

IEEE *violet* BOOK™



551™

IEEE Recommended Practice for

**Calculating
Short-Circuit
Currents in
Industrial and
Commercial
Power Systems**

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IEEE Recommended Practice for Calculating Short-Circuit Currents in Industrial and Commercial Power Systems

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**Power Systems Engineering Committee
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Abstract: This recommended practice provides short-circuit current information including calculated short-circuit current duties for the application in industrial plants and commercial buildings, at all power system voltages, of power system equipment that senses, carries, or interrupts short-circuit currents. Equipment coverage includes, but should not be limited to, protective device sensors such as series trips and relays, passive equipment that may carry short-circuit current such as bus, cable, reactors and transformers as well as interrupters such as circuit breakers and fuses.

Keywords: available fault current, circuit breaker, circuit breaker applications, fuse, power system voltage, reactors, short-circuit applications guides, short-circuit duties

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Introduction

This introduction is not part of IEEE Std 551-2006, IEEE Recommended Practice for Calculating Short-Circuit Currents in Industrial and Commercial Power Systems.

This recommended practice is intended as a practical, general treatise for engineers on the subject of ac short-circuit currents in electrical power systems. The focus of this standard is the understanding and application of analytical techniques of short-circuit analysis in industrial and commercial power systems. However, the same engineering principles apply to all electrical power systems, including utilities and systems other than 60 Hz.

More than any other book in the IEEE Color Book[®] series, the “Violet Book” covers the basics of short-circuit currents. To help the reader, the same one-line diagram that is used in several of the other color books is used in sample calculations. Items covered in the Violet Book that are not covered in the other color book chapters on short-circuit currents are the contributions of regenerative SCR drives and capacitors to faults. The reference data chapter in this recommended practice is quite extensive and should be very useful for any type of power system analysis.

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Contents

Chapter 1	
Introduction	1
1.1 Scope.....	1
1.2 Definitions	2
1.3 Acronyms and abbreviations	8
1.4 Bibliography	10
1.5 Manufacturers' data sources	11
Chapter 2	
Description of a short-circuit current	13
2.1 Introduction.....	13
2.2 Available short-circuit	13
2.3 Symmetrical and asymmetrical currents.....	14
2.4 Short-circuit calculations	17
2.5 Total short-circuit current	20
2.6 Why short-circuit currents are asymmetrical.....	22
2.7 DC component of short-circuit currents	22
2.8 Significance of current asymmetry	22
2.9 The application of current asymmetry information	23
2.10 Maximum peak current.....	24
2.11 Types of faults	31
2.12 Arc resistance.....	32
2.13 Bibliography	34
Chapter 3	
Calculating techniques	37
3.1 Introduction.....	37
3.2 Fundamental principles.....	37
3.3 Short-circuit calculation procedure.....	42
3.4 One-line diagram	43
3.5 Per-unit and ohmic manipulations	50
3.6 Network theorems and calculation techniques	52
3.7 Extending a three-phase short-circuit calculation procedures program to calculate short-circuit currents for single-phase branches.....	67
3.8 Representing transformers with non-base voltages	69
3.9 Specific time period and variations on fault calculations.....	78
3.10 Determination of X/R ratios for ANSI fault calculations.....	81
3.11 Three winding transformers.....	81
3.12 Duplex reactor	82
3.13 Significant cable lengths.....	83
3.14 Equivalent circuits	84
3.15 Zero sequence line representation	85
3.16 Equipment data required for short-circuit calculations	86
3.17 Bibliography	94

Chapter 4	
Calculating short-circuit currents for systems without ac delay	95
4.1 Introduction.....	95
4.2 Purpose.....	95
4.3 ANSI guidelines.....	96
4.4 Fault calculations	97
4.5 Sample calculations	98
4.6 Sample computer printout.....	103
4.7 Conclusions.....	113
4.8 Bibliography	114

Chapter 5	
Calculating ac short-circuit currents for systems with contributions from synchronous machines	115
5.1 Introduction.....	115
5.2 Purpose.....	115
5.3 ANSI guidelines.....	115
5.4 Fault calculations	116
5.5 Nature of synchronous machine contributions	116
5.6 Synchronous machine reactances	119
5.7 One-line diagram data.....	121
5.8 Sample calculations	121
5.9 Sample computer printout.....	123
5.10 Sample computer printout for larger system calculations	124
5.11 Conclusions.....	126
5.12 Bibliography	126

Chapter 6	
Calculating ac short-circuit currents for systems with contributions from induction motors	127
6.1 Introduction.....	127
6.2 Purpose.....	127
6.3 ANSI guidelines.....	127
6.4 Fault calculations	129
6.5 Nature of induction motor contributions	129
6.6 Large induction motors with prolonged contributions	132
6.7 Data accuracy.....	133
6.8 Details of induction motor contribution calculations according to ANSI standard application guides.....	133
6.9 Recommended practice based on ANSI-approved standards for representing induction motors in multivoltage system studies	135
6.10 One-line diagram data.....	137
6.11 Sample calculations	138
6.12 Sample computer printout.....	142
6.13 Bibliography	145

Chapter 7	
Capacitor contributions to short-circuit currents	147
7.1 Introduction.....	147
7.2 Capacitor discharge current	147
7.3 Transient simulations	149
7.4 Summary	165
7.5 Bibliography	165
Chapter 8	
Static converter contributions to short-circuit currents.....	167
8.1 Introduction.....	167
8.2 Definitions of converter types.....	167
8.3 Converter circuits and their equivalent parameters	168
8.4 Short-circuit current contribution from the dc system to an ac short circuit.....	170
8.5 Analysis of converter dc faults	176
8.6 Short circuit between the converter dc terminals.....	177
8.7 Arc-back short circuits.....	187
8.8 Examples.....	191
8.9 Conclusions.....	197
8.10 Bibliography	197
Chapter 9	
Calculating ac short-circuit currents in accordance with ANSI-approved standards	199
9.1 Introduction.....	199
9.2 Basic assumptions and system modeling.....	199
9.3 ANSI recommended practice for ac decrement modeling.....	200
9.4 ANSI practice for dc decrement modeling	204
9.5 ANSI-conformable fault calculations	212
9.6 ANSI-approved standards and interrupting duties.....	214
9.7 One-line diagram layout and data	216
9.8 First cycle duty sample calculations	219
9.9 Interrupting duty sample calculations.....	223
9.10 Applying ANSI calculations to non-60 Hz systems	228
9.11 Normative references	229
9.12 Bibliography	230
Chapter 10	
Application of short-circuit interrupting equipment.....	231
10.1 Introduction.....	231
10.2 Purpose.....	231
10.3 Application considerations	231
10.4 Equipment data	233
10.5 Fully rated systems	234
10.6 Low voltage series rated equipment	234
10.7 Low voltage circuit breaker short-circuit capabilities less than rating	235
10.8 Equipment checklist for short-circuit currents evaluation.....	236

10.9 Equipment phase duty calculations	237
10.10 Equipment ground fault duty calculations.....	245
10.11 Capacitor Switching	245
10.12 Normative references	246
Chapter 11	
Unbalanced short-circuit currents	249
11.1 Introduction	249
11.2 Purpose	249
11.3 ANSI guidelines	250
11.4 Procedure	251
11.5 Connection of sequence networks	257
11.6 Sample calculations	258
11.7 Conclusions	271
11.8 Bibliography	271
Chapter 12	
Short-circuit calculations unuser international standards	273
12.1 Introduction	273
12.2 System modeling and methodologies.....	273
12.3 Voltage factors	275
12.4 Short circuit currents per IEC 60909.....	275
12.5 Short circuits “far from generator”	276
12.6 Short circuits “near generator”	281
12.7 Influence of the motors.....	290
12.8 Fault calculations in complex systems.....	292
12.9 Comparing the ANSI-approved standards with IEC 909.....	292
12.10 Sample calculations.....	293
12.11 Normative references	299
12.12 Bibliography	300

IEEE Recommended Practice for Calculating Short-Circuit Currents in Industrial and Commercial Power Systems

Chapter 1 Introduction

1.1 Scope

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 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. 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 that is connected into 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, resolidification 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 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.

1.2 Definitions

For the purpose of this document, the following terms and definitions apply. *The Authoritative Dictionary of IEEE Standards Terms* [B3]¹ should be referenced for terms not defined in this clause.

1.2.1 30 cycle time: The time interval between the time when the actuating quantity of the release circuit reaches the operating value, and the approximate time when the primary arcing contacts have parted. The time period considers the ac decaying component of a fault current to be negligible.

¹The numbers in brackets correspond to those of the bibliography in 1.4.

1.2.2 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.

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

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

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

1.2.6 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.

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

1.2.8 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.

1.2.9 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 to breakers under 1000 V, it is the sum of the sensor time, plus opening time and the arcing time. For breakers rated above 1000 V, it is the sum of the minimum relay time (usually 1/2 cycle), plus contact parting time and the arcing time. Sometimes referred to as *total clearing time* or *interrupting time*.

1.2.10 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.

1.2.10.1 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 breaker first cycle symmetrical ac rms short-circuit current. Also called first cycle duty (formerly, momentary duty).

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

1.2.11 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.

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

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

1.2.14 direct axis subtransient reactance: X''_{dv} (saturated, 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.

1.2.15 direct axis subtransient reactance: X''_{di} (unsaturated, 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.

1.2.16 direct axis transient reactance: X'_{dv} (saturated, 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 (1/2) second or longer, depending upon the design of the machine and is determined by the machine direct-axis transient time constant.

1.2.17 direct axis transient reactance: X'_{di} (unsaturated, 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.

1.2.18 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.**

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

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

1.2.21 field: The exciting or magnetizing winding of a machine.

1.2.22 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.

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

1.2.24 frequency: The rated frequency of a circuit.

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

1.2.26 high voltage: Circuit voltages over nominal 34.5 kV.

NOTE—ANSI standards are not unanimous in establishing the threshold of “high-voltage.”²

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

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

1.2.29 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*.

1.2.30 low voltage: Circuit voltage under 1000 V.

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

1.2.32 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 “high-voltage.”

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

1.2.34 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 breakers manufactured before 1965. See presently used terminology of **close and latch rating**.

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

1.2.36 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

²Notes in text, tables, and figures are given for information only and do not contain requirements needed to implement the standard.

original vectors. For a three-phase system, the angular different is 120 degrees. *See also:* **symmetrical components**.

1.2.37 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.

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

1.2.39 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.

1.2.40 peak current: The highest instantaneous current during a period.

1.2.41 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 different is 120 degrees. *See also:* **symmetrical components**.

1.2.42 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.

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

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

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

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

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

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

1.2.49 rating: The designated limit(s) of the operating characteristic(s) of a device. This data is usually on the device nameplate.

1.2.50 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.

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

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

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

1.2.54 rotor: The rotating member of a machine.

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

1.2.56 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.

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

1.2.58 stator: The stationary member of a machine.

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

1.2.60 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 degrees 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 degrees 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 degrees. This set of vectors is called the zero sequence component.

1.2.61 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 a synchronous machine terminals.

1.2.62 three-phase open circuit time constant: 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.

1.2.63 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**.

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

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

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

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

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

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

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

1.2.71 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 zero (0) degrees and rotating in the same direction as the original vectors. *See also:* **symmetrical components**.

1.3 Acronyms and abbreviations

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

a	symmetrical component operator = 120 degrees
e	instantaneous voltage
e_0	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
$I_{\max,\text{s}}$	symmetrical peak current
$I_{\max,\text{ds}}$	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 degree rotative operator, imaginary unit
L	inductance
Q	electric charge
R	resistance
R_{a}	armature resistance
t	time
T_{a3}	three-phase open-circuit 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 rated voltage
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

1.4 Bibliography

The IEEE publishes several hundred standards documents covering various fields of electrical engineering. Appropriate IEEE standards are routinely submitted to the American National Standards Institute (ANSI) for consideration as ANSI-approved standards. Standards that have also been submitted and approved by the Canadian Standards Association carry CSA letters. Basic standards of general interest include the following:

[B1] ANSI/IEEE Std 91TM-1984, IEEE Standard Graphic Symbols for Logic Diagrams.³

[B2] ANSI 268-1992, American National Standard Metric Practice.

[B3] IEEE 100, *The Authoritative Dictionary of IEEE Standards Terms*, Seventh Edition.^{4, 5}

³ANSI publications are available from the Sales Department, American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA (<http://www.ansi.org/>).

⁴IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (<http://standards.ieee.org/>).

⁵The IEEE standards or products referred to in this clause are trademarks of the Institute of Electrical and Electronics Engineers, Inc.

[B4] IEEE Std 260.1TM-2004, IEEE Standard Letter Symbols for Units of Measurement (SI Units, Customary Inch-Pound Units, and Certain Other Units).

[B5] IEEE Std 280TM-1985 (Reaff 2003), IEEE Standard Letter Symbols for Quantities Used in Electrical Science and Electrical Engineering.

[B6] IEEE Std 315TM-1975 (Reaff 1993)/ANSI Y32.2-1975 (Reaff 1989) (CSA Z99-1975), IEEE Standard for Graphic Symbols for Electrical and Electronics Diagrams.

The IEEE publishes several standards documents of special interest to electrical engineers involved with industrial plant electric systems, which are sponsored by the Power Systems Engineering Committee of the IEEE Industry Applications Society:

[B7] IEEE Std 141TM-1993, IEEE Recommended Practice for Electric Power Distribution of Industrial Plants (*IEEE Red Book*).

[B8] IEEE Std 142TM-1991, IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems (*IEEE Green Book*).

[B9] IEEE Std 241TM-1990, IEEE Recommended Practice for Electric Power Systems in Commercial Buildings (*IEEE Gray Book*).

[B10] IEEE Std 242TM-2001, IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems (*IEEE Buff Book*).

[B11] IEEE Std 399TM-1997, IEEE Recommended Practice for Power Systems Analysis (*IEEE Brown Book*).

[B12] IEEE Std 446TM-1995, IEEE Recommended Practice for Emergency and Standby Power Systems for Industrial and Commercial Applications (*IEEE Orange Book*).

[B13] IEEE Std 493TM-1997, IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems (*IEEE Gold Book*).

[B14] IEEE Std 602TM-1996, IEEE Recommended Practice for Electric Systems in Health Care Facilities (*IEEE White Book*).

[B15] IEEE Std 739TM-1995, IEEE Recommended Practice for Energy Management in Industrial and Commercial Facilities (*IEEE Bronze Book*).

[B16] IEEE Std 1100TM-2005, IEEE Recommended Practice for Powering and Grounding Sensitive Electronic Equipment (*IEEE Emerald Book*).

1.5 Manufacturers' data sources

The last chapter in this reference book contains a collection of data from various manufacturers. While reasonable care was used compile this data, equipment with the

same identification and manufactured during different periods may have different ratings. The equipment nameplate is the best source of data and may require obtaining the serial number and contacting the manufacturer.

The electrical industry, through its associations and individual manufacturers of electrical equipment, issues many technical bulletins and data books. While some of this information is difficult for the individual to obtain, copies should be available to each major design unit. The advertising sections of electrical magazines contain excellent material, usually well-illustrated and presented in a clear and readable form, concerning the construction and application of equipment. Such literature may be promotional; it may present the advertiser's equipment or methods in a best light and should be carefully evaluated. Manufacturers' catalogs are a valuable source of equipment information. Some of the larger manufacturers' complete catalogs are very extensive, covering dozens of volumes; however, these companies may issue abbreviated or condensed catalogs that are adequate for most applications. Data sheets referring to specific items are almost always available from the sales offices. Some technical files may be kept on microfilm at larger design offices for use either by projection or by printing. Manufacturers' representatives, both sales and technical, can do much to provide complete information on a product.

Chapter 2

Description of a short-circuit current

2.1 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 used, faults do occur. Some of the causes of faults are as follows:

- a) Presence of animals 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 and 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”

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

- 1) The short-circuit currents may be very high, introducing a significant amount of energy into the fault.
- 2) At the fault location, arcing and burning can occur damaging adjacent equipment and also possibly resulting in an arc-flash burn hazard to personnel working on the equipment.
- 3) Short-circuit current may flow from the various rotating machines in the electrical distribution system to the fault location.
- 4) 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.
- 5) 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.

2.2 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 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 upon 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.

2.3 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 2-1). The envelope is a line drawn through the peaks or crests of the waves.

If the envelopes of positive and negative peaks are not symmetrical around the zero axis, they are called “asymmetrical current” envelopes. Figure 2-2 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 full) and gradually the current will become symmetrical (because of the decay of the offset) around the zero axis.

As stated previously, induction and synchronous machines connected on 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 2-3 shows the symmetrical portion of a decaying fault current waveform typical for such equipment.

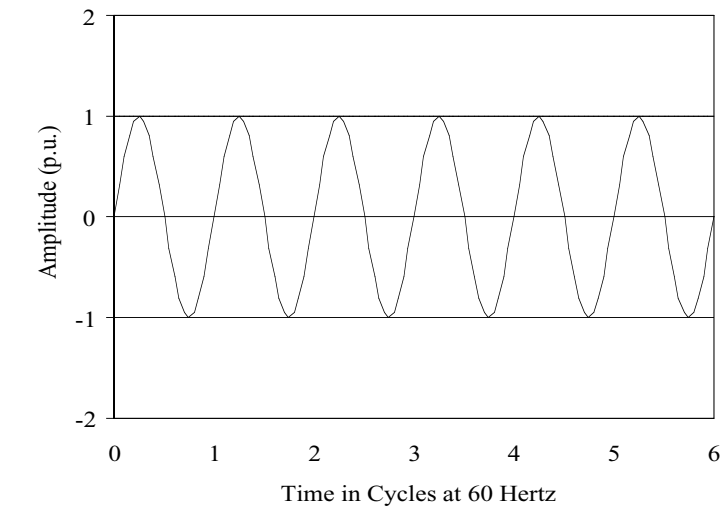


Figure 2-1—Symmetrical ac wave

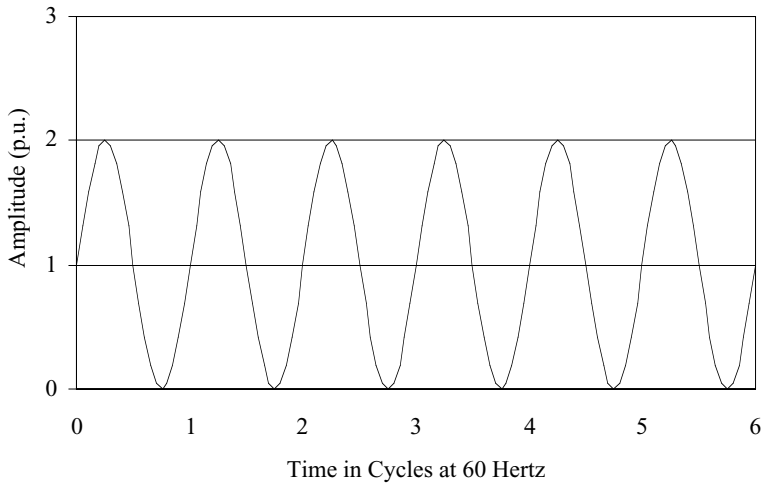


Figure 2-2—Totally offset ac wave

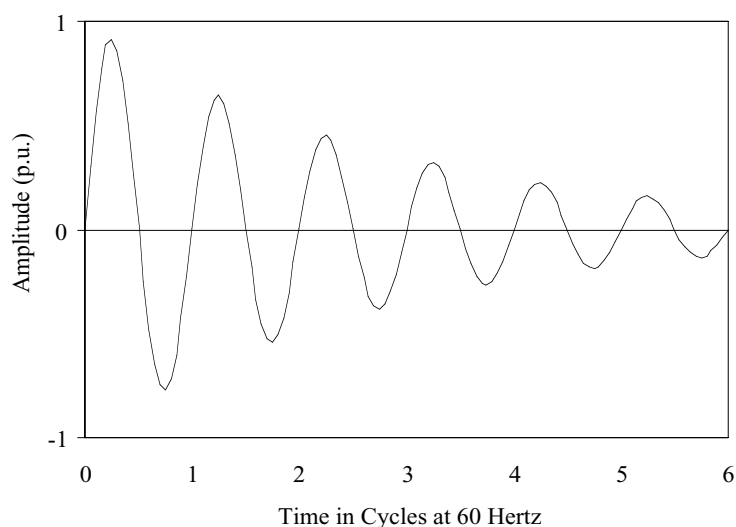


Figure 2-3—Decaying symmetrical ac wave

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 2-4. 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 2-5.

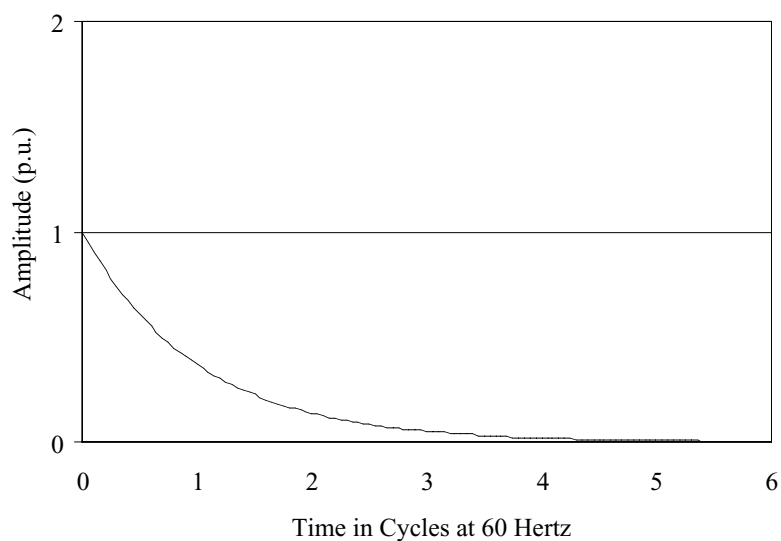


Figure 2-4—Decaying dc wave

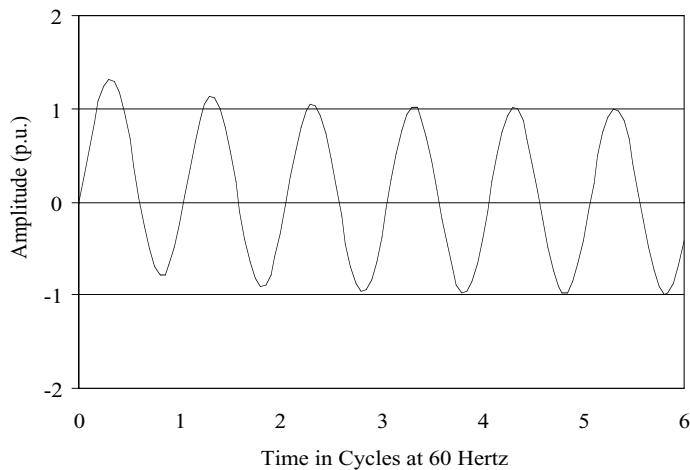


Figure 2-5—Asymmetrical fault current ac wave

2.4 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 2-6 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 (2.1):

$$I = \frac{E}{Z} \quad (2.1)$$

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

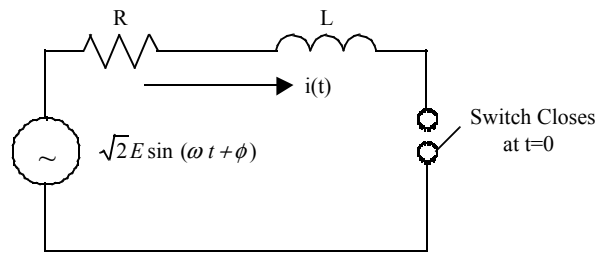


Figure 2-6—Circuit model for asymmetry

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 (1.5–8 cycles), which uses a higher impedance.

The determination of how the fault current behaves as a function of time involves expansion of Equation (2.1) and the solution of the following differential equation [Equation (2.2)] for current i :

$$Ri + L \frac{di}{dt} = \sqrt{2} E \sin(\omega t + \phi) \quad (2.2)$$

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 (= circuit reactance divided by ω)
- t is time in seconds
- ϕ is the angle of the applied voltage in radians when the fault occurs
- ω is the $2\pi f$ where f is the system frequency in hertz (Hz)

The details of the solution of Equation (2.2) are well covered in the references listed at the end of this chapter and in electric power textbooks, so only the solution of the equation

will be stated here. Assuming the pre-fault current through the circuit to be zero (i.e., load current = 0), then the instantaneous current solution to Equation (2.2) is

$$i = -\frac{\sqrt{2}E}{Z} \sin(\alpha - \phi) e^{-\frac{\omega t R}{X}} + \frac{\sqrt{2}E}{Z} \sin(\omega t + \alpha - \phi) \quad (2.3)$$

$$i = -i_{dc} \sin(\alpha - \phi) e^{-\frac{\omega R t}{X}} + \sqrt{2} I_{ac, rms} \sin(\omega t + \alpha - \phi) \quad (2.4)$$

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 (2.4) becomes

$$i = -i_{dc} \sin(\alpha - \phi) e^{-\frac{2\pi R t}{X}} + \sqrt{2} I_{ac, rms} \sin(2\pi t + \alpha - \phi) \quad (2.5)$$

The first term in Equation (2.3) 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 2-6.

The significance of the transient and steady-state components of the fault current is best illustrated by considering an actual example. Figure 2-5 shows the response of a specific circuit with an X/R ratio of 7.5. The circuit is supplied by a 60 Hz source ($\omega = 377$), with the fault occurring (switch closes) when the voltage is at $\alpha = 58$ degrees. The plot of the current is obtained from the general solution of Equation (2.3).

2.5 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 ten 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 2-4). 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 (2.6). Figure 2-7 shows the circuit diagram and Figure 2-8 shows the response curve corresponding to Equation (2.6). Note that ac decaying sources cannot be specifically included in the equivalent circuit, but are assumed to be present.

$$i = i_{dc\ decay} + i_{ac\ steady\ state} + i_{ac\ decay} \quad (2.6)$$

With

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

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

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

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:

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

The greater the fault point X/R ratio, the longer will be 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.

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.

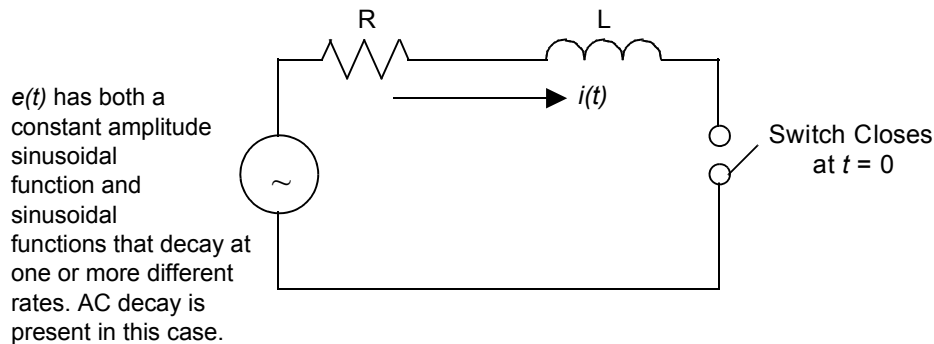


Figure 2-7—Circuit model with steady-state and decaying ac current sources

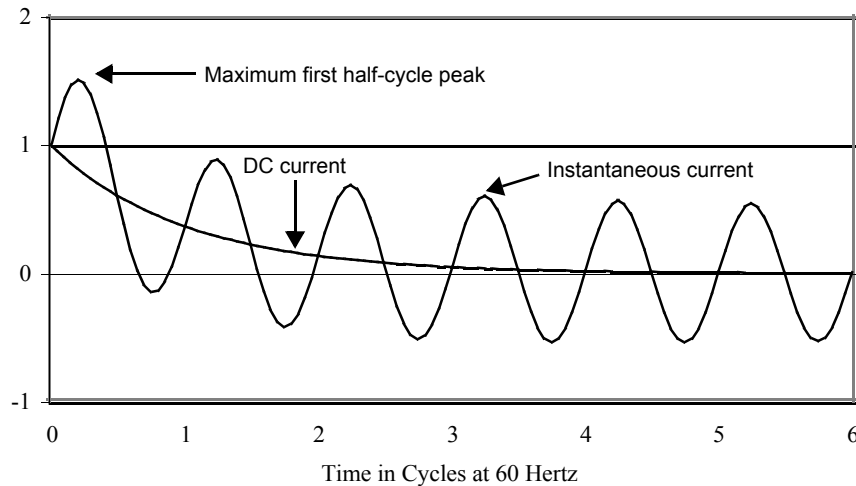


Figure 2-8—Asymmetrical ac short-circuit current made up of dc, decaying ac, and symmetrical ac current

2.6 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 2-1). 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 2-2. The two cases shown in Figure 2-1 and Figure 2-2 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.

2.7 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 2-1 and Figure 2-4, 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.

2.8 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 2-8, 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.

2.9 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 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 minimum test X/R ratio or maximum power factor of the applied fault current used in the acceptance test by ANSI, NEMA, or UL is also required. Peak fault current magnitudes are significant for some

devices, such as low-voltage 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 application of equipment is detailed in Chapter 10.

The bibliography at the end of this chapter provides a thorough treatment of the mathematics involved in analyzing the maximum current under the conditions of asymmetry. While this chapter provides a summary, the details of this analysis are worthwhile for a clear understanding of the implications of asymmetry. In this summary, it has been shown that the effects of asymmetry are dependent only upon the fault point X/R ratio of the circuit and the instant of fault initiation.

The references 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 correction is covered in Chapter 10.

2.10 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 one 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 2-9. Figure 2-9 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 Hz voltage, linear impedances, no ac decaying sources, and no pre-fault load currents. The largest of these fault current peaks can be found mathematically by differentiating the current expression in Equation (2.2) 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 2-9.

Important characteristics shown on Figure 2-9 are as follows:

- 1) The short circuit starts at zero voltage.
- 2) The initial asymmetrical current is zero, due to the assumption of no pre-fault load current and item 3) below.
- 3) 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.
- 4) The maximum fault current peak occurs before the first positive symmetrical fault current peak.

The maximum peak current is obtained by manipulation of partial derivatives of Equation (2.2) using an iterative approach and results in maximum peak and maximum rms currents multipliers as shown in Table 2-1 and Table 2-2. The values listed under the column headed "exact" have been calculated from these partial derivatives and are theoretically exact.

For circuit X/R ratios between 0.5 and 1000, the second column in Table 2-1 and Table 2-2 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 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.

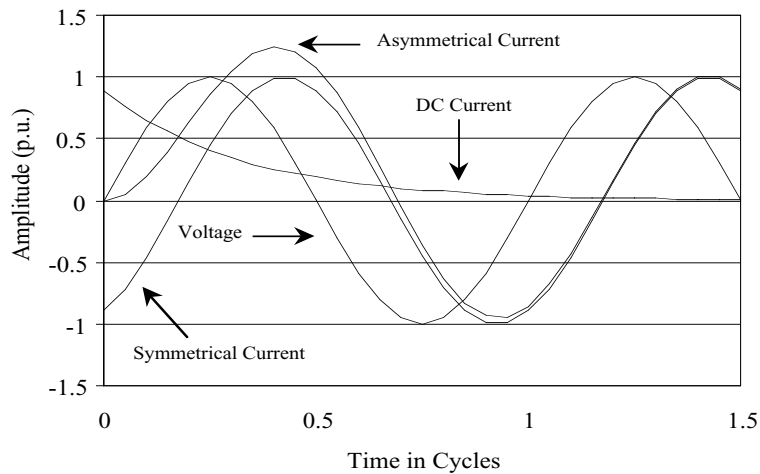


Figure 2-9—Maximum peak asymmetrical short-circuit current

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 2-9 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 Hz base by Equation (2.7) 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 2-1 and Table 2-2 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 shown in Equation (2.7):

$$I_{peak} = I_{ac\ peak} + I_{dc} = \sqrt{2}I_{ac, rms} + \left(1 + e^{-\frac{2\pi t}{X/R}}\right) \quad (2.7)$$

where $t = 0.5$ cycles

The IEC calculating procedure for short-circuit currents includes the following empirical formula [Equation (2.8)] 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 three. Determining peak currents for circuit X/R ratio less than three is rarely necessary. Because most types of protective equipment short-circuit ratings are based on fault point X/R ratios greater than three (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 2-1 and Table 2-2 under the columns labeled “IEC.” The form of

Equation (2.7) 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 (2.8):

$$I_{peak} = \sqrt{2} I_{ac, rms} \left(1.02 + 0.98 e^{-\frac{3}{X/R}} \right) \quad (2.8)$$

From the IEC Equation (2.8), the dc component would be as shown in Equation (2.9):

$$I_{dc} = \sqrt{2} I_{ac, rms} \left(0.02 + 0.98 e^{-\frac{3}{X/R}} \right) \quad (2.9)$$

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 (2.10) and then substituted into Equation (2.7) for t . For convenience, Equation (2.7) is listed below Equation (2.10).

$$\tau = 0.49 - 0.1 e^{-\frac{X/R}{3}} \quad (2.10)$$

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

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 2-1 under the columns labeled “violet approx.”

Equation (2.11), Equation (2.12), and Equation (2.13) are used for peak current factors in Table 2-1.

$$Half\ cycle_{peak} = I_{ac\ peak} \left(1 + e^{-\frac{\pi}{(X/R)}} \right) \quad (2.11)$$

$$IEC_{peak} = I_{ac\ peak} \left(1.02 + 0.98 e^{-\frac{3}{(X/R)}} \right) \quad (2.12)$$

$$Violet\ approx_{peak} = I_{ac\ peak} \left(1 + e^{-\frac{2\pi\tau}{(X/R)}} \right) \quad (2.13)$$

where

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

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

$$I_{rms} = \sqrt{I_{ac\ rms}^2 + I_{dc}^2} \quad (2.14)$$

Recall the difficulty in determining the rms value of a non-periodic waveform. Equation (2.14) 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 1/2 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 2-2.

$$IEC_{rms} = I_{ac\ rms} \sqrt{1 + 2 \left(1.02 + 0.98e^{-\frac{3}{(X/R)}} \right)^2} \quad (2.15)$$

$$Half\ cycle_{rms} = I_{ac\ rms} \sqrt{1 + 2 \left(e^{-\frac{\pi}{(X/R)}} \right)^2} \quad (2.16)$$

$$Violet\ approx_{rms} = I_{ac\ rms} \sqrt{1 + 2e^{-\frac{4\pi\tau}{(X/R)}}} \quad (2.17)$$

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 (2.16) 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 2-1—Differences in per-unit peak currents based on Equation (2.11), Equation (2.12), and Equation (2.13) (one per-unit equals ac peak)

Exact				IEC		Half-cycle		Violet approx	
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	0.4997	0.9969	1.9969	1.9971	0.01	1.9969	-0.00	1.9969	0.00

Table 2-2—Per-unit rms currents at peak ac current based on Equation (2.15), Equation (2.16), and Equation (2.17) (one per-unit equals ac rms)

Exact				IEC		Half cycle		Violet approx	
X/R	Time to peak (CY)	DC	Max-imum peak	Max-imum peak	Per-cent error	Max-imum peak	Per-cent error	Max-imum peak	Per-cent 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	0.4997	1.4099	1.7285	1.7287	0.01	1.7284	−0.00	1.7285	0.00

2.11 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 2-10, 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.

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 2-10(a) provides a graphical representation of a bolted three-phase fault.

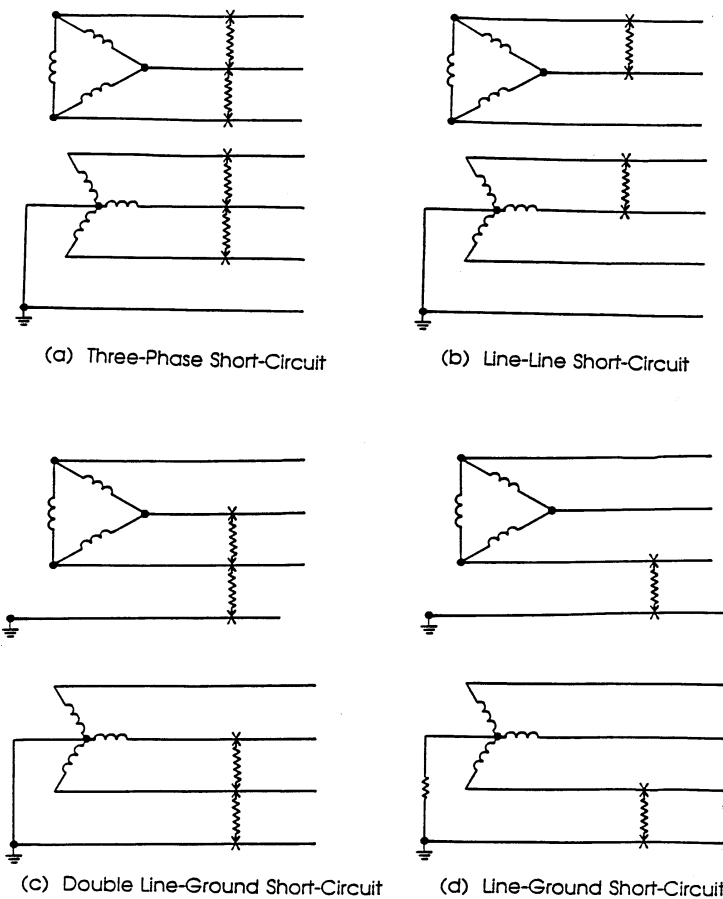


Figure 2-10—Designation of short-circuit categories

Bolted line-to-line faults, Figure 2-10(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 2-10(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 2-10(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 method in which the system is grounded 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. 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 system 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.

2.12 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 (< 500 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 2-3. On higher-voltage networks (> 500 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.

Table 2-3—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%

The environment in which the fault takes place has an effect on the fault resistance and its continuity. 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.

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, Brown, and Strom [B1]¹ provide an approximation [Equation (2.18), Equation (2.19), and Equation (2.20)].

$$\frac{V}{\text{cm}} = 50 \left(\frac{P}{I^2} \right)^{1/6} \quad (2.18)$$

or in terms of resistance

$$\frac{R}{\text{cm}} = 50(P)^{1/6}(I)^{3/4} \quad (2.19)$$

where

V = voltage, volts

cm = arc length, centimeters

P = pressure in atmosphere (1 atm = 14.696 PSIA)

I = current in kiloamperes

R = resistance in ohms

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

¹The numbers in brackets correspond to those of the bibliography in 2.13.

and resistance per centimeter. Therefore, the total arc voltage or resistance can be determined by multiplying Equation (2.18) and Equation (2.19) by the total arc length.

The instantaneous arc resistance at current peak can be calculated using Equation (2.20).

$$R = 11.6 \times l \times \frac{1.1}{I_x} \quad (2.20)$$

where

l = length of arc in centimeters
 I_x = peak current in kiloamperes

In the calculation of fault current magnitudes, maximum ampere conditions for equipment evaluation is often the concern and arcing fault impedance or arc resistance is considered zero.

2.13 Bibliography

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