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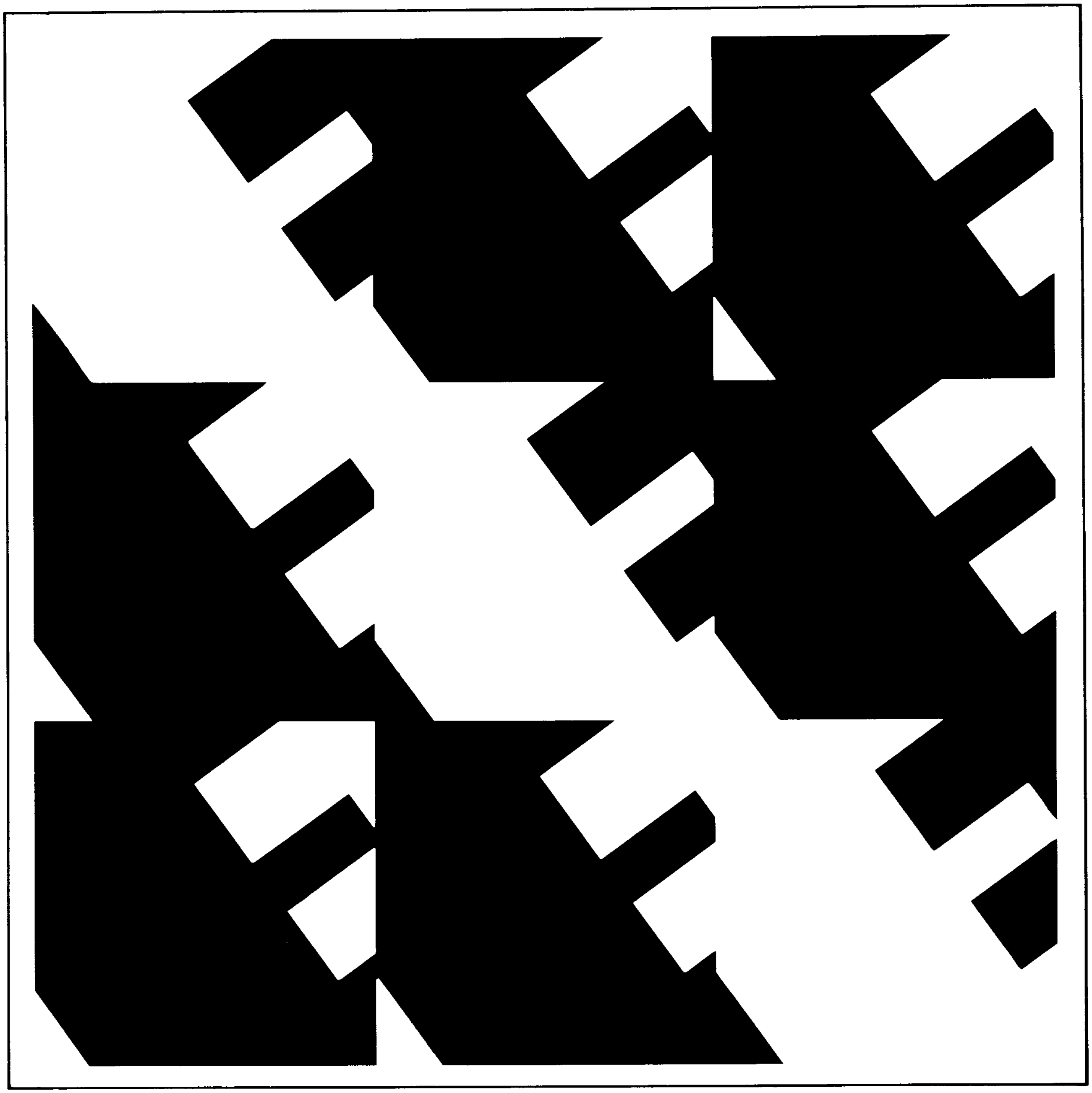
IEEE Guide for the Design and Installation of Cable Systems in Substations



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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 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.

[1] Numbers 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.

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

[3] ANSI/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 Varembé, 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 cm^3. When the earth resistance is not known, a value of 90 °C per watt per cm^3 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 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.

(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:

$$X_M = 2\pi f \left(0.1404 \log_{10} \frac{S}{r_m}\right) \mu\Omega/\text{ft}$$

$$a = 2\pi f (0.1404 \log_{10} 2)\ \mu\Omega/\text{ft}$$

$$b = 2\pi f (0.1404 \log_{10} 5)\ \mu\Omega/\text{ft}$$

$$R_s = \frac{\rho}{8 r_m t}\ \mu\Omega/\text{ft}$$

where

X_M = mutual inductance of shield and conductor ($\mu\Omega$/ft)

a, b = mutual inductance correction factors ($\mu\Omega$/ft)

$\mu\Omega$ = micro-ohm - $\Omega \times 10^{-6}$

R_s = resistance of shield ($\mu\Omega$/ft)

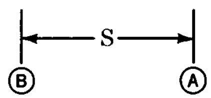
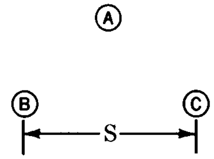
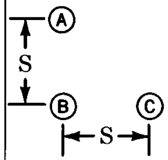
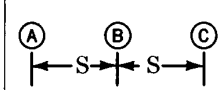
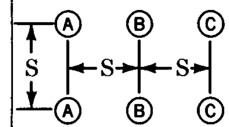
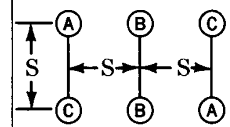
t = thickness of metal tapes used for shielding (inches)

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
						
Induced Shield Voltage-Shields Open Circuited			μV to neutral/ft (multiply by 10^{-6} to obtain V/ft)			
Cable — A, Cable — C	IX_M	IX_M	$\frac{I}{2}\sqrt{3Y^2+\left(X_M-\frac{a}{2}\right)^2}$	$\frac{I}{2}\sqrt{3Y^2+\left(X_M-a\right)^2}$	$\frac{I}{2}\sqrt{3Y^2+\left(X_M-\frac{b}{2}\right)^2}$	$\frac{I}{2}\sqrt{3Y^2+\left(X_M-\frac{b}{2}\right)^2}$
Cable — B	IX_M	IX_M	IX_M	IX_M	$I\left(X_M+\frac{a}{2}\right)$	$I\left(X_M+\frac{a}{2}\right)$
Shield Loss — Shields Solidly Bonded			μW/ft (multiply by 10^{-6} to obtain W/ft)			
Cable — A, Cable — C	$I^2 R_s \frac{X_M^2}{R_s^2+X_M^2}$	$I^2 R_s \frac{X_M^2}{R_s^2+X_M^2}$	$I^2 R_s \left[\frac{(P^2+3Q^2)+2\sqrt{3}(P-Q)+4}{4(P^2+1)(Q^2+1)}\right]$			
Cable — B	$I^2 R_s \frac{X_M^2}{R_s^2+X_M^2}$	$I^2 R_s \frac{X_M^2}{R_s^2+X_M^2}$	$I^2 R_s \left[\frac{1}{Q^2+1}\right]$			
Total Loss	$2I^2 R_s \frac{X_M^2}{R_s^2+X_M^2}$	$3I^2 R_s \frac{X_M^2}{R_s^2+X_M^2}$	$3I^2 R_s \left[\frac{P^2+Q^2+2}{2(P^2+1)(Q^2+1)}\right]$			
	$P = \frac{R_2}{Y}$	$Y =$	$X_M + \frac{a}{2}$	$X_M + a$	$X_M + a + \frac{b}{2}$	$X_M + a - \frac{b}{2}$
	$Q = \frac{R_s}{Z}$	$Z =$	$X_M - \frac{a}{6}$	$X_M - \frac{a}{3}$	$X_M + \frac{a}{3} - \frac{b}{6}$	$X_M + \frac{a}{3} - \frac{b}{6}$

I = Conductor current (amperes)

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.

Table 6-2
Maximum Lengths for Single-Conductor Cables Operating at Rated Ampacity with Single-Point Shield Grounding

Conductor Size	One Cable Per Duct (1)				Three Cables Per Duct (2)			
	Copper		Aluminum		Copper		Aluminum	
	(A)	(ft)	(A)	(ft)	(A)	(ft)	(A)	(ft)
1/0	249	1465	194	1875	214	4965	167	3655
4/0	371	1055	290	1350	278	3530	248	4480
350	496	820	387	1050	418	2610	329	3310
500	608	695	472	890	504	2200	400	2770
750	762	595	601	750	626	1800	497	2260
1000	890	565	707	710				
2000	1237	420	1022	508				

NOTES: (1) 15 kV cables in ducts on 7.5 in centers operating at 75% load factor.
(2) Three single-conductor 15 kV cables in one duct operating at 75% load factor. The length listed is the duct length.

(3) Junction or thermal potentials due to the use of dissimilar metals in the connection system.

(4) Common mode to normal-mode noise conversion.

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.

NOTE: When electromagnetic shielding is intended, the term *electromagnetic* is usually included to indicate the difference in shielding requirement as well as material. To be effective at power system frequencies, electromagnetic shields would have to be made of high-permeability steel. Such shielding material is expensive and is not normally applied. Other less expensive means for reducing low-frequency electromagnetic induction, as described herein, are preferred.

6.3.2 Methods for Noise Reduction

6.3.2.1 Ground Signal Circuit at One Point. The signal circuit may originate at a source such as a transducer and terminate at a load such as a recorder, supervisory remote terminal unit, etc, either directly or through an intervening amplifier.

If the recorder, supervisory remote terminal, etc, is fed directly from a grounded voltage generating transducer such as a thermocouple, the terminal circuits must be capable of high-common-mode rejection, or they should be isolated from ground. Isolating the circuits from ground effectively opens the ground common-mode voltage path through the signal circuit. If an intervening amplifier is a single-ended amplifier, the low side of the signal circuit is not broken and is grounded at the terminal. Therefore, the situation is not changed, so the same procedure should be followed with the terminal as indicated above.

A guarded isolated differential amplifier provides isolation of both input terminals from the chassis (or ground) and from the output. This amplifier is capable of high-common-mode rejection and provides the input-output isolation so that the output ground will not affect the input circuit.

Typically, the common-mode rejection ratio of an isolated differential amplifier used in instrumentation systems is about 10^6:1 (120 dB) and is the ratio of common-mode voltage applied to the amount of normal-mode voltage developed in the process.

When an ungrounded transducer is used, it may be possible to obtain satisfactory results by leaving the transducer circuit ungrounded, connecting the cable shield to the amplifier guard shield, and grounding the shield at either the transducer end or the amplifier end. However, it is considered that connecting the cable shield to the amplifier guard shield and grounding both transducer cable shield and circuit at the transducer will result in a less noisy, more stable system. See 6.3.2.6 for additional information on shield grounding.

6.3.2.2 Electrostatically Coupled Noise. Shielding of signal cables will reduce electrostatically coupled noise voltage. See 6.3.2.6 for additional information on shield grounding. A properly grounded shield will greatly reduce the capacitance between the signal conductors and external sources of electrostatic noise so that very little noise voltage can be coupled in the signal circuit.

6.3.2.3 Electromagnetically Induced Noise. The use of twisted pair cables is an effective method of electromagnetic noise reduction. By alternately presenting each conductor to the same electromagnetic field, voltages of equal magnitude and opposite polarity are induced in each conductor with respect to ground. The common-mode voltage so developed is converted to a small amount of normal-mode noise as determined by the common-mode rejection ratio of the signal amplifier (isolated differential or equivalent). The frequency of twisting (lay) affects noise reduction ability and, therefore, should be considered in specifying twisted pair cable.

The materials normally used for shielding of instrumentation cable are nonferrous and cannot shield against power frequency electromagnetic fields. The steels normally used in conduit or tray are not of high enough permeability to provide very effective shielding at power frequencies. However, some benefit may accrue from the use of rigid steel conduit or steel trays with solid bottoms and tightly fitting solid steel covers.

6.3.2.4 Crosstalk. Using cables with twisted pair conductors and individually insulated shields over each pair is a method to minimize crosstalk.

6.3.2.5 Separation (Segregation). Physical separation of instrumentation cables can be utilized to reduce noise pickup. However, physical separation in itself, unless carefully analyzed, may not achieve the desired degree of immunity. Cables should be run in accordance with Section 4.

6.3.2.6 Shield Grounding. The shield should be connected to ground at only one point, preferably, where the signal equipment is grounded. An exception to this is where the shield is used for the excitation of a neutralizing transformer. If the shield is grounded at some point other than where the signal equipment is grounded, charging currents may flow in the shield because of differences in potential between signal and shield ground locations. If the shield is grounded at more than one point, differences in ground potential will drive current through the shield. In either case, shield current can induce common-mode noise current into the signal leads, and by conversion to normal-mode noise, voltage proportional to signal circuit resistance unbalance can reduce accuracy of signal sensing. In a system with grounded transducer and isolated-input differential amplifier, the cable shield should connect to the amplifier guard shield, but grounding the shield at the amplifier will reduce the amplifier's common-mode rejection capability. Grounding the shield only at the transducer will maintain the shield at the same ground potential as the transducer, which will minimize shield-induced common-mode current while permitting the amplifier to operate at maximum common-mode rejection capability. Also see 6.3.2.1 for shield and signal circuit grounding of ungrounded transducers.

6.3.2.7 Other Methods. Other methods for reducing noise voltages are

(1) Drainage unit (drainage reactor/mutual drainage reactor) is a center-tapped inductive device designed to relieve conductor-to-conductor and conductor-to-ground voltage stress by draining extraneous currents to ground.

(2) Isolating (insulating) transformers provide longitudinal (common mode) isolation for the facility. They can also be used in a combined isolating-drainage transformer configuration.

(3) Neutralizing transformers introduce a voltage into a circuit pair to oppose an unwanted voltage. They neutralize extraneous longitudinal voltages resulting from ground potential rise or longitudinal induction, or both, while simultaneously allowing ac or dc metallic signals to pass.

(4) Optical couplers (isolators) provide isolation using a short length, optical path.

For additional information on these methods, refer to ANSI/IEEE Std 487-1980 [11].

6.3.3 Shielding Practices

(1) The cable for computer or high-speed data logging applications, using low-level analog signals, should be made up of twisted and shielded pairs. For noncomputer type applications, such as annunciators, shielding may not be required.

(2) Twisting and shielding requirements for both digital input and digital output signals vary between different manufacturers of computerized instrumentation systems. Separation of digital input cables and digital output cables from each other and from power cables may be required. Where digital inputs originate in close proximity to each other, twisted pair multiple conductor cables with overall shield should be used or multiple conductor cable with common return may be permitted, and overall shielding may not be required. Digital output cables of similar constructions may also be permitted. Individual twisted and shielded pairs should be considered for pulse-type circuits.

(3) Cable shields should be electrically continuous except where specific reasons dictate otherwise. When two lengths of shielded cable are connected together at a terminal block, an insulated point on the terminal block should be used for connecting the shields.

(4) Shields should be isolated and insulated except at their selected grounding point to prevent stray and multiple grounds to the shield.

(5) At the point of termination, the shield should not be stripped back any further than necessary from the terminal block.

(6) The shield should not be used as an electrical conductor except for neutralizing transformer excitation.

(7) For signal circuits, the shield must not be part of the signal circuit. Furthermore, the use of shielded, twisted pairs into balanced terminations greatly improves transient suppression. It is never acceptable to use a common line return both for a low-voltage signal and a power circuit [B14].

6.3.4 Grounding Practices

(1) All shields should be grounded in accordance with 6.3.2.6.

(2) Signal circuits, if grounded, should be grounded at only one point.

(3) Digital signal circuits should be grounded only at the power supply.

(4) The shields of all grounded junction thermocouple circuits and the shields of thermocouple circuits intentionally grounded at the thermocouple should be grounded at or near the thermocouple well.

(5) Multipair cables used with thermocouples should have twisted pairs with individually insulated shields so that each shield may be maintained at the particular thermocouple ground potential.

(6) Each resistance temperature detector (RTD) system consisting of one power supply and one or more ungrounded RTDs should be grounded only at the power supply.

(7) Each grounded RTD should be on a separate ungrounded power supply except as follows:

Groups of RTDs embedded in the windings of transformers and rotating machines should be grounded at the frame of the respective equipment for safety. A separate ungrounded power supply should be furnished for the group of RTDs installed in each piece of equipment.

(8) When a signal circuit is grounded, the low or negative potential lead and the shield should be grounded at the same point.

6.4 Control Cable. This section provides information on surge voltages which originate in control circuits and guidance for shielding and grounding control cable.

6.4.1 Sources Within the Control Circuit. During interruption of direct current in an inductor, such as a relay coil, a large induced voltage may appear across the inductor due to the L di/dt effect [B52]. Normally, the maximum voltage will exist at the instant of interruption. Magnitude is very dependent on supply circuit impedance. If impedance is high, voltage will be proportionally high. The surge voltage will equal the extinction voltage across the contact plus the drop through the rest of the circuit. The higher the speed of interruption, the higher the surge voltage generated. Voltages in excess of 10 kV have been observed across a 125 V coil in laboratory tests, but 2.5 kV is a more typical value to be expected.

Direct-current circuit energization has an effect on adjacent circuits where capacitive coupling exists. Full battery voltage appears initially across the impedance of the adjacent circuit and then decays exponentially in accordance with the RC time constant of the circuit [B38].

The extensive use of surge capacitors on solid-state equipment and the longer cable runs associated with EHV stations have substantially increased the capacitance between control wiring and ground. Inadvertent momentary grounds on control wiring cause a discharge or a redistribution of charge on this capacitance. Although this seldom causes failure, misoperation of equipment may occur.

Saturation of current transformers by high-magnitude fault currents, including the dc offset, can result in the induction of very high voltages in the secondary windings. This phenomenon is repeated for each transition from saturation in one direction to saturation in the other. The voltage appearing in the secondary consists of high-magnitude spikes with alternating polarity persisting for an interval of a few milliseconds every half cycle [B38].

6.4.2 Protective Measures. The design of control, protection, and metering circuits in modern substations must include provisions for reducing unwanted interference to tolerable levels. The most significant interference comes from voltages or currents, or both, induced in the circuits as a result of exposure to nearby conductors in which transient currents or voltages appear as a result of switching or faults. Although voltages used in the transmission of power have been increasing over the years, the level of control voltages and signal power has had a tendency to remain constant or even decrease. Since induced interference increases with the use of higher voltages and increased fault current levels, the ratio of unwanted signal (noise) to useful signal will be increased if precautions are not taken to protect the signal circuits.

Transient voltages on cables cannot be completely eliminated, but can be limited in magnitude. In the interest of compatibility with solid-state relaying systems, one suggested limit is the peak of the surge withstand capability (SWC) test ANSI/IEEE C37.90.1-1974 [3]. Many different things can be done separately or in combination to reduce the magnitude of the transients, depending upon economics and equipment configuration. The following methods are primarily confined to control cable installation.

6.4.2.1 Physical Location and Grouping. Physical separation between transient source and control cables is an effective means of transient control. Because mutual capacitance and mutual inductance are greatly influenced by circuit spacing, small increases in distance may produce substantial decreases in interaction between circuits [B11].

Where possible, control cables should be routed perpendicular to high-voltage buses [B18], [B38]. When control cables must be run parallel to high-voltage buses, maximum practical separation should be maintained between the cables and the buses [B11].

NOTE: Tests indicate that in some cases, nonshielded control cables may be used without paralleling ground cables when they are parallel and are located at a distance greater than 50 ft from or are perpendicular to a typical 345 kV bus [B14].

Great care should be exercised in routing cables through areas of potentially high ground grid current (either 60 Hz or high-frequency currents) [B18].

All cables from the same equipment should be close together, particularly to the first manhole or equivalent in the switchyard [B18].

Cables connected to equipment having comparable sensitivities should be grouped together and then the maximum separation should be maintained between groups. High-voltage cables should not be in duct runs or trenches with control cables [B11], [B18], [B38].

Radial arrangement of control circuitry will reduce transient voltages. Circuits routed into the switchyard from the control house must not be looped from one piece of apparatus to another in the switchyard with the return conductor in another cable. All supply and return conductors must be in a common cable to avoid the large electromagnetic induction possible because of the very large flux-linking-loop that the loop arrangement provides [B11], [B38].

6.4.3 Grounding. The design of ground grid systems, the methods of grounding equipment, and shielding of control circuits have a large influence on transient voltages which will be impressed on control equipment.

The ground grid, even when designed with a very low resistance, cannot be considered as an equipotential surface. Substantial grid potential rise differences may occur which will be directly influenced by a number of factors, for example, grid resistance, grid geometry distribution of ground currents ANSI/IEEE Std 80-1986 [5], earth resistivity [B52], ANSI/IEEE Std 81-1983 [6], and frequency of the transient [B15].

Since it is impractical to eliminate grid potential rise differences, their effects must be neutralized. Neutralization can be accomplished by a low resistance shield conductor parallel to and in close proximity to the affected control circuits. Such a conductor may be the shield of a shielded control cable, unused conductors of an unshielded control cable, or a separate shield conductor. These conductors will carry currents proportional to the grid potential rise differences and induce a counter voltage in the control circuits, thus effecting neutralization.

Grounding, neutralizing, and shielding methods which have been found to be effective are as follows:

(1) In trench systems, shield conductors which are grounded to the substation grid as necessary, should be attached to the top sides of the trench. This places the shield conductors between the transient source and the control cables [B52]. These shield conductors should have sufficient conductivity to carry fault currents without damage and have adequate mechanical strength.

(2) In substation manholes, ground buses should be established around the perimeter of the manhole with at least two ties to the substation grid. This ground bus provides a convenient means of grounding individual cable shields.

(3) Where duct runs are used, a minimum of two grounded shield conductors should be included at the top edges of the duct run.

(4) For direct-burial control cables, several grounded shield conductors should be buried with each cable run. For equivalent conductivity, several smaller shield conductors are more effective than a single large conductor.

(5) Unused conductors, grounded at both ends, in an unshielded control cable may be used as shield conductors [B52] on an equivalent conductivity basis. Provisions should be made for replacement with shield conductors should the unused conductors later be used for active circuits.

(6) Shield conductors are effective for either shielded or unshielded control cables. To be most effective, shield conductors must be in the closest possible proximity to the control cables, particularly where unshielded cables are used.

(7) Instrument transformer secondaries should be connected to ground at only one point ANSI/IEEE C57.13.3-1983 [4]. Making the ground connection at the relay or control building has the following advantages:

(a) Potential rise is minimized near the relay equipment

(b) The shock hazard to personnel in the building is reduced

(c) All grounds are at one location, facilitating checking

(8) High-voltage shunt capacitor banks of a given voltage should have the neutrals from individual banks connected together and then connected to the station ground grid at only one point. To facilitate one point grounding, all capacitor banks of a given voltage should be at one location.

If shield resistance is neglected, the fraction of the induced voltage on a control cable which is cancelled by the shield current is equal to the ratio of the mutual impedance between shield and conductor to the self-impedance of the shield. For a concentric shield, this ratio should be one. For an adjacent shield wire, the ratio must always be less than one.

If the resistance of the shield is considered, then the cancelling voltage generated by the shield current is reduced by the ratio of the self-inductive reactance of the shield to the total complex self-impedance of the shield. The resistance becomes significant at low frequencies where the inductive reactance of the shield is low and can generally be neglected at high frequencies. ANSI/IEEE Std 518-1982 [12]

6.4.4 Metallic Shielding of Control Cables Can Reduce Induced Transient Voltages. Protection may take the form of surrounding the sensitive circuits with an equipotential surface to prevent capacitive coupling to high-voltage conductors, and magnetic shielding to mitigate the effect of strong magnetic fields. When shielded control cable is used, grounding the shield at both ends is recommended [B14]. Care should be exerted in keeping the shield intact, as a broken or separated shield can greatly reduce the shield efficiency.

If only one end of the shield is grounded, large transient shield-to-ground and conductor-to-ground voltages may be present at the ungrounded end [B11], [B34].

Grounding a shield at both ends allows shield current to flow. The shield current resulting from magnetic induction creates a counter-flux which will tend to cancel the flux that created the shield current. The net effect of the shield on the lead is to reduce the noise level. An exception to this is that the current flowing in shields not produced by flux linking the lead will cause the surge or noise voltage on the lead to be higher than it would be if there were no shield [B38], [B14], [B52].

The lower the shield impedance, the greater is the amount of transient voltage cancellation because of greater current flow. Generally a lower surge impedance permits larger induced transient currents to flow in the shield [B34].

A grounding conductor may be run parallel to the shielded cable to help protect the shield from being damaged when fault currents are present [B52].

If electrostatic shields are required, they should be within the outer shield [B34].

Auxiliary power and yard lighting circuits should not be installed without adequate shielding near shunt capacitor banks [B11].

Experience has shown that in high-voltage substations, steps should be taken to reduce the transients in auxiliary power cables, lighting cables, etc, in addition to control circuits [B3].

6.5 Coaxial and Triaxial Cable and Tuning Leads. Coaxial cable and leads are an integral part of the coupling and tuning portions of a power-line carrier channel. Three specific types of conductors are normally used: insulated single conductor, coaxial cable, and triaxial cable. For additional guidance on tuning units, refer to ANSI/IEEE Std 643-1980 [14].

6.5.1 Insulated Single Conductors. An insulated single conductor is used to connect a coupling capacitor to line-tuning equipment or outdoor transmitting and receiving equipment. It can also be used as the interconnecting lead for short bypasses.

Bare conductors and coaxial cables should be avoided for these applications, since one will introduce excessive leakage currents and the other will introduce excessive stray capacitance.

Since a single conductor is at a high impedance point when connected between a coupling capacitor and a line tuner, stray capacitance to ground and leakage currents can affect the coupling circuit performance. The stray capacitance can cause a reduction in bandwidth, and the leakage currents can cause a loss in carrier power.

To reduce stray capacitance and leakage currents, either of the following methods may be used:

(1) An insulated single conductor should be run as directly as possible between its required terminations. It should be mounted on insulators and fed through bushings at each end. The conductor insulation should be unbroken between its ends to maintain low leakage.

(2) An insulated single conductor can be installed in a nonmagnetic flexible metal conduit which is sheathed in a vinyl jacket. The insulated single conductor should be isolated from the flexible metal conduit with Teflon washers spaced about 6 in (150 mm) apart. If the conductor has a significant portion of its length outside the flexible metal conduit, it should be mounted on insulators and fed through bushings at its ends as in (1).

A typical insulated carrier lead, 0.48 in (12.2 mm) in diameter, consists of a single AWG No. 8, 19-strand conductor having rubber insulation and a neoprene outer jacket.

6.5.2 Coaxial Cables. This type of cable is sometimes used for a low-impedance interconnection between a line tuner and a transmitter/receiver or between line tuners in a long bypass. It is sometimes used between an impedance-matching transformer in a coupling capacitor base and a transmitter/receiver.

In these applications, the copper braid (shield) which forms the outer conductor of the cable should be grounded at the transmitter/receiver end only (or at only one end of a bypass). If both shield ends are grounded, large surge currents can flow under certain conditions, causing saturation of the impedance-matching transformer and resulting in an inoperative carrier channel.

6.5.3 Triaxial Cables. On transmission lines operating at voltages greater than

230 kV, triaxial cable may be used instead of coaxial cable. This cable provides an additional heavy shield which does not carry signal currents. The outer shield is capable of carrying large induced surge currents under fault conditions and is grounded at both ends. This arrangement provides very effective shielding against both magnetic and electrostatic induction so that surges induced in the signal leads are small.

6.5.4 Insulation Requirements. In some cable installations, specifications may call for safe operation under high-temperature conditions. Polyethylene has a maximum service temperature of 80 °C, and, therefore, it must be replaced by other dielectrics where high-temperature operation is required. Chlorosulfonated polyethylene and silicone rubber compounds are examples of materials that have been used in high-temperature cables or where cable fire propagation is a consideration.

6.6 Coupling Capacitor Voltage Transformer Considerations. CCVTs can produce high transient common-mode secondary voltages because of the surge impedance that exists between the CCVT base and the ground grid, and between phases. This voltage can be reduced by lowering the surge impedance, which is achieved by mounting the CCVTs as close to the ground as permitted by clearance standards and by providing multiple low-resistance conductors between the CCVT base and the station ground grid, and between phases. All secondary circuits from the CCVTs should be radial and contained within a single shielded cable to provide cancellation of the differences in ground grid potential [B11]. The secondary cables should follow the ground conductor as closely as possible.

7. Cable Penetration Fire Stops, Fire Breaks, System Enclosures, and Cable Coatings

This section provides guidance for the selection and application of cable penetration fire stops, cable fire breaks, cable system enclosures (cocoons), and coatings for cable systems.

NOTE: Several types of fire stops, cable system enclosures, fire barriers and coatings are made from materials which are thermal insulators. Their use can result in significant cable derating which should be considered in sizing cables.

7.1 Definitions

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.

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.

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.

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.

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.

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

NOTE: To be effective, fire barriers must have sufficient fire resistance to withstand the effects of the most severe fire that may be expected to occur in the area adjacent to the fire barrier, and must provide a complete barrier to the spread of fire.

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.

NOTE: The test fire procedure and acceptance criteria are defined in ASTM E119-1983 [19].

7.2 Cable Penetration Fire Stops. The fire stop should prevent fire propagation along a cable system through a fire-rated wall, floor, or floor-ceiling barrier while maintaining the integrity of the fire barrier through which the cable system penetrates.

7.2.1 Design Considerations. In selecting materials for use as fire stops, the following factors should be considered:

(1) Physical and chemical compatibility between the penetration fire stop material and the cable covering and raceway materials.

(2) Reduce heat dissipation resulting in power cable ampacity derating.

(3) Thermal expansion which might crush insulation or jacket during installation and operation.

(4) Toxic or corrosive gases developed during installation or during a fire.

(5) Ability to withstand pressure differentials.

(6) Aging.

(7) Temperature rise during curing of material.

(8) Ease of installation.

(9) Provision for the installation of additional cables.

(10) Ability to withstand a hose-stream test that is acceptable for use on an electrical fire.

The cable penetration fire stop should have a fire rating equal to or greater than the required fire rating of the wall, floor, or ceiling. Modifications or additions of cables through the fire stop should not compromise the integrity of the fire stop.

7.2.2 Sleeve and Tray Penetrations. Where pressure integrity or liquid seals are required, conduit sleeves may be used with a fire-resistive sealant or a compound packed into the area between the cable and sleeve walls. A special example of this method is using a solid section of tray which is then filled with sealant. The sealant or compound should be compatible with the cable outer surface material.

Where penetrations are made into areas classified as NEC Class I Hazardous (Classified) Areas, explosion-proof fittings should be used. The void around the cable should be filled with a fire-resistive seal.

Cable penetration fire stops should be used where sleeve or tray penetrations are used beneath control boards or other panels.

7.3 Cable Fire Breaks. When cable does not meet the flame propagation characteristics of 2.3.5, cable fire breaks should be installed in the tray at intervals not exceeding 20 ft.

7.4 Cable System Enclosure. Consideration should be given to utilizing cable system enclosures when redundant or critical cables are routed through fire hazard areas.

7.5 Cable Coatings. Consideration should be given to applying flame-retardant coatings on all cables in open raceways that do not meet the flame propagation characteristics of 2.3.5.

7.6 Practices. For additional fire protection practices, see ANSI/IEEE Std 979-1984 [16].

8. Fire Detection Systems

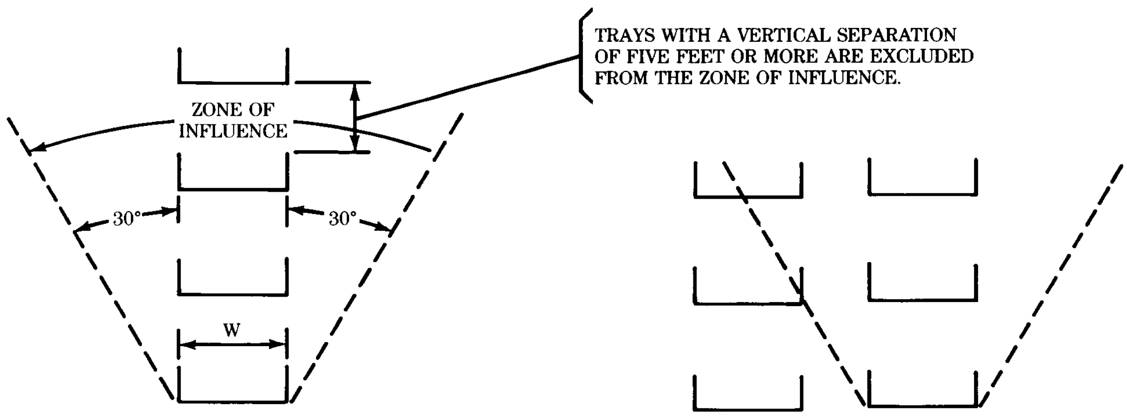
This section provides guidance or information for the selection of fire detection systems for cable systems.

8.1 Detection Systems. Automatic fire detection systems may be installed in areas of high cable concentration. One method of determining an area of high cable concentration is as follows:

An area of high cable concentration (actual or potential) exists for horizontal cable trays when more than 7-1/2 ft of total cable tray width exists in the zone of influence. The zone of influence is determined by extending lines from the bottom of the side rails of the lowest cable tray at a 30 degree angle from vertical (see Fig 8-1).

Fire detection systems may also be considered in areas of lesser cable concentration which provide vital service, or areas where, because of its location, a cable fire may go unnoticed for a relatively long period of time.

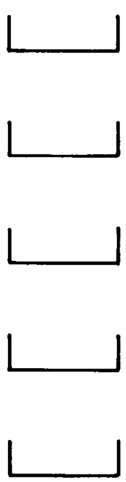
For additional information on heat, smoke, and fire detectors, see ANSI/IEEE Std 979-1984 [16].



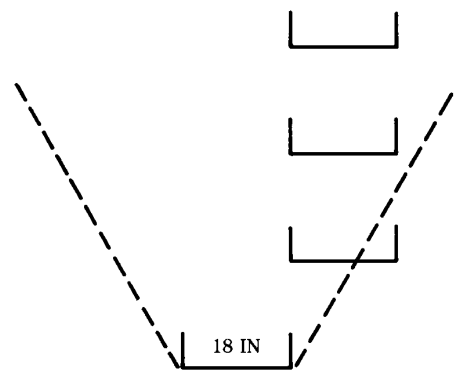
Determination of Zone of Influence

NOTES: (1) N · W ≤ 7½ ft - no protection.
(2) N · W > 7½ ft - protection suggested.
(3) N = number of trays within zone of influence.
(4) W = width of tray.

NOTES: (1) 5 · 18 in = 7½ ft - no protection.
(2) 5 · 24 in = 10 ft - protection suggested.
(3) Trays that are partially within the zone of influence are considered as being totally within the zone.



NOTES: (1) 5 · 18 in = 7½ ft - no protection.
(2) 5 · 24 in = 10 ft - protection suggested.



NOTES: (1) 18 in + 3(24 in) = 7½ ft - no protection.
(2) 18 in + 3(30 in) = 9 ft - protection suggested.

Fig 8-1
Determination of Potential High-Cable Concentration

9. Fire Extinguishing Systems

This section provides guidance for the selection and application of fire extinguishing systems protecting cable systems.

9.1 Fixed Fire Extinguishing System Application and Design. Fire extinguishing systems may be utilized for the protection of cable systems. Additional information may be found in ANSI/IEEE Std 979-1984 [16].

10. Installation and Handling

This section provides guidance for the construction methods, materials, and precautions in handling and installing cable systems.

10.1 Storage. Reels should be stored upright on their flanges and handled in such a manner as to prevent deterioration of or physical damage to the reel or to the cable. During storage, the ends of the cables should be sealed against the entrance of moisture or contamination. Reels should be stored on solid ground to prevent the flanges from sinking into the earth.

10.2 Installation.

(1) The cable manufacturers' recommended temperature limits should be followed when pulling or handling cables during extreme low temperatures. Handling or pulling cables in extremely low temperatures can cause damage to the cable sheathing, jacketing or insulation. To prevent damage of this nature, store cables in a heated building at least 24 h prior to installation.

Table 10-1 provides cable manufacturers' recommended low temperature limits for handling and pulling cables with various types of jackets or insulations.

Table 10-1
Low Temperature Limits for Cable Handling and Pulling

Cable Insulation or Jacket Material	Low Temperature Limits Celsius	Fahrenheit
EPR (Ethylene Propylene Rubber)	-40	-40
CPE (Chlorinated Polyethylene)	-35	-31
PVC (Polyvinyl Chloride)	-10	+14
CSPE (Chlorosulfonated Polyethylene)	-20	-4
Neoprene (Polychloroprene)	-20	-4
XLP (Cross-Linked Polyethylene)	-40	-40
Paper Insulated, Lead Sheathed	-12	+10

(2) Cable pulling lubricants should be compatible with cable outer surface and should not set up or harden during cable installation. The lubricant should not set up so as to prevent the cable from being pulled out of the conduit at a later time.

(3) Pulling winches and other necessary equipment should be of adequate capacity to ensure a steady continuous pull on the cable.

(4) Cable reels should be supported so that the cable may be unreeled and fed into the raceway without subjecting the cable to a reverse bend as it is pulled from the reel.

(5) A tension measuring device should be used on runs when pulling-force calculations indicate allowable stresses may be approached.

(6) Pulling tension will be increased when the cable is pulled off the reel. Turning the reel and feeding slack cable to the duct entrance will reduce the pulling tension.

(7) The direction of pulling has a large influence on the pulling tension in conduit runs containing bends. Whenever a choice is possible, the cable should be pulled so that the bend or bends are closest to the reel. The worst condition possible is to pull out of a bend at or near the end of the run.

(8) Sufficient cable slack should be left in each manhole and temporarily supported so that the cable can be trained to its final location on racks, hangers, or trays along the sides of the manhole. Cable splices should not be placed directly on racks or hangers.

(9) The use of single-roller or multi-roller cable sheaves of the proper radius should be used when installing cable around corners or obstructions.

(10) Guidance on conduit fill can be found in ANSI/NFPA 70-1987 [17].

(11) Cables should be identified by a permanent marker at each end, in accordance with the design documents.

(12) Careful consideration should be given not only to design engineering and material cost, but also to the installed cost for the initial as well as the ultimate installation. Maintenance and replacement costs also

should be considered. It is desirable that the system be designed so that additions and changes can be made with ease, economy, and minimum outages.

(13) If the cable manufacturers' recommended maximum pulling tension, sidewall pressure, or the minimum bending or training radius is violated, damage could occur to the cable conductor, insulation, shield, or jacket.

10.2.1 Protection of Cable

(1) Special care should be exercised during welding, soldering, and splicing operations to prevent damage to cables. If necessary, cables should be protected by fire-resistant material.

(2) After cable installation has started, trays and trenches should be periodically cleaned as necessary to prevent the accumulation of debris.

(3) A suitable feeder device should be used to protect and guide the cable from the cable reel into the raceway. The radius of the feeder devices should not be less than the minimum bending radius of the cable. If a feeder device is not used, the cable should be hand-guided into the raceway.

(4) Bare wire rope should not be used to pull cables in conduits.

(5) The ends of high-voltage power cables should be properly sealed during and after installation. The ends of all other cables should be properly sealed during and after installation in wet locations. Cables such as aluminum, mineral-insulated, paper, and varnished cambric should be resealed after pulling regardless of location.

If water has entered the cable, a vacuum should be pulled on the cable or the cable should be purged with nitrogen to extract the water.

(6) A swivel should be attached between the pulling eye and the pulling cable. Projections and sharp edges on pulling hardware should be taped or otherwise covered to protect against snagging at conduit joints and to prevent damage to conduit.

(7) Cable should be pulled only into clean raceways. A mandrel should be pulled through all underground ducts prior to cable pulling. Any abrasions or sharp edges which might damage the cable should be removed.

(8) Cables should be installed in raceway systems that have adequately sized bends, boxes, and fittings so that cable manufacturers' minimum allowable bending radii and sidewall pressures for cable installations are not violated. Guidance for the number of bends between pull points can be found in ANSI/NFPA 70-1987 [17].

(9) Pulling instructions for all cable should follow the cable manufacturers' recommendations.

(10) Cables should not be pulled around sharp corners or obstructions.

(11) The cable end within a pulling device should be removed from the cable prior to termination.

(12) After the cable pull is complete, cable manufacturers' recommendations for minimum training radii should be followed.

(13) Where single conductors are used in trays for two-wire or three-wire power circuits, these conductors should be securely bound in circuit groups to prevent excessive movements caused by fault-current magnetic forces and to minimize inductive heating effects in tray sidewalls and bottom.

10.2.2 Supporting Cables in Vertical Runs. The weight of a vertical cable should not be supported by the terminals to which it is connected. To prevent damage by deformation due to excessive bearing pressure or cable tension, vertically run cables should be supported by holding devices in the tray, in the ends of the conduit, or in boxes inserted at intervals in the conduit system.

Cables, regardless of their voltage class, installed in vertical runs should be supported in accordance with the following:

Maximum Distances Between Cable Supports

Conductor Sizes AWG or kcmil	Maximum Distance feet	meters
14 to 1/0	100	30
2/0 to 4/0	80	24
250 to 350	60	18
Over 350 to 500	50	15
Over 500 to 750	40	12
Over 750	35	10

Recommendations for supporting special cables such as armored, shielded, coaxial, etc, should be obtained from the cable manufacturer.

10.2.3 Securing Cables in Vertical Runs. Cable installed in vertical cables trays should be secured to the cable tray at least every 5 ft.

10.2.4 Training Cables. Cables installed in trays should be neatly trained to facilitate identification and removal and to maximize tray fill.

10.3 Cable Pulling Design Limits and Calculations. The following design limits and formulae provided in this section should be utilized when determining the maximum safe pulling lengths and tensions. Raceway fill, maximum sidewall pressure, jam ratio, and minimum bending radius are design limits which should be examined in designing a proper cable pull. These design limits are prerequisites needed in designing a cable raceway system. Once these limits are determined for a particular cable, the raceway system can then be designed. If the system has already been designed, modifications may be required in order to pull the cable without damage.

Conduit and duct system design should consider the maximum pulling lengths of cable to be installed. The maximum pulling length of a cable or cables is determined by the maximum allowable pulling tension and sidewall pressure. The pulling length will be limited by one of these factors.

Pull points or manholes should be installed wherever calculations show that expected pulling tensions exceed either maximum allowable pulling tension or sidewall pressure.

A sample calculation for determining cable pulling tensions is shown in Appendix A.

10.3.1 Design Limits

10.3.1.1 Raceway Fill and Determining Raceway Sizes. Raceways should be adequately sized as determined by the maximum recommended percentage fill of the raceway area. Raceway fill is based on the following equation:

$$\%\ \text{Fill} = \frac{\Sigma\ \text{Cable Area}}{\text{Raceway Area}} \times 100\% \qquad \text{(Eq 1)}$$

Raceway fill limitations are given in the National Electrical Code, ANSI/NFPA 70-1987 [17]. If the fill limitations and cable area are known, the raceway area can be calculated and an adequate size can be selected.

10.3.1.2 Maximum Allowable Pulling Tension. The maximum allowable pulling tension should be determined from the following formula, unless otherwise indicated by the cable manufacturer.

Based on a pull on the conductor or by a device attached to the conductor

$$T_{max} = K \times N \times \text{cmil} \qquad \text{(Eq 2)}$$

where

T_{max} = maximum allowable pulling tension, in pounds
cmil = circular mil area of each conductor
K = 0.008 lb/cmil for annealed copper and hard aluminum
K = 0.006 lb/cmil for ¾ hard aluminum
N = number of conductors

In pulling three single conductors of equal size in parallel, triangular or cradled configuration, a value of N equal to 2 should be used since two of the conductors may sustain the total pulling tension. When more than three single conductors of equal size are pulled in parallel, the maximum tension should be limited to 60% of the value determined by the equation.

When pulling conductors of different sizes, consult the cable manufacturer(s).

When pulling using a pulling eye, the maximum tension for a single-conductor cable should not exceed 5000 lbs, and the maximum tension for two or more conductors should not exceed 6000 lbs. The cable manufacturer should be consulted when tensions exceeding these limits are expected.

Based on pull by basket grip applied over nonleaded jacketed cable

$$T_{max} = 1000\ \text{lb} \qquad \text{(Eq 3)}$$

When using a basket-weave type pulling grip applied over a lead-sheathed cable, the force should not exceed 1500 lb as determined by the following formula:

$$T_{max} = K_m \pi t\,(D - t) \qquad \text{(Eq 4)}$$

where

t = lead sheath thickness, in inches
D = outside diameter of lead sheath, in inches
K_m = maximum allowable pulling stress in pounds per square inch (1500 psi to 2000 psi depending on lead alloy).

NOTE: For lead-sheathed cables with neoprene jackets, T_{max} equals 1000 lb.

When using a pulling grip, the maximum pulling tension should not exceed the smaller of the values calculated above.

Pulling instructions for coaxial, triaxial, and other special cables should follow the manufacturers' recommendations.

10.3.1.3 Maximum Allowable Sidewall Pressure. Sidewall pressure, P, is defined as the tension out of a bend expressed in pounds divided by the radius of the bend expressed in feet. The sidewall pressure on a cable can be calculated by the following equations:

$$P = \frac{T_o}{r} \quad \text{Single cable in conduit.} \qquad \text{(Eq 5)}$$

$$P = \frac{(3c - 2)\,T_o}{3r} \quad \text{Three cables in cradle configuration where the center cable presses hardest against the conduit.} \qquad \text{(Eq 6)}$$

$$P = \frac{c\,T_o}{2r} \quad \text{Three cables in triangular configuration where the pressure is divided between the two bottom cables.} \qquad \text{(Eq 7)}$$

$$P = \frac{(c - 1)\,T_o}{2r} \quad \text{Four cables in diamond configuration where the bottom cable is subjected to the greatest crushing force.} \qquad \text{(Eq 8)}$$

where

- P = sidewall pressure, in lbs/ft of radius
- T_o = tension out of the bend, in lbs
- c = weight correction factor (refer to 10.3.2.1)
- r = inside radius of bend, in feet

Equations (6), (7), and (8) calculate the sidewall pressure for the worst case cable.

The maximum allowable sidewall pressure is 500 lb per ft of radius for multiconductor power and control cables and single-conductor power cables #6 AWG and larger, subject to verification by the cable manufacturer. The recommended maximum allowable sidewall pressure for single-conductor power cable #8 AWG and smaller is 300 lb per ft of radius subject to verification by the cable manufacturer. For instrumentation cable, the cable manufacturer's recommendations should be obtained.

10.3.1.4 Jam Ratio. Jamming is the wedging of cables in a conduit when 3 cables lay side-by-side in the same plane. Jam ratio is defined for three cables of equal diameter as the ratio of the conduit inside diameter (D) to the cable outside diameter (d). The jam ratio is a concern because jamming in the conduit could cause damage to one or more of the cables. The possibility of jamming is greater when the cables change direction. Therefore, the inside diameter of the conduit at the bend is used in determining the jam ratio.

$$\text{Jamming cannot occur when } \frac{D}{d} > 3.0 \qquad \text{(Eq 9)}$$

$$\text{Jamming is not likely when } \frac{D}{d} < 2.8 \qquad \text{(Eq 10)}$$

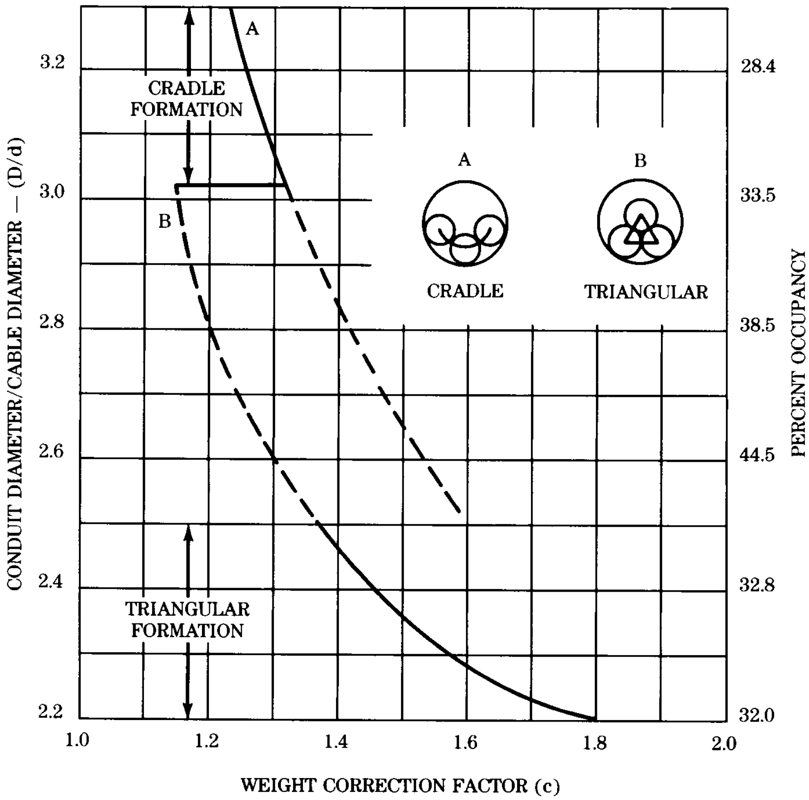
$$\text{Jamming is probable when } 2.8 \leq \frac{D}{d} \leq 3.0 \qquad \text{(Eq 11)}$$

A 40% conduit fill gives a jam ratio of 2.74, which is in the region where jamming is not likely. The inside diameter of a field bent conduit is usually increased by 5% to account for the oval cross-section which occurs. Adding 5% for a field bent conduit yields a jam ratio of 2.87, which is in the region where jamming is probable.

10.3.1.5 Minimum Bending Radius. The minimum bending radius is the minimum radius a cable can be bent to while under a pulling tension, providing the maximum sidewall pressure is not exceeded. The values given are usually stated as a multiple of cable diameter and are a function of the cable diameter, and whether the cable is nonshielded, shielded, armored, or single or multiple conductor. Guidance for minimum bending radii can be obtained from the National Electrical Code ANSI/NFPA 70-1987 [17] or the cable manufacturer.

10.3.2 Cable Pulling Calculations. The equations used to calculate the expected cable pulling tension are based on the number of cables to be pulled, the type of raceway, the cable configuration in the raceway and the raceway layout.

10.3.2.1 Straight Sections of Conduit or Duct. For a straight section of conduit or duct,



NOTES: (1) Curve "A" is for cradle formation.
(2) Curve "B" is for triangular formation.
(3) Curve "B" usually joins curve "A" at point shown.
(4) Dotted portion shows where both formations can exist.

Fig 10-1
Weight Correction Factor (c)

the pulling tension is equal to the length of the straight run multiplied by the weight per foot of cable, the coefficient of friction and the weight correction factor.

$$T = L w f c \qquad \text{(Eq 12)}$$

where

T = total pulling tension of straight run, in lbs
L = length of the straight run, in ft
w = weight of the cable(s), in lbs/ft
f = coefficient of friction
c = weight correction factor

The coefficient of friction is usually assumed to be as follows:

Dry cable or ducts	0.5
Well lubricated cable and ducts	0.35

The weight correction factor takes into account the added frictional forces that exist between triangular or cradle arranged cables resulting in a greater pulling tension than when pulling a single cable. The weight correction factor can be calculated by the following equations:

$$c = 1 + 4/3 \left(\frac{d}{D-d}\right)^2 \qquad \text{Three single cables in cradled configuration} \qquad \text{(Eq 13)}$$

$$c = \frac{1}{\sqrt{1 - \left(\frac{d}{D-d}\right)^2}} \qquad \text{Three single cables in triangular configuration} \qquad \text{(Eq 14)}$$

$$c = 1 + 2 \left(\frac{d}{D-d}\right)^2 \qquad \text{Four single cables in diamond configuration} \qquad \text{(Eq 15)}$$

where

D = conduit inside diameter
d = single conductor cable outside diameter

The weight correction factor for three single-conductor cables can be determined from Fig 10-1.

10.3.2.2 Inclined Sections of Raceway. The expected pulling tension of a cable in an inclined section of duct may be calculated from the following formulae:

$$T_{up} = w\,L\,(cf \cos \alpha + \sin \alpha) \qquad \text{(Eq 16)}$$

$$T_{down} = w\,L\,(cf \cos \alpha - \sin \alpha) \qquad \text{(Eq 17)}$$

where

α is the angle of the incline from horizontal

10.3.2.3 Horizontal and Vertical Bends. The tension out of a horizontal or vertical conduit bend is normally calculated from the following approximate formula:

$$T_{out} = T_{in} e^{cf\theta} \qquad \text{(Eq 18)}$$

where

T_{out} = tension out of bend, in lbs
T_{in} = tension into the bend, in lbs
θ = angle of the change in direction produced by bend, in radians

This is a simplified equation which ignores the weight of the cable. It is very accurate where the incoming tension at a bend is equal to or greater than 10 times the product of cable weight per foot times the bend radius (10 w r) expressed in feet. If the tension into a bend is less than 10 w r, the exact equations can be found in reference [B42]. Cases in which the exact equations may become necessary are where light tensions enter large radii bends. Usually equation (18) is precise enough for normal installations.

11. Acceptance Testing of Installed Cables

This section provides guidance for the testing of cables after installation, but before their connection to equipment, and includes cable terminations, connectors, and splices.

11.1 Purpose. The purpose of these tests is to verify that major cable insulation damage did not occur during storage and installation and that the cable was properly spliced and terminated. It should be noted, however, that these tests may not detect damage that may eventually lead to cable failure in service, for example, damage to the cable jacket or insulation shield on high-voltage cable, or to low-voltage cable insulation.

11.2 Tests. Safety precautions should be observed during all phases of testing. Cable ends should be properly cleaned of all conducting material. Cable test results, environmental conditions, and data should be recorded and filed for maintenance reference. The following tests should be performed, as applicable, in conjunction with the cable manufacturer's recommendations:

(1) Low-voltage power, control, and instrumentation cables should be either insulation-resistance tested prior to connecting cables to equipment or functionally tested (at equipment operation voltage) as part of the checkout of the equipment system.

(2) The low-voltage power cable insulation resistance tests should measure the insulation resistance between any possible combination of conductors in the same cable and between each conductor and station ground, with all other conductors in the same cable grounded.

The test voltage should be a minimum of 500 V dc. The minimum acceptable insulation resistance is:

R in megohms = (rated voltage in kV + 1) x 1000/length in feet

(3) Testing of control cable and prefabricated cable assemblies in a similar manner is suggested. Cable manufacturers' recommendations should always be considered.

(4) Shielded high-voltage power cables should be dc high-potential tested in accordance with ICEA, ANSI/IEEE Std 400-1980 (R 1987) [9], or AEIC standards prior to equipment connection. Unshielded high-voltage cables should not be subjected to high-voltage dc tests; insulation resistance tests are suggested.

(5) Instrumentation cables should be subjected to insulation resistance measurements if circuit performance is dependent upon insulation resistance. Cable

manufacturers' testing recommendations should always be considered.

12. Raceways

This section provides guidance for both a means of supporting cable runs between electrical equipment and physical protection to the cables. Raceway systems consist primarily of cable tray and conduit.

12.1 Definitions. NEMA TC2-1983 [26], NEMA TC6-1983 [27].

ABS. Conduit fabricated from acrylonitrile-butadiene-styrene.

EMT. Electrical metallic tubing.

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

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

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

FRE. Conduit fabricated from fiberglass reinforced epoxy.

IMC. Intermediate metal conduit.

PE. Conduit fabricated from polyethylene.

PVC. Conduit fabricated from polyvinyl chloride.

RMC. Rigid metal conduit.

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

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

Applications:

Type I. Designed to be encased in concrete.

Type II. Designed for underground installation without encasement in concrete.

Type III. Designed for normal-duty applications above grade.

Type IV. Designed for heavy-duty applications above grade.

12.2 Conduit

12.2.1 Conduit Application

(1) RMC or IMC zinc-coated conduit may be used exposed in wet and dry locations, embedded in concrete, and directly buried in soil. If they are installed directly buried in soil, consideration should be given to the zinc coating having a limited life, and corrosion may be rapid after the zinc coating is consumed or damaged.

When used in cinder fills, the conduit should be protected by noncinder concrete at least 2 in thick. When used where excessive alkaline conditions exist, the conduit should be protected by a coat of bituminous paint or similar material. PVC-coated steel conduit may be used in corrosive environments. Plugs should be used to seal spare conduits in wet locations.

(2) EPC-40 or EPC-80 conduit may be used exposed. EPT and Type EB duct must be encased in concrete, and Type DB duct may be direct buried without concrete encasement.

Since ABS and PVC conduit may have different properties, a review should be made of their brittleness and impact strength characteristics. Coefficient of expansion should also be considered for outdoor applications. Flammability of such conduits is of particular concern in indoor exposed locations. Burning or excessive heating of PVC in the presence of moisture may result in the formation of hydrochloric acid which can attack reinforcing steel, deposit chlorides on stainless steel surfaces, or attack electrical contact surfaces. The use of exposed PVC conduit indoors should generally be avoided, but may be considered for limited use in corrosive environments.

(3) EMT may be used in dry accessible locations to perform the same functions as RMC conduit except in hazardous areas (as defined by NEC).

(4) Aluminum conduit (Alloy 6061), plastic-coated steel conduit, Type DB PVC or ABS duct, EPC-40 or EPC-80 PVC conduit and Type FRE conduit may be used in areas

where a high corrosive environment may exist and for other applications where uncoated steel conduit would not be suitable. Aluminum conduit may be used exposed in wet and dry locations. Aluminum conduit should not be embedded in concrete or directly buried in soil unless coated (bitumastic compound, etc) to prevent corrosion. Aluminum conduit may be used, exposed or concealed, where a strong magnetic field exists; however, conduit supports should not form a magnetic circuit around the conduit if all the cables of the electrical circuit are not in the same conduit.

(5) The cable system should be compatible with drainage systems for surface water, oil, or other fluids, but preferably should be installed to avoid accumulated fluids.

(6) The cable system should be capable of operating in conditions of water immersion, ambient temperatures, and limited concentrations of chemicals. Protection should be provided against attack by insects, rodents, or other indigenous animals.

(7) Cable trays, conduits, and troughs are sometimes run above grade in substations, supported from equipment structures or specially designed ground-mounted structures. Troughs constructed of concrete or other material may be laid on the grade. Cost savings may be realized when comparing above grade trays, conduit and troughs to similar below-grade systems.

Care should be taken in routing above grade systems to minimize interference with traffic and equipment access, and to avoid a reduction in minimum electrical clearances.

These systems are more vulnerable to fires, mechanical damage, environmental elements, and seismic forces, and offer greater susceptibility to electrostatic and electromagnetic coupling than if the cables were below grade.

(8) Above ground pull boxes are sometimes used for distribution panels and for common connections such as current or potential leads. The judicious location of these boxes may result in considerable savings.

12.2.2 Conduit System Design

12.2.2.1 Exposed Conduit

(1) Flexible conduit should be used between rigid conduit and equipment connection boxes where vibration or settling is anticipated or where the use of rigid conduit is not practical. Liquid-tight flexible conduit is commonly used for this application. Flexible conduit length should be as short as practical, but consistent with its own minimum bending radius, the minimum bending radius of the cable to be installed, and the relative motion expected between connection points. A separate ground wire should be installed if the flexible conduit is not part of the grounding and bonding system. See ANSI/NFPA 70-1987 [17] for additional guidance.

(2) Where it is possible for water or other liquids to enter conduits, sloping of conduit runs and drainage of low points should be provided.

(3) Electrical equipment enclosures should have conduit installed in a manner to prevent the entrance of water and condensation. Drain fittings and air vents in the equipment enclosure should also be considered. Expansion couplings should be installed in the conduit run or at the enclosure to prevent damage caused by frost heaving or expansion.

(4) The entire metallic conduit system, whether rigid or flexible, should be electrically continuous and grounded.

(5) When installed in conduit of magnetic material, all phases of three-phase ac circuits and both legs of single-phase ac circuits should be installed in the same conduit or sleeve.

(6) All conduit systems should have suitable pull points (pull boxes, manholes, etc) to avoid over-tensioning the cable during installation.

12.2.2.2 Embedded Conduits and Manholes

(1) Spacing of embedded conduits should permit fittings to be installed.

(2) Conduit in duct runs containing one phase of a three-phase power circuit or one leg of a single-phase power circuit should not be supported by reinforcing steel forming closed magnetic paths around individual conduits. Reinforcing steel in the manhole walls should not form closed loops around individual nonmetallic conduit entering the manhole. Nonmetallic spacers should be used.

(3) Concrete curbs or other means of protection should be provided where other

than RS conduits turn upward out of floor slabs.

(4) The lower surface of concrete-encased duct banks should be located below the frost line. Where this is not practical, lean concrete or porous fill can be used between the frost line and the duct bank.

(5) Concrete-encased duct banks should be adequately reinforced under roads and in areas where heavy equipment may be moved over the duct bank.

(6) Directly buried nonmetallic conduits should not be installed under roadways or in areas where heavy equipment may be moved over them unless the conduits are made from resilient compounds suitable for this service or are protected structurally.

(7) Conduits in duct banks should be sloped downward toward manholes or drain points.

(8) Duct lengths should not exceed those which will develop pulling tensions or sidewall pressures in excess of those allowed by the cable manufacturers' recommendations.

(9) Manholes should be oriented to minimize bends in duct banks.

(10) Manholes should have a sump, if necessary, to facilitate the use of a pump.

(11) Manholes should be provided with means for attachment of cable-pulling devices to facilitate pulling cables out of conduits in a straight line.

(12) Provisions should be made to facilitate racking of cables along the walls of the manhole.

(13) Exposed metal in manholes, such as conduits, racks, and ladders, should be grounded.

(14) End bells should be provided where conduits enter manholes or building walls.

(15) Manholes and manhole openings should be sized so that the cable manufacturers' minimum allowable cable bending radii are not violated.

(16) When installed in conduit of magnetic material, all phases of three-phase ac circuits and both legs of single-phase ac circuits should be installed in the same conduit or sleeve.

12.2.3 Conduit Installation

(1) Supports of exposed conduits should follow NEC recommendations or industry standards.

(2) When embedded in concrete, installed indoors in wet areas, and in all outdoor locations, threaded conduit joints and connections should be made watertight and rustproof by means of the application of a conductive thread compound which will not insulate the joint. Each threaded joint should be cleaned to remove all of the cutting oil before the compound is applied. The compound should be applied only to the male conduit threads to prevent obstruction.

(3) Running threads should not be utilized, and welding of conduits should not be done.

(4) Field bends should not be of lesser radius than suggested by ANSI/NFPA 70-1987 [17], and should show no appreciable flattening of the conduit.

(5) Large radius bends should be used to reduce the cable sidewall pressure during cable installation and in conduit runs when the bending radius of the cable to be contained in the conduit exceeds the radius of standard bends.

(6) Conduits installed in concrete should have their ends plugged or capped before the concrete is poured.

(7) All conduit interiors should be free of burrs and should be cleaned after installation.

(8) Exposed conduit should be marked in a distinct permanent manner at each end and at points of entry to and exit from enclosed areas.

(9) Flexible conduit connections should be used for all motor terminal boxes and other equipment which is subject to vibration. The connections should be of minimum lengths and should employ at least the minimum bending radii established by the cable manufacturer.

(10) Conduit should not be installed in close proximity to hot pipes or other heat sources.

(11) Proper fittings should be used at conduit ends to prevent cable damage.

(12) Conduits should be installed so as to prevent damage to the cable system from the movement of vehicles and equipment.

(13) Conduit entrances to control buildings should be provided with barriers against rodents and fire.

12.3 Cable Tray

12.3.1 Tray Design

(1) Cable tray design should be based upon the required loading and the maximum spacing between supports. Loading calculations should include the static weight of cables and a concentrated load of 200 lb at midspan. The tray load factor (safety factor) should be at least 1.5 based on collapse of the tray when supported as a simple beam NEMA VE 1-1984 [28].

(2) When ladder-type tray is specified, rung spacing should be a nominal 9 in. For horizontal elbows, rung spacing should be maintained at the centerline.

(3) Design should minimize the possibility of the accumulation of fluids and debris on covers or in trays.

12.3.2 Tray System Design

(1) In general, vertical spacing for cable trays should be 12 in, measured from the bottom of the upper tray to the top of the lower tray. A minimum clearance of 9 in should be maintained between the top of a tray and beams, piping, etc, to facilitate installation of cables in the tray.

(2) Cables installed in stacked cable trays should be arranged by descending voltage levels, with the higher voltage at the top.

(3) When stacking trays, the structural integrity of components and the pullout values of support anchors and attachments should be verified.

(4) Provisions for horizontal and vertical separation of redundant system circuits are described in Section 5.

12.3.3 Tray Application. The usual materials from which tray is fabricated are aluminum, galvanized steel, and fiberglass. In selecting material for trays, the following should be considered:

(1) Galvanized tray will corrode in locations such as outdoors near the ocean or immediately adjacent to a cooling tower where the tray is continuously wetted by chemically treated water. If aluminum tray is used for such applications, a corrosive-resistant type should be specified. Special coatings for steel tray may also serve as satisfactory protection against corrosion. The use of nonmetallic tray should also be considered for such applications.

(2) For cable trays and tray supports located outdoors, the effect of the elements on both the structure and the trays should be considered. Ice, snow, and wind loadings must be added to loads described in 12.3.4. Aluminum Alloys 6061-T6, 6063-T6, and 5052-M34 are acceptable, with careful recognition of the differences in strength. Mill-galvanized steel should normally be used only for indoor applications in noncorrosive environments. Hot-dipped galvanized-after-fabrication steel should be used for outdoor and damp locations.

(3) When the galvanized surface on the steel tray is broken, the area should be coated to protect against corrosion.

(4) Consideration should be given to the relative structural integrity of aluminum versus steel tray during a fire.

12.3.4 Tray Load Capacity

(1) The quantity of cable installed in any tray may be limited by the structural capacity of the tray and its supports. Tray load capacity is defined as the allowable weight of wires and cables carried by the tray. This value is independent of the dead load of the tray system. In addition to and concurrent with the tray load capacity and the dead load of the tray system, any tray should neither fail nor be permanently distorted by a concentrated load of 200 lb at midspan at the centerline of the tray or on either side rail.

(2) A percentage fill limit is needed for randomly filled trays, because cables are not laid in neat rows and secured in place. This results in cable crossing and void areas, which take up much of the tray cross-sectional area. Generally, a 30% to 40% fill for power and control cables and a 40% to 50% fill for instrumentation cables is suggested. This will result in a tray loading in which no cables will be installed above the top of the side rails of the cable tray, except as necessary at intersections and where cables enter or exit the cable tray systems.

(3) The quantity of cables in any tray may be limited by the capacity of the cables at the bottom of the tray to withstand the bearing load imposed by cables located adjacent and above. This restraint is generally applicable to instrumentation cables, but may also apply to power and control cables.

12.3.5 Cable Tray Installation

12.3.5.1 Dropouts

(1) Drop-out fittings should be provided

where required to maintain the minimum cable training radius.

(2) Where conduit is attached to the tray to carry exiting cable, the conduit should be rigidly clamped to the side rail. When conduit is rigidly clamped, consideration should be given to the forces at the connection during dynamic (seismic) loading of the tray and conduit system. Conduit connections through the tray bottom or side rail should be avoided.

12.3.5.2 Covers

(1) Horizontal trays exposed to falling objects or to the accumulation of debris should have covers.

(2) Covers should be provided on exposed vertical tray risers at floor levels and other locations where possible physical damage to the cables could occur.

(3) Where covers are used on trays containing power cables, consideration should be given to ventilation requirements and cable ampacity derating.

12.3.5.3 Grounding. Cable tray systems should be electrically continuous and solidly grounded. When cable trays are used as raceways for solidly grounded or low-impedance grounded power systems, consideration should be given to the tray system ampacity as a conductor. Inadequate ampacity or discontinuities in the tray system may require that a ground conductor be attached to and run parallel with the tray or a ground strap be added across the discontinuities or expansion fittings. The ground conductor may be either bare, coated, or insulated, depending upon metallic compatibility.

12.3.5.4 Identification. Cable tray sections should be permanently identified with the tray section number as required by the drawings or construction specifications.

12.3.5.5 Supports. The type and spacing of cable tray supports will depend on the loads. Tray sections should be supported near section ends and at fittings such as tees, crosses, and elbows NEMA VE1-1984 [28].

12.3.5.6 Location. Trays should not be installed in close proximity to heating pipes and other heat sources.

12.4 Wireways. Wireways are generally sheet metal troughs with hinged or removable covers for housing and protecting wires and cables. Wireways are for exposed installations only and should not be used in hazardous areas. Consideration should be given to the wireway material where corrosive vapors exist. In outdoor locations, wireways should be of raintight construction. The sum of the cross-sectional areas of all conductors should not exceed 40% of the interior cross-sectional area of the wireway. Taps from wireways should be made with rigid, intermediate metal, electrical metallic tubing, flexible-metal conduit, or armored cable.

13. Direct Burial, Tunnels, and Trenches

This section provides guidance for the installation of cables that are direct buried or installed in permanent tunnels or trenches.

13.1 Direct Burial. Direct burial of cables is a method whereby cables are laid in an excavation in the earth with cables branching off to various pieces of equipment. The excavation is then backfilled.

A layer of sand is usually installed below and above the cables to prevent mechanical damage. Care must be exercised in backfilling to avoid large or sharp rocks, cinders, slag, or other harmful materials.

A warning system to prevent accidental damage during excavation is advisable. Several methods used are treated wood planks, a thin layer of colored lean concrete, a layer of sand, strips of plastic, and markers above ground. Untreated wood planks may attract termites, but overtreatment may result in leaching of chemicals harmful to the cables.

Spare cables or empty capped ducts for future cables may be installed before backfilling.

This system has low initial cost, but does not lend itself to changes or additions, and provides limited protection against the environment. Damage to cables is more difficult to locate and repair in a direct burial system than in a permanent trench system.

13.2 Cable Tunnels. Walk-through cable tunnels can be used where there will be a large number of cables.

This system has the advantages of minimum interference to traffic and drainage, good physical protection, ease of adding cables, shielding effect of the ground mat, and the capacity for a large number of cables.

Disadvantages include high first cost and danger that fire could propagate between cable trays and along the length of the tunnel. If fire stops are provided, hazards can be minimized.

13.3 Permanent Trenches. Trench systems consist of main runs located to bring large groups of cables through the centers of equipment groups, with short runs of conduit, smaller trenches, or direct-burial cable branching off to individual pieces of equipment.

Duct entrances may be made at the bottom of open-bottom trenches or through knockouts in the sides of solid trenches.

Trenches may be made of cast-in-place concrete, bituminized fiber pipes, or precast material.

Where trenches interfere with traffic in the substation, vehicle crossovers, permanent or temporary, may be provided as needed. Warning posts or signs may be used to warn vehicular traffic of the presence of trenches.

The trenches may interfere with surface drainage and can be sloped to storm sewers, sump pits, or French drains. Open-bottom trenches may dissipate drainage water but are vulnerable to rodents. A layer of sand applied around the cables in the trench may protect the cables from damage by rodents. Trenches at cable entrances into control buildings should be sloped away from the building for drainage purposes. The trenches also should have a barrier to prevent fire or rodents from entering the control building.

The tops of the trench walls may be used to support hangers for grounded shield conductors. The covers of trenches may be used for walkways. Consideration should be given to grounding metal walkways and also to providing safety clearance above raised walkways. Added concern should be given to the flammability of wood.

13.3.1 Floor Trenches. Trenches cast into concrete floors may be extensive, with trenches run wherever required; or a few trenches may be run under the switchboards, with conduits branching to various pieces of equipment.

Removable covers may be made of metal, plywood, or other materials. Nonmetallic cover materials should be fire retardant. Trenches cast into concrete floors should be covered. It should be noted that metal covers in the rear of switchboards present a handling hazard; and nonmetallic, fire-retardant material should be used.

Where cables pass through holes cut in covers, for example, in rear or inside of switchboards, the edges should be covered to prevent cable damage from sharp edges.

13.3.2 Raised Floors. Raised floors provide maximum flexibility for additions or changes. Entrance from the outside into the raised floor system may be made at any point along the control house wall.

Use of a fire protection system under the floor should be considered.

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Appendix

(This Appendix is not a part of ANSI/IEEE Std 525-1987, IEEE Guide for the Design and Installation of Cable Systems in Substations.)

Appendix A
Sample Calculation for Cable Pulling Tension

This Appendix is intended to illustrate the calculations required to determine cable pulling tensions in a typical run from a manhole to a riser pole. The typical duct run used for the calculations is shown in Fig Al.

The cable to be used in this example installation is 3-1/c 750 kcmil triplexed aluminum cable with 1/3 concentric neutral. The completed weight of this cable is 5.375 lb/ft and the outside diameter (OD) for each conductor is 1.61 in. Plastic conduit suitable for direct burial (Type DB) is to be used for this example installation.

Al. Conduit Fill and Jam Ratio

In determining the size of conduit required, consideration should be given to conduit fill and jam ratio. Using equation (1) of this guide, the % fill is

$$\%\ \text{Fill} = \frac{\Sigma\ \text{Cable Area}}{\text{Raceway Area}} \times 100\%$$

Using 4 in conduit (with an internal diameter of 4.026 in),

$$\%\ \text{Fill} = \frac{3\pi\left(\frac{1.61}{2}\right)^2}{\pi\left(\frac{4.026}{2}\right)^2} \times 100 = 47.98\%$$

Since 47.98% exceeds the maximum allowable fill of 40% by ANSI/NFPA 70-1987 [17], the % fill should be calculated for the next larger size conduit, 5 in.

$$\%\ \text{Fill} = \frac{3\pi\left(\frac{1.61}{2}\right)^2}{\pi\left(\frac{5.047}{2}\right)^2} \times 100 = 30.5\%$$

This is an acceptable fill.

The jam ratio as discussed in 10.3.1.4 of this guide should be calculated next. Assuming field bending of the conduit,

$$\text{Jam Ratio} = \frac{1.05D}{d}$$

where

D = conduit inside diameter
d = single conductor cable outside diameter

$$\text{Jam Ratio} = \frac{1.05\ (5.047)}{1.61} = 3.29$$

Jamming cannot occur based on equation (9) of this guide. Also, where triplexed cable is used, jamming is not a problem since jamming is the wedging of cables in a conduit when three cables lay side by side in the same plane.

A2. Maximum Allowable Pulling Tension

The maximum allowable pulling tension for this example cable is calculated by using equation (2) of this guide.

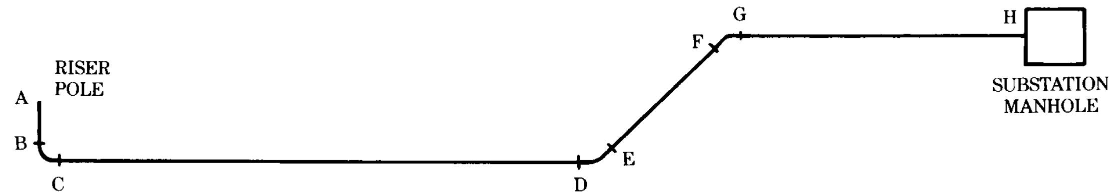
$$T_{max} = K \times N \times \text{cmil}$$

$$T_{max} = (0.006)(3)(750\,000) = 13\,500\ \text{lb}$$

However, as indicated in 10.3.1.2 of this guide, the maximum tension for two or more conductors should not exceed 6000 lb, when pulling using a pulling eye.

A3. Minimum Bending Radius

The minimum bending radius in accordance with ANSI/NFPA 70-1987 [17] for the example cable is 12 times the overall



A-B = 10 ft. Vertical Rise
B-C = 90°, 4 ft. Inside Radius Vertical Curve
C-D = 500 ft
D-E = 45°, 12.5 ft. Inside Radius Horizontal Curve
E-F = 100 ft
F-G = 45°, 12.5 ft. Inside Radius Horizontal Curve
G-H = 200 ft

Fig A1
Duct Layout for Example Calculations

diameter of the cable. The cabling factor for three conductors triplexed is 2.155.

Minimum Bending Radius =
(12)(2.155)(1.61) = 41.6 in

A4. Pulling Tension

The pulling tensions for the example are calculated using equation (12) for straight runs and equation (18) for vertical or horizontal bends.

Pulling from A to H

Since pulling down the vertical section A-B and around the curve B-C would require a negligible tension, the calculations are started at C.

$$T_D = Lwfc$$

where

L = length of straight run, in feet
w = weight of cable, in lbs/ft
f = coefficient of friction
c = weight correction factor

The weight correction factor (c) for three single cables in a triangular configuration is calculated using equation (14) of this guide.

$$c = \frac{1}{\sqrt{1 - \left(\frac{d}{D-d}\right)^2}}$$

$$c = \frac{1}{\sqrt{1 - \left(\frac{1.61}{(5.047 - 1.61)}\right)^2}}$$

$$c = 1.13$$

Therefore, assuming a dry cable or duct with a coefficient of friction of 0.5,

$$T_D = (500)(5.375)(0.5)(1.13) = 1518 \text{ lbs}$$
$$T_E = T_D e^{cf\theta}$$

where

θ = Angle of the change in direction produced by bend in radians.

NOTE: Conversion factor from degrees to radians is 0.01745.

$$T_E = 1518\ e^{(1.13)(0.5)(45)(0.01745)}$$
$$T_E = 1518\ e^{0.4437}$$
$$T_E = 2366 \text{ lbs}$$
$$T_F = T_E + (100)(5.375)(0.5)(1.13)$$

T_F = 2366 + 304
T_F = 2670 lbs
T_G = $T_F e^{cf\theta}$
T_G = 2670 $e^{(1.13)(0.5)(45)(0.01745)}$
T_G = 2670 $e^{0.4437}$
T_G = 4161 lbs
T_H = T_G + (200)(5.375)(0.5)(1.13)
T_H = 4161 + 607
T_H = 4768 lbs

This is within the maximum allowable tension of 6000 lb. However, the maximum sidewall pressure of 500 lb/ft should also be checked. The maximum sidewall pressure for this pull will occur at curve F-G and is calculated using equation (7) of this guide.

$$P = \frac{cT_o}{2r}$$

where

P = sidewall pressure, in lbs/ft of radius
c = weight correction factor
T_o = tension out of the bend, in lbs
r = inside radius of bend, in ft

$$P = \frac{(1.13)(4161)}{(2)(12.5)}$$

P = 188 lbs/ft

This is acceptable.

Pulling from H to A

T_G = Lwfc
T_G = (200)(5.375)(0.5)(1.13)
T_G = 607 lbs
T_F = $T_G e^{cf\theta}$
T_F = 607 $e^{(1.13)(0.5)(45)(0.01745)}$
T_F = 607 $e^{0.4437}$
T_F = 946 lbs
T_E = T_F + (100)(5.375)(0.5)(1.13)
T_E = 946 + 304
T_E = 1250 lbs
T_D = 1250 $e^{cf\theta}$
T_D = 1250 $e^{(1.13)(0.5)(45)(0.01745)}$
T_D = 1250 $e^{0.4437}$
T_D = 1948 lbs
T_C = T_D + (500)(5.375)(0.5)(1.13)
T_C = 1948 + 1518
T_C = 3466 lbs
T_B = 3466 $e^{cf\theta}$
T_B = 3466 $e^{(1.13)(0.5)(90)(0.01745)}$
T_B = 3466 $e^{0.8873}$
T_B = 8417 lbs

This tension exceeds the maximum allowable tension of 6000 lbs. Therefore, a cable pull from H to A should not be permitted. The cable should be pulled from A to H. The let-off reel should be at the riser pole and the cable should be pulled toward the manhole, in order not to exceed the maximum allowable pulling tension or sidewall pressure.