

IEEE Guide for the Design and Installation of Cable Systems in Substations

Sponsor
**Substations Committee
of the
IEEE Power Engineering Society**

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Abstract: Guidance for the design, installation, and protection of wire and cable systems in substations with the objective of minimizing cable failures and their consequences is provided. The design of wire and cable systems in generating stations is not covered.

Keywords: cable, cable installation, cable testing, fire protection, raceway, substations, wire cable shield

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Introduction

(This introduction is not a part of IEEE Std 525-1992, IEEE Guide for the Design and Installation of Cable Systems in Substations.)

This revision of the guide incorporates various changes in cable installation philosophies that have occurred since the 1987 version of the guide. Significant changes have been made in the following areas:

- a) Conductor sizing and voltage rating of power cable in clause 3 was rewritten.
- b) Guidelines were added for the installation of optical cable.
- c) Maximum allowable pulling tension calculation methodology in clause 10 was rewritten.

In the 1992 IEEE style, notes in text are not a normative part of a standard. This standard makes an exception to that rule. In future revisions, this exception will not occur.

This guide was prepared by the Wire and Cable Systems Working Group of the Substations Committee, Transmission Substations Subcommittee. The following is a list of participants of the working group who were involved in this effort:

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J. B. Cannon

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R. Janezic
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L. Maiocco
S. G. Patel
M. Thaden, Jr.
B. W. Wray

The following persons were on the balloting committee that approved this document for submission to the IEEE Standards Board:

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IEEE Guide for the Design and Installation of Cable Systems in Substations

1. Overview

1.1 Scope

This document has been developed as a guide for the design, installation, and protection of wire and cable systems in substations with the objective of minimizing cable failures and their consequences. This guide is not intended for use in the design of wire and cable systems in generating stations, which is adequately covered in IEEE Std 422-1986¹ and IEEE Std 690-1984. Guidance for wire and cable design for gas-insulated substations (GIS) is available in IEEE Std C37.122-1983.

1.2 Purpose

The purpose of this guide is to give guidance to the substation engineer in established practices for the application and installation of metallic and optical cables in electric power transmission and distribution substations. This guide emphasizes reliable electrical service during the design life of the substation.

Solutions presented in this guide may not represent the only acceptable practices for resolutions of problems.

This guide should not be referred to or used as an industry standard. It is being presented to aid in the development of wire and cable system installations and should not be taken as a compliance standard.

1.3 References

This standard shall be used in conjunction with the following publications:

Accredited Standards Committee C2-1993, National Electrical Safety Code (NESC).²

¹Information on references can be found in 1.3.

²The National Electrical Safety Code is available from the Institute of Electrical and Electronics Engineers, Service Center, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

AEIC CS5-1987, Specifications for Thermoplastic and Cross-linked Polyethylene Insulated Shielded Power Cables Rated 5 kV through 35 kV.³

AEIC CS6-1987, Specifications for Ethylene Propylene Rubber Insulated Shielded Power Cables Rated 5 kV through 69 kV.

AEIC CS7-1987, Specifications for Cross-linked Polyethylene Insulated Shielded Power Cable Rated 69 kV through 138 kV.

ANSI/NFPA 70-1990, National Electrical Code (NEC).⁴

ANSI/NFPA 72D-1990, Installation, Maintenance and Use of Proprietary Signaling Systems.

ASTM E119-1988, Standard Methods of Fire Tests of Building Construction and Materials.⁵

IEC 183-1984, Guide to the Selection of High-Voltage Cables.⁶

IEC 228-1978, Conductors of Insulated Cables.

IEC 331-1970, Fire-Resisting Characteristics of Electric Cables.

IEC 332-1 (1979), Test on a Single Vertical Insulated Wire or Cable.

IEC 332-3 (1982), Tests on Bunched Wires or Cables.

IEEE Std 80-1986 (Reaff 1991), IEEE Guide for Safety in AC Substation Grounding (ANSI).

IEEE Std 81-1983, IEEE Guide for Measuring of Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Ground System.

IEEE Std 100-1992, The New IEEE Standard Dictionary of Electrical and Electronics Terms.

IEEE Std 367-1987 IEEE Recommended Practice for Determining the Electric Power Station Ground Potential Rise and Induced Voltage from a Power Fault (ANSI).

IEEE Std 383-1974 (Reaff 1992), IEEE Standard for Type Test of Class 1E Electric Cables, Field Splices, and Connections for Nuclear Power Generating Stations (ANSI).

IEEE Std 400-1991, IEEE Guide for Making High-Direct-Voltage Tests on Power Cable Systems in the Field (ANSI).

IEEE Std 422-1986, IEEE Guide for the Design and Installation of Cable Systems in Power Generating Stations (ANSI).

IEEE Std 442-1981 (Reaff 1991), IEEE Guide for Soil Thermal Resistivity Measurements (ANSI).

³AEIC publications can be obtained from the Sales Department, Association of Edison Illuminating Companies, 600 North 18th Street, P.O. Box 2641, Birmingham, AL 35291-0992, USA.

⁴NFPA publications are available from Publications Sales, National Fire Protection Association, 1 Batterymarch Park, P.O. Box 9101, Quincy, MA 02269-9101, USA.

⁵ASTM publications are available from the Customer Service Department, American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103, USA.

⁶IEC publications are available from IEC Sales Department, Case Postale 131, 3 rue de Varembe, CH 1211, Genève 20, Switzerland/Suisse. IEC publications are also available in the United States from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

IEEE Std 487-1992, IEEE Recommended Practice for the Protection of Wire-Line Communication Facilities Serving Electric Power Stations.

IEEE Std 518-1982 (Reaff 1990), IEEE Guide for the Installation of Electrical Equipment to Minimize Noise Inputs to Controllers from External Sources (ANSI).

IEEE Std 575-1988, IEEE Guide for the Application of Sheath-Bonding Methods for Single-Conductor Cables and the Calculation of Induced Voltages and Currents in Cable Sheaths (ANSI).

IEEE Std 634-1978, IEEE Standard Cable Penetration Fire Stop Qualification Test.⁷

IEEE Std 643-1980, IEEE Guide for Power-Line Carrier Applications (Reaff 1991) (ANSI).

IEEE Std 690-1984, IEEE Standard for the Design and Installation of Cable Systems for Class 1E Circuits in Nuclear Power Generating Stations (ANSI).

IEEE Std 979-1984 (Reaff 1988), IEEE Guide for Substation Fire Protection (ANSI).

IEEE Std 1050-1989, IEEE Guide for Instrumentation and Control Equipment Grounding in Generating Stations (ANSI).

IEEE Std C37.1-1987, IEEE Standard Definition, Specification, and Analysis of Systems Used for Supervisory Control, Data Acquisition, and Automatic Control (ANSI).

IEEE Std C37.90.1-1989 (Reaff 1991), IEEE Standard Surge Withstand Capability (SWC) Tests for Protective Relays and Relay Systems (Supplement to IEEE C37.90-1989) (ANSI).⁸

IEEE Std C37.122-1983, IEEE Standard for Gas-Insulated Substations.

IEEE Std C57.13.3-1983 (Reaff 1991), IEEE Guide for the Grounding of Instrument Transformer Secondary Circuits and Cases (ANSI).

IEEE S-135 (1962), IEEE/IPCEA Power Cable Ampacities.

NEMA TC 2-1990, Electrical Plastic Tubing (EPT) and Conduit (EPC-40 and EPC-80).⁹

NEMA TC 6-1990, PVC and ABS Plastic Utilities Duct for Underground Installation.

NEMA VE1-1991, Metallic Cable Tray Systems.

NEMA WC 3-1980 (R 1986), Rubber-Insulated Wire and Cable for the Transmission and Distribution of Electrical Energy (ICEA S-19-81 6th ed.).

NEMA WC 5-1973 (R 1985), Thermoplastic-Insulated Wire and Cable for the Transmission and Distribution of Electrical Energy. (ICEA S-61-402 3rd ed.).

NEMA WC 7-1988, Cross-Linked-Thermosetting-Polyethylene-Insulated Wire and Cable for the Transmission and Distribution of Electrical Energy (ICEA S-66-524).

⁷IEEE Std 634-1978 has been withdrawn; however, copies can be obtained from the IEEE Standards Department, IEEE Service Center, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA, (908) 562-3800.

⁸IEEE publications are available from the Institute of Electrical and Electronics Engineers, Service Center, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

⁹NEMA publications are available from the National Electrical Manufacturers Association, 2101 L Street NW, Washington, DC 20037, USA.

NEMA WC 8-1988, Ethylene-Propylene-Rubber-Insulated Wire and Cable for the Transmission and Distribution of Electrical Energy (ICEA S-68-516).

NEMA WC 50-1976 (R 1988), Ampacities, Including Effect of Shield Losses for Single-Conductor Solid-Dielectric Power Cable 15 kV through 69 kV (ICEA P-53-426 2nd ed.).

NEMA WC 51-1986 (R 1991), Ampacities of Cables in Open-Top Cable Trays (ICEA P-54-440 3rd ed.).

NEMA WC 55-1986, Instrumentation Cables and Thermocouple Wire (ICEA S-82-522).

1.4 Definitions

The following definitions appear again in this standard in the clauses specific to the respective term.

1.4.1 ABS: Conduit fabricated from acrylonitrile-butadiene-styrene.

1.4.2 cable fire break: Material, devices, or an assembly of parts installed in a cable system, other than at a cable penetration of a fire-resistive barrier, to prevent the spread of fire along the cable system.

1.4.3 cable penetration: An assembly or group of assemblies for electrical conductors to enter and continue through a fire-rated structural wall, floor, or floor-ceiling assembly.

1.4.4 cable penetration fire stop: Material, devices, or an assembly of parts providing cable penetrations through fire-rated walls, floors, and floor-ceiling assemblies and maintaining their required fire rating.

1.4.5 cable system enclosure (cocoon): An assembly installed around a cable system to maintain circuit integrity, for a specified time, of all circuits within the enclosure when it is exposed to the most severe fire that may be expected to occur in the area.

1.4.6 common-mode noise (longitudinal): The noise voltage that appears equally and in phase from each signal conductor to ground. Common-mode noise may be caused by electrostatic or electromagnetic induction.

1.4.7 common-mode to normal-mode conversion: In addition to the common-mode voltages which are developed in the single conductors by the general environmental sources of electrostatic and electromagnetic fields, differences in voltage exist between different ground points in a facility due to the flow of ground currents. These voltage differences are considered common mode when connection is made to them either intentionally or accidentally, and the currents they produce are common mode. These common-mode currents can develop normal-mode noise voltage across unequal circuit impedances.

1.4.8 crosstalk: The noise or extraneous signal caused by ac or pulse-type signals in adjacent circuits.

1.4.9 design life of a substation: The time during which satisfactory substation performance can be expected for a specific set of operating conditions.

1.4.10 EMT: Electrical metallic tubing.

1.4.11 EPT: Electrical plastic tubing for type I applications, fabricated from PVC.

1.4.12 EPC-40: Electrical plastic conduit for type II applications, fabricated from PE; or for type II and III applications, fabricated from PVC.

1.4.13 EPC-80: Electrical plastic conduit for type IV applications, fabricated from PVC.

1.4.14 fire-protective coatings: A material applied to a completed cable or assembly of cables to prevent the propagation of flame. Fire-protective coatings include liquids, mastics, and tapes.

1.4.15 fire-resistive barrier: A wall, floor, or floor-ceiling assembly erected to prevent the spread of fire.

1.4.16 fire-resistive barrier rating: This is expressed in time (hours and minutes) and indicates that the wall, floor, or floor-ceiling assembly can withstand, without failure, exposure to a standard fire for that period of time.

1.4.17 FRE: Conduit fabricated from fiberglass reinforced epoxy.

1.4.18 IMC: Intermediate metal conduit.

1.4.19 normal-mode noise (transverse or differential): The noise voltage which appears differentially between two signal wires and which acts on the signal sensing circuit in the same manner as the desired signal.

1.4.20 PE: Conduit fabricated from polyethylene.

1.4.21 PVC: Conduit fabricated from polyvinyl chloride.

1.4.22 RMC: Rigid metal conduit.

1.4.23 service life of cable: The time during which satisfactory cable performance can be expected for a specific set of service conditions.

1.4.24 shield (cable systems) (instrumentation cables): A metallic sheath (usually copper or aluminum), applied over the insulation of a conductor or conductors for the purpose of providing means for reducing electrostatic coupling between the conductors so shielded and others which may be susceptible to or which may be generating unwanted (noise) electrostatic fields.

1.4.25 Type DB: Duct designed for direct burial without encasement in concrete (also referred to as Type II duct), fabricated from PVC or ABS.

1.4.26 Type EB: Duct designed to be encased in concrete when installed (also referred to as Type I duct), fabricated from PVC or ABS.

1.4.27 Type I: Duct designed to be encased in concrete.

1.4.28 Type II: Duct designed for underground installation without encasement in concrete.

1.4.29 Type III: Duct designed for normal-duty applications above grade.

1.4.30 Type IV: Duct designed for heavy-duty applications above grade.

2. Cable performance

This clause provides guidance for establishing cable performance and should be considered in specifying cable for installation in substations. No single cable characteristic should be emphasized to the serious detriment of others. A balance of cable characteristics, as well as good installation, design, and construction practices, is necessary to provide a reliable cable system.

2.1 Service conditions

- a) Cables should be suitable for all environmental conditions that occur in the areas where they are installed.
- b) Cable operating temperatures in substations are normally based on 40 °C ambient air or 20 °C ambient earth. Special considerations should be given to cable installed in areas where ambient temperatures differ from these values.
- c) Cables may be direct buried, installed in duct banks, conduits, and trenches below grade, or in cable trays, conduits, and wireways above ground. Cable should be suitable for operation in wet and dry locations.

2.2 Cable characteristics

2.2.1 Service life

The service life of the cable should be at least equal to the design life of the substation.

2.2.2 Thermal stability

The cable should maintain its required insulating properties when subjected to its rated thermal limit (the combination of its maximum ambient temperature and its own generated heat) during the service life.

2.2.3 Moisture resistance

The cable should maintain its required insulating properties for its service life when installed in wet locations, especially underground.

2.2.4 Chemical resistance

The cable should maintain its required insulating properties when exposed to chemical environments.

2.2.5 Flame propagation resistance

Cables installed in open or enclosed cable trays, wireways, or in other raceway systems where flame propagation is of concern should pass the IEEE Std 383-1974¹⁰ flame tests.

3. Conductor sizing and voltage rating of power cables

This clause provides guidance for conductor sizing and determining voltage ratings of power cables for various types of installations.

3.1 Design considerations

The proper design of power cable systems requires the consideration of many factors. These factors include ambient temperature, conductor temperature, earth thermal resistivity, load factor, current loading, system fault level, voltage drop, system nominal voltage and grounding, method of installation, and number of conductors being installed.

3.2 Cable construction

Cable insulation and shielding materials, dimensions, and configurations have been arranged in NEMA and AEIC standard rating structures with ratings for standard insulation and shielding configurations. The cable insulation system is determined by selection of a standard voltage rating.

The cable conductor is selected to meet ampacity and voltage drop criteria.

The cable jacket, or outer covering (if any), is selected to meet mechanical protection, fire resistance, and environmental criteria, or to provide a moisture barrier for the insulation system.

3.2.1 Voltage rating

The selection of the cable voltage rating is based on the service conditions of 2.1, the electrical circuit frequency, phasing, and grounding configuration, and the steady-state and transient conductor voltages with respect to ground and other energized conductors.

A voltage rating has been assigned to each standard configuration of shield and insulation material and thickness in NEMA WC 3-1980, NEMA WC 5-1973, NEMA WC 7-1988, NEMA WC 8-1988, and in AEIC CS5-1987,

¹⁰Information on references can be found in 1.3.

AEIC CS6-1987, and AEIC CS7-1987. The selected voltage rating must result in a cable insulation system that maintains the energized conductor voltage, without installation breakdown under normal operating conditions.

For high-voltage cables, it is usual practice to select an insulation system that has a voltage rating equal to or greater than the expected continuous phase-to-phase conductor voltage. The NEMA standards provide for a cable voltage rating that is only 95% of the actual continuous voltage. For solidly grounded systems, it is usual to select the 100 Percent Insulation Level, but the 133 Percent Insulation Level is often selected where additional insulation thickness is desired. The 133 Percent Insulation Level is also applied on systems without automatic ground fault protection.

Distribution substations often utilize cable for the distribution circuits from the substation secondary switch-yard (substation getaways). The insulation system selected for this distribution cable may have a voltage rating that is a class above the minimum NEMA rating for the actual circuit voltage and ground fault protection, because it is believed that the additional insulation will result in a lower probability of insulation failure.

Research conducted by the Electric Power Research Institute has led to cable construction recommendations published in EPRI EL-6271 [B10].¹¹ The EPRI recommendations for cable insulation systems have insulation thickness that are the same as those of the NEMA and AEIC standards.

For power and control cables applied at 600 V and below, some engineers use 1000 V-rated insulation because of past insulation failures caused by inductive voltage spikes from de-energizing electromechanical devices, e.g., relays, spring winding motors. The improved dielectric strength of today's insulation materials prompted some utilities to return to using 600 V rated insulation for this application. Low voltage power and control cable rated 600 V and 1000 V is currently in use.

The selection of the power cable insulation system also includes consideration of cost and performance under normal and abnormal conditions. Dielectric losses, resistance to flame propagation, and gas generation when burned are the most common performance considerations.

3.2.2 Ampacity

The ampacity of a cable depends on the temperature of the surrounding air or earth, and the temperature rise of the cable materials. The maximum temperature usually occurs at the conductor-insulation interface. The maximum allowable insulation temperature limits cable ampacity.

Maximum allowable insulation temperature has been determined through testing and experience for the commonly used materials, and it is a function of time. For example, 250 °C has been found to be an acceptable insulation temperature for some material for very short time durations, but 130 °C is the maximum for the duration of an emergency, and 90 °C is the maximum acceptable continuous temperature. The length of time for a fault to clear, emergency load duration, short time cyclic loads, and steady state load are the time durations usually considered in determining the ampacity required for a cable.

Losses (I^2R) in the conductor and magnetically induced losses in the insulation shield and the raceway are the principal causes of the insulation temperature rise. Shields or sheaths that are grounded at more than one point may carry induced circulating currents and reduce the ampacity of the cable. The magnitude of circulating currents flowing in shields grounded at more than one point depends on the mutual inductance between the cable shielding and the cable conductors, the mutual inductance to the conductors in other cables, the current in these conductors, and the impedance of the shield.

Below grade cables are usually installed in trench or duct, or direct buried. Above grade cables are usually installed in conduit, wireway, tray, or suspended between supports. Cables may be routed through foundations, walls, or fire

¹¹The numbers in brackets preceded by the letter B correspond to those in the bibliography in clause 14..

barriers, and raceway may be partially or totally enclosed. The installation that results in the highest insulation temperature should be used to determine the ampacity of a cable routed through several configurations.

The cable materials themselves can affect heat transfer and ampacity. For example, the thermal conductivity of ethylene propylene rubber (EPR) is lower than that of cross-linked polyethylene (XLPE) and the ampacity of the EPR cable will be less for the same insulation thickness.

The thermal conductivity of earth surrounding below grade cables is one of the most important parameters in determining ampacity. There is significant variation of earth thermal conductivity with location and time, and IEEE 442-1981 provides guidance for earth conductivity measurements. However, many engineers have found it acceptable to use typical values. For a typical loam or clay containing normal amounts of moisture, the resistivity is usually in the range of 60–120 °C-cm/W. When the earth resistivity is not known, a value of 90 °C-cm/W is suggested in IEEE S-135 (1962).

The ampacity of below grade cable is also dependent upon the load factor, which is the ratio of the average current over a designated period of time to the peak current occurring in that period. Ampacities for typical load factors of 50, 75, and 100% are given in IEEE S-135 (1962).

Methods for determining ampacity, and the tables of ampacities for a large number of typical cable and below grade and above grade installation configurations are included in IEEE S-135 (1962) and NEMA WC 50-1988. In addition, IEEE S-135 (1962) and NEMA WC 50-1988 include guidance for determination of ampacities for configurations not included in the tables.

Although not prescribed by standards applicable to substations, a common practice is to select a cable with an ampacity that equals or exceeds the trip rating of the circuit thermal overload protection. The trip rating of the thermal overload protection (if any) is frequently selected to be approximately 1.25 times the expected circuit load.

Finite element techniques have been used to calculate below grade cable ampacity with results that are generally considered to be more satisfactory than those obtainable from IEEE S-135 (1962). However, neither the finite element methodologies nor the resultant cable ampacities are available in the US standards.

The IEEE S-135 (1962) method for determination of ampacity of cable installed in tray was found to be unsatisfactory. The industry accepted method for randomly installed cable in tray is given in NEMA WC 51-1986.

Besides ampacity, selection of power cable conductors may include consideration of the cost of losses.

3.2.3 Voltage drop

Voltage regulation requirements should be considered in the selection of conductor size. Motor feeder voltage drop under starting and running conditions should be limited to allow the motor to operate within its design specifications.

4. Electrical segregation of cable systems

This clause provides guidance for the electrical segregation of cable systems according to voltage levels, signal levels, and vulnerability to electrical noise pickup.

4.1 Cable classifications

High-voltage power cables are designed to supply power to substation utilization devices, other substations, or customer systems rated higher than 1000 V.

NOTE — Oil-filled and gas-insulated cables are excluded from this definition and are not covered in this guide.

Low-voltage power cables are designed to supply power to utilization devices of the substation auxiliary systems rated 1000 V or less.

Control cables are applied at relatively low current levels or used for intermittent operation to change the operating status of a utilization device of the substation auxiliary system.

NOTE — As used in this document, leads from current and voltage transformers are considered control cables since in most cases they are used in relay protection circuits. However, when current transformer leads are in a primary voltage area exceeding 600 volts they should be protected as required by the NESC, Rule 150.

As used in this document, instrumentation cables consist of cables for Supervisory Controls and Data Acquisition (SCADA) systems or event recorders, and thermocouple and resistance temperature detector cables.

Instrumentation cables are used for transmitting variable current or voltage signals (analog) or transmitting coded information (digital).

4.2 Segregation

Segregating low-voltage power cables, control cables, and instrumentation cables in the substation cable trench or cable tray system is generally not necessary. High-voltage power cables should be segregated from all other cables. Cables installed in stacked cable trays should be arranged by descending voltage levels, with the higher voltages at the top.

4.2.1 High-voltage power cables

These cables should be installed so that the high voltage cannot be impressed on any lower voltage system. Methods for achieving this segregation are

- a) Installation of high-voltage cables in raceways that are separated from low-voltage power and control cables and from instrumentation cables. Installation of different voltage classes of high-voltage power cables in separate raceways is also suggested.
- b) Utilization of armored shielded cables (separate raceways are still suggested).

4.2.2 Low-voltage power and control cables

These cable classifications may be mixed. Consideration should be given to insulation deformation when cable diameters differ greatly. When cable classifications are mixed, the power cable ampacity is calculated as if all the cables were power cables.

4.2.3 Instrumentation cables

These cables should be installed to minimize noise pickup from adjacent circuits and equipment. Methods for achieving segregation are

- a) Installations that provide physical separation between the instrumentation cables and any electrical noise source [B15], [B38].
- b) Installation in separate enclosed magnetic raceways.
- c) Cable construction configurations, such as twisted conductors and shielding.
- d) Installation of analog signal cables separate from all power and control cables, and from unshielded cables carrying digital or pulse type signals. Shielded voice communications cable (without power supply conductors) may be included in raceways with analog signal cables.
- e) Segregation of telephone and other communication type cables from all other substation cables.

Additional information on instrumentation cable may be found in NEMA WC 55-1989.

4.2.4 Optical cable

From the outside, an optical cable looks like any electrical multiconductor cable; however, it is lightweight and flexible compared to metal conductor cable. Typical optical cable diameter ranges from less than 1/8 in (3.175 mm) to 3/4 in (19.4 mm), depending on fiber numbers and cable construction. The most common optical cable jacket materials are polyethylene (all types), PVC, and polyurethane.

The placement of optical cable in conduit is quite common. Conduit offers protection from crushing, ground disruption, rodents, and other environmental abuse. In addition, the cable is easier to replace or upgrade in the future. Several methods and types of conduit systems are used. For example, one configuration includes pre-manufactured segregated ducts or large ducts with multiple plastic, high-density polyethylene “inner ducts” installed inside. The inner ducts can be smooth walled or corrugated either longitudinally or horizontally.

One method of installation involves a composite optical overhead ground wire (OPGW) on a transmission line to link substations together. The OPGW is usually terminated in a standard splice case at a substation structure. At this splice case, it is interfaced with the substation optical cable.

The substation optical cable should be installed in conduit from the splice case into the substation cable duct or trench system. The optical cable should be installed in conduit from the substation cable duct or trench system to the control house where it is terminated on a fiber termination panel. There are important differences to be considered in the handling and installation of fiber optic cable, as compared to metallic cable. In ladder type cable tray, optical cable may be subjected to stress due to the weight of other cables which can induce microbending into the optical cable. Therefore, it may be a better practice to place the optical cable in a separate duct installed in the tray.

Optical cables in substations should be installed in the same manner as metallic conductor cables. This practice requires robust optical cables that can withstand normal construction handling and still protect the fibers inside.

5. Separation of redundant cable systems

This clause provides guidance for the separation of redundant cable systems.

5.1 Redundant cable systems

Redundant cable systems are two or more systems serving the same objective. They may be systems where personnel safety is involved, such as fire pumps, or systems provided with redundancy because of the severity of economic consequences of equipment damage or system reliability. Cables meeting the requirements of IEEE Std 383-1974 should be considered for application for these functions.

NOTE — Primary and backup relaying are examples that may utilize redundant cable systems.

5.2 Design considerations

Redundant cable systems should be separated to ensure that no single event will prevent a required particular substation operation. The degree of separation required varies with the potential hazards to the cable systems in particular areas of the substation.

6. Shielding and shield grounding

This clause provides information on the origin of transients in substations and guidance for shielding and shield grounding of high-voltage power, instrumentation, control, coaxial, and triaxial cable systems.

6.1 Origin of transients in substations

- a) *High-voltage switching.* Opening or closing a switching device to de-energize or energize a section of substation bus is generally accompanied by arcing and will initiate a high-frequency transient. The frequency will be determined by the self-inductance and shunt capacitance of the high-voltage conductors involved. The resulting overvoltages can exceed two per unit. Both electric and magnetic coupling between high-voltage and low-voltage conductors can result in high-level transients in the low-voltage system.
- b) *Capacitor switching.* Switching a capacitor bank causes a current transient which is a function of the bank size and the circuit constants back to the source. If other capacitors are already connected nearby to the same line or bus, they lower the impedance seen by the switched capacitor, increasing the magnitude and frequency of the transient. Energy stored in the nearby bank may contribute further to the severity. The circuit between banks is likely to ring at a high frequency because of the low inductance in the short line connecting the banks and the reduced effective capacitance considering the banks in series [B39]. This phenomenon further enhances the tendency of the transient to interfere with nearby circuits.
- c) *Transmission line switching.* This phenomenon is similar to capacitor bank switching, with the difference being the distributed nature of the inductance and capacitance of the line. The magnitude of the line charging current tends to be substantially less than that for capacitor bank switching. The frequency of the transient current or voltage is inversely proportional to the line length [B38].
- d) *Coupling capacitor voltage transformers (CCVT).* The capacitors in these devices, in conjunction with inductances of the power system conductors, constitute a resonant circuit whose frequency can be in the megahertz range. Unless the base of the CCVT has a low-surge impedance to the substation ground grid, a high voltage can appear between the CCVT secondary terminals and the grid. The high voltage will be generated primarily during air-break switching operations.
- e) *Ground voltage rise (GVR).* GVR is the voltage rise proportional to the magnitude of the ground current and to the ground resistance. Under normal conditions, the grounded electrical equipment operates at essentially zero ground voltage within the substation yard. During a fault, the portion of fault current which is conducted by a ground electrode in the earth causes a rise of the electrode voltage with respect to remote earth (see IEEE Std 80-1986 and [B26]).
- f) *Ground voltage rise differences.* Both electromagnetic coupling and conduction can contribute to substantial ground voltage rise differences, particularly at the higher frequencies typical of many transients occurring on a high-voltage power system. Even well designed grounding grids that extend over the large areas needed for high-voltage switchyards have sufficient inductance to cause high voltage differences. Electromagnetic coupling to the ground grid is directly proportional to the rate of change of flux and the length and orientation of the current-carrying conductor and inversely proportional to the height of the conductor above the ground grid. Conduction of power system transients to the ground grid is typically provided through metallic grounding of transformer neutrals and capacitive paths, such as bushings, coupling capacitors, and CCVTs. These are low-impedance high-energy paths that can induce common-mode voltages on control circuits (see IEEE Std 367-1987).
- g) *Other transient sources.* Other phenomena that generate transients occur in power systems. Some examples are undesirable time spans between the closing of the poles of a circuit breaker, fault occurrence, fault clearing, load tap-changing, line reactor de-energizing, series capacitor gap flashing, arcing ground faults, failing equipment, lightning, GIS surges, and capacitor reinsertion. Normally, the magnitudes of such transients are less than those of other phenomena described herein.

6.2 High-voltage power cable

The use of shielding and shield grounding of high-voltage power cables is a common practice to reduce the hazard of shock to personnel, to confine the electric field within the cable, to minimize deterioration of cable insulation or jackets caused by surface discharges, and to minimize radio interference. The selection of the shield grounding locations and the effects of single and multiple grounds are points to be considered for the proper installation of shielded cable.

6.2.1 Definition

The following definition is used in this clause.

6.2.1.1 cable shielding:

A nonmagnetic metallic material applied over the insulation of the conductor or conductors to confine the electric field of the cable to the insulation of the conductor or conductors.

6.2.2 Shielding practices

Single conductor cables rated above 2 kV and multiconductor cables with a common overall discharge-resisting jacket rated above 5 kV should be shielded, except for special applications or cable designs. Multiconductor cable applications in the operating range of 2 kV to 5 kV require careful judgment, and each installation should be evaluated based on the existing and anticipated conditions. Shielding can be used to monitor or test cable installation for additional assurance of insulation integrity. The following shielding recommendations contained in the NEMA standards publications for the type of insulation being utilized should be followed: NEMA WC 3-1980, NEMA WC 5-1973, NEMA WC 7-1988, and NEMA WC 8-1976.

A shield screen material is applied directly to the insulation and in contact with the metallic shield. It can be semiconducting material or, in the case of at least one manufacturer, a stress control material. At the high voltages associated with shielded cable applications, a voltage gradient would exist across any air gap between the insulation and shield. The voltage gradient may be sufficient to ionize the air, causing small electric arcs or partial discharge. These small electric arcs burn the insulation and eventually cause the cable to fail. The semiconducting screen allows application of a conducting material over the insulation to eliminate air gaps between insulation and ground plane.

Various shield screen material systems include:

- a) Extruded semiconducting thermoplastic or thermosetting polymer
- b) Semiconducting woven fabric tape
- c) Semiconducting coating (paint) used with semiconducting woven fabric tape
- d) Extruded high-dielectric-constant thermoplastic or thermosetting polymer, referred to as a stress control layer

NEMA and AEIC standards require shielded power cable to be partial-discharge or corona tested. This test evaluates the effectiveness of the conductor and shield insulation screen materials and application, and verifies the absence of voids within the insulation. A cyclic aging test is required by AEIC as a qualification of the cable design to ensure gaps do not develop between tape layers as a result of expansion and contraction cycles.

Multiconductor cable shielding should be considered in the 2 kV to 5 kV range where any of the following conditions exist:

- a) Transition from conducting to nonconducting environment
- b) Transition from moist to dry environment
- c) Dry soil, such as in a desert
- d) Damp conduits
- e) Connections to overhead lines
- f) Locations where the cable surface collects conducting materials, such as soot or salt deposits
- g) Electrostatic discharges are sufficient in magnitude to interfere with control and instrumentation circuit functions
- h) Safety to personnel is involved
- i) Long underground cables
- j) Direct earth burial