-to-ground fault currents are near zero. Line-to-ground fault current magnitudes in distribution systems with resistance grounded system neutrals can be estimated by dividing the system line-to-neutral voltage by the total value of the system ground-to-neutral resistance. Line-to-ground fault current magnitudes in distribution systems with a solidly grounded system will be approximately equal to the three-phase fault current magnitudes. Determining line-to-ground fault currents on long cable runs or transmission lines will require detailed ground return path impedance data and detailed calculation techniques.

5.12 Arc resistance

Fault arc resistance is a highly variable quantity and changes non-linearly with the current during a cycle and on a cycle-by-cycle basis. The higher the current, the greater the ionized area, and the lower the resistance of the arc. The voltage across the arc, although not fixed, is more constant than the resistance. Arcing fault current magnitudes on low-voltage systems (< 1000 V) are more affected by fault resistance than are higher voltage systems, and the fault current can be considerably smaller in magnitude than the bolted fault current values, as shown in Table 3. On higher-voltage networks (> 1000 V), the fault arc resistance (and therefore the arc voltage) often is very low and approaches zero (bolted fault). Arcing faults in higher voltage systems have been shown to have a ground fault current ranging from 0% to 100% of the bolted-fault current depending on the system voltage and the type of fault involved. The higher the possible fault current magnitude, the lower the fault resistance will be.

The environment in which the fault takes place has an effect on the fault resistance and its being sustained. An arcing fault in a confined area is easily perpetuated due to the concentration of ionized gases allowing easy current flow. An arc occurring on open conductors is elongated due to heat convection, thereby allowing cooling of ionized gas and the arc may extinguish itself.

**Table 3—Approximate minimum value of arcing fault current
in per unit of three-phase bolted fault**

Type of arcing fault	System voltage	
	480Y/277V	208Y/120V
Three-phase	89%	12%
Line-to-line	74%	2%
Line-to-ground	38%	1%

Arcing fault currents are known to be very erratic in nature and do not provide a constant resistance during any one cycle. Over several cycles, the arc ignites due to uncooled ionized gases, almost extinguishes, then fully ignites again with varying current. There is not an exact equation available to determine arcing fault resistance. However, the reference works of Alm [B1], Brown [B8], and Strom [B61] provide an approximation [Equation (19), Equation (20), and Equation (21)].

$$\frac{V}{\text{cm}} = 50 \left(\frac{P}{I^2} \right)^{1/6} \quad (19)$$

or in terms of resistance:

$$\frac{R}{\text{cm}} = 50(P)^{1/6}(I)^{3/4} \quad (20)$$

where

- V is voltage, volts
- R is resistance in ohms
- cm is arc length, centimeters
- P is pressure in atmosphere (1 atm = 14.696 PSIA)
- I is current in kiloamperes (kA)

Note that the equation parameters contain currents that make the application of Ohm's law non-linear and more complex. It should also be noted that the equations provide voltage and resistance per centimeter. Therefore, the total arc voltage or resistance can be determined by multiplying Equation (19) and Equation (20) by the total arc length.

The instantaneous arc resistance at current peak can be calculated using Equation (21).

$$R = 11.6 \times \ell \times \frac{1.1}{I_x} \quad (21)$$

where

- ℓ = length of arc in centimeters
- I_x = peak current in kiloamperes (kA)

In the calculation of fault current magnitudes, when maximum ampere conditions for equipment evaluation is the concern, arcing fault impedance or arc resistance is considered zero. For other calculation purposes, some assessment of fault impedance may be necessary. Note that in practice, arc length varies substantially over time, even if the end points of the arc are fixed.

6. General short-circuit calculation method

6.1 Introduction

In order to calculate, with a reasonable degree of accuracy, the short-circuit current that can be expected to flow in a system, it is necessary to find an equivalent circuit for each system element that will adequately represent its performance under short-circuit conditions. Without the use of simplifying techniques, one is often faced with the necessity of solving complex differential equations to determine the short-circuit current.

In this clause, various calculating techniques will be discussed with particular emphasis placed on simplifying techniques and manipulations that will provide acceptable results using system conditions that are recognized and accepted.

6.2 Fundamental principles

A basic ac power circuit containing resistance (R), inductance (L), and capacitance (C) is shown in Figure 11. For completeness, the series capacitor is shown, although its use in power circuits is limited. The general expression relating the instantaneous current response (i) and the instantaneous exciting source voltage (e) in such a circuit will take the form (see IEEE Std 141™-1993 [B31]):

$$e = L \frac{di}{dt} + Ri + \frac{1}{C} \int i dt + e_0 \quad (22)$$

$$e = L \frac{d^2Q}{dt^2} + R \frac{dQ}{dt} + \frac{Q}{C} + e_0 \quad (23)$$

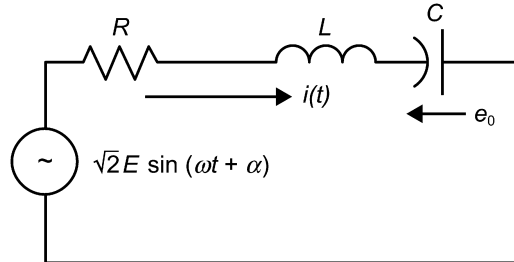


Figure 11 —Series RLC circuit

The expression for the response (for current) involves the solution of a differential equation as shown in many electrical engineering textbooks. However, industrial and commercial power system networks contain many branches composed of series and parallel combinations of resistance, inductance, and capacitance, which add greatly to the complexity of using the fundamental expression for circuit analysis. In addition, the calculation of system short-circuit currents is further complicated by the varying fluxes (driving voltages) in equipment along with the prefault and post-fault steady-state behavior. In calculating short-circuit currents, it is expedient to use techniques that will simplify the general circuit equation as much as possible while still providing valid results that are sufficiently accurate for their intended purpose.

Each of the network theorems and calculating techniques described in this recommended practice are valid for a specific calculation. They place various constraints on the general circuit equation in order to achieve calculation simplicity. It must be emphasized that these constraints must have some basis in order to obtain valid results. Fortunately, it is often possible to introduce appropriate corrections artificially when restraints are violated by system conditions. However, in certain cases it may be necessary to use the formal differential equations to obtain a valid solution.

The following constraints are common to all of the techniques that will be discussed, with the exception of the Fourier representation:

- a) The ac source frequency must be constant. In power system short-circuit analysis, it is reasonable to assume constant system frequency for the fault duration except for very rare and special cases.
- b) The impedance coefficients R , L , and C must be constant (saturated values). Again, for the majority of short-circuit calculations this restraint causes no difficulty since the maximum fault current is of concern and the fault resistance is taken to be zero when the equipment rating is evaluated. The following, however, are examples of system conditions where the restraint will be violated. When an arc becomes a series component of the circuit impedance, the R that it represents is not constant. For example, at a current of 1 A, it is likely to be 100 Ohm, yet at a current of 1000 A it would very likely be about 0.1 Ohm (see IEEE Std 141™-1993 [B31]). During each half-cycle of current flow, the arc resistance would traverse this range. It is difficult to determine a proper resistance value to insert in the 60 Hz network. A correct value of R does not compensate for the violation of the constraint that demands that R be a constant. The variation in R lessens the impedance to high-magnitude current, which results in a wave shape of current that is more peaked than a sine wave. The current now contains harmonic terms. Because they result from a violation of analytical restraints, they will not appear in the calculated results. Their character and magnitude must be determined by other means and the result artificially introduced into the solution for fault current.

A similar type of non-linearity may be encountered in electromagnetic elements in that iron plays a part in setting the value of L . If the ferric parts are subject to large excursions of magnetic density, the value of L may be found to drop substantially when the flux density is driven into the saturation region. The effect of this restraint violation will, like the case of variable R , result in the appearance of harmonic components in the true circuit current.

- c) The driving voltage and its phase angle are assumed to be constant. In reality, however, a machine's internal driving voltage varies with machine loading and time. During a fault, the machine's magnetic energy or internal voltage is reduced faster than it can be replaced by energy supplied by the machine's field. The rate of decay differs for each source. In addition, the angles between machines begin to change as some accelerate and others slow down.

The resistance and reactance of machines are fixed values based on the physical design of the equipment. Solving a system with many varying driving voltage sources becomes cumbersome. The same current can be determined by holding the voltage constant and varying the machine impedance. This interchange helps to simplify the mathematics. The value of the impedance that must be used in these calculations depends on the basis of rating for the protective device or equipment under consideration. Different types of protective devices or equipment require different machine impedances to determine the fault current duty. Equipment evaluated on first-cycle criteria would use a lower machine impedance, and hence a higher current, than equipment evaluated on an interrupting-time basis.

- d) The fault current source must be sinusoidal. Most voltages and currents used for transmission and utilization of electric power are generated by the uniform rotation of an armature in a magnetic field; the resulting steady-state voltage is periodic and has a waveform that is nearly a pure sine wave or one that can be resolved into a series of sine waves.

The vector impedance analysis recognizes only the steady-state sine wave electrical quantities and does not include the effects of abrupt switching. Fortunately, the effects of switching transients can be analyzed separately and added, provided the network is linear. An independent solution can be obtained from a solution of the formal differential equations of the form of Equation (22) (see IEEE Std 141-1993 [B31]).

In the case of a totally resistive (R) network, (Figure 12), the closure of the switch SW causes the current to immediately assume the value that would exist in steady-state. No transient will be produced.

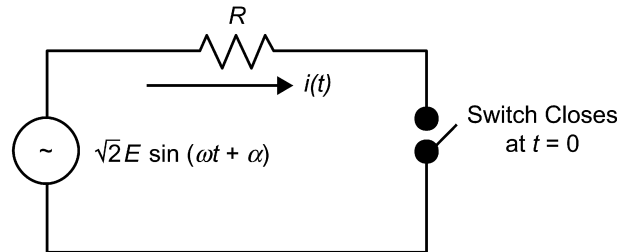


Figure 12—Switching a resistive circuit

In the case of inductance (L), (Figure 13), an understanding of the switching transient can be best acquired using the expression shown in Equation (24).

$$e = L \frac{di}{dt} \quad (24)$$

Or expressed in terms of i :

$$\frac{di}{dt} = \frac{e}{L} \quad (25)$$

This expression tells us that the application of a driving voltage to an inductance will create a time-rate-of-change in the resultant current flow. The current waveform, one example of which is shown in Figure 13, may be fully offset or not offset at all, depending on the point on the applied voltage wave at which the switch is closed. The waveform in Figure 13 assumes a voltage angle (at switch closing) of 180° , so a full negative offset will be produced.

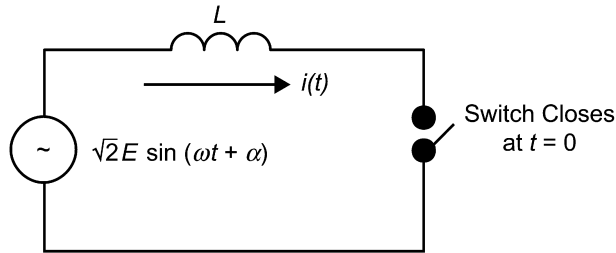


Figure 13—Switching an inductive circuit

At half-cycle in Figure 13, the steady-state current curve waveform begins with a maximum negative dc offset. The offset is negative because the voltage at half-cycle is *zero going negative*, meaning that the instantaneous value is zero at half-cycle, but the next value will be negative. At this same instant (half-cycle), the 90° lagging current through the inductor will be at a positive peak. Because the switch has been open prior to this instant, the inductor current must be zero at the instant the switch closes. Because the steady-state inductor current will be at its positive peak value at half-cycle, a constant current equal to the negative of this peak value must be produced starting at half-cycle such that the sum of the steady-state waveform and the constant is zero at half-cycle. In general, the transient that is produced when the switch is closed will take the form of a dc current component whose value may be anything between zero and the steady-state crest value (either positive or negative), depending on the angle of closing.

If the circuit contained no resistance, as depicted in Figure 13, the constant current would continue forever and the total waveform (the sum of this constant value and the sinusoidal steady-state current) would remain in the offset form. The presence of resistance causes the constant (often called *dc*) component to be dissipated exponentially. The complete expression for the current would take the form shown in Equation (26):

$$i = -\frac{\sqrt{2}E}{Z} \sin(\alpha - \phi) e^{-\frac{\omega t R}{X}} + \frac{\sqrt{2}E}{Z} \sin(\omega t + \alpha - \phi) \quad (26)$$

In Equation (26), the first part of the expression for the current has a constant term modified by a decaying exponential term (often called a *decaying dc term*). The second part of the equation is a steady-state sinusoidal term. To help distinguish these two terms, $\sqrt{2} E/Z$ will be identified as i_{dc} in the first term and $\sqrt{2} I_{ac,rms}$ in the second term. Note that at time $t = 0$ (the instant of fault initiation), these two terms are equal.

$$i = -i_{dc} \sin(\alpha - \phi) e^{-\frac{\omega t R}{X}} + \sqrt{2} I_{ac,rms} \sin(\omega t + \alpha - \phi) \quad (27)$$

where

$$f = \tan^{-1}(\omega L / R) = \tan^{-1}(X / R)$$

$$X = \omega L$$

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

If time t is expressed in cycles, Equation (27) becomes:

$$i = -i_{dc} \sin(\alpha - \varphi) e^{-\frac{2\pi t R}{X}} + \sqrt{2} I_{ac,rms} \sin(2\pi t + \alpha - \varphi) \quad (28)$$

The presence of dc current components may introduce unique problems in providing selectivity in relay coordination between some types of overcurrent devices. It is particularly important to keep in mind that these transitory dc currents are not disclosed by the steady-state circuit solution often used in short-circuit fault calculations, but must be introduced artificially by the analyst, or by established rules and guidelines. A detailed differential equation model of the entire network, including machines using a dynamic flux model, would be required to obtain the transient currents.

It is common practice that the analyst considers the switching transient to occur only once during one excursion of short-circuit current flow. An examination of representative oscillograms of short-circuit currents will often display repeated instances of momentary current interruptions. At times, an entire half-cycle of current will be missing. In other cases, especially in low-voltage circuits, there may be present a whole series of chops and jumps in the current pattern. A switching interrupter, especially when switching a capacitor circuit, may be observed to restrike two, or perhaps three times before complete interruption is achieved. The restrike generally occurs when the potential difference across the switching contacts is high. It is entirely possible that switching transients, both simple dc and ac transitory oscillations, may be created in the circuit current a number of times during a single incident of short-circuit current flow. The analyst must remain mindful of possible trouble.

6.3 Short-circuit calculation procedure

The procedure for calculating short-circuit currents in industrial and commercial power systems can be described in five basic steps. With the help of an advanced computer software, steps c) to f) below are conducted automatically by the program.

- a) Prepare a system one-line diagram showing all elements to be included in the analysis. The diagram should provide significant details to allow the user to identify the system nodes (buses) that will be considered in the short-circuit analysis. Transformers should be drawn with a transformer symbol, motors with a motor symbol, and so on. Depending on the complexities of the system drawing, the amount of equipment detail shown will vary. However, too much data will make it difficult to locate any item of concern. A separate equipment list can be used to reduce the data placed on the one-line diagram.

When the single line is drawn in many of the available software analysis tools, this equipment list is automatically created as part of the model database. The ability to manipulate the representation of these data on the one-line diagram varies greatly between software vendors.

- b) Prepare an impedance diagram showing the system impedances. Most engineers show impedance in per unit on a common MVA base. However, ohms can be used if the voltage for each bus is also given. The one-line diagram may be used together with the equipment list identifying the impedance data for the various components shown on the one-line diagram. Many computer programs allow the raw data to be used, thus eliminating the need for the impedance diagram. However, the impedance diagram must be considered when doing manual spot-checks of the software calculations. With manual calculations it is normal to show impedance in ohms.
- c) Develop an equivalent circuit of the “outside world.” This circuit represents the part of the system for which short-circuit calculations are not required, but its effect on the total fault current is

important and must be included. In the analysis of industrial and commercial power systems, the utility system is often represented as an equivalent circuit.

In representing multiple utility connections by multiple Thevenin equivalent circuits, it is essential to ensure that these are truly independent. If any utility connection points are interconnected, they cannot be represented by two Thevenin equivalent sources. This issue is discussed as *network diakoptics* (Happ [B16]). If the multiple utilities can be reduced to one common bus, then a single Thevenin equivalent can be derived and used in the industrial system model.

- d) Calculate the symmetrical short-circuit current at the buses of concern. This is normally done by a computer program for large-scale systems. Hand calculation can also be done for small system, or as a spot check on computer calculations.
- e) For ANSI short-circuit current calculations, apply appropriate multiplication factors to symmetrical short-circuit currents, as required to reflect the asymmetry of the short-circuit current. First-cycle and interrupting-time calculations may need multipliers if they are used for equipment evaluation, while steady-state (or 30 cycle) calculations used mainly for time-delay relay settings may not.
- f) Compare the calculated short-circuit duties to the ratings of existing equipment or use the short-circuit duties to select equipment ratings.

6.4 One-line diagram

6.4.1 Introduction

When preparing the data for short-circuit studies, the first step is to develop a one-line diagram of the electrical system. In a balanced three-phase system, the circuit impedance for each phase is the same as for the other two phases. This symmetrical property is taken advantage of by drawing the electrical system as a single-phase drawing. This drawing is referred to as a *one-line*. Standard symbols from IEEE Std 315™-1975 or IEC 60617 are used to represent electrical apparatus. Figure 14, Figure 15, and Figure 16 provide the more commonly used symbols. The drawing should include all sources of short-circuit current, (utilities, generators, synchronous motors, induction motors, condensers, etc.) and all significant circuit elements, (transformers, cables, circuit breakers, fuses, etc.).

In developing the one-line diagram, the engineer must decide how much detail should be represented. Too much data can make the drawing cluttered and hard to read. For example, transformers can be labeled with the voltage rating, tap, kVA, and impedance, or be limited to the kVA rating and the percent impedance.

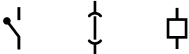
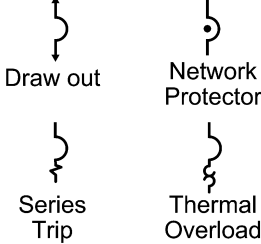
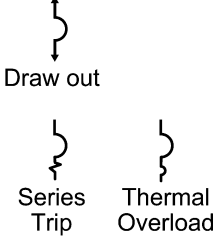
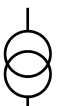
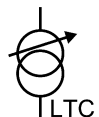
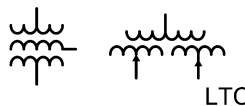
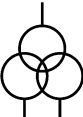
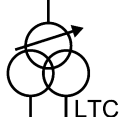
Item	ANSI		IEC	
	Symbol	Alternate	Symbol	Alternate
High Voltage Breaker		 Draw out		
Low Voltage Breaker		 Draw out Network Protector Series Trip Thermal Overload		 Draw out Series Trip Thermal Overload
Transformer 2 windings		 LTC LTC LTC		 LTC
Transformer 3 windings		 LTC		 LTC

Figure 14—Typical symbols used on one-line diagrams

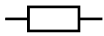
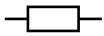
Item	ANSI		IEC	
	Symbol	Alternate	Symbol	Alternate
Resistor				
Capacitor				 
Reactor		 Iron core  Tapped		 Tapped
Fuse		 Draw Out 		 Fused Switch 
Switch		 NO  NC  Double Throw		 NO  NC

Figure 15—Typical symbols used on one-line diagrams

Item	ANSI		IEC	
	Symbol	Alternate	Symbol	Alternate
Contactor		 Fused Thermal Overload		 Fused Thermal Overload
Generator		 GEN G wavy line		 GEN G
Motor		 Induction Synchronous		 Synchronous Induction

Figure 16—Typical symbols used on one-line diagrams

6.4.2 Single-phase equivalent circuit

The single-phase equivalent circuit is a tool for simplifying the analysis of balanced three-phase circuits, yet it is the solution method because the restraints are often disregarded (see Griffith [B11]). Its use is best understood by examining a three-phase diagram of a simple system and its single-phase equivalent, as shown in Figure 17. Also illustrated is the popular one-line diagram representation that is commonly used to describe the same three-phase system on drawings.

For a three-phase system known to have perfectly balanced symmetrical source excitation (voltage), loads, and shunt and series line impedances connected to all three phases (upper diagram), the neutral conductor (shown dashed), whether physically present or inserted for mathematical convenience, will carry no current. Under these conditions, the system can be accurately described by either of the two lower diagrams of Figure 17. The single-phase equivalent circuit is useful because the solution to the classical loop equations is much easier to obtain than for the more complicated three-phase network.

In the discussion that follows, it is assumed that there is no coupling between phases of the loads and power delivery equipment. Such coupling would not allow a “decoupled” analysis of one phase of the balanced circuit. Symmetrical component techniques (to be described later) can effectively decouple the three-phase circuits, assuming balanced (equal) coupling between phases, into zero, positive, and negative sequence equivalent circuits. Under balanced three-phase operating conditions, it can be shown that an analysis of the positive sequence equivalent circuit gives results that are identically equal to “a” phase values. For this reason, the concepts of *per phase*, *single-phase*, and *positive sequence* analysis are often used interchangeably. Note that this usage is not rigorously correct and can lead to confusion. The references should be consulted for a complete development of the equivalence (or lack thereof) of these various descriptive terms.

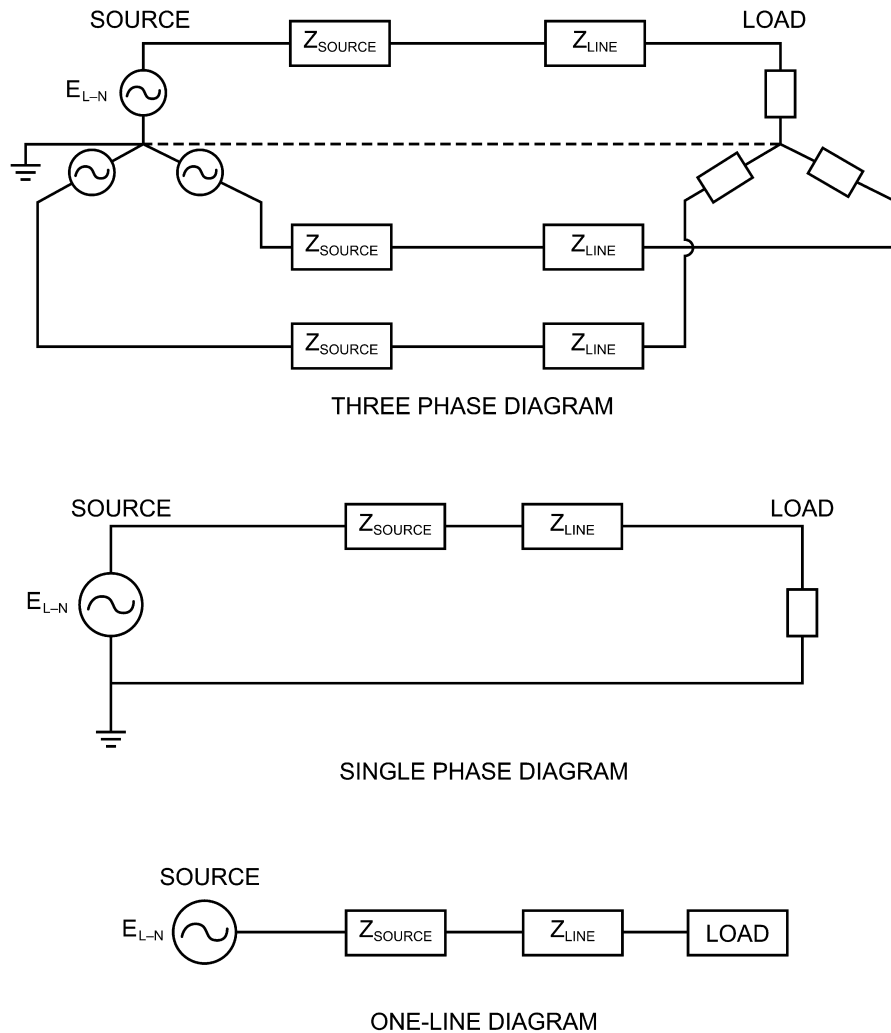


Figure 17—Electrical power diagrams

In determining the complete short-circuit solution, the other two phases will have responses that are shifted by 120° and 240° , but are otherwise identical to that of the reference phase.

Anything that upsets the balance of the network renders the model invalid unless special calculating techniques are used. One instance for which this might occur is the line-to-ground fault shown in Figure 18. For this fault condition, the balance or symmetry of the circuit is destroyed. Neither the single-phase equivalent circuit nor the one-line diagram representation is valid. The single-phase and the one-line diagram representations would imply that the load has been disconnected. However, it continues to be energized by two-phase power as shown on the three-line diagram. So-called “single-phase operation” of three-phase equipment can cause serious damage to motors, for example, and may also result in unacceptable operating condition of certain load apparatus.

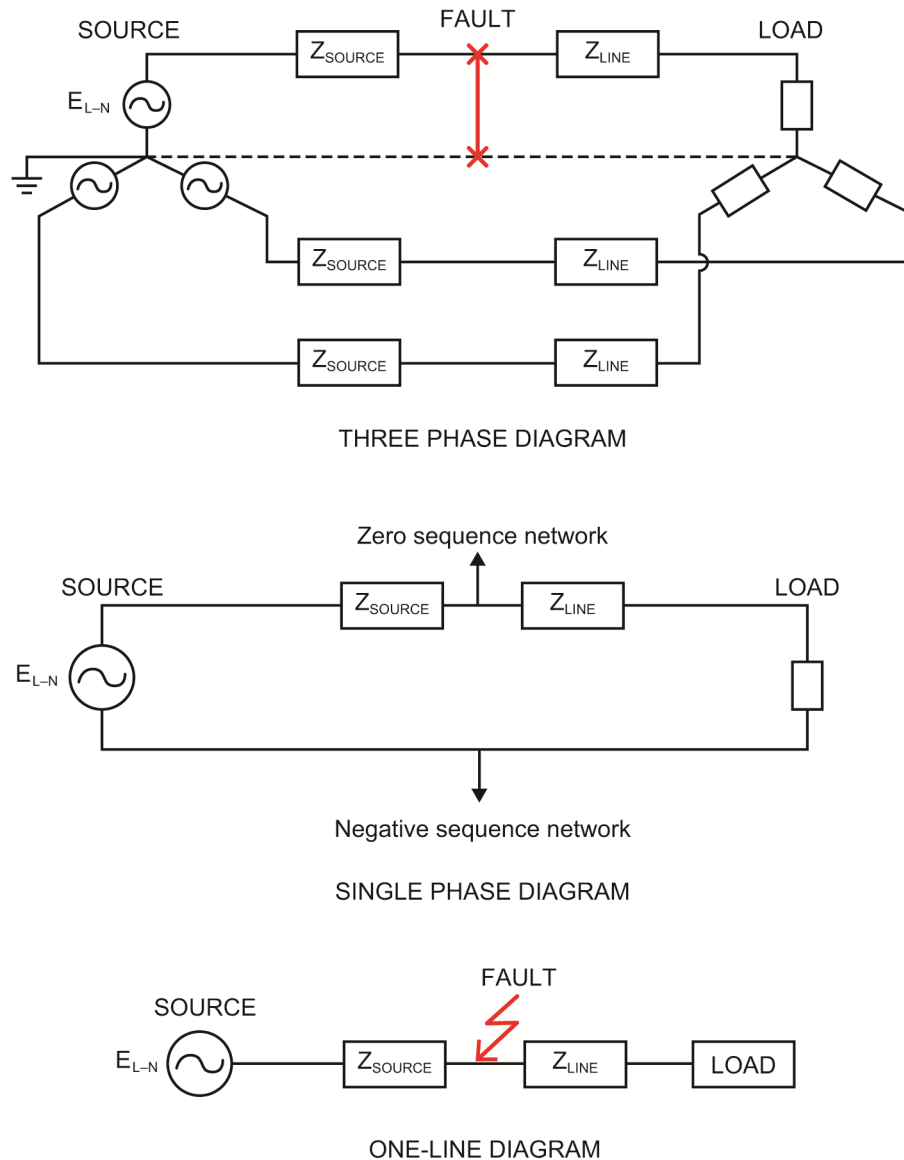


Figure 18—Electrical power diagrams showing a line-to-ground fault

6.4.3 Bus numbers

Some short-circuit analysis computer programs require the use of bus numbers identifying each individual bus on the one-line diagram to assist the engineer with the printed computer results. When bus numbers are required, each branch element of the electrical system must be between two distinct bus numbers. The one-line diagram is divided into circuit segments by assigning bus numbers as follows:

- To a bus with three or more connections to it. These often are pieces of major equipment, such as switchgear buses, motor control center buses, substations, etc.
- At utility connections and generator terminals.
- At the terminals of motors when the cable connection to the motor is represented.