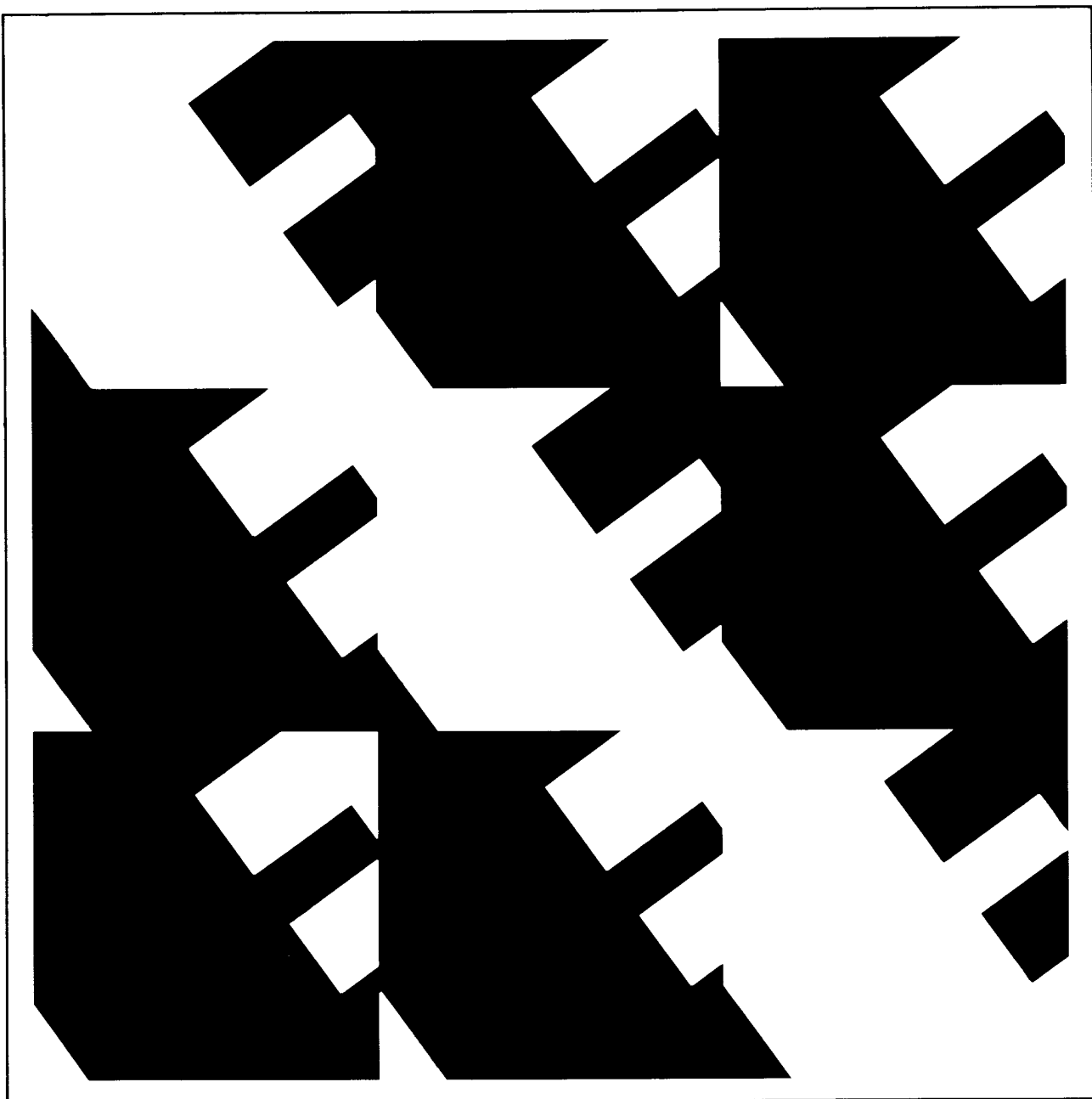


IEEE Guide for the Design and Installation of Cable Systems in Substations

ANSI/IEEE Std 525-1987



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

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 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 ANSI/IEEE Std 422-1986 [10]¹ and ANSI/IEEE Std 690-1984 [15].

1.1 Purpose. The purpose of this guide is to give direction to the substation engineer in established practices for the application and installation of metallic cables in electric power transmission and distribution substations. This guide emphasises 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 code-type standard.

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

[1] AEIC CS5-87, Specifications for Thermoplastic and Crosslinked Polyethylene

¹Numbers in brackets correspond to those of the references in 1.2 of this standard; when preceded by B, they correspond to the bibliography in Section 14 of this standard.

Insulated Shielded Power Cables Rated 5 kV through 35 kV.²

[2] AEIC CS6-87, Specifications for Ethylene Propylene Rubber Insulated Shielded Power Cables Rated 5 kV through 69 kV.

[3] ANSI/IEEE C37.90.1-1974, IEEE Guide for Surge Withstand Capability (SWC) Tests (Supplement to ANSI/IEEE C37.90-1978).³

[4] ANSI/IEEE C57.13.3-1983, IEEE Guide for the Grounding of Instrument Transformer Secondary Circuits and Cases.

[5] ANSI/IEEE Std 80-1986, IEEE Guide for Safety in AC Substation Grounding.

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

[7] ANSI/IEEE Std 367-1987, IEEE Recommended Practice for Determining the Electric Power Station Ground Potential Rise and Induced Voltage from a Power Fault.

²AEIC publications can be obtained from the Sales Department, Association of Edison Illuminating Company, 51 East 42nd Street, Suite 1202, New York, N.Y. 10017.

³ANSI/IEEE publications can be obtained from the Sales Department, American National Standards Institute, 1430 Broadway, New York, NY 10018, or from the Service Center, The Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331.

- [8] ANSI/IEEE Std 383-1974 (R 1980), IEEE Standard for Type Test of Class 1E Electric Cables, Field Splices, and Connections for Nuclear Power Generating Stations.
- [9] ANSI/IEEE Std 400-1980 (R 1987), IEEE Guide for Making High-Direct-Voltage Tests on Power Cable Systems in the Field.
- [10] ANSI/IEEE Std 422-1986, IEEE Guide for the Design and Installation of Cable Systems in Power Generating Stations.
- [11] ANSI/IEEE Std 487-1980, IEEE Guide for the Protection of Wire-Line Communication Facilities Serving Electric Power Stations.
- [12] ANSI/IEEE Std 518-1982, IEEE Guide for the Installation of Electrical Equipment to Minimize Noise Inputs to Controllers from External Sources.
- [13] 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.
- [14] ANSI/IEEE Std 643-1980, IEEE Guide for Power Line Carrier Applications.
- [15] ANSI/IEEE Std 690-1984, IEEE Standard for the Design and Installation of Cable Systems for Class 1E Circuits in Nuclear Power Generating Stations.
- [16] ANSI/IEEE Std 979-1984, IEEE Guide for Substation Fire Protection.
- [17] ANSI/NFPA 70-1987, National Electrical Code (NEC).⁴
- [18] ANSI/NFPA 72D-1986, Installation, Maintenance and Use of Proprietary Signaling Systems.
- [19] ASTM E119-1983, Standard Methods of Fire Tests of Building Construction and Materials.⁵
- [20] ICEA P-32-382 (1969), Short Circuit Characteristics of Insulated Cable.⁶
- [21] ICEA P-46-426, Power Cable Ampacities for Copper and Aluminum Conductors.
- [22] IEC 183-1984, Guide to the Selection of High-Voltage Cables.⁷
- [23] IEC 228-1978, Conductors of Insulated Cables.
- [24] IEC 331-1970, Fire-Resisting Characteristics of Electric Cables.
- [25] IEC 332-1970, Tests on Electric Cables Under Fire Conditions.
- [26] NEMA TC2-1983, Electrical Plastic Tubing (EPT), Conduit (EPC-40 and EPC-80) and Fittings.⁸
- [27] NEMA TC6-1983, PVC and ABS Plastic Utilities Duct for Underground Installations.
- [28] NEMA VE1-1984, Metallic Cable Tray Systems.
- [29] NEMA WC 3-1980 (R 1986), Rubber-Insulated Wire and Cable for the Transmission and Distribution of Electrical Energy (ICEA S-19-81 7th ed).
- [30] NEMA WC 5-1973 (R 1979, 1985), Thermoplastic-Insulated Wire and Cable for the Transmission and Distribution of Electrical Energy. (ICEA S-61-402 3rd ed).

⁴ NFPA publications are available from the National Fire Protection Association, Publications Sales Division, Batterymarch Park, Quincy, MA 02269. Copies are also available from the Sales Department of American National Standards Institute, 1430 Broadway, New York, NY 10018.

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

⁶ ICEA publications are available from the Insulated Cable Engineers Association, Inc, P.O. Box P, South Yarmouth, MA 02664.

⁷ IEC publications are available in the US from the Sales Department, American National Standards Institute, 1430 Broadway, New York, NY 10018, USA. The IEC publications are also available from the International Electrotechnical Commission, 3, rue de Varembe, Case postale 131, 1211-Geneve 20, Switzerland/Suisse.

⁸ NEMA publications are available from the National Electrical Manufacturers Association (NEMA), 2101 L Street, N.W., Washington, DC 20037.

[31] NEMA WC 7-1982, Cross-Linked-Thermosetting-Polyethylene-Insulated Wire and Cable for the Transmission and Distribution of Electrical Energy (ICEA S-66-524).

[32] NEMA WC 8-1976 (R 1982), Ethylene-Propylene-Rubber-Insulated Wire and Cable for the Transmission and Distribution of Electrical Energy (ICEA S-68-516).

[33] NEMA WC 51-1986, Ampacities in Open-Top Cable Trays (ICEA P-54-440).

2. Cable Performance

This section 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 Definitions

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

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

2.2 Service Conditions

(1) Cables should be suitable for all environmental conditions that occur in the areas where they are installed.

(2) 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.

(3) Cables may be directly 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.

2.3 Cable Performance

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

2.3.2 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.

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

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

2.3.5 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 ANSI/IEEE Std 383-1974 (R 1980) [8] flame tests.

3. Conductor Sizing and Voltage Rating of Power Cables

This section provides guidance for the determination of conductor sizing and 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.

3.1.1 Ambient Temperature. This factor is an important design parameter in establishing the continuous current-carrying capability (ampacity) of a cable of a given size in a particular type of installation. Where cables are routed through several types of environmental conditions (buried, sun

exposure, exposed conduit, covered cable trays, wireways, near heating equipment, etc), the conductor size, insulation and jacketing materials should be selected for the most severe environmental condition.

3.1.2 Conductor Temperature. The rated conductor temperature is dependent upon the type of cable insulation utilized. The maximum conductor temperature limit is the highest conductor temperature attained by any part of the cable under operating conditions, but not greater than the rated conductor temperature.

3.1.3 Earth Thermal Resistivity. The thermal resistivity of the soil in which cables are installed may vary greatly from location to location. It is affected primarily by the type and density of the soil and the amount of moisture present. For a typical loam or clay containing normal amounts of moisture, the resistivity is usually in the range of 60-120 °C per watt per cm³. When the earth resistance is not known, a value of 90 °C per watt per cm³ ICEA P-46-426 [21] is suggested for determining the cable ampacity.

3.1.4 Load Factor. The ampacity of a cable is also dependent upon the load factor for the cable. The load factor of a circuit is the ratio of the average hourly load to the maximum hourly load for a given time period, usually 24 h. ICEA P-46-426 [21] utilizes possible load factors of 30, 50, 75, and 100% for single-conductor cables and 50, 75, and 100% load factors for all other cables. The ampacity of a cable decreases as the load factor increases.

3.1.5 Current Loading. Power cables should be capable of carrying normal and emergency load currents. ICEA P-46-426 [21] provides cable ampacity tables for various cable constructions and methods of installation. These tables are based on 40 °C ambient air and 20 °C ambient earth and include data for various conductor temperature ratings. Appropriate factors for cable and conduit grouping are also given as well as an adjustment formula for change in conductor temperature and ambient temperature parameters. It is to be noted that the ampacities for cables in underground duct banks are based on all ducts being peripherally located with 30 in cover. The ampacities of single-conductor nontriplexed cables are based on shields grounded at one point. For ampacity

derating because of circulating currents in the shields of high-voltage cables with shields grounded at more than one point, refer to 6.2.5. The ampacities for single-conductor triplexed and three-conductor cables are based on short-circuited shields. It should be noted that power cable spacing in trays requires a minimum of one cable diameter between cables and sidewalls to avoid derating.

Ampacities for nonspaced cables in open top trays should be determined from NEMA WC 51-1986 (ICEA P-54-440) [33], rather than from ICEA P-46-426 [21].

The application of fire-retardant coverings, penetration fire stops, etc, may affect cable ampacities and should be considered.

3.1.6 System Fault Level. It is necessary to consider the effect of short circuit currents on the heating of cables. The conductor size must be large enough to carry the short circuit current for sufficient length of time to permit the circuit breakers to open before the conductor is heated to the point where it damages the insulation. Fault current capabilities of insulated conductors are given in ICEA P-32-382 (1969) [20].

3.1.7 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.

3.1.8 System Nominal Voltage and Grounding. These factors determine the cable voltage rating and insulation level. ICEA and AEIC standards provide guidelines for the proper selection of cable rating and insulation level as well as the overvoltage capabilities associated with cable voltage ratings.

4. Electrical Segregation of Cable Systems

This section 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.

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

NOTE: As used in this document, instrumentation cables consist of paired cables for supervisory systems or event recorders, and thermocouple and resistance temperature detector cables.

NOTE: This document excludes fiber optic cables and their installations which are covered in IEEE 83 WM025-4 [B58] and telephone type cables, whether owned or leased and used for voice communication or intersubstation relaying, such as pilot wire.

4.2 Segregation. 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

(1) 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.

(2) Utilization of armored shielded cables (separate raceways are not required).

4.2.2 Low-Voltage Power and Control Cables. These cable classifications may be mixed if their respective diameters do not differ greatly and they have compatible operating temperatures and voltage ratings. When this is done, 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

(1) Installations that provide physical separation between the instrumentation cables and any electrical noise source [B16] [B38].

(2) Installation in separate enclosed magnetic raceways.

(3) Cable construction configurations, such as twisted conductors and shielding.

(4) 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.

(5) Telephone and other communication type cables should be kept segregated from all other substation cables.

5. Separation of Redundant Cable Systems

This section 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 or public 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.

NOTE: Primary and back-up relaying, breaker failure relaying, etc are examples of equipment which 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.

NOTE: Administrative controls should be taken for transient fire loads such as temporary storage of flammable materials, etc.

These areas may be classified as follows:

- (1) Mechanical damage area
- (2) Fire hazard area
- (3) Cable spreading area (or areas above or below control and relay panels or racks, etc)

5.2.1 Potential Hazard Areas. Potentially hazardous areas requiring special consideration are

(1) *Mechanical Damage Area.* Physical arrangement or protective barriers, or both, should be provided so that no event can cause the destruction of the redundant cable systems. Such events include vehicle movement and failure of equipment, such as

- (a) Large rotating equipment (synchronous condensers, diesel generators, etc)
- (b) Transformers and switchgear
- (c) Surge arresters, cable potheads, etc

(2) *Fire Hazard Areas.* Redundant cable systems should be arranged so that a fire cannot

(a) Damage more than one system. Routing of redundant cable systems through an area where there is potential for accumulation of large quantities of combustible material should be avoided.

(b) Propagate from one system to another. Cables of redundant systems should have sufficient horizontal and vertical separation to prevent ignition of the cables in one system by a fire in the other. If this separation is not attainable, a fire-resistant barrier should be installed.

(3) *Cable Spreading Area.* The cable spreading area is normally adjacent to or part of the control room where cables leaving the panels are dispersed into various cable trays for routing to all parts of the substation.

(a) Where cables of redundant systems, approach each other with space less than adequate to prevent ignition of one redundant cable system by a fire in the other, the cables of one system should be installed in metallic conduit until sufficient separation exists, or barriers should be installed as necessary.

(b) The cable spreading area should not contain equipment such as switchgear, transformers, rotating equipment, or potential sources of projectiles, and should not be used for storing flammable materials. Circuits in

the cable spreading area should be limited to control and instrument functions and those power supply circuits and facilities serving the control room and instrument systems. Power supply feeders to instrument and control room distribution panels should be installed in enclosed metallic raceways.

Other power circuits that are required to traverse this area should be assigned routes consistent with their separation requirements and allocated solely for these power circuits. Such power circuits should be separated from other circuits in this area in accordance with 4.2.

NOTE: An acceptable alternative routing for such traversing power circuits would be to route them in embedded conduit or in a separate enclosure which, in effect, removes them from the cable spreading area.

6. Shielding and Shield Grounding

This section 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.

(1) *High-Voltage Switching.* Opening or closing a disconnecting switch to deenergize or energize a section of substation bus is 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 over-voltages 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.

(2) *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 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.

(3) *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].

(4) *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 (disconnecting) switch operations.

(5) *Ground Potential Rise (GPR)*. GPR 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 zero ground potential. That is, the ground potential of a grounded neutral conductor is nearly identical to the potential of remote earth. During a fault, the portion of fault current which is conducted by a ground electrode into the earth causes a rise of the electrode potential with respect to remote earth ANSI/IEEE Std 80-1986 [5], [B20].

(6) *Ground Potential Rise Differences*. Both electromagnetic coupling and conduction can contribute to substantial ground potential 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-potential 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 groundings of transformer neutrals and capacitive paths, such as bushings, coupling capacitors, and CCVTs. These are low-impedance high-energy sources that can induce common-mode voltages on control circuits ANSI/IEEE Std 367-1987 [7].

(7) *Other Switching Type Operations*. Other switching type operations 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 deenergizing, series capacitor gap flashing, 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 dielectric 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 standard.

cable shielding. An electrical conducting 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. Cables rated above 5 kV should be shielded, except for special applications or cable designs. Cable applications in the operating range of 2 kV to 5 kV require careful judgement, 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 shielding recommendations contained in the ICEA-NEMA Standards Publications for the type of

insulation being utilized should be followed NEMA WC 3-1980 (R 1986) (ICEA S-19-81 7th ed) [29], NEMA WC 5-1973 (R 1979, 1985) (ICEA S-61-402 3rd ed) [30], NEMA WC 7-1982 (ICEA S-66-524) [31], NEMA WC 8-1976 (R 1982) (ICEA S-68-516) [32].

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

- (1) Transition from conducting to non-conducting environment
- (2) Transition from moist to dry environment
- (3) Dry soil, such as in a desert
- (4) Damp conduits
- (5) Connections to overhead lines
- (6) Locations where cable surface collects conducting materials, such as soot or salt deposits
- (7) Electrostatic discharges are sufficient in magnitude to interfere with control and instrumentation circuit functions
- (8) Safety to personnel is involved
- (9) Long underground cables
- (10) Single-conductor cables in trays
- (11) Direct earth burial

6.2.3 Shield Termination Practices. The insulation shield system must be removed carefully and completely, and proper stress control materials or devices used. Manufacturer's instructions and recommendations as to termination of shielded cables should be followed in detail. If all elements of the shield are not removed, excessive leakage current with tracking or flashover may result.

6.2.4 Grounding Practices. Cable shields and metallic sheath/armor should be solidly grounded at one or more points so that they operate at or near ground potential at all times ANSI/IEEE Std 575-1988 [13]. The length of cable run should be limited by the acceptable voltage rise of the shield if the shield is grounded at only one point. The derating of ampacity due to multiple-point short circuited shields has a negligible effect in the following cases for three-phase circuits:

- (1) Three-conductor cables encased by a common shield or metallic sheath.
- (2) Single-conductor shielded cables 500 kcmil copper or smaller installed together in a common duct.
- (3) Triplexed or three-conductor individually shielded cables 500 kcmil copper or smaller.

- (4) Single-conductor lead sheathed cables 250 kcmil copper or smaller installed together in a common duct.

Because of the frequent use of window type or zero-sequence current transformers for ground overcurrent protection, care must be taken in the termination of cable shield wires at the source. If the shield wire is passed through the window-type current transformer, it should be brought back through this current transformer before connecting to ground in order to give correct relay operation.

6.2.5 Shield Losses that Affect Ampacity. Shields or sheaths that are grounded at more than one point carry induced circulating currents. Compensation for the heating effect of the induced circulating current should be considered when calculating the cable ampacity. 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. Circulating currents heat the shield and reduce the effective ampacity of the cable. Table 6-1 gives formulae for calculating the shield loss for single-conductor cables.

Table 6-1 has been derived from Chapter 10, Table 26, of [B1].

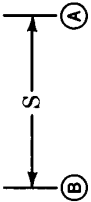
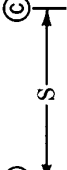
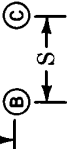
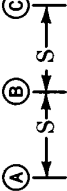
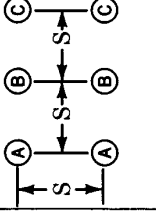
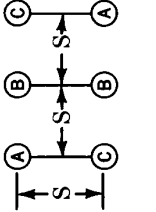
To facilitate calculating the mutual reactance and shield resistance, the following formulae which neglect proximity loss, may be used for practical purposes:

$$\begin{aligned}
 X_M &= 2 \pi f (0.1404 \log_{10} \frac{S}{r_m}) \mu\Omega/\text{ft} \\
 a &= 2 \pi f (0.1404 \log_{10}^2) \mu\Omega/\text{ft} \\
 b &= 2 \pi f (0.1404 \log_{10}^5) \mu\Omega/\text{ft} \\
 R_s &= \frac{\rho}{8r_m t} \mu\Omega/\text{ft}
 \end{aligned}$$

where

- X_M = mutual inductance of shield and conductor ($\mu\Omega/\text{ft}$)
- a, b = mutual inductance correction factors ($\mu\Omega/\text{ft}$)
- $\mu\Omega$ = micro-ohm - $\Omega \times 10^{-6}$
- R_s = resistance of shield ($\mu\Omega/\text{ft}$)
- t = thickness of metal tapes used for shielding (inches)
- f = frequency (Hertz)
- S = spacing between center of cables (inches)
- r_m = mean radius of shield (inches)

Table 6-1
Formulas for Calculating Induced Shield Voltages and Shield Losses for Single-Conductor Cables

Cable Arrangement Number and Diagram	I One Phase 	II Equilateral 	III Rectangular 	IV Flat 	V Two Circuit 	VI Two Circuit 
μV to neutral/ft (multiply by 10^{-6} to obtain V/ft)						
Cable — A Cable — C	IX_M	IX_M	$\frac{1}{2} \sqrt{3Y^2 + \left(X_M - \frac{a}{2}\right)^2}$	$\frac{1}{2} \sqrt{3Y^2 + \left(X_M - a\right)^2}$	$\frac{1}{2} \sqrt{3Y^2 + \left(X_M - \frac{b}{2}\right)^2}$	$\frac{1}{2} \sqrt{3Y^2 + \left(X_M - \frac{b}{2}\right)^2}$
Cable — B	IX_M	IX_M	IX_M	IX_M	$I \left(X_M + \frac{a}{2}\right)$	$I \left(X_M + \frac{a}{2}\right)$
μW /ft (multiply by 10^{-6} to obtain W/ft)						
Shield Loss — Shields Solidly Bonded						
Cable — A Cable — C	$I^2 R_s \frac{X_M^2}{R_s^2 + X_M^2}$	$I^2 R_s \frac{X_M^2}{R_s^2 + X_M^2}$	$I^2 R_s \left[\frac{P^2 + 3Q^2}{4(P^2 + 1)(Q^2 + 1)} + 2 \sqrt{\frac{3(P-Q) + 4}{(Q^2 + 1)}} \right]$	$I^2 R_s \left[\frac{1}{Q^2 + 1} \right]$	$I^2 R_s \left[\frac{1}{Q^2 + 1} \right]$	$I^2 R_s \left[\frac{1}{Q^2 + 1} \right]$
Cable — B	$I^2 R_s \frac{X_M^2}{R_s^2 + X_M^2}$	$I^2 R_s \frac{X_M^2}{R_s^2 + X_M^2}$	$3I^2 R_s \left[\frac{P^2 + Q^2 + 2}{2(P^2 + 1)(Q^2 + 1)} \right]$	$3I^2 R_s \left[\frac{P^2 + Q^2 + 2}{2(P^2 + 1)(Q^2 + 1)} \right]$	$3I^2 R_s \left[\frac{P^2 + Q^2 + 2}{2(P^2 + 1)(Q^2 + 1)} \right]$	$3I^2 R_s \left[\frac{P^2 + Q^2 + 2}{2(P^2 + 1)(Q^2 + 1)} \right]$
Total Loss	$2I^2 R_s \frac{X_M^2}{R_s^2 + X_M^2}$	$3I^2 R_s \frac{X_M^2}{R_s^2 + X_M^2}$	$3I^2 R_s \frac{X_M^2}{R_s^2 + X_M^2}$	$3I^2 R_s \frac{X_M^2}{R_s^2 + X_M^2}$	$3I^2 R_s \frac{X_M^2}{R_s^2 + X_M^2}$	$3I^2 R_s \frac{X_M^2}{R_s^2 + X_M^2}$
I = Conductor current (amperes)						
	$P = \frac{R_2}{Y}$	$Y =$	$X_M + \frac{a}{2}$	$X_M + a$	$X_M + a + \frac{b}{2}$	$X_M + a - \frac{b}{2}$
	$Q = \frac{R_s}{Z}$	$Z =$	$X_M - \frac{a}{6}$	$X_M - \frac{a}{3}$	$X_M + \frac{a}{3} - \frac{b}{6}$	$X_M + \frac{a}{3} - \frac{b}{6}$

ρ = apparent resistivity of shield in Ω -cmil/ft at operating temperature (assumed 50 °C). This includes allowance for the spiraling of the tapes or wires.

Typical values of ρ :

Overlapped helical copper tape	30 Ω -cmil/ft
Lead sheath	150 Ω -cmil/ft
Aluminum sheath	20 Ω -cmil/ft
Bare copper wires	10.6 Ω -cmil/ft

For 60 Hz:

$$X_M = 52.92 \log_{10} \frac{S}{r_m} \mu\Omega/\text{ft}$$

$$a = 15.93 \mu\Omega/\text{ft}$$

$$b = 36.99 \mu\Omega/\text{ft}$$

It is assumed that the cables are carrying balanced currents.

For cables installed three per conduit, use Arrangement II in Table 6-1. The spacing, S , in this case will be equal to the outside diameter of the cable increased by 20% to allow for random spacing in the conduit.

All three phases of a circuit should be installed in the same conduit. When it is necessary to run only one phase per conduit, then nonmetallic or nonmagnetic metallic conduit should be used. If nonmagnetic metallic conduits are used, the reduction of cable ampacity due to conduit heating should be considered. Also, no magnetic metal, such as clamps or rebar, should form a closed ring around the conduit.

6.2.6 Induced Shield Voltages. Shields of single-conductor cable carrying alternating current will have a voltage buildup if grounded at only one point. Table 6-1 can be used to calculate the induced shield voltage. A maximum voltage of 25 V, under normal operating conditions, is a commonly accepted limit.

Table 6-2 gives the maximum lengths of single conductor cable with shields grounded at one point to stay within the 25 V maximum for the conditions stated. Other conditions will permit different lengths. For example, cables operated at less than rated ampacity will allow longer lengths. Direct-buried cables operating at their rated ampacity, with all other conditions being the same, will require shorter lengths to stay below the 25 V maximum.

6.3 Instrumentation Cable. This section provides guidance for shielding and

grounding of signal cables used with instrumentation systems.

The general rules set forth should be tempered by specific manufacturer's recommendations.

6.3.1 Definitions

common-mode noise (longitudinal). The noise voltage which appears equally and in phase from each signal conductor to ground. Common-mode noise may be caused by one or more of the following:

(1) *Electrostatic induction.* With equal capacitance between the signal wires and the surroundings, the noise voltage developed will be the same on both signal wires.

(2) *Electromagnetic induction.* With the magnetic field linking the signal wires equally, the noise voltage developed will be the same on both signal wires.

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.

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

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. Normal-mode noise may be caused by one or more of the following:

(1) Electrostatic induction and differences in distributed capacitance between the signal wires and the surroundings.

(2) Electromagnetic induction and magnetic fields linking unequally with the signal wires.