

IEEE Std 3004.7™-2021

Recommended Practice
for Conductor Protection in
Industrial and Commercial
Power Systems



IEEE Recommended Practice for Conductor Protection in Industrial and Commercial Power Systems

Developed by the

Industrial and Commercial Power Systems Standards Development Committee
of the
IEEE Industry Applications Society

Approved 9 February 2021

IEEE SA Standards Board

Abstract: The protection of power cables used in industrial and commercial power systems is covered in this recommended practice. It is likely to be of greatest value to the power-oriented engineer with limited experience in the area of protection and control. It can also be an aid to all engineers responsible for the electrical design of industrial and commercial power systems.

Keywords: conductors, IEEE 3004.7™, overcurrent protection, power distribution protection, power system protection, wire

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Introduction

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This recommended practice was developed by the Industrial and Commercial Power Systems Standards Development Committee of the Industry Applications Society, as part of a project to repackage the popular IEEE Color Books®. The goal of this project is to speed up the revision process, eliminate duplicate material, and facilitate use of modern publishing and distribution technologies.

When this project is completed, the technical material included in the 13 “color books” will be included in a series of new standards. Approximately 60 additional “dot” standards, organized into the following categories, will provide in-depth treatment of many of the topics formerly covered in the color books:

- Power Systems Design (3001 series)
- Power Systems Analysis (3002 series)
- Power Systems Grounding (3003 series)
- Protection and Coordination (3004 series)
- Emergency, Standby Power, and Energy Management Systems (3005 series)
- Power Systems Reliability (3006 series)
- Power Systems Maintenance, Operations, and Safety (3007 series)

In many cases, the material in a dot standard comes from a particular chapter of a particular IEEE Color Book. In other cases, material from several IEEE Color Books has been combined into a new dot standard.

IEEE Std 3004.7™

This publication provides a recommended practice for the electrical design of commercial and industrial facilities. This recommended practice covers the protection of conductors used in industrial and commercial power systems. It is likely to be of greatest value to the power-oriented engineer with limited commercial or industrial plant experience. It can also be an aid to all engineers responsible for the electrical design of commercial and industrial facilities. However, it is not intended as a replacement for the many excellent engineering texts and handbooks commonly in use, nor is it detailed enough to be a design manual. It should be considered a guide and general reference on electrical design for commercial and industrial facilities.

Tables, charts, and other information that have been extracted from codes, standards, and other technical literature are included in this publication. Their inclusion is for illustrative purposes; where technical accuracy is important, the latest version of the referenced document should be consulted to assure use of complete, up-to-date, and accurate information.

This publication is based on North American installation codes and product standards, primarily those in the United States and Canada, and thus will be most useful in those jurisdictions and in jurisdictions that follow North American codes and standards. Elsewhere similar codes and standards may apply, such as those published by the International Electrotechnical Commission (IEC).

The material in this recommended practice was originally published in Chapter 9 of IEEE Std 242™-2001 (*IEEE Buff Book*™) [B16] and has been updated as required based on US codes and standards.

Contents

1. Overview	10
1.1 Scope	10
1.2 Purpose	10
1.3 Word usage	10
2. Normative references	10
3. Definitions, acronyms, and abbreviations	11
3.1 Definitions	11
4. General discussion	13
4.1 Introduction	13
4.2 Code requirements for cable protection	13
5. Cable protection	15
6. Short-circuit current protection of conductors	16
6.1 General	16
6.2 Short-circuit current	17
6.3 Conductor temperature rise caused by short circuits	19
6.4 Protective devices	25
6.5 Application of short-circuit current protective devices	27
7. Overload protection of conductors	42
7.1 Introduction	42
7.2 Normal current-carrying capacity	42
7.3 Overload capacity	44
7.4 Overload protective devices	53
7.5 Application of overload protective devices	55
8. Physical protection of cables	55
8.1 General	55
8.2 Mechanical hazards	56
8.3 Exposed raceways	56
8.4 Underground systems	56
8.5 Direct buried cables	56
8.6 Aerial cable systems	57
8.7 Portable cables	57
8.8 Adverse ambient conditions	57
8.9 Attack by foreign elements	58
9. Busway	58
9.1 Introduction	58
9.2 Busway-related definitions	59
9.3 Busway protection	59
9.4 Types of faults	60
9.5 Types of protection	62
Annex A (informative) Bibliography	65

IEEE Recommended Practice for Conductor Protection in Industrial and Commercial Power Systems

1. Overview

1.1 Scope

This recommended practice covers the protection of conductors used in main and branch power circuits in industrial and commercial power systems against damage from short circuits and overloads as well as against physical damage from mechanical hazards, adverse environmental conditions, and improper handling.

1.2 Purpose

1.3 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).^{1,2}

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

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.

¹The use of the word *must* is deprecated and cannot be used when stating mandatory requirements, *must* is used only to describe unavoidable situations.

²The use of *will* is deprecated and cannot be used when stating mandatory requirements, *will* is only used in statements of fact.

CSA C22.1-2018, Canadian Electrical Code (CE Code-2018).³

ANSI/ICEA P-32-382-2007 (R2013), Short-Circuit Characteristics of Insulated Cables.⁴

ANSI/ICEA P-45-482-2017, Short-Circuit Performance of Metallic Shields and Sheaths on Insulated Cable.

ANSI/NEMA WC 51/ICEA P-54-440-2009 (R2014) Ampacities of Insulated Cables Installed in Open-Top Cable Trays, Ampacities of Cables in Open-Top Cable Trays.

NFPA 70-2020, National Electrical Code® (NEC® 2020).^{5,6}

The United States Department of Agriculture (USDA) Rural Utilities Service, Design Guide for Rural Substations, RUS Bulletin 1724E-300, June 2001.

3. Definitions, acronyms, and abbreviations

3.1 Definitions

3.1.1 General

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.⁷

Arriving at definitions for the terms used in this document has been challenging as there seems to be as many different definitions for the terms as there are sources for such definitions. While the following are descriptive, it should be recognized that they are not perfect and that other reputable sources may vary slightly.

cable: A factory assembly of one or more wires with or without an additional outer jacket, sheath, or armor, or a single wire with an additional outer jacket or armor.

conductor: A conductive material, such as wire or bus bar, that is constructed for the purpose of carrying electric current from one piece of electrical equipment to another or to ground.

jacket: A non-metallic covering on a cable which provides mechanical and environmental protection for the cable.

raceway: An exposed channel designed expressly for holding wire, cables, or bus bars. Cable tray and conduit are not considered raceways (per the National Electric Code, NEC 2020).

shield: A conducting envelope enclosing an insulated conductor or conductors, sometimes also referred to as a *sheath*.

wire: A single bare, covered or insulated conductor composed of one or more strands of metal.

3.1.2 Cable current (*I*)

I is current flowing in cable

³CSA publications are available from the Canadian Standards Association (<https://www.csa.ca/>).

⁴ANSI publications are available from the American National Standards Institute (<https://www.ansi.org/>).

⁵NFPA publications are published by the National Fire Protection Association (<https://www.nfpa.org/>).

⁶The NEC is published by the National Fire Protection Association (<https://www.nfpa.org/>). Copies are also available from The Institute of Electrical and Electronics Engineers (<https://standards.ieee.org/>).

⁷*IEEE Standards Dictionary Online* is available at: <http://dictionary.ieee.org>. An IEEE account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

I_O	is initial current prior to a current change
I_F	is final current after a current change
I_N	is normal loading current on base ambient temperature
I_{N1}	is normal loading current on non-base ambient temperature
I_E	is emergency loading current on base ambient temperature
I_X	is current at values other than normal or emergency loading
I_{SC}	is three-phase short-circuit current

3.1.3 Cable temperature (°C)

T	is temperature, in general
T_O	is initial temperature prior to a current change
T_f	is final temperature after a current change
T_N	is normal loading temperature
T_E	is emergency loading temperature
T_X	is temperature at any loading current
T_t	is temperature at time t after a current change
T_a	is base ambient temperature
T_{a1}	is non-base ambient temperature

3.1.4 Miscellaneous

t	is time (units as noted)
CM	is conductor size (circular mils)
EPR	is ethylene propylene rubber
F_{ac}	is skin effect ratio or ac/dc ratio. This ratio may be calculated from the conductor properties in Table 8 and Table 9 of the 2020 National Electrical Code® (NEC®)
K	is time constant or geometric factor of cable heat flow
K_t	is correction factor for initial and final short-circuit temperature
$PILC$	is paper insulated lead covered
TCC	is time-current characteristic curve (There is no clear definition for this acronym. In prior standards it is sometimes referred to as <i>time-current characteristic</i> and in other instances <i>time-current curve</i> .)
$XLPE$	is cross-linked polyethylene

3.1.5 Reactances (%)

X_T	is transformer reactance
$X_{d''}$	is subtransient reactance of a rotating machine
X_d'	is transient reactance of a synchronous machine

4. General discussion

4.1 Introduction

This recommended practice deals with insulated power cable protection. The primary considerations are presented along with some methods of application. It is based on North American codes, standards, and practices (NEC, CE Code, UL, CSA, ANSI, NEMA, ICEA, etc.), not IEC standards and practices. Offshore, shipboard, submarine, and mining cables are not completely covered in this recommended practice. There are additional issues to be managed with electrical heat tracing cables; refer to IEEE Std 515™ [B25], IEEE Std 60079-30-1 [B40], and IEEE Std 60079-30-2 [B41]. For overhead distribution lines with bare conductors, protection should be based on IEEE Std C37.230™ [B43]. Some industrial applications may require some adaptations from this standard, which is based on power distribution utility practices.

The proper selection and rating or derating of power cables is as much a part of cable protection as the application of the short-circuit and overcurrent protection devices. The whole scheme of protection is based on a cable rating that is based on the environment and the operating conditions. Methods of assigning these ratings are discussed.

Power cables require short-circuit current, overload current, and physical protection in order to meet the requirements of the applicable installation codes.⁸ A brief description of the phenomena of short-circuit current, overload current, and their temperature rises is presented, followed by a discussion of the time-current characteristics of both cables and protective devices. In addition, a number of illustrations of cable systems and examples of cable selection considering the protective device settings are included.

The general intent of this recommended practice is to provide a basis for design, to point out the problems involved, and to provide guidance in the application of power cable protection. Each specific case and type of cable requires attention. In most cases, the attention is routine, but the out-of-the-ordinary cable schemes require careful consideration. The application of cables, both single and multi-cable configurations, in factory assembled products, such a low-voltage and medium-voltage motor control centers for example, may utilize different cable application principles based on the requirements of the standards associated with those products. Different utilization characteristics may be applied in these products, based on the specific design standards and may be validated through temperature and environmental type testing.

Electrical installation codes are location specific; consult the version authorized by the relevant authority having jurisdiction (AHJ).

4.2 Code requirements for cable protection

Codes and regulations are established to control the installation and operation of electric cable systems. Although many different codes and regulations may be applied, depending on governmental, geographical, or company requirements, the NEC is most often quoted; and portions of it are mandatory by the Occupational Safety and Health Administration's (OSHA) 29 CFR Part 1910.302–1910.309. The engineer is responsible for determining which codes are applicable to each project. The discussion in this clause is limited to the national installation codes (NEC and Canadian Electrical Code [CE Code]), which is principally concerned with overtemperature (or overcurrent), short-circuit, and mechanical protection in regard to cable applications.

Overcurrent protection is covered in NEC 2020 Article 240 and CE Code-2018 Rule 14–100, both of which require all conductors to be protected in accordance with their current-carrying capacities (or ampacity), as discussed in 7.2.2 below. In general, the current-carrying capacity of cables is determined from the tables contained in NEC 2020 Article 310, which concerns the installation of conductors, or from the CE Code Section 4 and associated tables.

⁸Local authorities do not necessarily enforce the most current revision of national codes. Check with local authorities to determine the revision that is being enforced for a specific location.

Overcurrent protection of feeders or conductors rated 1000 V or less should be in accordance with their current-carrying capacities as given in code tables or an alternate method in accordance with the NEC 2020 and CE Code-2018. When the ampacity of a conductor requires a protective device rated 800 A or less, and the ampacity does not correspond to a standard rating size, the next higher standard protective device rating may be used to protect the conductor. However, protective devices rated over 800 A may not be used to protect conductor ampacities lower than the device's rating. Other exceptions may be allowed by the installation codes based on the specific types of loads to be supplied, such as capacitors or welders or transformer secondary conductors.

The NEC 2020 permits protection device ratings or settings for transformers to be set higher than the maximum current rating of a transformer. See NEC 2020 Articles 240 and 450 for requirements pertaining to the maximum ratings and settings of protection devices and minimum conductor ampacities for transformer primary and secondary conductors.

The minimum motor branch-circuit conductor ampacity depends on many factors. The codes may permit protection device ratings or settings for motors to be higher than the full-load current rating of the motor. However, the minimum ampacities of motor branch-circuit conductors are based on the NEC 2020 full-load current values found in NEC 2020 Article 430 tables for motors up to 600 V, nominal. For minimum motor branch-circuit ampacities for motors greater than 1000 V, see NEC 2020 Article 430 Part XI, in addition to other applicable articles.

For minimum conductor ampacity of feeders where there is more than a single motor served, see NEC 2020 Articles 215, 220, 240, 310, 311, and 430.

Cables are also required by the installation codes to have short-circuit protection, which may be provided by a fuse or circuit breaker with the ratings complying with the specific requirements of the codes. For some circuits over 1000 V, such as those for motor branch-circuits, engineering supervision is required by the NEC 2020 when determining protection settings to include at a minimum appropriate short-circuit analysis and time-current coordination analysis of protective device characteristics and cable damage curves.

Feeders rated more than 1000 V are required by the NEC 2020 to have short-circuit protection, which may be provided by a fuse rated at no more than 300% of the conductor ampacity or by a circuit breaker set to trip at no more than 600% of the conductor ampacity. The NEC 2020 also requires that overcurrent protection for circuits over 1000 V be developed under engineering supervision, to include at a minimum appropriate short-circuit analysis and time current coordination analysis of protective device characteristics and cable damage curves. Although not required by the NEC 2020, improved protection of these circuits is possible when overload protection is also provided in accordance with the conductor ampacity.

The minimum required ampacity of motor feeder and branch circuit conductors for motors 600 V, nominal, or less, are based on the motor full-load current table values in NEC 2020, Article 430, Parts II and XIV. For motors 600 V, nominal, or less, nameplate full-load current ratings must not be used when calculating motor feeder and branch circuit conductors, unless specifically allowed by the NEC 2020. For motors greater than 600 V, nominal, the protection device settings for the motor and conductors must be determined under engineering supervision.

NOTE—Although the discussion in this recommended practice concerns only cables, motor overload and overcurrent protective devices may also provide the required overcurrent protection. In addition, maximum permitted ratings or settings of the short-circuit and ground-fault protection devices for motor feeder conductors are addressed in Articles 220, 240, and 430, Part V. Maximum ratings or settings for the motor branch-circuit short-circuit and ground-fault protective devices are addressed in NEC 2020, Part IV.

NEC 2020 Article 310 ensures that cables are adequate for their service applications by specifying currents that may be carried by particular conductors with specific insulation classifications and under specific governing conditions. It also requires the selection of cable materials that are suitable for application conditions,

including moisture, chemicals, and nonstandard temperatures. This article permits the use of multiple cables if means are provided to ensure the equal division of current, and if essentially identical conditions and materials are used for each of the parallel paths.

NEC 2020 Chapter 3 specifies wiring methods and protection required for cables subject to physical damage.

These articles pertain specifically to cable protection, but are not the only provisions of the NEC that deal with the subject. Any specific cable or cable system comes under the provisions of one or more sections of the NEC, and responsible parties should ensure that the protective methods they have selected comply with both the relevant provisions and any special requirements that they may impose.

5. Cable protection

Cables are the essential connecting links between equipment in an electric system. If the cable system is inadequate or inadequately protected, unsatisfactory operation inevitably results. Cables are not unlimited in power capability and, therefore, must be applied within their listing and provided protection to prevent possible operation beyond their capabilities. Improper application and protection of cables can result in premature cable failure and unsafe operation, posing a danger to personnel and therefore must be addressed.

Cables are generally classified as either power or control. Power cables are divided into two voltage classes based on the cable manufacturing standards: 2000 V and below, and above 2000 V. Control cables include cables used in the control of equipment and for voice communication, metering, and data transmission.

Excessive conductor temperature due to overload currents, nonlinear loads, or mechanical damage, is a frequent cause of decreased cable life and failure. Power cables, internally heated primarily as a result of their resistance to the current being carried, can undergo insulation failure if the temperature buildup becomes excessive. Proper selection of a cable for an application is necessary to assure a long and safe life. Suitable protection is provided to address concerns about abnormal operating conditions and faults. Traditionally, time-current sensitive protection functions are used among other protection functions to provide cable protection. In addition to insulation breakdown, protection is also required against unexpected overload and short-circuit current. Overcurrent can occur due to an increase in the number of connected loads, or due to overloading of existing equipment, or due to nonlinear loads causing excessive neutral conductor current.

While the extraordinary temperature of a short-circuit arc produces extensive destruction of materials at a fault location, cables carrying energy to (and from) a fault may also incur thermal damage over their entire length if the fault current is not interrupted quickly enough. Depending on conductor size, insulation type, and available fault current, the clearing time of the protection system should be short enough (i.e., coordinated) to stop the current flow before damaging temperatures are reached.

Physical conditions can also cause cable damage and failure. Failure due to excessive heat may be caused by high ambient temperature conditions or by fire. Mechanical damage may result in short circuits or reduced cable life and may be caused by persons, equipment, animals, insects, fungi, or strand breakage due to frequent flexing.

Cable protection is required to protect personnel and equipment and to ensure continuous service. From the standpoint of equipment and process, the type of protection selected is generally determined by economics and the engineering requirements. Personnel protection also receives careful engineering attention and special consideration to ensure compliance with the various codes that may be applicable to a particular installation.

Protection against overload is generally achieved by a device sensitive to current magnitude and duration. Short-circuit-protective devices are sensitive to much greater currents and shorter times. Protection against environmental conditions takes on many forms.

Cables may also be damaged by sustained overvoltages that exist during a ground fault on one phase conductor. While low-voltage (LV) cable insulation thickness is governed by mechanical constraints, which result in a greater thickness than the utilization voltage would indicate (i.e., insulation volts/mil capability), medium-voltage (MV) cable insulation is different. MV cable insulation systems in North America are rated based on a system voltage; the voltage capability of one MV conductor is only the system (or rated) voltage/ $\sqrt{3}$. Hence, while a 600 V conductor is designed to continuously withstand 600 V applied between the conductor and an adjacent grounded metal object, a MV conductor rated 5 kV 100% insulation level (IL) should only be expected to perform satisfactorily when placed against a grounded metal plate if subjected to a voltage of $5000/\sqrt{3} = 2887$ V. While this is adequate for solidly grounded systems, cables will be damaged by overvoltages in ungrounded or resistance grounded systems. Modern medium-voltage cables now bear a rating called *percent insulation level* (or % IL). This rating is described as follows (refer to NEMA WC74/ICEA S-93-639-2012 Table 4-4 for additional details regarding cable construction for these insulation levels):

- a) 100% IL—Cables that shall not be required to operate longer than 1 min in case of a ground fault.
- b) 133% IL—Cables that shall not be required to operate longer than 1 h in case of a ground fault.
- c) 173% IL—Cables that may be required to operate longer than 1 h continuously with one phase conductor grounded (manufacturers should be consulted for suitability).

NOTE—This rating is not available in CSA certification standards. A higher base voltage rating must be chosen to achieve the equivalent IL of 173%, where required.

Cable insulation may also be damaged by transient overvoltages, such as from lightning strikes or switching transients. For a general treatment of this subject, refer to Chapter 6 of IEEE Std 141™ [B13]. For discussion regarding the analysis of switching transients, refer to Chapter 11 of IEEE Std 399™ [B18].

Subclause 7.1.3 of IEEE Std 1242™ [B30] notes that the various cable standards sometimes have slightly different requirements for insulation thickness for these ILs, and that common industry practice is to defer to the recommendations of cable manufacturers for insulation thickness in such cases. The timing of the permissible protective system should be in accordance with the IL rating of the cables involved.

In general, this recommended practice covers methods of rating cables and the conditions and problems listed in this clause. It also provides a starting point from which further refinements may be made and other features added for improved power cable protection.

6. Short-circuit current protection of conductors

6.1 General

A conductor should be protected from overheating due to excessive short-circuit current flow. The fault point may be on a section of the protected conductor or on any other load side part of the electric system. If the fault point is on the cable, the faulted cable section is, of course, to be replaced after the fault has been cleared.

During a fault between live conductors, the I^2R heating in the live conductors elevate first the temperature of the conductor, followed by the insulation materials, protective jacket, raceway, and surroundings. During a ground fault in a solidly grounded system, the I^2R heating in both the live conductor and any metallic raceway elevate the temperature in a similar manner to faults between live conductors.

For cables with metallic shielding, the shielding of the cable on the line side of the fault also carries part of the short-circuit return current, which may return along the shields of other conductors or equipment grounding paths, from common grounding points. Refer to 6.3.2 for additional discussion.

When the short-circuit current is interrupted either instantaneously or in a short time by the protective device, the amount of heat transferred from the metallic conductors outward to the insulation and other materials is small. Because the heat from I^2R losses is contained almost entirely in the conductors, it can be assumed that 100% of the I^2R losses result in elevating the conductor temperature. This is called *adiabatic heating*. During the period that the short-circuit current is flowing, the conductor temperature should not be permitted to rise to the point where it may damage the insulating materials. The task of providing cable protection during a short-circuit condition involves determining the following:

- Maximum available short-circuit currents
- Maximum conductor temperature that will not damage the insulation
- Cable conductor size, which affects the I^2R value and the capability of the cable to withstand the heat
- Longest time that the fault current can flow without insulation degradation

Molded-case circuit breakers (MCCBs) listed to UL 489 [B61] are required to be tested with rated wire if they are provided with wire connectors. (Note that UL 489 is a harmonized standard with CSA C22.2 No. Five in Canada and NMX-J-266 in Mexico.) Damage to the wire insulation during the interrupting tests is not permitted for all tested circuit breakers in order to pass such tests. (Exception: UL 489 allows 15 A or less 277 V, 347 V, 480 V, and 600 V rated circuit breakers to be tested with 12 AWG wire.) Because of this UL 489 requirement, it is not necessary to perform wire protection calculations for wires rated and tested with the subject breakers. Wire protection calculations should be conducted in instances where the protective device has not been tested with wire. It may be noted that that cable damage subjected to such tests is ascertained visually, and such criteria are not identical to those used by ICEA for short-circuit cable damage determination.

Cable protection calculations may be made by the following method:

$$I_p = I_a \times A \times B \times C \times D \times E \times G$$

where

- I_p is the circuit breaker rating
- I_a is the full-load rms current the circuit must be capable of carrying
- A is the wire size factor
- B is the ambient temperature factor
- C is the frequency factor
- D is the altitude rating factor
- E is the load class rating factor
- G is the safety factor normally 1.0 for intermittent loads and 1.25 for continuous loads

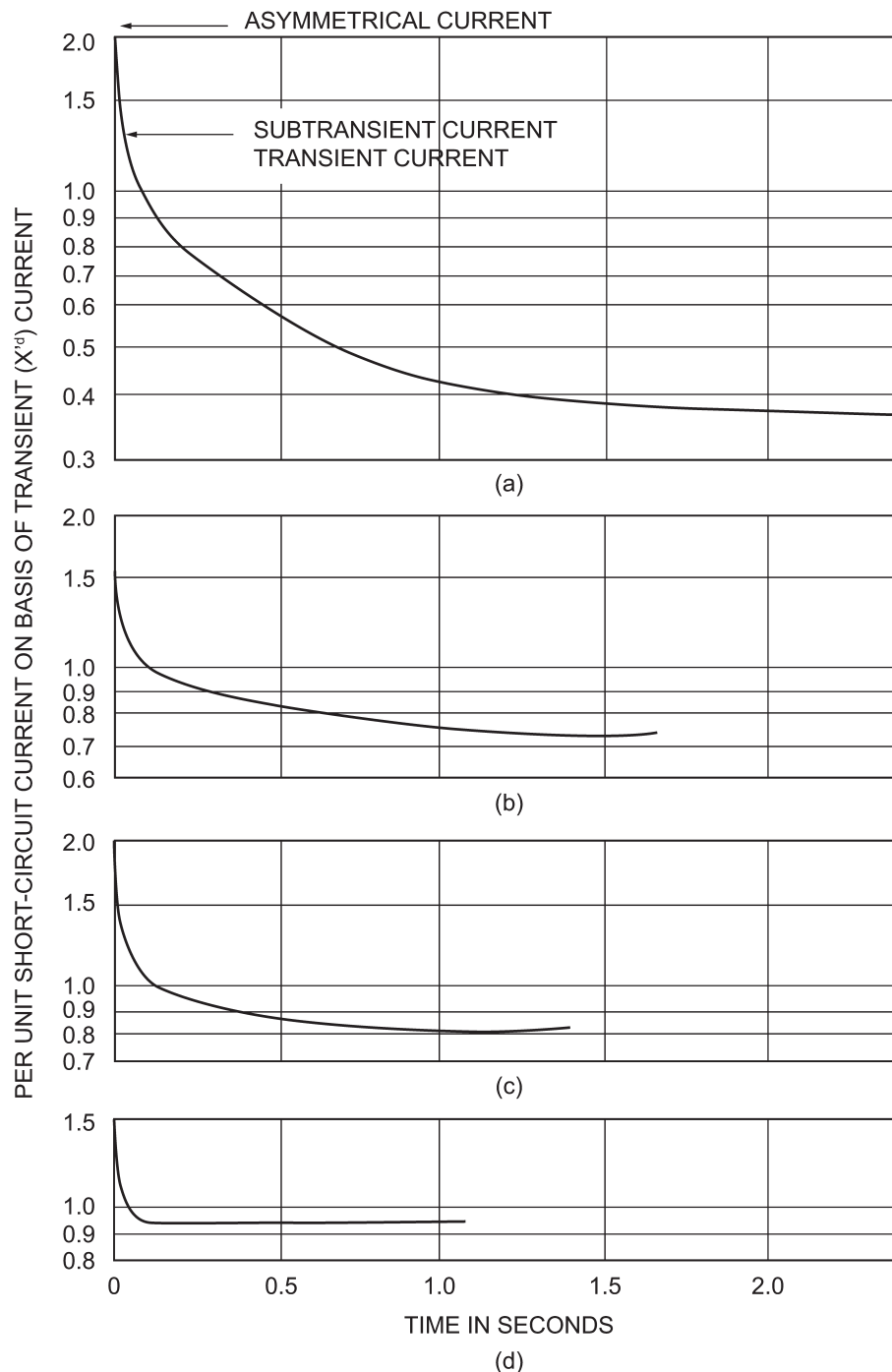
The above listed factors are discussed in the following subclauses of this recommended practice.

6.2 Short-circuit current

6.2.1 Phase-fault current and rates of decay

The fundamentals of short-circuit current behavior and the calculation of short-circuit currents are described in Chapter 4 of IEEE Std 141 [B13], Chapter 7 of IEEE Std 399 [B18], IEEE Std 551TM [B27], and IEEE Std 3002.3TM-2018 [B36]. The magnitude of short-circuit current should be properly determined. As illustrated in Figure 1, the initial peak current is called *asymmetrical current* (or *current for momentary duty*). This current then decays in sequence to the subtransient current, transient current, and symmetrical current or sustained short-circuit current. The short-circuit current contains a decaying exponential component superimposed on the symmetrical short-circuit current in the subtransient and transient periods. Figure 1 shows the approximate rate of decay of the total current. Four typical systems are illustrated in this figure to

give a general picture of the fault-current behavior. The decay rate in each system depends on the X/R ratio of the system; higher X/R ratios are found on medium-voltage systems with local generation.



- a) Plant generator system, medium voltage
- b) Utility-power supplied system, medium voltage, with large synchronous motors
- c) Utility-power supplied system, medium voltage, no synchronous motor
- d) Utility or plant generation, low-voltage 240 V or 480 V load centers

Figure 1—Typical rate of short-circuit decay

6.2.2 Maximum short-circuit currents

Generally, the subtransient current of a system is used to designate the maximum available short-circuit current in the cables protected by the instantaneous overcurrent relays that trip medium-voltage switchgear circuit breakers. For cables protected by noncurrent-limiting fuses or noncurrent-limiting low-voltage instantaneous trip circuit breakers, the asymmetrical current value is used. The effective current for cables protected by current-limiting devices [e.g., fuses, molded-case circuit breakers (MCCBs), cable limiters] in the current-limiting range is the root-mean-square (rms) value of the let-through current as determined from the manufacturers' let-through curves (see Example 1 in 6.5.1.2). For delayed tripping of 0.2 s or longer, the rms value of the decayed current over the flow period of fault current should be used.

6.2.3 Ground-fault currents and rates of decay

The fundamentals of ground short-circuit current behavior are similar to the characteristics of fault currents between current-carrying conductors, but the calculations are different, as described in IEEE Std 3003.2 [B36] and Chapter 8 of IEEE Std 242™ [B16]. For a solidly grounded system, the ground-fault current is of the same order of magnitude as the three-phase fault current. For a high-resistance-grounded system or low-resistance-grounded system, the magnitude of the ground-fault current is limited to a value determined by the resistor's current rating. See IEEE Std 3003.1™ [B35]. The decay of the dc component occurs so rapidly that the asymmetry effect in the current wave shape can be ignored.

NOTE—This subclause provides a glimpse of the information for system grounding and ground-fault protection, only highlighting the impacts on conductor insulation levels and ratings. See Dunki-Jacobs, Shields, with St. Pierre [B5], Shipp and Angelini [B57], IEEE Std 141 [B13], IEEE Std 142™ [B14], and IEEE Std 241™ [B15], as applicable, for more details on the selection and characteristics of different power system grounding techniques. Refer to IEEE Std 242 [B16] Chapter 8 for additional information on ground-fault protection and device clearing time. Discussed in Clause 5, cable insulation level should be compatible with the clearing time of protective devices for ground-fault conditions. Consult the applicable codes (such as the NEC or CE Code).

6.3 Conductor temperature rise caused by short circuits

6.3.1 Temperature rise of phase, neutral, or insulated grounding conductors

On the basis that all heat is absorbed by the conductor metal and no heat is transmitted from the conductor to the insulation material, the temperature rise is a function of the size of the metallic conductor (CM), the magnitude of the fault current (I), and the time of the current flow (t). These variables are related by the following empirical equations (see ANSI/ICEA P-32–382–2007):

for copper,

$$\left(\frac{I}{CM}\right)^2 (tF_{ac}) = 0.0297 \log_{10} \frac{T_f + 234}{T_o + 234} \quad (1)$$

for aluminum,

$$\left(\frac{I}{CM}\right)^2 (tF_{ac}) = 0.0125 \log_{10} \frac{T_f + 228}{T_o + 228} \quad (2)$$

The initial temperature T_o is typically the maximum continuous temperature rating of the conductor as listed in Table 2. T_o may include the effects of derating due to the maximum temperature rating of the conductor terminations. In special cases, if the actual continuous operating temperature of the conductor has been

calculated, this temperature may be used as the initial temperature. The final temperature T_F is based on the insulation material as shown in Table 2.

The ac/dc ratio (or skin effect ratio) F_{ac} is approximately 1 for conductors 500 kcmil and smaller, so F_{ac} may be neglected (set equal to 1) and the results will be slightly conservative. For larger conductor sizes with more pronounced skin effects, setting F_{AC} equal to 1 becomes increasingly conservative, so it may be desirable to include actual values of F_{AC} in the calculation. F_{AC} may be obtained from the conductor manufacturer or calculated based on Table 8 and Table 9 in the 2020 NEC.

If the initial temperature T_O and final temperature T_f are predetermined as described above, the current I versus time t relation of current flow can be plotted for each conductor size (CM) of a particular conductor type.

6.3.2 Temperature rise of shield and sheath

On the same basis as for phase currents, the temperature rise of the shield or sheath due to fault currents can be related to the magnitude of the fault current I in amperes flowing in the shield or sheath, the effective cross-sectional area of the shield and sheath A in circular mils, the time t in seconds the fault current is flowing, and the initial and final temperature of the shield or sheath. Some commonly used values are shown in Table 1. Note that the final temperature is governed by the allowable temperature of the material adjacent to the shield or sheath; the maximum allowable temperature recommended by ICEA for thermoplastic materials (commonly used for inner jackets in industrial cables) is 200 °C. For additional guidance and other operating conditions, refer to ANSI/ICEA P-45–482–2017.

NOTE—Typically, only conductors rated over 2000 V (NEC) or 5000 V (CE Code) have a ground plane shield or sheath. Conductors rated lower than this are not usually shielded/sheathed.

Table 1—Temperature rise of shield and sheath due to ground-fault current

Temperature rise of shield and sheath due to ground-fault current shield or sheath material	Initial shield operating temperature/maximum allowable shield temperatures			
	65 °C/150 °C	65 °C/200 °C	90 °C/200 °C	90 °C/250 °C
Copper	$I = 0.0568 \frac{CM}{\sqrt{t}}$	$I = 0.0694 \frac{CM}{\sqrt{t}}$	$I = 0.062 \frac{CM}{\sqrt{t}}$	$I = 0.0779 \frac{CM}{\sqrt{t}}$
Aluminum	$I = 0.0371 \frac{CM}{\sqrt{t}}$	$I = 0.0453 \frac{CM}{\sqrt{t}}$	$I = 0.041 \frac{CM}{\sqrt{t}}$	$I = 0.0509 \frac{CM}{\sqrt{t}}$
Lead	$I = 0.0103 \frac{CM}{\sqrt{t}}$	$I = 0.0124 \frac{CM}{\sqrt{t}}$	$I = 0.012 \frac{CM}{\sqrt{t}}$	$I = 0.0141 \frac{CM}{\sqrt{t}}$
Steel	$I = 0.0205 \frac{CM}{\sqrt{t}}$	$I = 0.0249 \frac{CM}{\sqrt{t}}$	$I = 0.023 \frac{CM}{\sqrt{t}}$	$I = 0.0281 \frac{CM}{\sqrt{t}}$
where CM is effective cross-sectional area of the shield or sheath in circular mils I is fault current flowing in the shield or sheath in amperes t is time the fault current is flowing in seconds				
NOTE—The temperatures in Table 1 are temperatures of the shield or sheath, and are normally different from those of the conductor.				

A comprehensive study has been conducted of the flow of ground-fault currents through shields, conduits, and ground wires during ground faults in connected equipment (see Hamer and Wood [B6]). Contrary to intuition, most of the ground-fault return current does not return through the shields of the cables connected to the phase that includes the equipment ground fault. (In a fault between a conductor and its own metallic shield, the faulted shield would carry most of the ground return current, but external ground faults in connected equipment are the major concern of this subclause.) Tests show that little difference exists in the magnitudes of the ground-

fault return currents through the shields of individual cables connected to equipment that contains a ground fault. The impedances of cable shields routinely used in industry are relatively high compared with other ground return paths, such as ground wires within conduits or the conduit itself. Accordingly, the ground-fault return current divides among several paths with most of the current diverted away from the shields. While the scope of this recommended practice does not include covering the actual division of these currents, guidelines for protecting shields can be provided. For ground faults of under 1000 A and conventional operating times of ground protection relays, Hamer and Wood have concluded that metallic shields are not being damaged during ground faults. For ground faults exceeding 1000 A, a ground wire should be included within the conduits to provide a reliable low-impedance ground return path. This setup is especially applicable for systems using rigid-steel conduit as the return path. Without ground wires within the conduit, sparking at the couplings (see Kaufmann [B44]) may occur during faults with the resulting risks for conduits routed through hazardous (or classified) locations (see the NEC and CE Code). The use of a ground wire also eliminates concern over corroded or loose couplings and bushings. Installation codes and IEEE Std 3003.2 [B36] contain information regarding the sizing of grounding (earthing) conductors.

6.3.3 Maximum short-circuit temperature ratings

ANSI/ICEA P-32–382–2007 established a guideline for short-circuit temperatures for various types of insulation as shown in Table 2. The short-circuit temperature ratings are considered the maximum temperatures and, to protect the cable insulation from damage, should not be exceeded. General agreement does not exist that the temperatures from ANSI/ICEA P-32–382–2007 accurately depict conductor temperatures because they are calculated rather than measured. However, agreement does exist that the temperatures shown in Table 2 are higher than actual and, therefore, conservative for the purposes of this recommended practice.

Table 2—Examples of conductor insulation types and their maximum short-circuit temperature^a

Type of insulation, NEC designation, trade name	Type letter	Continuous temperature rating T_o (°C): dry	Continuous temperature rating T_o (°C): wet	Short-circuit current temperature rating T_f (°C)
Thermoset (2001 V to 46 kV shielded) ^b and (2001 V to 5000 V nonshielded) ^c				
Cross-linked polyethylene (XLPE or TR-XLPE)	MV-90	90 dry	90 wet	250
	MV-105	105 dry	105 wet	
Ethylene propylene rubber (EPR)	MV-90	90 dry	90 wet	250
	MV-105	105 dry	105 wet	
Low-voltage thermoset (up to 1000 V) ^d				
Cross-linked polyethylene (XLPE) ^e	RHH, XHH	90 dry	90 damp	250
	XHWW	90 dry	90 damp/75 wet	
	RHW, RW75, RWU75	75 dry	75 wet	
	RHW-2, XHHW-2 RW90, RWU90	90 dry	90 wet	
Cross-linked polyvinyl chloride (XL-PVC)	XHHW	90 dry	90 damp	250
Chlorinated polyethylene (CPE)	RHH	90 dry	90 damp	250
	RHW-2, RW90, RWU90	90 dry	90 wet	

Table continues