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IEEE Guide for the Application of Metal-Oxide Surge Arresters for Alternating-Current Systems

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IEEE Guide for the Application of Metal-Oxide Surge Arresters for Alternating-Current Systems

Sponsor

Surge-Protective Devices Committee
of the
IEEE Power Engineering Society

Approved December 5, 1991

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Abstract: The application of metal-oxide surge arresters to safeguard electric power equipment against the hazards of abnormally high voltage surges of various origins is covered. Step-by-step directions toward proper solutions for various applications are provided. In many cases, the prescribed steps are adequate. More complex and special situations requiring study by experienced engineers are described, but specific solutions are not always given. The procedures are based on theoretical studies, test results, and experience.

Keywords: electric power equipment, high-voltage surges, metal-oxide surge arresters, surge arresters, surge-protective devices

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Foreword

(This foreword is not a part of IEEE Std C62.22-1991, IEEE Guide for the Application of Metal-Oxide Surge Arresters for Alternating-Current Systems.)

This guide supplements IEEE Std C62.11-1987, IEEE Standard for Metal-Oxide Surge Arresters for AC Power Circuits, to assist users in the selection and application of surge arresters.

Material for this guide was developed by Working Groups 3.4.10, 3.4.14, and 3.4.16 of the Application of Surge-Protective Devices (ASPD) Subcommittee, Surge-Protective Devices (SPD) Committee. Specific sections developed by these Working Groups were

Sections 1, 2, and 3 and Appendix A	Working Group 3.4.10
Section 4	Working Group 3.4.14
Appendix C	Working Group 3.4.16

This document was assembled and processed by Working Group 3.4.14. At the time work on this document was completed, Working Group 3.4.14 consisted of the following members:

S. S. Kershaw, Jr., *Chair*

R. D. Ball
C. L. Ballentine
R. G. Black
S. Brewer
J. J. Burke
M. G. Comber
J. G. Dalton
J. P. DuPont
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D.W. Jackson
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M. V. Lat
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J. C. Osterhout
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T. E. Royster
E. C. Sakshaug
G. L. Schmidt
R. M. Simpson, III
K. B. Stump
A. Sweetana
E. R. Taylor, Jr.
A. C. Westrom
C. W. Williams, Jr.
J. W. Wilson, Jr.

Working Group 3.4.10 consisted of:

A. Sweetana, *Chair*

M. G. Comber
J. G. Dalton
C. C. Erven
G. L. Gaibrois
D. F. Goodwin
J. A. Hetrick
A. R. Hileman
H. Huynh
D. W. Jackson
B. Johnnerfelt
R. A. Jones
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J. P.. Skliutas
K. B. Stump
R. Thallam
S. G. Whisenant
J. W. Wilson, Jr.
J. J. Woodworth
E. J. Yasuda

Working Group 3.4.16 consisted of:

G. S. Haralampu, *Chair*

J. J. Burke
J. G. Dalton
D. F. Goodwin
A. R. Hileman
J. A. Jones
R. T. Leskovich
Y. I. Musa
K. B. Stump
A. Sweetana
E. R. Taylor, Jr.
J. W. Wilson, Jr.

The following persons were members of the balloting group that approved this guide for submission to the IEEE Standards Board:

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IEEE Guide for the Application of Metal-Oxide Surge Arresters for Alternating-Current Systems

1. Scope and Definitions

1.1 Scope. This guide covers the application of metal oxide surge arresters (see IEEE Std C62.11-1987 [9])[1] to safeguard electric power equipment against the hazards of abnormally high voltage surges of various origins. Such overvoltages may cause flashovers and serious damage to equipment and thereby jeopardize the supply of power to users. It is essential to prevent this by the proper coordination of surge-protective devices with the insulation strength of the protected equipment.

The subject is broad, with many ramifications, and it requires a volume of considerable bulk to explain all possible cases in detail. Section 3 of this guide covers the basic cases for stations used to supply and switch electric power transmission, subtransmission, or distribution feeders. Information is included in Section 4 on application of arresters for protection of overhead and underground distribution systems, all distribution transformers, and other electric distribution equipment.

Step-by-step directions toward proper solutions for various applications are provided. In many cases, the prescribed steps are adequate. More complex and special situations requiring study by experienced engineers are described, but specific solutions may not be given. These procedures are based on theoretical studies, test results, and experience.

1.2 Definitions

1.2.1 Overvoltages

1.2.1.1 Overvoltage. Abnormal voltage between two points of a system that is greater than the highest value appearing between the same two points under normal service conditions. Overvoltages may be low-frequency, temporary, and transient (surge).

1.2.1.2 Surge. A transient wave of current, potential, or power in an electric circuit; see IEEE Std C62.1-1989 [8].

1.2.1.2.1 Lightning Surge. A transient electric disturbance in an electric circuit caused by lightning; see IEEE Std C62.1-1989 [8].

1.2.1.2.2 Lightning Overvoltage. The crest voltage appearing across an arrester or insulation caused by a lightning surge.

1.2.1.3 Switching Overvoltage. Any combination of switching surge(s) and temporary overvoltage(s) associated with a single switching episode.

1.2.1.3.1 Switching Surge. A heavily damped transient electrical disturbance associated with switching. System insulation flashover (see 1.2.4.7) may precede or follow the switching in some cases but not all.

---

[1] The numbers in brackets correspond to the references in Section 5.

1.2.1.3.2 Temporary Overvoltage. An oscillatory overvoltage, associated with switching or faults (for example, load rejection, single-phase faults) and/or nonlinearities (ferroresonance effects, harmonics), of relatively long duration, which is undamped or slightly damped.

1.2.1.3.3 Coefficient of Grounding (COG). The ratio, E_{LG}/E_{LL} (expressed as a percentage), of the highest root-mean-square (rms) line-to-ground power-frequency voltage E_{LG} on a sound phase, at a selected location, during a fault to ground affecting one or more phases to the line-to-line power-frequency voltage E_{LL} that would be obtained at the selected location with the fault removed.

1.2.1.4 Traveling Wave. The resulting wave when an electrical variation in a circuit such as a transmission line takes the form of translation of energy along a conductor, such energy being always equally divided between current and potential forms; see IEEE Std 100-1988 [11].

1.2.2 Impulses

1.2.2.1 Impulse. A surge of unidirectional polarity.

1.2.2.2 Crest (Peak) Value (of an Impulse). The maximum value that an impulse attains.

1.2.2.3 Wave Front of an Impulse. That part of an impulse that occurs prior to the crest value.

1.2.2.4 Wave Tail (of an Impulse). That part between the crest value and the end of the impulse; see IEEE Std C62.1-1989 [8].

1.2.2.5 Wave Shape (of an Impulse Test Wave). The graph of the wave as a function of time; see IEEE Std C62.1-1989 [8].

1.2.2.6 Wave Shape Designation (of an Impulse)

(1) The wave shape of an impulse (other than rectangular) of a current or voltage is designated by a combination of two numbers. The first, an index of the wave front, is the virtual duration of the wave front in microseconds, as defined in 1.2.2.8. The second, an index of the wave tail, is the time in microseconds from virtual zero to the instant at which one-half of the crest value is reached on the wave tail. Examples are 1.2/50 μs and 8/20 μs waves; see IEEE Std C62.1-1989 [8].

(2) The wave shape of a rectangular impulse of current or voltage is designated by two numbers. The first designates the minimum value of current or voltage that is sustained for the time in microseconds designated by the second number. An example is the 75 A · 2000 μs wave; see IEEE Std C62.1-1989 [8].

1.2.2.7 Virtual Zero Point (of an Impulse). The intersection with the zero point of the time axis of a straight line drawn through points on the front of the current wave at 10% and 90% crest value or through points on the front of the voltage wave at 30% and 90% crest value; see IEEE Std C62.1-1989 [8].

1.2.2.8 Virtual Duration of Wave Front (of an Impulse). The virtual value for the duration of the wave front is as follows:

(1) For voltage waves with wave front durations less than 30 µs, either full or chopped on the front, crest, or tail, 1.67 times the time for the voltage to increase from 30% to 90% of its crest value.
(2) For voltage waves with wave front durations of 30 µs or more, the time taken by the voltage to increase from actual zero to maximum crest value.
(3) For current waves, 1.25 times the time for the current to increase from 10% to 90% of crest value.

1.2.2.9 Nominal Rate of Rise (of an Impulse). For a wave front, the slope of the line that determines the virtual zero. It is usually expressed in volts or amperes per microsecond.

1.2.3 Standard Impulses

1.2.3.1 Standard Lightning Impulse. The wave shape of standard impulse used (when not in conflict with products standards) is 1.2/50 µs.

1.2.3.2 Standard Switching Impulses. The wave shapes of standard impulse tests depend on equipment being tested.

(1) For air insulation and switchgear: 250/2500 µs; see ANSI C92.1-1982 [2].
(2) For transformer products: 100/1000 µs.
(3) For arrester sparkover tests
    (a) 30–60/90–180 µs
    (b) 150–300/450–900 µs
    (c) 1000–2000/3000–6000 µs

(The tail duration is not critical: see IEEE Std C62.11-1987 [9].)

1.2.4 Insulation Coordination

1.2.4.1 Coordination of Insulation. The process of correlating the insulation strengths of electric equipment with expected overvoltages and with the characteristics of surge-protective devices: see ANSI C92.1- 1982 [2].

1.2.4.2 Withstand Voltage. The voltage that electric equipment is capable of withstanding without failure or disruptive discharge when tested under specified conditions; see ANSI C92.1-1982 [2].

1.2.4.3 Insulation Level. A combination of voltage values (both power frequency and impulse) that characterize the insulation of an equipment with regard to its capability of withstanding dielectric stresses.

1.2.4.4 Basic Lightning Impulse Insulation Level (BIL). A specific insulation level expressed as the crest value of a standard lightning impulse; see ANSI C92.1-1982 [2].

1.2.4.5 Basic Switching Impulse Insulation Level (BSL). A specific insulation level expressed as the crest value of a standard switching impulse; see ANSI C92.1-1982 [2].

1.2.4.6 Disruptive Discharge. The sudden and large increase in current through an insulating medium due to the complete failure of the medium under electrical stress; see IEEE Std C62.1-1989 [8].

1.2.4.7 Flashover. A disruptive discharge around or over the surface of a solid or liquid insulator: see IEEE Std C62.1-1989 [8].

1.2.5 Arresters

1.2.5.1 Surge Arrester. A protective device for limiting surge voltages on equipment by discharging or bypassing surge current; it prevents continued flow of follow current to ground, and is capable of repeating these functions as specified; see IEEE Std C62.1-1989 [8].

1.2.5.2 Valve Arrester. An arrester that includes one or more valve elements; see IEEE Std C62.1-1989 [8].

1.2.5.2.1 Arrester Duty Cycle Rating. The designated maximum permissible root-mean-square (rms) value of power-frequency voltage between its line and earth terminals at which it is designed to perform its duty cycle.

1.2.5.2.2 Maximum Continuous Operating Voltage (MCOV) Rating. The maximum designated root-means-square (rms) value of power frequency voltage that may be applied continuously between the terminals of the arrester.

1.2.5.3 Series Gap (When Used). An intentional gap(s) between spaced electrodes in series with the valve elements across which all or part of the impressed arrester terminal voltage appears.

1.2.5.4 Valve Element. A resistor that, because of its nonlinear current-voltage characteristic, limits the voltage across the arrester terminals during the flow of discharge current and contributes to the limitation of follow current at normal power-frequency voltage; see IEEE Std C62.1-1989 [8].

1.2.5.5 Unit Operation. Discharging a surge through an arrester while the arrester is energized; see IEEE Std C62.1-1989 [8].

1.2.5.6 Arrester Discharge Current. The current that flows through an arrester due to a surge.

1.2.5.6.1 Arrester Discharge Voltage. The voltage that appears across the terminals of an arrester during the passage of discharge current.

1.2.6 System Voltages

1.2.6.1 System Voltage. The root-mean-square (rms) power-frequency voltage from line-to-line as distinguished from the voltage from line-to-neutral.

1.2.6.2 Maximum System Voltage. The highest voltage at which a system is operated. (This voltage excludes voltage transients and temporary overvoltages caused by abnormal system conditions such as faults, load rejection, etc.)

NOTE: This is generally considered to be the maximum system voltage as prescribed in ANSI C84.1-1989 [1].

1.2.6.3 Nominal System Voltage. A nominal value assigned to designate a system of a given voltage class. (The nominal voltage of a system is near the voltage level at which the system normally operates and provides a per-unit base voltage for system study purposes. To allow for operating contingencies, systems generally operate at voltage levels about 5% to 10% below the maximum system voltage for which system components are designed.)

NOTE: See ANSI C84.1-1989 [1].

2. General Considerations

2.1 Overvoltages. Overvoltages in power systems may be generated by lightning or by system conditions (such as switching operations, faults, load rejection, etc.), or both. Broadly, the overvoltage types will be classified herein as lightning-generated and all others as switching generated. The magnitude of these overvoltages can be above maximum permissible levels and therefore need to be reduced and protected against if damage to equipment and possible undesirable system performance are to be avoided.

2.1.1 Lightning Currents and Overvoltages. Lightning surge voltages that arrive at the line entrance of a station are caused either by

(1) A lightning flash terminating on the overhead shield wire or structure with a subsequent flashover to the phase conductor (denoted as a backflash) or by
(2) A lightning flash termination on the phase conductor (denoted as a shielding failure).

The lightning surge voltage magnitude and wave shape that enter a station are functions of the magnitude, polarity, and shape of the lightning stroke current, the tower and line surge impedance, the tower footing impedance, and the lightning impulse critical flashover voltage (CFO) of the line insulation.

The crest magnitude of the surge voltage arriving at the station caused by a backflash is generally considered to be 1 to 1.2 times the positive polarity CFO of the line that represents a reasonable worst-case condition. The wavefront or time-to-crest is dependent on the distance between the station and location of the backflash. The front time increases approximately 1 μs/km of distance from the station to the backflash location. Fronts in the range of 0-5–4.0 μs have been used. The tail of the surge is typically between 10 μs and 20 μs, depending on the tower footing resistance. (Higher footing resistances produce shorter tails).

Lightning surge crest voltages caused by shielding failures are generally limited to the negative polarity CFO of the line. The fronts and tails are equal to those of the lightning stroke current and are therefore greater than those resulting from a backflash. Fronts are typically 0.3–1.0 μs longer than those for a backflash and the tails average about 90 μs.

For lines that are effectively shielded, the surge voltages caused by a backflash are usually more severe and therefore are the only ones considered for the analysis of station protection.

Appendix A contains a more detailed review of lightning flashes and lightning stroke currents and addresses lightning protection techniques such as shielding.

2.1.2 Switching Overvoltages. Switching overvoltages occur on all systems ([B1], [B25], and [B26][2]) and usually result from a circuit-breaker operation or the occurrence of a fault. Generally, these overvoltages are an important consideration in systems above 115 kV and in all systems where the effective surge impedance as seen from the arrester location is low (e.g., cable and capacitor bank circuits).

The switching surge duty on metal-oxide arresters applied on overhead transmission lines increases for increased system voltage and increased length of switched line. Typically, transients occurring from high speed reclosing impose greater duty than do energy transients.

On extra high-voltage (EHV) systems, it is particularly important that transients on the high-voltage network do not transfer excessive energy to arresters on the low side windings of step-down transformers. This situation arises when a line is switched at one end and the other end of the line is transformer terminated. The per-unit protective levels of the low side arrester should be higher than the high-voltage winding arresters so they do not respond to high side surges.

Because of the likelihood of unusually high discharge currents, the application of arresters to shunt capacitor banks or cables may require a special review, such as a detailed analytical

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[2] The "B" numbers in brackets refer to the bibliography in Appendix D.

system study. Arresters of higher than standard energy or parallel arresters may be required (see 3.11).

2.1.3 Temporary Overvoltages. Temporary overvoltages consist of lightly damped power frequency voltage oscillation, often with harmonics usually lasting a period of hundreds of milliseconds or longer. See Appendix B. Situations that may give rise to these overvoltages include single line-to-ground faults, ferroresonance, load rejection, loss of ground, long unloaded transmission lines (Ferranti rise), coupled line resonance, and transformer-line inrush. The system configuration and operating practices should be reviewed to identify the most probable forms of temporary overvoltages that may occur at the arrester location. In addition, proper application of metal-oxide arresters requires that the duration of these overvoltages be known (see 2.2.3).

When detailed system studies or detailed calculations are unavailable, it is recommended that as a minimum the overvoltages due to line-to-ground faults be addressed. Single line-to-ground faults are the most common type of system disturbance, The magnitude of these overvoltages are related to system grounding and can be estimated by the "coefficient of grounding" (COG) as outlined in 3.3.2.1. Arresters on a well-grounded system are normally exposed to low-magnitude temporary overvoltages during single line-to-ground faults, whereas they are exposed to higher voltages when the system is either ungrounded or grounded through an impedance. This is also true of arresters installed on the neutral of reactance- or resistance-grounded transformers and for systems using resonant grounding and Peterson coils [10].

2.2 Metal-Oxide Arresters

2.2.1 Design. Metal-oxide arresters fall into three broad design categories, namely: gapless arresters, shunt-gapped arresters, and series-gapped arresters. The general principles of these three design types are described in the following subsections.

2.2.1.1 Gapless Arresters. Gapless arresters utilize a single stacked column or parallel columns of metal oxide elements (disks), as schematically shown in Fig 1(a). A typical voltampere characteristic for such an arrester is illustrated in Fig 1(b). Above the knee of the voltampere curve, the metal-oxide elements exhibit a very nonlinear behavior that may be approximated by the relationship $I = kV^{\alpha}$. Alpha (α) values will normally vary from 10 to 50, depending on the disk formulation and current range being studied. Typically, higher current values and wider ranges will yield lower values of α. For example, α may be 50 over a current range of 1–600 A and may average 26 over the wider range of 1–10 000 A. The arrester discharge voltage for a given surge-current magnitude is directly proportional to the height of disk stack and is thus more or less proportional to the arrester rated voltage. Additionally, the arrester discharge voltage is a function of the rate of rise of the current surge, with higher voltages occurring for faster rates of rise and vice versa. Typically, for the same current magnitude, the voltage occurring for a current cresting in 1 μs is 8–12% higher than that occurring for a standard 8/20 μs lightning current wave. The voltage occurring for a current cresting in 45–60 μs is 2–4% lower than that for the 8/20 μs wave.

The MCOV of the arrester is typically in the range of 75% to 85% of the duty cycle voltage rating. At MCOV, the arrester current is usually not more than a few milliamperes, typically less than 10 mA. On the arrival of a surge, the increasing surge current is accompanied by a rise in arrester voltage to a maximum level determined by the voltampere characteristic. As the surge current decreases, the discharge voltage will decrease back towards the pre-surge level.

2.2.1.2 Shunt-Gapped Arresters. For surge currents above a certain magnitude, the discharge voltage of a column or columns of metal-oxide valve elements can be reduced by shunting a portion of the stack. This is the basic principle of a shunt-gapped arrester, schematically shown in Fig 2(a). A typical voltampere characteristic of such an arrester is illus-

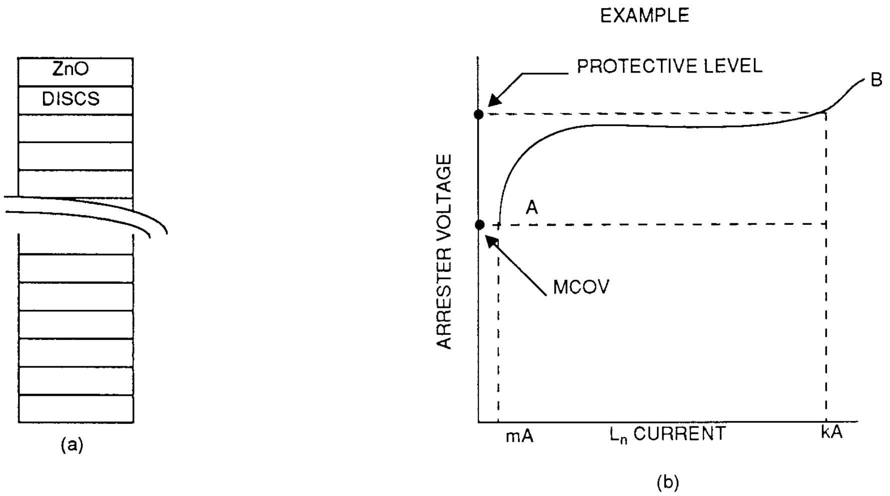


Fig 1
Gapless Metal-Oxide Surge Arrester

trated in Fig 2(b). On arrival of a surge, the arrester voltage initially increases with increasing surge-current magnitude according to the voltampere characteristics A-B. When the surge current magnitude reaches 250–500 A (range B to C on voltampere characteristic), sparkover of a gap electrically connected in parallel with a few metal-oxide disks results in a shunting of the surge current around these disks, thereby proportionally lowering the discharge voltage (in the range D to E). For further increases in surge current, the voltage increases according to the characteristic E-F. As the surge current decreases, the arrester voltage decreases accordingly, following the characteristic F-G until the shunt gaps extinguish at a low level of current. Following the extinction of the arrester leakage current, the arrester operating point returns to A.

From an energy standpoint, the energy absorption capability is less after gap sparkover than before.

2.2.1.3 Series-Gapped Arresters. Another approach to obtain reduced protective levels is to use fewer disks in conjunction with series-connected spark gaps, as depicted in Fig 3(a). The series gaps are shunted by a linear component impedance network of such characteristic that the applied voltage is divided between the impedance network and the metal oxide disks. A typical voltampere characteristic is illustrated in Fig 3(b). On the arrival of a surge, the arrester voltage begins to rise (A-B), the total voltage being the vector sum of the voltages across the metal-oxide disks and the series gap impedance network. At a level of current in the vicinity of 1 A (depending on rate of rise in the range B to C), the gaps sparkover and the arrester voltage is reduced to the discharge voltage of the metal-oxide elements only. For further increase in surge current, the voltage increases according to the characteristic D-E-F. As the surge current decreases, the arrester voltage decreases accordingly, following the characteristic F-G until the series gaps extinguish at a low level of current.

2.2.1.4 Test Procedures. IEEE Std C62.11-1987 [9] contains test procedures that consider all three types of arrester design. The standard includes tests for both series- and shunt-gapped arresters to obtain the protective level that is the higher of either the gap sparkover or discharge voltage. Protective levels for metal-oxide arresters can be treated in the same man-

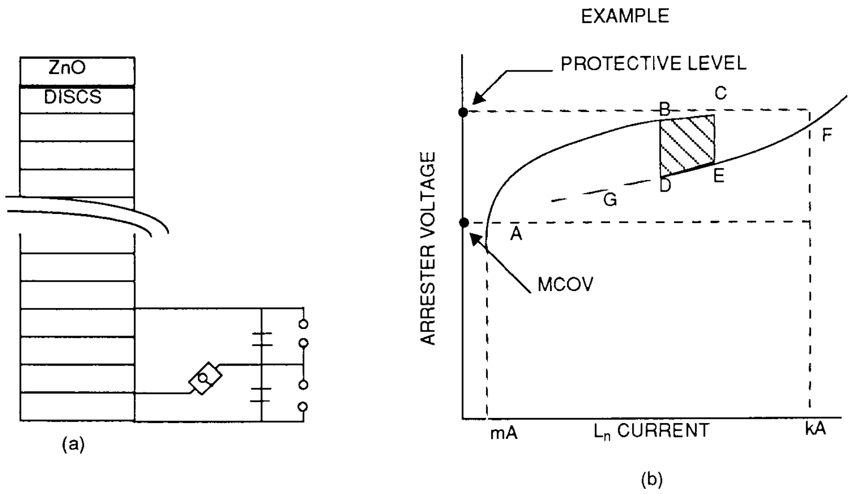


Fig 2
Shunt-Gapped Metal-Oxide Surge Arrester

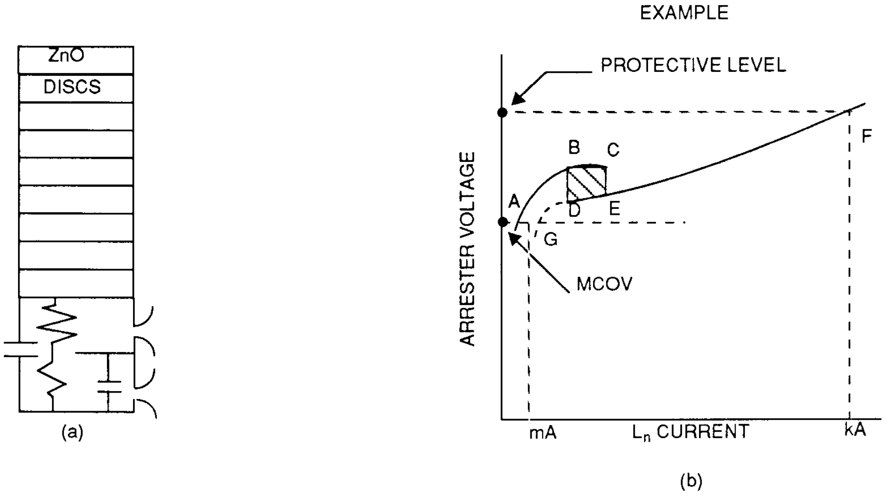


Fig 3
Series-Gapped Metal-Oxide Surge Arrester

ner irrespective of whether the levels are limited by sparkover or by discharge voltage (see 2.3).

2.2.1.5 Usual Operating Conditions. Arresters are designed to operate properly in continuous air temperatures in the general vicinity of the arrester between -40 °C and 40 °C, in temporary maximum air temperatures due to external heat sources near the arrester that do not exceed 60 °C, and at altitudes that do not exceed 1800 m (6000 ft).

NOTE: Usual operating temperatures for special-application arresters, such as oil- or liquid-immersed, gas insulated, and dead-front arresters, will typically differ from the above, but such operating temperatures had not yet been standardized at the time this guide was prepared.

2.2.1.6 Unusual Conditions. In addition to operation beyond the limits of 2.2.1.5, exposure to damaging fumes, vapors, steam, salt spray, or excessive amounts of contamination may require special consideration. Arresters should not be installed so that mechanical stresses are excessive or be subjected to abnormal vibrations or shocks.

2.2.2 Standard Voltage Ratings. The present metal-oxide design standard, IEEE Std C62.11-1987 [9], specifies a dual voltage rating for each arrester. The conventional duty-cycle voltage rating (see 1.2.5.2.1) now has a corresponding MCOV rating (see 1.2.5.2.2). Refer to Table 1 of IEEE Std C62.11-1987 [9].

In applying the metal-oxide arrester, it is critically important that the arrester MCOV rating be equal to or greater than the *maximum continuous* voltage to which the arrester is exposed at any time.

2.2.3 Temporary Overvoltage Capability. The MCOV rating defines the maximum *continuous* voltage at which an arrester is designed to operate. However, metal-oxide arresters are capable of operating for limited periods of time at voltages in excess of the MCOV rating. Although there is presently no standard test to establish overvoltage capability, all manufacturers publish information on overvoltage capability. A typical 60 Hz temporary overvoltage capability curve is shown in Fig 4.

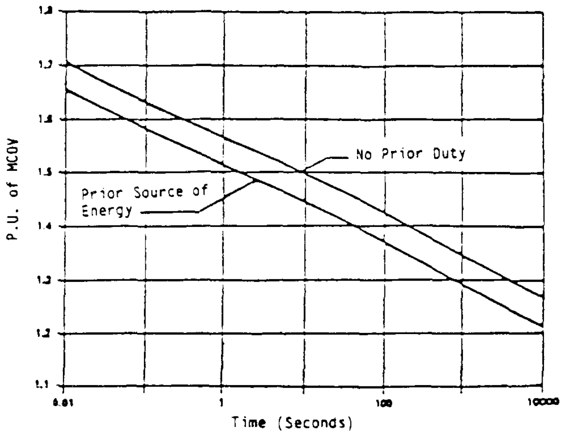


Fig 4
Typical 60 Hz Temporary Overvoltage Capability Curve

2.3 Protective Levels. The protective level of an arrester is the maximum crest voltage that appears across its terminals under specified conditions of operation. For metal-oxide arresters without gaps, the protective level is the arrester discharge voltage for a specified discharge current. For arresters with gaps (shunt or series), the protective level is the higher of the gap sparkover voltage or the discharge voltage (see 2.2.1).

2.3.1 Classification Current. Table 3 in IEEE Std C62.11-1987 [9] specifies magnitudes of lightning impulse "classification current" for each class of arrester. For station-class arresters, the classification current magnitude also depends on the voltage of the system to which the arresters are applied. For station- and intermediate-class arresters, IEEE Std C62.11-1987 [9] also specifies, in Table 4, magnitudes of switching impulse classification current. These classification currents are, in effect, reference discharge currents and represent appropriate levels of discharge current for general considerations of insulation coordination. (See 3.4.2 and 3.4.3). IEEE Std C62.11-1987 [9] requires that certain tests, including discharge voltage measurements, be made at the specified classification current magnitude.

2.3.2 Lightning Impulse Protective Level (LPL). LPL is the higher of the discharge voltages established by tests using 8/20 μs discharge current impulses or gap sparkover voltages for specified surge voltage waves. The discharge voltage is a function of current magnitude. IEEE Std C62.11-1987 [9] specifies that tests should be made with 8/20 μs currents of 1 500 A, 3 000 A, 5 000 A, 10 000 A, and 20 000 A. If the arrester lightning impulse classification current shown in Table 3 of IEEE Std C62.11-1987 [9] is not one of these, an additional test must be made at the classification current given for the particular arrester class.

2.3.3 Front-of-Wave (FOW) Protective Level. FOW protective level for metal-oxide arresters is the higher of

(1) The crest discharge voltage resulting from a current wave through the arrester of Lightning Impulse Classifying Current magnitude with a rate-of-rise high enough to produce arrester crest voltage in 0.5 μs; or
(2) Gap sparkover for specified rates-of-rise of wave shapes in IEEE Std C62.11-1987 [9].

2.3.4 Switching Impulse Protective Level (SPL). SPL is the higher of

(1) The discharge voltage measured with a current wave through the arrester of Switching Impulse Classifying Current magnitude and a time to actual current crest of 45–60 μs, or
(2) Gap sparkover voltage on similar wave shapes

The switching impulse classifying currents of Table 4 of IEEE Std C62.11-1987 [9] were calculated by dividing the line charge voltage (E), minus the switching surge-protective level of the minimum arrester rating used at that voltage, by one-half of the surge impedance (Z_L) given in Table 5 of IEEE Std C62.11-1987 [9]. These currents are considered conservative for most arrester applications, but they may be exceeded in applications involving capacitor banks or cables or in other low-impedance circuits. Manufacturers should be consulted for information on protective levels for currents that exceed the Switching Impulse Classifying Current.

2.4 Insulation Withstand. Insulation strength is expressed in terms of the withstand voltage that the equipment can tolerate without failure. The withstand voltages of interest in arrester applications are taken from the list of preferred BIL and BSL values in ANSI C92.1-1982 [2].

The following withstand levels for equipment and bus insulation are of interest in arrester application:

(1) *Chopped Wave Withstand (CWW).* Tests are made with a 1.2/50 μs impulse chopped by the action of a gap in a minimum time as specified in the appropriate product standard.
(2) *Basic Lightning Impulse Insulation Level (BIL).* Tests are made with full-wave 1.2/50 μs impulses as specified in the appropriate equipment standard.
(3) *Basic Switching Impulse Insulation Level (BSL).* The test impulse depends on the type of equipment.

2.5 Separation Effects. The voltage at the protected insulation will usually be higher than at the arrester terminals due to oscillations on connecting leads [B55]. This rise in voltage is called a separation effect (SE).

Separation effects increase with the increasing rate of rise of the incoming surge and with increasing distances between the arrester and protected equipment. For evaluation of separation effects due to lightning surges, refer to Appendix C. Due to the relatively slow rates of rise of switching surges, separation effects need not be considered in applying the fundamental protective ratio formula to switching surge withstand (BSL).

Other considerations in locating arresters are discussed in 3.5.

2.6 Insulation Coordination. Insulation coordination is defined in ANSI C92.1-1982 [2] as "the process of correlating the insulation strengths of electrical equipment with expected overvoltages and with the characteristics of surge-protective devices."

Degree of coordination is measured by the protective ratio (PR). The fundamental definition of PR is

$$\mathrm{PR} = \frac{\text{Insulation Withstand Level}}{\text{Voltage at Protected Equipment}}$$

"Voltage at protected equipment" includes separation effect, if significant. If not, it is equal to arrester protective level.

There are three protective ratios in common use that compare protective levels with corresponding insulation withstands.

$$\mathrm{PR}_{\mathrm{L1}} = \frac{\mathrm{CWW}}{\mathrm{FOW}}$$

$$\mathrm{PR}_{\mathrm{L2}} = \frac{\mathrm{BIL}}{\mathrm{LPL}}$$

$$\mathrm{PR}_{\mathrm{S}} = \frac{\mathrm{BSL}}{\mathrm{SPL}}$$

The protective margin (PM) in percent is defined as: PM = (PR - 1)100. PR and PM applications are covered in Sections 3 and 4.

A graphical approach to insulation coordination is also discussed in Section 3.

3. Protection of Stations

3.1 Introduction. The general procedures given here are applicable where transformers and other equipment and station components have a chopped-wave voltage withstand level at least 1.10 times the BIL. For this withstand level, the procedures for the selection and location of arresters in relation to the insulation system to be protected can generally be reduced to a series of steps. These are summarized in 3.2 and elaborated upon in 3.3 through 3.8.

Arrester applications for transformer or other series windings, unloaded windings, and ungrounded neutrals are discussed in 3.9.

Where a lower chopped-wave insulation level is specified in equipment such as dry-type transformers, the protection procedures are covered in 3.10.

Basic to the application theory presented by this guide are the presumptions that

(1) Surge arrester ground terminals are connected to the grounded parts of the protected equipment
(2) Both line and ground surge arrester connections are as short as practical
(3) The station is shielded against direct strokes

3.2 Step-by-Step Procedures and Generalized Arrester Characteristics. Fig 5 and Table 1 are designed for ready reference in arrester application.

3.2.1 Steps Required to Select Arresters. A summary of the steps required to select arresters is provided in Fig 5.

The following sequence is used:

(1) Select an arrester and determine its protective characteristics.
(2) Select (or determine) the insulation withstand.
(3) Evaluate the insulation coordination.

Other sequences may be equally acceptable. The key step is insulation coordination evaluation. Withstand voltages may be selected to match the characteristics of certain arresters, or arresters may be matched to available insulation.

3.2.2 Summary of Information Applicable to Station Class and Intermediate Class Arresters. Information applicable to station class and intermediate class arresters is summarized in Table 1.

Distribution class arresters are sometimes used in stations, and information applicable to distribution arresters may be found in Section 4.

Protective levels are given in per-unit values of crest arrester MCOV rating. As explained in Table 1, per-unit values may be converted to kilovolts and used in preliminary selection of arresters. Values in the numbered columns under "Durability Characteristics" are specified requirements for the range of ratings as prescribed in IEEE Std C62.11-1987 [9]. Additional application information is found in notes numbered to correspond with the columns.

3.3 Arrester Selection (Item 1, Fig 5). For a given application, the selection of an appropriate arrester involves considerations of maximum continuous operating voltage; protective characteristics (lightning and switching impulse); durability (temporary overvoltage and switching surge); service conditions; and pressure relief requirements. Durability and protective level considerations will primarily determine the class of arrester selected: station, or intermediate, or occasionally distribution.

Station arresters are designed for heavy-duty applications. They have the widest range of ratings (see Table 1), the lowest protective characteristics, and the most durability.

Intermediate arresters are designed for moderate duty and for maximum system voltages of 169 kV and below. Distribution arresters (see Tables 5 and 6 of Section 4) are used to protect lower voltage transformers and lines where the system-imposed duty is minimal and there is a need for an economical design.

3.3.1 Maximum Continuous Operating Voltage (MCOV). For each arrester location, arrester MCOV has to equal or exceed the expected MCOV of the system. Proper application requires that the system configuration (single-phase, delta, or wye) and the arrester connection (phase to ground, phase to phase, or phase to neutral) be evaluated. For example, in EHV systems the arrester is typically connected phase to ground, and therefore, is exposed to system phase-to-ground voltages on a steady-state basis. On the other hand, an arrester connected to a tertiary winding with one corner grounded, or a delta-connected system, is exposed to phase-to-phase voltage during intervals when the system is operated with a fault on one phase.

Table 1
Station- and Intermediate-Class Arrester Characteristics

Station Class									
Steady-State Operation System Voltage and Arrester Ratings				Protective Levels Range of Industry Maxima Per Unit—Crest of MCOV			Durability Characteristics (IEEE Std C62.11-1987 [9])		
Maximum System Voltage L-L (kV/rms)	Maximum System Voltage L-G (kV/rms)*	Minimum MCOV Rating (kV/rms)	Duty Cycle Ratings (kV/rms)	0.5 μs FOW Discharge Voltage (DV) (NOTE 1)	8/20 μs wave DV (NOTE 1)	Switching Surge—DV (NOTE 2)	High-Current Withstand Crest (Amperes)	Transmission Line Discharge (Miles)	Pressure Relief (A rms) (Symmetrical) (NOTE 3)
4.37	2.52	2.55	3–	2.32–2.48	2.10–2.20	1.70–1.85	65 000	150	40 000–65 000
8.73	5.04	5.1	6–9	2.33–2.48	1.97–2.23	1.70–1.85	65 000	150	40 000–65 000
13.1	4.56	7.65	9–12	2.33–2.48	1.97–2.23	1.70–1.85	65 000	150	40 000–65 000
13.9	8.00	7.65	9–15	2.33–2.48	1.97–2.23	1.70–1.85	65 000	150	40 000–65 000
14.5	8.37	8.4	10–15	2.33–2.48	1.97–2.23	1.70–1.85	65 000	150	40 000–65 000
26.2	15.12	15.3	18–27	2.33–2.48	1.97–2.23	1.70–1.85	65 000	150	40 000–65 000
36.2	20.92	22	27–36	2.43–2.48	1.97–2.23	1.70–1.85	65 000	150	40 000–65 000
48.3	27.89	29	36–48	2.43–2.48	1.97–2.23	1.70–1.85	65 000	150	40 000–65 000
72.5	41.86	42	54–72	2.19–2.40	1.97–2.18	1.64–1.84	65 000	150	40 000–65 000
121	69.86	70	90–120	2.19–2.40	1.97–2.18	1.64–1.84	65 000	150	40 000–65 000
145	83.72	84	108–144	2.19–2.39	1.97–2.17	1.64–1.84	65 000	150	40 000–65 000
169	97.57	98	120–172	2.19–2.39	1.97–2.17	1.64–1.84	65 000	175	40 000–65 000
242	139.72	140	172–240	2.19–2.36	1.97–2.15	1.64–1.84	65 000	175	40 000–65 000
362	209.00	209	258–312	2.19–2.36	1.97–2.15	1.71–1.85	65 000	200	40 000–65 000
550	317.54	318	396–564	2.01–2.25	2.01–2.25	1.71–1.85	65 000	200	40 000–65 000
800	461.88	462	576–612	2.01–2.25	2.01–2.25	1.71–1.85	65 000	200	40 000–65 000
Intermediate Class									
4.37–169	2.52–97.67	2.8–98	3–144	2.38–2.85	2.28–2.55	1.80–2.10	65 000	100	16 100 (NOTE 3)

*Voltage range A, ANSI C84.1-1989 [1].

NOTE 1: Equivalent FOW producing a voltage wave cresting in 0.5 μs. Protective level is maximum DV for a 10 kA impulse current wave on arrester duty cycle rating through 312 kV, 15 kA for duty cycle ratings 396–564 kV, and 20 kA for duty cycle ratings 576–612 kV, per IEEE Std C62.11-1987 [9].

NOTE 2: Switching surge characteristics based on maximum switching surge classifying current (based on an impulse current wave with a time to actual crest of 45 μs to 60 μs) of 500 A on arrester duty cycle ratings 3–108 kV, 1000 A on duty cycle ratings 120–240 kV, and 2000 A on duty cycle ratings above 240 kV, per IEEE Std C62.11-1987 [9].

NOTE 3: Test values for arresters with porcelain tops have not been standardized.

Fig 5
Summary of Procedures for Arrester Selection and Insulation Coordination

1. Select surge arrester (see 3.3)
   1.1 MCOV ≥ Maximum Line-to-Neutral Voltage
   1.2 TOV Capability ≥ System TOV
   1.3 Switching Impulse Energy Capability ≥ that produced by the system
   1.4 Arrester Class:

      (1) Available ratings
      (2) Pressure relief
      (3) Durability

2. Determine protective characteristics (see 3.4)
   2.1 Lightning Impulse Protective Level, LPL
   2.2 Front-of Wave Protection Level, FOW
   2.3 Switching Impulse Protective Level, SPL

3. Locate surge arrester (see 3.5)
   As close as possible to equipment to be protected

4. Select Insulation Strength (see 3.6)
   See equipment standards for BILs and BSLs and for CWW

5. Determine voltage at equipment terminals (see 3.5)
   Arrester lead length and transformer-to-arrester separation distance effects can be determined per Appendix C

6. Evaluate coordination (see 3.7)
   6.1 If effects of separation distance can be disregarded, the protective ratios for lightning, PR_{L1} and PR_{L2}, and switching impulses, PR_S, are:

$PR_{L1} = CWW/FOW \geq 1.2$
$PR_{L2} = BIL/LPL \geq 1.2$
$PR_S = BSL/SPL \geq 1.15$

For acceptable coordination, PR_{L1} and PR_{L2} should be equal to or greater than 1.2, and PR_S should be equal to or greater than 1.15.

6.2 If the voltage at the equipment terminals, V_T, is calculated per Appendix C, the protective ratios are as follows:

If the time-to-crest of the arrester voltage is equal to or less than 2 µs:

(1) $PR_{L1} = CWW/V_T \geq 1.15$

where CWW is the chopped-wave withstand voltage of the equipment. If a CWW level does not exist for the equipment, use the equation in (2) below.

(2) Otherwise

$PR_{L2} = BIL/V_T \geq 1.15$

(3) For switching impulse, as in step 6.1

$PR_S = BSL/SPL \geq 1.15$

For acceptable coordination, the PRs should be equal to or greater than 1.15.

7. Evaluate alternates (see 3.8)

   If acceptable coordination cannot be achieved, evaluate the following measures:

   (1) Increase BIL and BSL
   (2) Decrease arrester separation distance
   (3) Add additional arresters
   (4) Use arrester with lower protective characteristics

3.3.2 Temporary Overvoltage (TOV) Durability. An arrester has to be capable of withstanding the maximum anticipated TOV. TOV requirements have to take into account both magnitudes and durations of temporary overvoltages, the combinations of which have to be equal to or less than the capability of the arrester as shown by the TOV capability curves of the manufacturer.

There are several sources of TOV and operating conditions that affect arrester operation, as discussed in the following subsections.

3.3.2.1 Fault Conditions. The most common source of TOV is voltage rise on unfaulted phases during a line-to-ground fault. The curves of Appendix B may be used to determine quickly temporary overvoltages during fault conditions on applications involving short lines operating at voltages through 242 kV.

The numbers adjacent to each of the curves of Appendix B are the coefficients of grounding in percent (see 1.2.1.3.3). From known values of R_0/X_1 and X_0/X_1, determine the corresponding coefficient of grounding, interpolating between curves as necessary. Multiply the coefficient of grounding by maximum system phase-to-phase operating voltage to determine the temporary overvoltage to ground at the point of fault. Alternatively, the voltage can be calculated from the equations in Fig 6 using equivalent system impedances as seen from the fault location. The effect of shunt reactors, shunt and series capacitors, and distributed line capacitances have to be included in the calculations where significant. This applies particularly to applications involving long lines and EHV lines [B1]. Where the shunt capacitance of lines is large, there may be significant additional voltage rise due to line-charging currents, harmonics due to transformer saturation, and (less frequently) resonance effects.

Fig 6
COG Calculations

The following equations can be used to calculate the COG. The equations are applicable for $Z_1 = Z_2$, but do not include fault resistance.

Single line-to-ground (SLG) fault on phase a:

$$\text{COG (phase b)} = -\frac{1}{2}\left[\frac{\sqrt{3}k}{2+k} + j1\right]$$

$$\text{COG (phase c)} = -\frac{1}{2}\left[\frac{\sqrt{3}k}{2+k} - j1\right]$$

Double line-to-ground (DLG) fault on phases b and c:

$$\text{COG (phase a)} = \frac{\sqrt{3}k}{1+2k}$$

where:

$$k = \frac{Z_0}{Z_1} = \frac{R_0 + jX_0}{R_1 + jX_1}$$

In general, fault resistance tends to reduce COG, except in low-resistance systems. To include fault resistance (R_f), the definitions of k above would have to be modified as follows:

For SLG fault:

$$k = \frac{R_0 + R_f + jX_0}{R_1 + R_f + jX_1}$$

For DLG fault:

$$k = \frac{R_0 + 2R_f + jX_0}{R_1 + 2R_f + jX_1}$$

where:

R_f = Fault resistance

NOTE: Appendix A of IEEE Std C62.92-1987 [10] contains additional information for determining coefficients of grounding, more thoroughly addressing this subject.

3.3.2.2 Other Causes of Temporary Overvoltages. Other causes of TOV include, but are not limited to

(1) Loss of neutral ground on a normally grounded system.
(2) Sudden loss of load or generator overspeed, or both.
(3) Resonance effects and induction from parallel circuits.

(4) Accidental contact with conductors of a higher voltage system.

3.3.3 Switching Surge Durability. Surge arresters dissipate switching surges by absorbing thermal energy. The amount of energy is related to the prospective switching surge magnitude, its waveshape, the system impedance, circuit topology, the arrester voltage-current characteristics, and the number of operations (single, multiple events). The selected arrester should have an energy capability greater than the energy associated with the expected switching surges on the system.

The actual amount of energy discharged by a metal-oxide arrester during a switching surge can be determined through detailed system studies performed with a Transient Network Analyzer (TNA) and/or a digital circuit analysis program such as the Electromagnetic Transients Program (EMTP). When such study results are not available, the approximate arrester duty due to energizing and reclosing operations on transmission lines can be estimated from the following equation and curves.

The energy discharged by an arrester, J, in kilojoules, may be conservatively estimated by the equation

$$J = \frac{2D_L E_A I_A}{v} \qquad \text{(Eq 1)}$$

where:

E_A = Arrester switching impulse discharge voltage (in kilovolts) for I_A
I_A = Switching impulse current (in kiloamperes)
D_L = Line length (in miles or kilometers)
v = The speed of light (190 miles/ms or 300 km/ms)

The equation assumes that the entire line is charged to a prospective switching surge voltage and is discharged through the arrester during twice the travel time of the line. The discharge voltage and current are related by the equation:

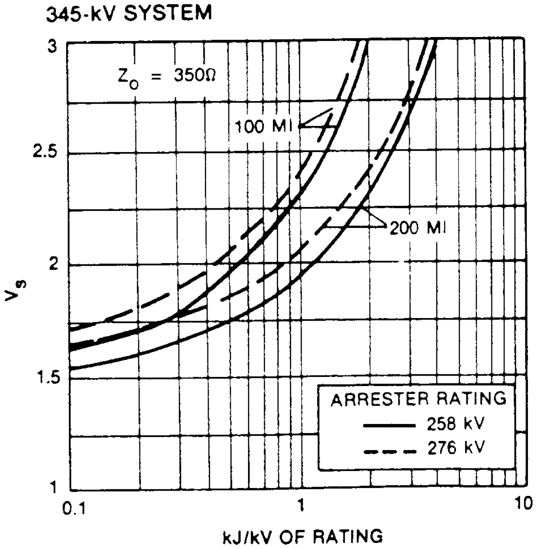
$$I_A = \frac{E_S - E_A}{Z} \qquad \text{(Eq 2)}$$

where:

E_S = Prospective switching surge voltage (in kilovolts)
Z = Single-phase surge impedance of line (in ohms)

To determine the prospective discharge energy, manufacturer data should be consulted to first determine consistent values of E_A and I_A per Eqs 1 and 2.

The calculated energy can then be plotted in curve form for varying quantities of line length, switching impulse voltage, and surge impedance. A typical curve is shown in Fig 7 for a 209 kV MCOV rated arrester (258 kV duty cycle rating) on a 345 kV, 100 mile transmission line that dissipates approximately 0.33 MJ of energy during a 2.5 p.u. switching surge. Since arresters are constructed with series repeated sections, the energy can be presented in per-units on MCOV or duty cycle rating. In this case, 0.33 MJ translates to 1.58 kJ/kV of MCOV or 1.28 kJ/kV of duty cycle rating. The energy capability of station class arresters is within the range of 4.0 kJ/kV to 20.0 kJ/kV of MCOV and is a function of the volume, formulation, and processing of the metal-oxide disk. The number of discharges allowed in a short period of time (approximately 1 min or less) is the arrester energy capability divided by the energy per discharge. A curve is also shown for a 276 kV duty cycle rated arrester. Additional information is contained in the application guides of the manufacturer.



NOTE: V_s is prospective voltage in per unit of peak line-to-ground system voltage.

Fig 7
Typical Curve for a Prospective Switching Surge Voltage Versus Arrester Discharge Energy for a 345 kV Line

3.3.4 Tentative Selection of Arrester Voltage Rating.

The arrester voltage rating should be tentatively selected on the basis of MCOV (3.3.1), TOV (3.3.2), and switching surge durability (3.3.3).

Special conditions that should be considered in choosing the arrester voltage rating are:

(1) *Abnormal system operating voltages.* The selection of arrester voltage ratings based on maximum system voltages assumes that, in service, the maximum system voltage is exceeded only under abnormal operating conditions, and only for durations within the arrester TOV capability. However, if maximum system voltages used in determining temporary overvoltages as in 3.3.2.1 are likely to be exceeded frequently, increasing the probability of arrester operations during such conditions, it may be necessary to use an arrester with higher voltage ratings. Other causes of TOV as listed in 3.3.2.2 require consideration on an individual basis; no general rules are applicable.

If any grounding source could be disconnected by sectionalizing, the effect on the COG and the arrester rating should be checked.

(2) *Abnormal system frequency.* Normal system frequency of less than 48 Hz or more than 62 Hz may require special consideration in the design or application of surge arresters and should be a subject of discussion between the user and the manufacturer.

3.3.5 Selection of Arrester Class.

The arrester class should be selected on the basis of required level of protection (protective levels summarized in Table 1) and the following:

(1) Available voltage ratings
(2) Pressure relief current limits, which should not be exceeded by the system's available short-circuit current and duration at the arrester location
(3) Durability characteristics (see Table 1) that are adequate for systems requirements

The class of arrester selected may be influenced by the importance of the station or equipment to be protected. For example, station-class arresters should be used in large substations. Intermediate-class arresters may be used in smaller substations and on subtransmission lines and cable terminal poles at 161 kV and below. Distribution-class arresters might be used in small distribution substations to protect distribution voltage buses.

3.4 Protective Levels of Arrester (Item 2, Fig 5)

3.4.1 Determination of Protective Levels. Protective levels are determined by either sparkover voltages or discharge voltages of the arrester under consideration, based on the measurement procedure outlined in Sections 8.3 and 8.4 of IEEE Std C62.11-1987 [9]. The following protective levels should be considered.

(1) *FOW*: The higher value of FOW sparkover or arrester discharge voltage cresting in 0.5 μs at the classifying current.

(2) *LPL*: The higher value of lightning impulse sparkover for a 1.2/50 μs lightning impulse or arrester discharge voltage that results from a 8/20 μs current wave. The appropriate current magnitude is determined by the system voltage per Table 2.

(3) *SPL*: The higher value of switching impulse sparkover or arrester discharge voltage that results from a current wave with a time to actual crest of 45 μs to 60 μs. The appropriate current magnitude is based on the system voltage as contained in 3.4.3.

Table 2
Recommended Currents for Determining Discharge Voltage in Shielded Stations With Shielded Incoming Lines

Maximum System Voltage (kV)	Coordinating Current (kA)
72.5	5
121	5
145	5
242	10
362	10
550	15
800	20

3.4.2 Arrester Coordinating Currents for Lightning Surges

3.4.2.1 Factors That Affect the Selection of Discharge Currents to Determine Discharge Voltage. In order to determine the protective levels of the arrester for lightning surges, proper coordinating currents need to be determined. Factors that affect this selection include

(1) The importance and degree of protection desired. Basing protective levels on higher current magnitudes and rates-of-rise increases the reliability of protection.

(2) The line insulation. The potential for higher lightning currents increases with higher line insulations (e.g., fully insulated wood poles), unless the stroke occurs so close to the arrester that the impedance and insulation of the line cannot influence the surge.

(3) The probability of occurrence of the higher stroke currents. The magnitude of lightning currents vary over a wide range of values [B12]. Lines in areas of high keraunic levels have an increased chance of being struck by lightning with high current magnitudes. (see Appendix A).

(4) Line performance and lightning environment. Coordinating currents and rates-of-rise are functions of the backflash and shielding failure rates of the lines (or flashover rates of unshielded lines) that are within some limiting distance from the station. Higher (lower) failure rates increase (decrease) the coordinating current magnitude and rate-of-rise.

3.4.2.2 Recommended Arrester Coordinating Currents for Lightning Surges. The appropriate coordinating current for lightning surges depends strongly on the effectiveness of line shielding.

3.4.2.2.1 Recommended Currents for Shielded Stations With Completely Shielded Lines. The lightning performance of shielded lines is based on their shielding failure and backflashover rates. If the position of the ground wire(s) relative to the phase conductors is such that the line is considered "effectively shielded" (i.e., protected from direct lightning strokes), then the number of line insulation flashovers due to shielding failures will be negligible, and backflashovers will be the predominant mechanism of line insulation flashover. In either event, the magnitude of the arrester discharge current can be estimated from

$$I = I_C = \frac{2.4E_{CFO} - E_C}{Z_0} \qquad \text{(Eq 3)}$$

I = Arrester discharge current (in kiloamperes)

I_C = Arrester coordinating current (in kiloamperes)

E_{CFO} = Negative CFO of line insulation (in kilovolts)

E_C = Arrester discharge voltage (in kilovolts) for the estimated value of the coordinating current—see Table 2

Z_0 = Single-phase surge impedance of line (in ohms)

This relationship assumes the line flashover occurs at a considerable distance from the station or that the phase conductor is struck without ensuing flashover. Otherwise, the portion of the total stroke current discharged through the arrester can vary considerably depending upon the parameters involved.

Using typical system parameters and the above equation, Table 2 contains coordinating currents that have been found to be satisfactory in most situations.

3.4.2.2.2 Discharge Currents Where Lines Are Shielded for a Short Distance Adjacent to the Station. Where shielding does not include the entire line, increased arrester discharge currents become more probable. In assessing the probability of an arrester discharge current, it is necessary to consider

(1) The ground flash density

(2) The probability of strokes to the line exceeding a selected value

(3) The percentage of total stroke current that discharges through the arrester

(1) and (2) can be evaluated using the methods of [B8] or from the ground flash density maps published by EPRI [B12]. Conservative guidelines for (3) are contained in the table on the following page [B49].

Distance Line Shielding Extends From Station	Percent of Stroke Current Discharged Through Arrester
0.5 mi (0.8 km)	50
1.0 mi (1.6 km)	35
1.5 mi (2.4 km)	25

3.4.2.2.3 Discharge Currents in Stations Where Lines Are Not Shielded. Completely unshielded lines usually are limited to either

(1) Lower voltage lines, (i.e., 34.5 kV and below); and/or
(2) Lines located in areas of low lightning ground flash density

The probability may be high that arresters in the lower voltage stations are subjected to large currents and rates-of-rise in areas of high lightning ground flash density. In these cases, the coordinating current should not be less than 20 000 A. In severe thunderstorm areas, higher levels should be considered.

For lines located in areas of low lightning ground flash density, coordinating currents may be similar to those for completely shielded lines in areas of high lightning ground flash density. In this case, no specific guidelines can be given, and special studies are required.

3.4.3 Arrester Coordinating Currents for Switching Surges. The current an arrester conducts during a switching surge is a complex function of both the arrester and the details of the system. The effective impedance seen by the arrester during a switching surge can vary from several hundred ohms for an overhead transmission line to tens of ohms for arresters connected near cables and large capacitor banks. In these two cases, the arrester current and the resulting arrester energy vary significantly for a switching surge of a given magnitude and duration.

In the case of arresters connected to overhead transmission lines, the recommended - switching surge coordinating currents (per IEEE Std C62.11-1987 [9]) are listed in the following table:

Maximum System Voltage (kV)	Station Class (A crest)	Intermediate Class (A crest)
3–150	500	500
151–325	1000	----
326–900	2000	----

3.5 Locating Arresters and Determining Voltage at Protected Equipment (Item 3, Fig 5). A major factor in locating arresters within a station is the line and station shielding. It is usually feasible to provide shielding for the substation even if the associated lines are unshielded. Station shielding reduces the probability of high voltages and steep fronts within the station resulting from high-current lightning strokes. However, it should be recognized that the majority of strokes will be to the lines, creating surges that travel along the line and into the station [B24]. If the lines are shielded, the surges entering the station are less severe than those from unshielded lines. Consequently, the magnitude of the prospective arrester currents are lower, resulting in lower arrester protective levels.

As a general rule, the voltage at the protected equipment is higher than the arrester discharge voltage (see 2.5 and Appendix C). Therefore, it is always good practice to reduce separation between the arrester and major equipment to a minimum. However, it is sometimes possible to protect more than one piece of equipment with a single arrester installation provided that rates-of-rise can be restricted, as in the case where both the station and overhead feeder lines are shielded.

3.5.1 Locating Arresters in Unshielded Installations. Such installations are subjected to the highest lightning currents and voltage rates-of-rise. The minimum possible separation is recommended for installations where complete shielding is not used.

With a single unshielded incoming overhead line, the arrester should be located as near as possible to the terminals of the equipment (usually a transformer) to be protected.

When several unshielded incoming overhead lines meet in the station, the incoming overvoltage waves are reduced by refraction. However, consideration should be given to the case when one or more of the lines are out of service.

When one or more circuit breakers or disconnecting switches are open in such a station, the corresponding line entrances or certain parts of the station may be left without protection from the arresters at the transformers. Lightning flashover of insulation on a de-energized line is unlikely to cause damage, but other insulation in equipment such as circuit breakers, potential transformers, and current transformers connected on the line side might be damaged. If protection is required in such cases, arresters or gaps can be installed at the respective line entrances.

3.5.2 Locating Arresters in Shielded Installations. Incoming voltages from shielded lines are lower in amplitude and steepness than voltages from unshielded lines. In many cases, this will permit some separation between the arresters and the insulation to be protected.

With a single shielded incoming overhead line, one set of arresters may be located at a point that provides protection to all equipment but gives preference to the transformer. The method in Appendix C can be used to determine the maximum separation distance between the arrester and the transformer.

At stations with multiple shielded incoming overhead lines (associated with large installations with transformers, switchgear, and measuring equipment), arresters are not always placed at the terminals of every transformer. The methods described in 3.7.1 and Appendix C can be used to determine maximum separation distances for arresters used to protect more than one transformer. More important installations may justify a detailed transient study. Such studies and interpretation of their results are outside the scope of this guide.

Consideration has to be given in the calculations to the possibility that the station may become sectionalized, or that lines may be disconnected during service. Under all circumstances, it has to be possible to maintain proper protective ratios for both lightning and switching surges as given in 3.7.1.

3.5.3 Cable-Connected Equipment. Cable-connected equipment involves a station, substation, or individual apparatus connected to cable, which in turn is connected to an overhead line. The overhead line may or may not be shielded at the line-cable junction. In the case of unshielded overhead lines, it may be advantageous to mount additional protective devices a few spans before this junction.

3.5.3.1 Arresters at Protected Cable-Connected Equipment. If arresters can be installed at the equipment, a procedure analogous to that outlined in 3.5.2 should be followed. However, the methods of 3.7.1 and Appendix C are not applicable ([B14], [B46], [B56]).

The grounded end of any arrester installed at the protected equipment should be connected to the equipment ground and the station ground with the shortest possible lead.

3.5.3.2 Arresters at the Overhead Line-Cable Junction. It may be necessary to install arresters at the overhead line-cable junction for protection of junction equipment. If it is impossible or undesirable to install arresters at the protected equipment terminals, it is then necessary to determine whether adequate protection can be obtained with an arrester at the junction. The following procedure may be used.

(1) Determine the length of the cable connection.
(2) Determine the maximum impulse voltage at the protected equipment, using procedures and recommendations from either [B47] or [B56].

Arresters installed at the line-cable junction should be grounded to the station ground through a low-impedance path, which may be the cable shield if suitable. If the cable shield is not suitable, or for cables without a metallic shield, the grounded end of the arrester should be connected to the station ground with a conductor in proximity to the cable. Special consideration may be necessary for cables with shields that cannot be grounded at both ends because of shield currents.

Determining Insulation Strength (Item 4, Fig 5). BILs and BSLs and CWW voltages may be obtained from equipment standards. However, BSLs and CWWs do not exist for all equipment voltage ratings. Refer to IEEE Std C57.12.00-1987 [4], IEEE Std C57.13-1978 [6], IEEE Std C57.21-1990 [7], and IEEE Std C37.04-1979 [3].

The BSL for various types of equipment is presented in Table 3. The optional front-of-wave test for some transformers and reactors is also listed but is not used in this guide for purposes of insulation coordination.

The negative polarity lightning impulse CFO voltage of air insulation is approximately 180 kv/ft (600 kV/m). Bus and line support insulators have volt-time characteristics that in-

Table 3
Factors for Estimating Withstand Voltages of Mineral-Oil-Immersed Equipment

Impulse Duration	Withstand Voltage	Type of Equipment
Front of wave (0.5 μs)	1.30 to 1.50 x BIL	Transformers and reactors
Chopped wave (2 μs)*	1.29 x BIL	Breakers 15.5 kV and above
Chopped wave (3 μs)*	1.10 to 1.15 x BIL	Transformers and reactors
Chopped wave (3 μs)*	1.15 x BIL	Breakers 15.5 kV and above
Full wave (1.2/50 μs)	1.00 x BIL	Transformer and reactor windings
Switching surge—250/2500 μs wave	0.83 x BIL	Transformer and reactor windings
Switching surge—250/2500 μs wave	0.63 to 0.69 x BIL	Bushings
Switching surge—250/2500 μs wave	0.63 to 0.69 x BIL	Breakers 362–800 kV†

*Time to chop
†Includes air blast and SF_6 breakers

crease substantially at short times to flashover. At 3 μs the breakdown voltage is approximately 1.3 to 1.4 times the CFO.

3.6 Evaluating Insulation Coordination (Item 6, Fig 5). Insulation coordination is evaluated on the basis of the margin between the insulation strength and the surge voltage at the equipment terminals, which may be estimated by use of Appendix C. If separation distances are less than those shown in Table 4, use of Appendix C is not necessary.

In general, there are two methods of portraying insulation coordination

(1) The tabulation of protective ratios or margins; and
(2) The graphical presentation of coordination.

Regardless of the method, the same minimum protective ratios and margins apply. The graphical presentation is shown in Fig 8. It should be recognized that data from the four (at most) generally available insulation tests can be used to develop an approximate insulation volt-time curve. A curve plotted in accordance with Fig 8 is a graphical interpretation of the test results, which is presented as an aid to insulation coordination. It is not a true volt-time curve for the transformer. Similarly, the arrester curve is simply a representation of the three protective levels.

Evaluation of insulation coordination by the curve method is made in accordance with Fig 8.

3.6.1 Alternative Method (Item 6.1, Fig 5). If the sum of the arrester lead length and the transformer-to-arrester separation distance is less than the values presented in Table 4, the voltages at the equipment need not be determined. The assumptions made in developing the values in Table 4 are similar to those used in C5, using station-class surge arresters. The rate of rise of incoming surge on the transmission line was assumed to be 11 kV/μs per kilovolt of MCOV rating to a maximum of 2000 kv/μs as specified in IEEE Std C62.11-1987 [9].

For the situation discussed above, the following protective ratios for lightning overvoltages (PR_{L1} and PR_{L2}) and for switching overvoltages (PR_S) apply:

PR_{L1} = CWW/FOW
PR_{L2} = BIL/LPL
PR_S = BSL/SPL
PM_{L1} = $(PR_{L1} - 1)\,100\,(\%)$
PM_{L2} = $(PR_{L2} - 1)\,100\,(\%)$
PM_S = $(PR_S - 1)\,100\,(\%)$

For acceptable coordination, PR_{L1} and PR_{L2} have to be equal to or greater than 1.2 (PM_{L1} and $PM_{L2} \geq 20\%$), and PR_S has to be equal to or greater than 1.15 ($PM_S \geq 15\%$).

3.6.2 Voltage at Equipment Calculated (Item 6.2, Fig 5). If the alternate method is not applicable and the voltage at the equipment, E_T, is calculated by methods presented in Appendix C, the protective ratios and margins are as follows:

If the time-to-crest of the arrester voltage is equal to, or less than 2 μs:

PR_{L1} = CWW/E_T
PM_{L1} = $(PR_{L1} - 1)\,100\,(\%)$

If CWW does not exist or the time-to-crest of the arrester voltage is greater than 2 μs:

PR_{L2} = BIL/E_T
PM_{L2} = $(PR_{L2} - 1)\,100\,(\%)$

Also

PR_S = BSL/SPL
PM_S = (PRS – 1) 100 (%)

For acceptable coordination PR_{L1} or PR_{L2} and PR_S have to be equal to or greater than 1.15 (PM_{L1} or PM_{L2} and $PM_S \geq 15$).

3.7 Evaluation of Alternatives (Item 7, Fig 5). If acceptable coordination cannot be achieved, the following measures may be evaluated:

(1) Increase the BIL and BSL.
(2) Decrease arrester-transformer separation distance.
(3) Add additional arresters.
(4) Use arresters with lower protective characteristics.

Since the method presented in Appendix C is conservative, an additional suggestion is to determine the surge voltage at the equipment more accurately by the use of computers. The criteria per 3.7.2 are suggested for evaluation of insulation coordination.

3.8 Transformer or Other Series Windings, Unloaded Windings, and Ungrounded Neutrals

3.8.1 Protection of Series Windings. Sometimes it is desirable to provide surge protection across series windings of equipment. When arresters are connected in parallel with the series winding, it is necessary to insulate both arrester terminals from ground.

3.8.1.1 Location of Arrester. Install the arrester at or close to the terminals of the equipment.

3.8.2 Unloaded Transformer Windings. In some cases, multiwinding transformers have connections brought out to external bushings that do not have lines connected. Arresters should always be connected at or close to the terminals of such bushings.

3.8.3 Protection of Transformer Ungrounded Neutral. This section applies to wye-connected (Y-connected) transformers or transformer banks, with neutrals isolated or grounded through an impedance.

Neutral terminals are subjected to surge voltages as a result of overvoltages at the line terminals propagating through the windings, and thus may require arrester protection. Neutral terminals are also subjected to temporary voltages caused by line-to-ground faults.

In selecting an arrester voltage rating for protection of a neutral terminal, the general considerations of 3.3.1 and (1) of 3.3.2.2 are particularly applicable. The equations of Fig 6 cannot be used. The required overvoltage at the neutral is equal to system zero-sequence voltage during faults involving ground. Calculations using the method of symmetrical components are straightforward [B9].

If the transformer power source is switched with single-phase devices or protected by fuses, the voltage at the ungrounded neutral may become equal to system phase-to-neutral voltage for an extended period. This condition occurs when one fuse or switch remains closed while the other two remain open. Since the neutral voltage for this condition will generally be higher and of longer duration than the TOV due to ground faults, it should be taken into account when selecting the MCOV rating for the neutral arrester.

Care has to be taken to use the BIL of the neutral (which is not usually as great as the transformer BIL) in determining required arrester protective level. A protective level PR_{L2} = BIL (neutral)/LPL of 1.2 is required; where LPL is the discharge voltage (usually at 3 kA for determining this PR) or the gap sparkover voltage.

Table 4
Allowable Separation Distance in Meters for Single-Line, Single-Transformer Stations*

BIL (in kV)	MCOV Ratings (kV)†																							
	42	48	57	70	76	84	98	106	115	131	140	144	152	181	190	209	212	220	230	235	245	318	335	353	372	462	470	485
250	15	8	3																									
350	55	32	17	7	4																							
450				20	14	9	4	2																				
550				44	31	21	12	8	5																			
650						41	22	16	12	6	4																	
750							39	29	21	12	9	8	6															
825											14	12	10	4	2													
900											20	18	14	7	5	3												
1050																8	7	6	5	4	3							
1175																14	12	11	9	8	7							
1300																						2	1					
1475																						6	4	2				
1550																						11	8	6	4			
1675																						16	13	11	8			
1800																						22	19	16	13	2		
1925																										6	5	3
2050																										10	9	4

*This table is based on the following:
— Use of station-class surge arresters
— Use of maximum value for the 0.5 μs FOW protective level from Table 1
— Use of 7.6 m for the surge arrester lead length

†The MCOV ratings in this table are commonly used. Use Appendix C for other ratings.

NOTES: (1) Use Appendix C for all cases not covered by this table.
(2) Conversion factor to feet: meters divided by 0.30481.
(3) The allowable separation distances in this table were rounded off.

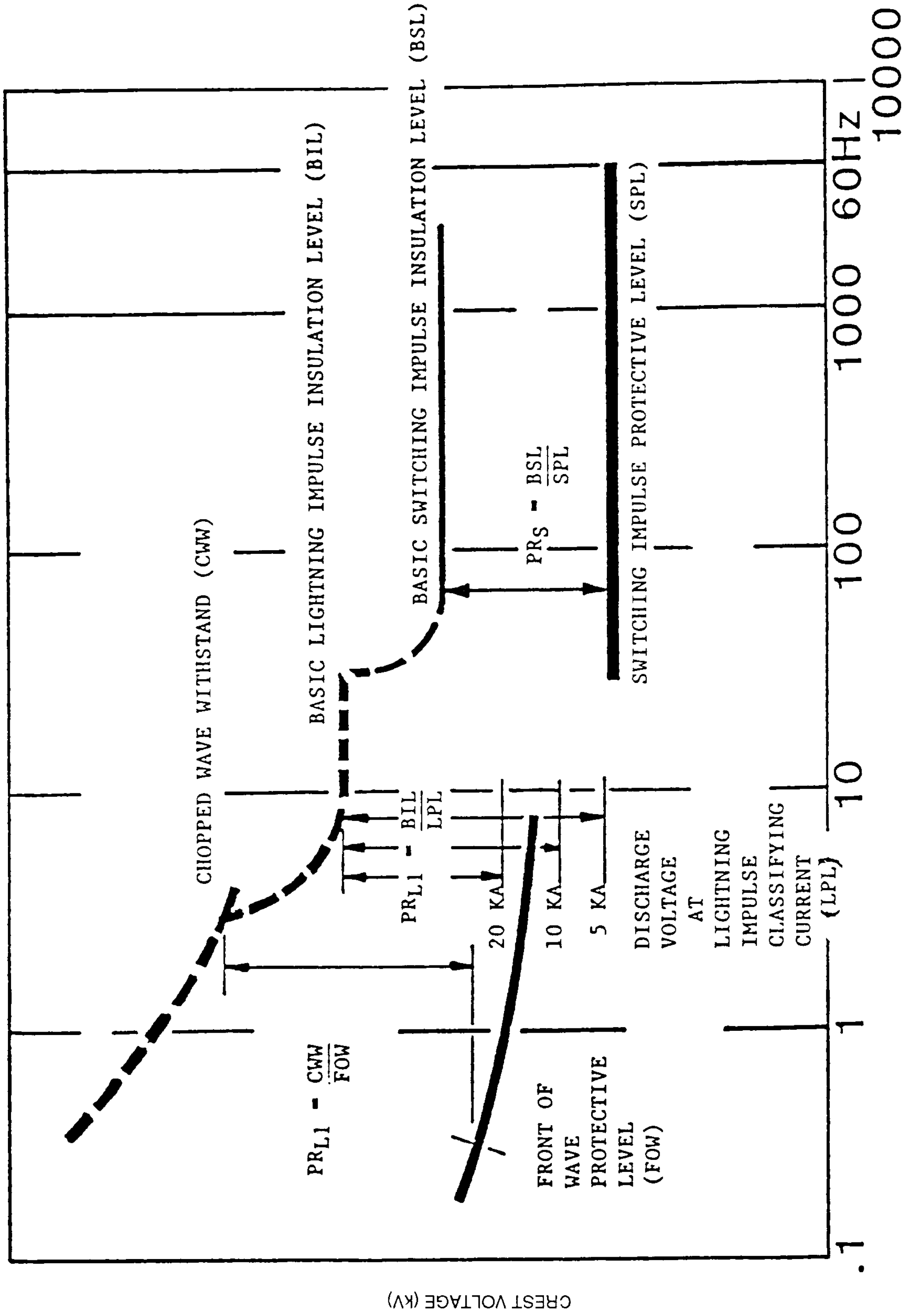


Fig 8
Typical Volt-Time Curve for Coordination of Arrester Protective Levels With Insulation Withstand Strength for Liquid-Filled Transformers

3.9 Protection of Dry-Type Insulation. The dry-type insulation equipment covered by this subsection includes such apparatus as dry-type transformers, which may have full-wave impulse withstand insulation strengths lower than liquid-immersed equipment of the same voltage rating. Generally, the impulse withstand strengths with waves of short duration are considered to be the same, or nearly the same, as the full-wave impulse withstand strength, as given for dry-type transformers in Table 3 of IEEE C57.12.01-1989 [5]. Check with the manufacturer of the equipment for specific values.

3.9.1 Protection of Dry-Type Transformers. The following procedure is recommended:

(1) Apply the information in 3.3 for selection of the arrester rating and class.
(2) Determine the minimum permissible full-wave impulse insulation strength (BIL) of the transformer by multiplying the FOW protective level of the arresters by 1.2.

3.10 Overvoltage Protection of Shunt Capacitor Banks. Overvoltage protection should be considered whenever shunt capacitor banks are installed regardless of connection.

The possibility of overvoltages from lightning, switching surges, and temporary overvoltages requires a detailed evaluation to determine the duty on surge arresters applied in the vicinity of a shunt capacitor bank. Due to the low surge impedance of large high-voltage shunt capacitor banks, it may not be necessary to add arrester protection against lightning beyond that which already exists in the substation. However, additional protection may be needed at the station and in the vicinity to protect equipment from overvoltages caused by capacitor switching or by switching of lines or transformers in the presence of capacitors. Also, some existing surge arresters, in particular gapped silicon-carbide, may have to be replaced with units of higher energy capability because of the higher duty imposed by the addition of shunt capacitors.

Overvoltage protection or other measures may be required

(1) On the capacitor primary and back-up switchgear to limit transient recovery voltages (TRVs) when shunt capacitor banks are switched off
(2) At the end of transformer terminated lines to limit phase-to-phase surges resulting from capacitor switching or line switching in the presence of shunt capacitor banks
(3) When transformers are energized in the presence of shunt capacitor banks
(4) Due to the resonances while switching shunt capacitor banks
    (a) Through or in parallel with transformers
    (b) In the presence of other capacitor banks.
(5) Due to voltage magnification on an inductively coupled lower voltage system when a capacitor is switched on the higher-voltage system
(6) For the neutrals of ungrounded shunt capacitor banks

For additional information, see IEEE Std 18-1980 [B27].

3.11 Overvoltage Protection of High-Voltage Underground Cables. Many of the concerns identified in 3.11 should be considered also for high-voltage cable installations. In addition, overvoltage protection of the junction between overhead lines and cables, as discussed in 3.5.3, should be evaluated. Lightning may also be an important consideration at cable terminals. Cables may require further consideration because of traveling wave phenomena and the effects of distributed and smaller capacitance values.

3.12 Overvoltage Protection of Gas-Insulated Substations (GIS). Overvoltage protection is required at the junction to overhead, and may be required within the GIS bus depending on arrangement and length. In addition, capacitor voltage transformers (CVT) have been used at the overhead junction to extend the protective zone of the arrester at that location.

The above arresters are in addition to those required for the protection of other equipment such as transformers and reactors.

3.13 Protection of Rotating Machines. At present a guide for the protection of rotating machines is in preparation.[3]

4. Protection of Distribution Systems

4.1 Introduction. This section covers the application of metal-oxide surge arresters to safeguard electrical distribution equipment and lines against the hazards of abnormally high voltage surges, particularly those caused by lightning. Although the basic principles of arrester selection and application as outlined in Section 3 also apply to distribution arresters, there are specific differences that require special consideration.

Distribution lines are generally not shielded and therefore are particularly susceptible to direct lightning strokes([B8], [B17], [B21], [B41], [B42], and [B43]). The transient overvoltages developed by lightning are of greater concern than those caused by switching of distribution systems. Insulation coordination based on lightning surge voltages is thus the major consideration for distribution systems.

A study has determined([B15] and [B18]) that lightning current through overhead distribution arresters occur as plotted in Fig 9(a). The coulombs discharged by arresters, taken from the same study, are plotted in Fig 9(b). The duty imposed on arresters connected to distribution lines can be severe because of lightning current discharge requirements.

Other potential causes of severe arrester duty occur when arresters are used to protect switched capacitor banks (see 4.8.1) or when arresters are subjected to ferroresonant overvoltages (see 4.4.4).

Distribution equipment, including arresters, is low in unit cost compared to station equipment, but it is used in large quantities. It is usually not economically feasible to make independent studies for each specific arrester application. Consequently, distribution arresters are usually selected so that they can be used for similar application anywhere on a system rather than for a particular location.

4.2 General Procedure. The general procedure for selecting a distribution arrester is to determine the proper arrester MCOV that can be used at all similar locations on the distribution system to be protected.

Also, the TOV capability of the arrester should not be exceeded by the magnitude and duration (total accumulated cycles) of any TOV of the system at the arrester location. For arrester application on distribution systems, the TOV is usually based on the maximum phase-to-ground voltage that can occur on unfaulted phases during single line-to-ground faults. Surge arrester selection is discussed in 4.3.

Insulation coordination is discussed in 4.5. For system voltages up to 15 kV, insulation coordination for overhead connected equipment has not been rigorously studied because the PM between standard equipment BIL and the protective characteristics of modern distribution arresters is substantially in excess of 20% in usual applications. Insulation coordination becomes a primary consideration for higher distribution voltage systems because PM is reduced (particularly when reduced BIL values are used). Insulation coordination may also be important for line protection (see 4.6) and for protection of underground distribution systems (see 4.8.4).

4.2.1 Installation Practices That Jeopardize Insulation Coordination. Installation practices that jeopardize insulation coordination include the following:

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[3] IEEE P687.

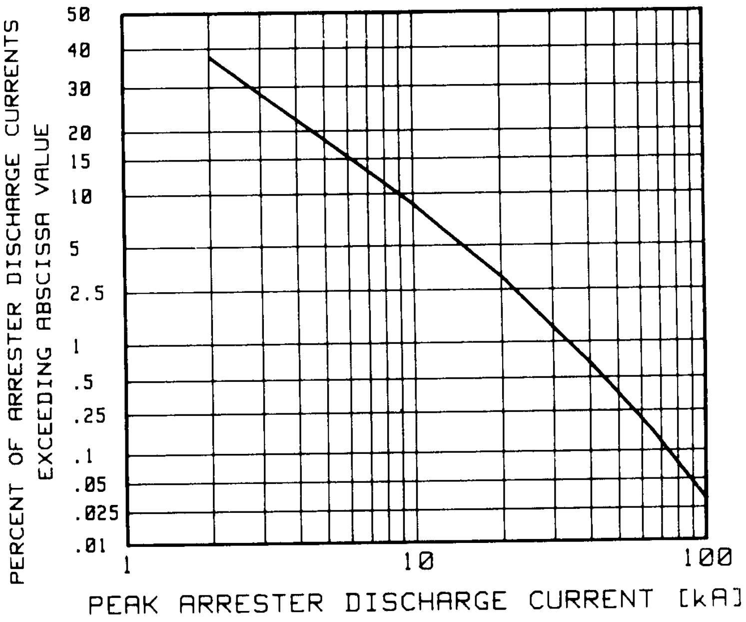


Fig 9a
Lightning Discharge Duty of Arresters on Distribution Systems [B15]*

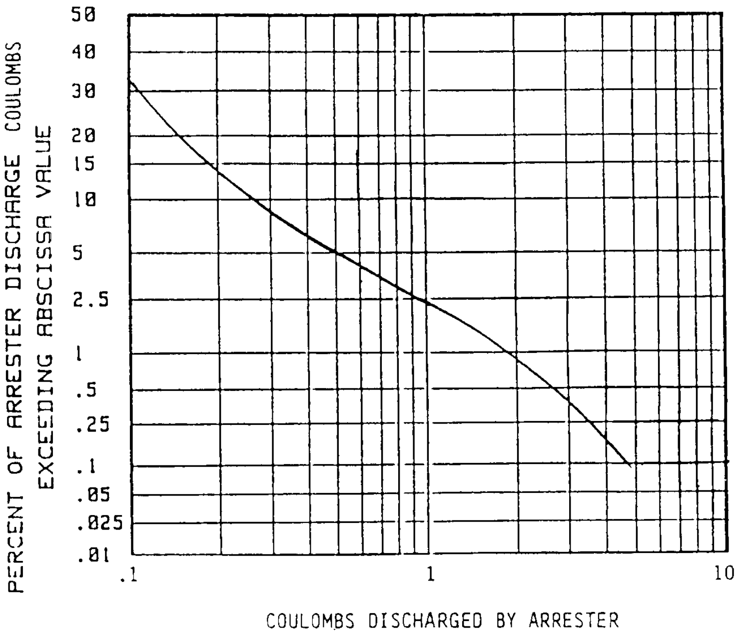


Fig 9b
Coulomb Discharge Duty of Arresters on Distribution Systems [B15]*

NOTE: Even though the data in Fig 9b exceed the test requirements of IEEE Std C62.11-1987 [9] in some tests, arresters meeting these requirements have been in service since the early 1980s with no indication of excessive failure rates due to discharges beyond their capability. Possible reasons for the relatively low failure rates may be

(1) Long duration lightning currents are shared by metal-oxide arresters more effectively than by silicon-carbide arresters.
(2) The frequency of occurrence of high coulomb lightning discharge per arrester has been shown to be low ([B15] and [B18]).
(3) Most arresters have capabilities higher than IEEE Std C62.11-1987 [9] requires.
(4) The curve of coulombs discharged might be somewhat higher than it should be, and this point is under study.

*Derived from data in [B15].

(1) Long leads between line and arrester line terminal and between arrester ground terminal and tap to the equipment case (see 4.7.1)

(2) Large separation distances between the arrester and the protected equipment (see 4.7.2)

(3) Failure to interconnect the arrester and equipment ground terminals (see 4.7.4)

4.2.2 Applications Requiring Special Considerations. Applications that require special considerations, either in regard to duty requirements imposed on the arrester or in regard to protection requirements, include the following:

(1) Ungrounded systems (see 4.4.5)

(2) Shunt capacitor banks (see 4.8.1)

(3) Switches, reclosers, etc. (see 4.8.2)

(4) Voltage regulators (see 4.8.3)

(5) Underground circuits (see 4.8.4)

(6) Contaminated atmospheres (see 4.8.5)

4.3 Selection of Arrester Ratings. Power systems to be protected by distribution arresters are either

(1) Three-wire wye or delta, high or low impedance grounded at the source, or

(2) Four-wire multigrounded wye

Construction includes open wire, spacer cable, and underground cable systems.

Proper application of metal-oxide surge arresters on distribution systems requires knowledge of

- The maximum normal operating voltage of the power system, and
- The magnitude and duration of TOVs during abnormal operating conditions

This information has to be compared to the arrester MCOV rating (see 4.3.1) and to the arrester TOV capability (see 4.3.2). The user has to be careful not to replace silicon-carbide arresters with metal-oxide arresters that have the same duty cycle voltage rating without first analyzing the expected magnitude and duration of TOVs [B37].

Commonly applied voltage ratings of metal-oxide arresters on distribution systems are shown in Table 5. Protective characteristics of metal-oxide distribution arresters are given in Table 6.

4.3.1 MCOV Rating. Unlike a silicon-carbide arrester, the nonlinear disks inside a gapless metal-oxide surge arrester are continuously exposed to line-to-ground power-frequency voltage. The MCOV rating of a metal-oxide arrester is the maximum designated rms value of power-frequency voltage (at maximum temperature levels as indicated in IEEE Std C62.11-1987 [9]) that may be applied continuously between the terminals of the arrester. Consequently, the MCOV rating has to be at least equal to the expected maximum continuous operating voltage at the location where the arrester is to be applied.

Table 5
Commonly Applied Voltage Ratings of Metal-Oxide Arresters on Distribution Systems[*]

System Voltage (V rms)		Commonly Applied Arrester Voltage Ratings (kV rms) Duty Cycle Voltage Rating (MCOV)[†]		
Nominal Voltage	Maximum Voltage Range B[‡]	Four-wire Multigrounded Neutral Wye	Three-Wire Low Impedance[§] Grounded[**]	Three-Wire High Impedance[§] Grounded
2400	2540			3 (2.55)
4160Y/2400	4400Y/2540	3 (2.55)	6 (5.1)	6 (5.1)
4260	4400			6 (5.1)
4800	5080			6 (5.1)
6900	7260			9 (7.65)
8320Y/4800	8800Y/5080	6 (5.1)	9 (7.65)	
12000Y/6930	12700Y/7330	9 (7.65)	12 (10.2)[††]	
12470Y/7200	13200Y/7620	9 (7.65) or 10 (8.4)	15 (12.7)[††]	
13200Y/7620	13970Y/8070	10 (8.4)	15 (12.7)[††]	
13800Y/7970	14520Y/8380	10 (8.4)	15 (12.7)[††]	
13800	14520			18 (15.3)
20780Y/12000	22000Y/12700	15 (12.7)	21 (17.0)[††]	
22860Y/13200	24200Y/13870	18 (15.3)	24 (19.5)[††]	
23000	24340			30 (24.4)
24940Y/14400	26400Y/15240	18 (15.3)	27 (22.0)[††]	
27600Y/15930	29255Y/16890	21 (17.0)	30 (24.4)[††]	
34500Y/19920	36510Y/21080	27 (22.0)	36 (29.0)[††]	

[*] Spacer cable circuits have not been included. There has been insufficient experience with the application of metal-oxide arresters on spacer cable circuits to include them in this table. Refer to [B10] for information on spacer cable circuit overvoltages.

[†] For each duty cycle rating the MCOV is also listed.

[‡] See ANSI C84.1-1989 [1].

[§] Low-impedance circuits are typically three-wire, unigrounded at the source. High-impedance circuits are generally ungrounded (i.e., delta). Additional information regarding system grounding is contained in IEEE Std C62.92-1987 [10].

[**] Line-to-ground fault duration not to exceed 30 min. For longer durations, consult the TOV capability of the manufacturer.

[††] Individual case studies may show lower voltage ratings may be used.

4.3.2 TOV. Metal-oxide surge arresters are capable of operating for limited periods of time at power-frequency voltages above their MCOV rating. The amount of overvoltage that a metal-oxide arrester can successfully tolerate depends on the length of time that the overvoltage exists. Manufacturers can describe the arrester overvoltage capability in the form of a curve that shows temporary power-frequency overvoltage versus allowable time. A typical curve is shown in Fig 10. (These curves are sensitive to ambient temperature and prior energy input.)

Table 6
Distribution Arrester Protective Characteristics[*]

Voltage Ratings		Protective Level—Range of Industry Maxima (kV)					
Duty Cycle (kV rms)	MCOV[†] (kV rms)	FOW Protective Level			Discharge Voltage With 8/20 μs Wave		
		5 kA ND (1)	10 kA HD (2)	10 kA RP (3)[‡]	5 kA ND (1)	10 kA HD (2)	10 kA RP (3)[‡]
3	2.55	11.2–17	13.5–17	10.4	10.2–16	9.1–16	8.2
6	5.1	22.3–25.5	25.0–27	17.4–18	20.3–24	18.2–25	16.2
9	7.65	33.5–36	26.5-35.3	22.5–36	30.0–33.5	21.7–31.5	20.0–24.9
10	8.4	36.0–37.2	29.4–39.2	26.0–36	31.5–33.8	24.5–35	22.5–26.6
12	10.2	44.7–50	35.3–50	34.8–37.5	40.6–44	32.1–44	30.0–32.4
15	12.7	54.0–58.5	42.0–59	39.0–54	50.7–52	35.9–52	33.0–40.2
18	15.3	63.0–67	51.0–68	47.0–63	58.0–60.9	43.4–61	40.0–48
21	17.0	73.0–80	57.0–81	52.0–63.1	64.0–75	47.8–75	44.0–56.1
24	19.5	89.0–92	68.0–93	63.0–72.5	81.1–83	57.6–83	53.0–64.7
27	22.0	94.0–100.5	77.0–102	71.0–81.9	87.0–91.1	65.1–91	60.0–72.1
30	24.4	107.0–108	85.0–109.5	78.0–85.1	94.5–99	71.8–99	66.0–79.5
36	29.0	125.0	99.0–136	91.0–102.8	116.0	83.7–125	77.0–96

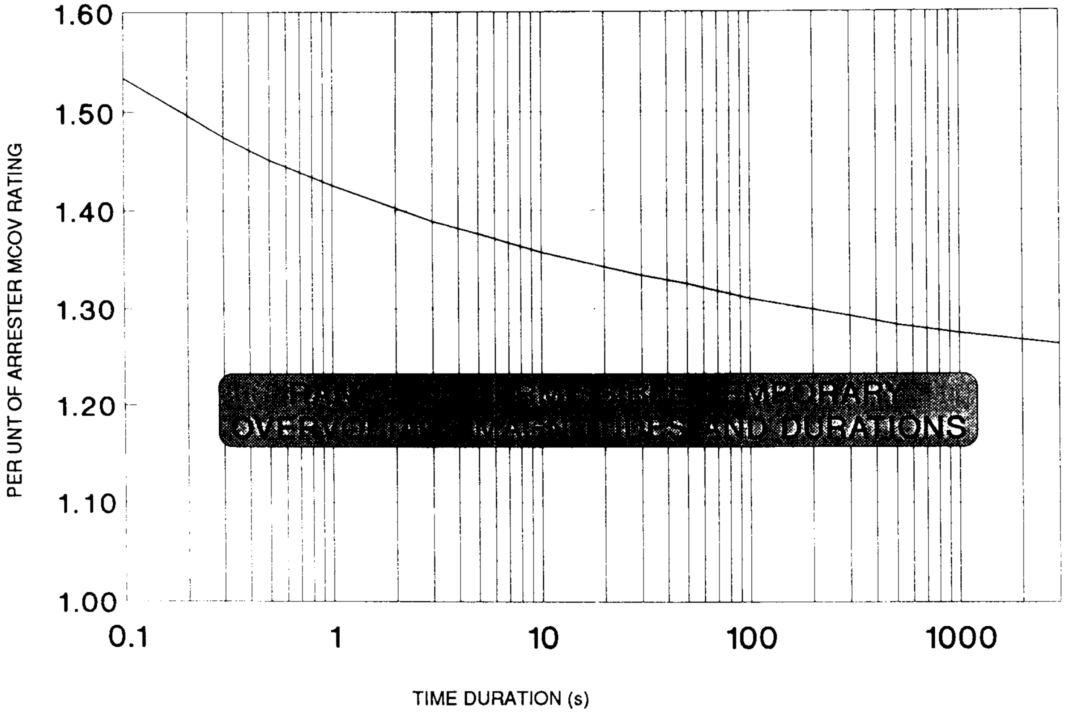
[*] Recent advances in arrester design may not be included in this table.

[†] MCOV = Maximum Continuous Operating Voltage

[‡] The term "Riser Pole" arrester is not a recognized arrester classification in IEEE Std C62.11-1987 [9]. It is, however, a designation commonly accepted in the industry and described in the published literature of manufacturers. RP arresters are characterized by their low protective characteristics, which make them suitable for protection of underground cable and equipment. They are normally installed at the riser, or dip, pole serving an underground system. Because of their lower protective characteristics, they may have overvoltage capabilities lower than normal or heavy-duty distribution arresters. Published TOV capabilities of the manufacturers should be consulted.

NOTES: (1) Classification current for ND (Normal Duty) arresters = 5 kA
(2) Classification current for HD (Heavy Duty) arresters = 10 kA
(3) Coordination current for RP (Riser Pole) arresters = 10 kA (see 4.8.4)

To ensure that the arrester TOV capability is not exceeded, the maximum TOV of the power system has to be determined along with the maximum time that the system is operated in the abnormal voltage state. This abnormal voltage state can result from several factors, some of which are: overvoltage on an unfaulted phase during a phase-to-ground fault, switching transients, and ferroresonance. In the case of the overvoltage due to a phase-to-ground fault, this voltage can be calculated using the equations shown in the Appendix of [B33], the methods described in [B39], or a computer program capable of modelling the distribution system. A conservative approach is to multiply the maximum phase-to-phase operating voltage by the coefficient of grounding (see Fig 6 and Appendix B). During this type of fault, the amount of time the surge arrester is subjected to the TOV is a function of the operating times of protective relays and fault interrupting devices. The MCOV of the arrester selected has to be high enough so neither the magnitude nor duration of the TOV exceeds the capability of the arrester.



NOTE: Example curve; consult manufacturer for exact curve.

Fig 10
Arrester Temporary Overvoltage Capabilities: No Prior Duty—Arrester Preheated to 60 °C

4.3.3 Normal-Duty Versus Heavy-Duty Surge Arresters. The application of normal or heavy-duty surge arresters is not well defined and is more a choice of the user than a decision based on actual firm requirements or performance data. To help the user make this decision, however, the background that led to the establishment of the heavy-duty arrester section of IEEE Std C62.1-1989 [8] (and that was carried over into IEEE Std C62.11-1987 [9]) may be useful.

In mid-1970, the industry sustained an unusually high failure rate of distribution arresters and transformers. Even though a limited amount of proven data was available, the industry attributed these failures to surges having greater energy than that for which the normal arrester was designed. Because of this assumption, the heavy-duty arrester section of IEEE Std C62.1-1989 [8] was established. The need for heavy-duty arresters was later questioned when it was discovered that the higher arrester failure rate was mostly due to moisture [B15] entering the arresters through an inadequate sealing system.

Distribution transformer failures in the same period were possibly due to high rate-of-rise lightning surges [B48], in combination with improper application of the arresters by some users, or induced surges in the secondary leading to primary winding failure [B11].

The table below compares tests performed on normal and heavy-duty arresters (IEEE Std C62.11-1987 [9]).

Test Performed	Normal Duty	Heavy Duty
High current-short duration	65 kA (4/10 μs)	100 kA (4/10 μs)
Low current-long duration	75 A · 2000 μs	250 A · 2000 μs
Duty cycle impulse current	5 kA (8/20 μs)	10 kA (8/20 μs)
Surges after duty cycle test	------	40 kA (4/10 μs)

The heavy-duty arrester is therefore capable of discharging a higher energy than a normal-duty arrester and should be used when greater than normal withstand capability is desired or required. High energies due to lightning are more likely to occur in areas with a high yearly number of thunderstorm days where lightning flashes are more frequent and there can be a higher number of lightning surges above 65 kA.

The total lightning current is unlikely to be discharged by a single arrester, and the amount of current discharged by an arrester depends on the distance between the strike and the arrester, the presence of other arresters, and the level of line insulation [B8].

Heavy-duty arresters could also be chosen to discharge higher energy surges, such as those generated while switching large capacitive loads. For these cases, other arrester classes may be considered.

Finally, it is to be noted that heavy-duty arresters may not necessarily have a lower discharge voltage characteristic than the normal-duty arrester, and that prior to selecting any arrester, all characteristics as well as the economics of one arrester type versus the other should be closely scrutinized.

4.4 Distribution System Overvoltages

4.4.1 Four-Wire Multigrounded-Wye Systems (Including Spacer-Cable Circuits). As mentioned above, the arrester MCOV has to be equal to, or greater than, the MCOV applied to the arrester.

Most distribution systems in use in North America are of the four-wire multigrounded type. In lieu of calculations to determine phase-to-ground voltages during ground faults, the general practice has been to assume the TOV on unfaulted phases rises above nominal line-to-ground voltage by a factor of 1.25 for four-wire multigrounded open-wire lines and 1.5 for spacer-cable circuits. The 1.25 factor for open-wire circuits only applies when line-to-ground resistance is low (i.e., less than 25 Ω) and neutral conductor size is at least 50% of the phase conductor [B39]. The factor can exceed 1.25 when small size neutral conductors are used (Appendix A of [B37]). Because the metal-oxide arrester may be more sensitive to overvoltages caused by poor grounding and poor regulation, and because the voltage-limiting effect of transformer saturation may be reduced in newer transformers, many utilities are using a factor of 1.35. The 1.5 factor remains valid for spacer cable circuits.

4.4.2 Three-Wire, Low-Impedance, Grounded Systems (Grounded at Source Only). As mentioned in 4.4.1, the arrester MCOV rating has to be greater than the MCOV applied to the arrester.

In lieu of calculations to determine phase-to-ground voltages during ground faults, the general practice has been to assume the TOV on the unfaulted phases rises to 1.4 p.u. [B4]. The maximum duration of this TOV has to be determined and the arrester overvoltage-versus-time curve examined to be sure the arrester can withstand the TOV for the duration of the fault.

If the unigrounded system is grounded through an impedance, the voltage rise on the unfaulted phases could easily be greater than 1.4 p.u. and therefore should be calculated. When a fault occurs at the arrester installation, the voltage on unfaulted phases can rise on the order of 80% [B4] due to the ground resistance at the point of fault. Values for both unfaulted phases should be calculated since grounding through a resistance can result in unequal voltages [B29].

Where it is possible to backfeed a portion of the circuit, which has been disconnected from the source, through devices such as transformers, or there are capacitors connected to that part of the circuit, the TOV should be assumed to be equal to the maximum phase-to-phase voltage. Again, be sure the duration of this situation is within the capability of the arrester. If duration cannot be determined, the arrester should be selected so that its MCOV rating equals or exceeds the maximum system phase-to-phase voltage.

4.4.3 Three-Wire, High-Impedance, Grounded or Delta-Connected Systems. As mentioned in 4.4.1, the arrester MCOV rating has to be equal to, or greater than, the MCOV applied to the arrester.

During a single line-to-ground fault, the line-to-ground voltage on the other two unfaulted phases will rise to line-to-line values. Because fault current values are extremely low, relaying schemes could allow this type of fault to exist for a considerable amount of time. Consequently, the general practice is simply to choose an arrester with an MCOV rating greater than the maximum system phase-to-phase voltage.

A lower MCOV rating may be used if fault detection relaying limits the duration, but the arrester has to have the capability to withstand line-to-line voltage for the maximum time required to clear the fault. This could result in a duty cycle rating lower than that recommended for a silicon-carbide arrester (but caution is advised in making this choice).

4.4.4 Overvoltages Caused by Ferroresonance Effects. Sustained ferrononlinear overvoltages, usually described as ferroresonant overvoltages, on multigrounded wye systems most commonly result from opening one or two phases of a circuit serving an ungrounded-wye or delta-primary-connected transformer bank, or an ungrounded capacitor bank, under light or no load conditions. Overvoltages are produced by a series-resonant circuit composed of shunt capacitance, bushing capacitance, or line or cable capacitance and a saturable device such as a transformer. The voltages are often of sufficient magnitude and duration to damage or destroy surge arresters.

A slightly different and less common ferroresonant situation involves the distribution transformer reactance, X_m, formed by the mutual impedance between windings at the same voltage level. This can only occur on three-phase transformers with four or five leg cores. These transformers may resonate even when connected in grounded-wye. In practice, overvoltages axe limited to about 1.5 p.u. because the equivalent circuit is a parallel LC configuration, and X_m limits the voltage by saturation [B4].

Although ferroresonance effects are more prevalent at system voltages of 24.9/14.4 kV [B51] or higher, they can occur at all voltage levels. It has been shown [B5] that for usual transformer bank sizes, a few miles of overhead line or equivalent cable are required to furnish the necessary capacitance. However, the likelihood of occurrences with shorter line lengths increases with increased system voltage and reduced transformer bank sizes.

Ferroresonant overvoltages that can develop during single-phase switching or fuse blowing can, under some conditions, be more damaging to a metal-oxide arrester than to a gapped silicon-carbide arrester. For instance, a 2.5 p.u. overvoltage on a 13.2 kV system would not cause most 10 kv rated silicon-carbide arresters (normal application) to spark over, but it could cause a metal-oxide arrester to go into thermal runaway.

Methods of controlling or eliminating ferroresonance effects are discussed in [B5], [B10], and [B23].

4.4.5 Overvoltage Caused by Backfeed

4.4.5.1 Ungrounded Wye-Delta Banks. Ungrounded wye-delta banks are particularly susceptible to ferroresonant overvoltages. On the other hand, ungrounded wye-delta banks have the advantage that, when both single- and three-phase loads need to be serviced, different impedance transformers can be used in the three-phase bank. Zero-sequence currents are eliminated in the primary, particularly during fault conditions.

Ungrounded wye-delta banks present an unusual condition for metal-oxide surge arresters installed on the open phase of the wye with an unbalanced load on the delta secondary. As shown in Appendix E, voltages of 2.7 p.u., high enough to force the normally applied arrester into thermal runaway, can exist on the open primary by feedback from the secondary. This condition can occur if a three-phase secondary load is removed during work on the system, leaving a single-phase load connected for lighting, refrigeration, etc. Rather than installing higher rated metal-oxide arresters on these wye-delta banks and thereby jeopardizing equipment protection, the following practices are recommended:

(1) Balance the load so that the load on each phase of the delta is no more than four times that on each of the other two phases. If nearly balanced three-phase loads are served from a transformer, it is not subject to this overvoltage.
(2) Ground the wye. This would eliminate the problem, but may raise concerns for serving unbalanced three-phase loads and single-phase loads. It also provides a path for zero-sequence currents that may be a problem.
(3) Close the disconnect last on the phase that has the largest single-phase load.
(4) Apply a grounding resistor or reactor in the neutral of the ungrounded-wye windings.
(5) Close a neutral grounding switch during the energization of the phases and open it after all three phases have been closed. The neutral switch has to be able to clear the unbalanced load current that may be flowing.
(6) Place arresters on the source side, instead of the load side, of circuit interrupters to prevent arrester damage due to overvoltages. (Locating arresters in this manner can also minimize fuse damage from lightning currents; refer to 4.7.3). This may, however, reduce the overvoltage protection level because of longer lead lengths.

4.4.5.2 Dual-Transformer Station. Appendix F shows a situation that can lead to overvoltage on surge arresters in dual-transformer substations. Although a single line-to-ground fault on the primary of one transformer is isolated from the HV supply system, the faulted circuit is still energized back through the transformer from the distribution system by the normally closed bus breaker. Surge arresters on the unfaulted phases at the fault location, therefore, see an overvoltage of 1.73 p.u. because the neutral voltage on the faulted primary is shifted until this breaker is opened.

4.4.6 Distribution System Neutral Conductors and Grounding Effect on Overvoltage Magnitude. A study on the effect of neutral wire size on distribution system overvoltages, Appendix A of [B37], shows that values as high as 1.68 p.u. can occur on unfaulted phases if the neutral conductor is inadequately grounded throughout the system and the wire size is too small. Although this would be unusual, it can occur when converting an older ungrounded system and emphasizes the importance of good grounding practices during construction and maintenance.

When earth resistivity or system conversion results in a system that is not effectively grounded, special attention has to be given to the TOV capability of the metal-oxide surge arrester. A higher duty cycle and MCOV rating may be required. It may be better to rebuild part of the system to bring it up to state-of-the-art technology. If the arrester duty cycle and

MCOV rating are increased, the insulation coordination of the system has to be rechecked to assure that the required protective margins are still met.

4.4.7 Regulated Voltage. Special attention has to be given to the actual voltage on distribution systems. Standards on voltage levels apply only at the metering point of the customer. Out on the distribution circuit, much larger voltage variations are permitted as long as the voltage at the metering point of the customer is within the standard. A study [B13] on a random sample of system voltages found some voltages 17% above nominal. Most voltage studies, until recently, did not take into consideration the mutual coupling effect between phases as a result of different load currents in the phases. Another possible cause can occur from some of the voltage regulating equipment that is used to control voltages on the circuits. Some three-phase switched capacitor banks sense only single-phase voltage. This can result in capacitor compensation being added to other phases at a time when they are not in need of voltage correction. Arrester MCOV and actual maximum phase-to-ground voltage has to be taken into account when selecting metal-oxide surge arresters for a specific application.

When regulators are used to control system voltage, special care is required to make sure the MCOV rating of metal-oxide surge arresters is not exceeded. For example, stable voltage swings may result when three single-phase voltage regulators are installed at an unstable system neutral point. When three single-phase regulators are connected wye, the controls measure line-to-neutral voltage so that, if the neutral is permitted to float, there is no stable reference point from which to excite the regulator controls. Each regulator control will measure this shift and try to correct it. The operation of regulators under these conditions will be erratic.

4.5 Insulation Coordination. Distribution system insulation coordination is normally based on the following protective margins:

$$PM_{L1} = (\mathrm{CWW}/\mathrm{FOW} - 1)\,100$$
$$PM_{L2} = [\mathrm{BIL}/(\mathrm{LPL} + L\mathrm{di/dt}) - 1]\,100$$

where:

PM_{L1} = FOW Protective Margin (in percent)
PM_{L2} = Full Wave Protective Margin (in percent)
CWW = Chopped Wave Withstand of protected equipment (in kilovolts)
FOW = Front-of-Wave protective level of arrester (in kilovolts)
BIL = Basic Impulse Insulation Level of protected equipment (in kilovolts)
LPL = Lightning Protective Level (in kilovolts)
Ldi/dt = Connecting lead wire voltage drop (in kilovolts)—see 4.7.1

For oil-filled, air, and solid (inorganic) insulation, CWW can be assumed to be 1.15 x BIL; for dry-type (organic) insulation, the CWW is assumed to be the same as the BIL.

The general rule is that PM_{L1} and PM_{L2} have to both be at least 20%. However, experience with surge protection of distribution systems (15 kV and less) has been gained with protective margins well above 20%, usually exceeding 50%. Separation effects (SE) are minimized by connecting distribution arresters directly across overhead equipment insulation.

The discharge voltage of an arrester is greater for the less frequent high-current lightning surges and increases with higher rates of rise of the lightning current [B48]. It is the usual practice to select a reference value of discharge current that will be exceeded infrequently. The discharge voltage at this reference level is used to calculate PM_{L2}. Obviously, the selection of a higher reference level will result in a smaller PM_{L2} for a given BIL.

There is no universally accepted surge-current level on which to base insulation coordination. Currents in the 10–20 kA range are often used, 10 kA for low flash density areas, 20 kA (or more) for high flash density areas. The range of arrester discharge voltage values at 10 kA

(8/20 μs wave) is shown in columns 7 and 8 of Table 6. Reference currents above 20 kA can be considered. This will account for lightning currents with faster rates of rise than the standard test waves used to make discharge voltage measurements [B5] or where severe lightning is common. (Arrester discharge voltage values can be obtained from the manufacturer for currents greater than 20 kA). Strict application of the 20% margin rule will then favor the use of arresters with low discharge voltages. PM_{L2} includes an allowance for the voltage developed across arrester connecting lead wires (see 4.7.1). The arrester discharge voltage characteristic to be used for insulation coordination purposes is the total of the arrester discharge voltage plus the connecting lead wire voltage. Maintaining lead wires as short as possible is particularly important when protecting underground systems (see 4.8.4).

4.6 Protection of Distribution Lines. Distribution arresters are frequently used, instead of overhead shield wires, to protect the distribution lines from flashover resulting from lightning strikes.

The protection of overhead distribution circuits has been studied, and reports ([B51] and [B52]) have been made regarding the degree of protection afforded by gapped silicon-carbide surge arresters. These reports indicate the number of line flashovers to be expected as a function of arrester spacing along the line, line design, and keraunic level. Similar studies have not yet been made based on the operational characteristics of metal-oxide arresters, but the application of metal-oxide surge arresters (MOSA) should result in an equal or possibly lower, number of outages per circuit mile than that expected using silicon-carbide arresters [B14]. Arrester ratings employed for circuit protection are the same as those used for equipment protection at the given line voltage level.

4.7 Arrester Connections

4.7.1 Effect of Connecting Lead Wires. Lightning currents discharging through the inductance of connecting lead wires produce a voltage that adds to the arrester discharge voltage. The total length of these wires is measured from the point at which the arrester line connection is made to the point where interconnection is made between the arrester ground lead and the protected equipment ground lead, excluding the arrester length. A commonly accepted voltage to be added to the arrester discharge voltage is 1.6 kv/ft (5.25 kV/m) of lead wire [B24]. [This assumes a 4 kA/μs rate-of-rise of current (di/dt) x 0.4 μH/ft (1.3 μH/m) (L) of leads = 1.6 kV/ft (5.25 kV/m).] Based on tests, this voltage develops from a 20 kA discharge current (4/10 μs wave) for lead lengths under 5 ft [B36]. Although the lead wire voltage developed at insulation coordination levels of 10 kA or 20 kA for the 8/20 μs wave are approximately one-fourth and one-half the value of 1.6 kv/ft (5.25 kV/m) [B36], it is important to keep lead lengths as short as possible. Higher rates-of-rise of current waves and long lead lengths produce substantially higher voltages and can eliminate the safety factor allowed for by the protective margin PM_{L2}.

4.7.2 Effect of Separation Distance. Distribution arresters are often used to protect a single piece of equipment and therefore should be connected as close as possible to that equipment. This reduces separation effects (see 2.5 and Appendix C). Arresters used to protect equipment should not be installed at locations a pole-span away from the equipment to be protected. This is particularly important where only one arrester is used to protect equipment (a transformer) that is connected to a line that runs in two directions from the tap point. In effect, surges approaching from the unprotected side can exceed the protective level of the arrester, diminishing the effectiveness of the arrester, and equipment failure may result. Surges approaching from the arrester side are limited by arrester action, but the separation effect can be very high.

4.7.3 Location of Arresters With Respect to Equipment Fuses. In general, it is good practice to connect fuses between the arrester and the transformer or other equipment being protected. This minimizes the magnitude of lightning current carried by the fuse during arrester operation and the possibility of fuse damage or blowing. Where fuses are connected ahead of arresters (for instance, to keep arrester lead wires short when protecting underground cable equipment), it is recommended that the surge-current withstand characteristics of the fuse be evaluated [B19].

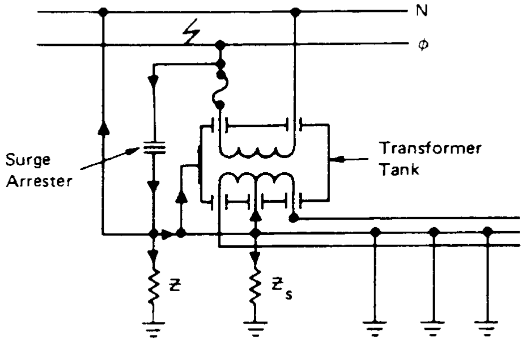


Fig 11
Arrester Protection With Solid Interconnection

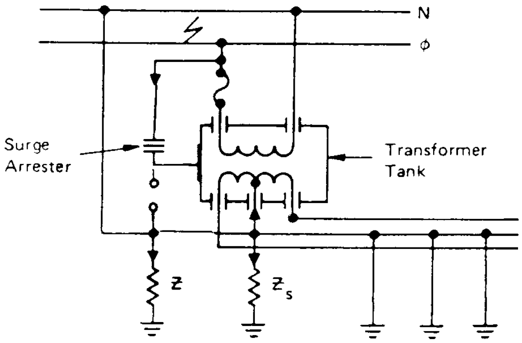


Fig 12
Arrester Protection With Interconnection Through Gaps

4.7.4 Interconnection of Grounds (Figs 11 and 12)

4.7.4.1 Primary and Secondary Ground. It is recommended that primary and secondary grounds of the distribution transformer be interconnected with the arrester ground terminal.

4.7.4.2 Tanks, Hardware, and Support Structures. Where possible and where local regulations permit, ground connections should be made to the tanks of transformers, reclosers, capacitor support frames, and all hardware associated with the protected equipment (Fig 11).

4.7.4.3 Protective Gaps. Where regulations do not allow grounding of equipment support structures, protective gaps should be connected between the arrester ground terminal and the structure. Transformer mounted arresters are grounded to the transformer tank, and the tank can be isolated from ground by inserting the protective gap between the transformer tank and ground (Fig 12).

4.7.4.4 Clearances of Arresters to Energized Conductors and Equipment and to Grounds. For proper insulation coordination, distribution arresters should be installed to maintain, as a minimum, the clearances listed in Table 7. Regulations or other considerations may dictate larger clearances in exposed locations. The listed clearances are suitable for arresters in metal enclosures.

Table 7
Recommended Minimum Clearances

		Recommended Minimum Clearances [Inches (Millimeters)]*	
Arrester Duty Cycle Voltage Rating (kV rms)	Surge Arrester Housing BIL (kV Crest)†	To Ground(s)	Between Phases
3	45	1-3/4 (45)	2 (51)
6	60	2-3/4 (70)	3-1/4 (83)
9	75	4 (102)	4-3/4 (121)
10	75	4 (102)	4-3/4 (121)
12	85	4-3/4 (121)	5-1/2 (140)
15	95	5-1/2 (140)	6-1/2 (165)
18	125	8 (203)	9 (229)
21	125	8 (203)	9 (229)
24	150	9-1/2 (241)	11 (279)
27	150	9-1/2 (241)	11 (279)
30	150	9-1/2 (241)	11 (279)

*Clearances measured from metal parts of arrester line terminal and dictated by minimum flashover to maintain BIL in accordance with IEEE Std C62.11-1987 [9], and to allow for the bias effect of 60 Hz voltage between adjacent phases. Air insulation between arrester and wall(s) or between arresters is assumed. Minimum clearances required between bottom stud on arrester and enclosure floor need be only that required to install ground connection and to provide sufficient space for free operation of the disconnector if used.
†1.2/50 μs full-wave BIL per Table 2 in IEEE Std C62.11-1987 [9].

4.8 Special Applications

4.8.1 Protection of Capacitor Banks. Pole-mounted shunt capacitor banks may be protected by line-to-ground connection of arresters mounted on the same pole as the bank. Connections should be as outlined in 4.7 (refer also to 3.11). The ratings of arresters used are usually the same as used elsewhere on the system.

Capacitor banks connected grounded-wye can be charged to high voltages by lightning currents. When protected by metal-oxide surge arresters, these capacitor banks can only be charged to the protective level of the arrester. The stroke current will then be shared by the arrester and bank for the duration of the stroke current. At the completion of the stroke current, the arrester will cease to conduct, leaving some charge on the capacitors. As a result, the actual amount of energy dissipated by the arrester is less than it would have been for a silicon-carbide arrester.

Arrester operation on ungrounded banks is usually caused by a high transient voltage transmitted from the line to the bank, developing between neutral and ground, such that relatively little of the transient energy is added to the stored energy in the capacitors. Therefore, no special high-energy capability is required for arresters protecting ungrounded capacitor banks against lightning surges.

If a capacitor bank is one that is being switched, arresters having high energy absorption capability may be required regardless of the circuit configuration. Surge arresters applied to switched capacitor banks can be exposed to high-energy surges if restriking of the switching device occurs when the bank is being de-energized. In the case of an ungrounded capacitor bank, a two-phase restrike can cause excessive current to flow in both arresters associated with the restruck phases. Arresters on either side of the switching device can experience high-energy switching transients. The arrester manufacturer should be consulted for aid in selecting arresters suitable for this duty.

4.8.2 Protection of Switches, Reclosers, Sectionalizers, etc. Switches operated in the open position should be protected by arresters at both sides of the switch. The special case of switches in an underground system is covered in 4.8.4.

Reclosers are best protected by installing arresters on both the source and load side. However, some reclosers are designed with a built-in bypass protector across the series coils. A fair degree of protection may therefore be obtained, assuming normal operation of the reclosers in the closed position, by applying one arrester from line to ground on the source side. However, it should be recognized that there is some risk of lightning damage when the recloser is open for any reason.

The arresters usually have the same rating as those used in other parts of the system. Connections should follow the recommendations outlined in 4.7.

4.8.3 Protection of Regulators and Series Apparatus

4.8.3.1 Line Voltage Regulators. If voltage regulators are connected to exposed circuits, they should be protected on both line and load sides with the same arresters used on other distribution apparatus. For the most effective protection, the arrester should be mounted on the tank with the arrester ground connected to the tank. The series winding is usually protected with an arrester selected by the regulator manufacturer and connected between the source and load bushings, or on winding terminals inside the tank.

4.8.3.2 Bus Voltage Regulators. Bus voltage regulators at substations are often protected by station- or intermediate-class arresters on the substation bus or on the substation transformer low-voltage bushings, and by distribution arresters adjacent to the substation on the outgoing feeders. The series winding is protected by arresters selected by the manufacturer of the regulator. The series winding arrester can get inordinate operating duty because a disproportionate share of the incoming current is discharged by the station arrester as a result of its low discharge voltage characteristic. In order to prevent premature failure of the series winding, it is recommended that at least intermediate arresters with lower discharge voltage characteristics be substituted for the distribution arresters on the outgoing line terminals.

4.8.3.3 Series Current-Limiting Reactors. Unless coil protection is built into a current-limiting reactor by the manufacturer, an arrester connected from terminal to terminal can be installed to prevent overvoltages due to incoming surges. In addition, an arrester connected between line and ground should be installed on the source side of the reactor. In all cases, the reactor manufacturer should be consulted.

4.8.3.4 Autotransformers. The remarks on series windings of regulators are generally applicable to autotransformers where the voltage across the series winding is small compared to the common winding (< 25%). For other applications, arresters at the high-voltage and low-voltage terminals with the arrester interconnection to the transformer tank will be adequate.

4.8.4 Protection of Equipment on Underground Systems (Including Cables). Underground sections of the distribution system usually take the form of relatively short cable runs to transformers or that of long loops that are open at the center. For longer cable lengths, equipment such as transformers or switchgear is installed along the entire cable length. In either case, the system can basically be described as a length of cable terminated by an open point.

Surge voltages enter the underground system from the overhead feeder at the riser pole. The magnitude of surge voltage entering the cable is limited by the arrester on the riser pole. However, surge voltage in excess of the protective level of the riser pole arresters can occur on the cable and at equipment locations remote from the riser pole because of amplification by reflection from the open point [B14].

Most of the problems associated with protection of underground systems result from the practical difficulties involved in locating arresters as close as desired to terminating points or points where substantial changes in surge impedance occur in the underground system. Sometimes, consideration has to be given to the installation of arresters on underground transformers to provide adequate protective margins ([B14], [B44], and [B46]). Recent developments in elbow and liquid-immersed arresters make individual equipment protection practical. When it is possible to install arresters at equipment locations, application procedures are similar to those used for protection of overhead equipment. When it is not possible to install arresters at individual equipment locations in the underground system, protection is usually provided by arresters located at the junction of the overhead line conductors and the underground system cables.

For system voltages of 15 kV and below, and where the arrester leads between the overhead line and the cable sheath are short [< 5 ft (1.6 m]), the use of a distribution arrester at the riser pole generally will provide an adequate margin of protection for cable-connected equipment. For 25 kV system voltages, an arrester with lower discharge voltage than a distribution arrester may have to be used. Other possibilities are discussed in [B32], [B34], and [B35]. For 28 kV and 34.5 kV systems, arresters at the riser pole only will not provide adequate protection, and the use of one or more arresters installed on the cable circuit is necessary.

When arrester protection is provided at the riser pole only, the voltage held at the riser pole by a gapless metal-oxide surge arrester is the sum of the arrester discharge voltage and the inductive voltage drop in the arrester connecting leads [B36] (see 4.7.1). This voltage propagates into the cable circuit and can approach double its value on the cable and at connected transformers because of the reflections at points such as open switches and terminating transformers. The following rules [B14] are directed toward determining the voltages at terminations to permit the calculation of protective margins:

(1) Assume no attenuation. This assumption becomes conservative for cable lengths greater than 3000 ft (900 m) [B53].
(2) Assume the incident voltages will double at open points and terminating transformers.
(3) Use the published maximum FOW protective level and discharge voltage values of the manufacturer, consistent with the considerations specified in 3.4. (Discharge voltage at 10 kA has been recommended [B24], but 20 kA is conservative for unshielded circuits.)
(4) Calculate inductive voltage drop in arrester connecting leads as L (ft) x 1.6 (kV/ft) [L (m) x 5.25 (kV/m)], based on linear surge current rise of 4 kA/μs and 0.4 μH/ft (1.3 μH/m) of lead inductance (see 4.7.1).
(5) For gapless arresters, compare the doubled sum of the FOW protective level and the connecting lead voltage with CWW (assumed to be 1.15 BIL) for liquid-filled transformers and with BIL for dry-type transformers and cables.
For gapped arresters, compare the greater of
    (a) Doubled FOW protective level (if determined by sparkover), or
    (b) Doubled sum of FOW protective level (if determined by discharge voltage) and connecting lead voltage with CWW for liquid-filled transformers and with BIL for dry-type transformers and cables.

For both gapless and gapped arresters, compare the doubled sum of the discharge voltage, at the assumed discharge current, and the connecting lead voltage with transformer and cable BIL. Then, using a recommended protective margin of 20%:

Oil insulation: $\mathrm{CWW} \geq 1.2 \times 2 \times \mathrm{FOW}$
Dry insulation: $\mathrm{BIL} \geq 1.2 \times 2 \times \mathrm{FOW}$
Both insulations: $\mathrm{BIL} \geq 1.2 \times 2 \times \mathrm{LPL}$

Another protection method, common for 34.5 kV circuits, is to use an arrester at the riser pole and a second arrester at the remote end of the cable, which is a reflection point for the traveling wave. The voltage at the reflection point will be limited to the discharge voltage of the remote arrester at a current of less than one-fourth of the current through the riser-pole arrester (unless the cable is very short) ([B44] and [B46]). Because the remote arrester appears as an open circuit until it becomes conductive, it permits the reflection of a portion of the incoming wavefront, which is then superimposed on the approaching surge voltage wave. Therefore, the voltage at intermediate points in the cable circuit will usually be higher than at either end. The maximum voltage at intermediate points will be the protective level of the riser-pole arrester (discharge voltage plus lead drop voltage), plus some fraction of the discharge voltage of the reflection point arrester. A conservative number to use for coordination is the discharge voltage of the riser-pole arrester plus one half of the 1.5 kA discharge voltage of the reflection point arrester. (The 1.5 kA value is obtainable from the published literature of the manufacturer and, because of the nonlinear characteristics of metal-oxide valve elements, will yield a value very close to one-fourth of any assumed current through the riser-pole arrester.) (A computer simulation of this effect can be found in [B50].)

The effectiveness of the previous method can be substantially improved by installing a single arrester at an equipment location about 300 ft (98.4 m) or more upstream from the open-point termination. This midcircuit arrester will suppress the reflected spike as it is being superimposed on the incoming surge voltage wave. A significant distance has to be present to allow for recombination of surge voltages with longer rise times [B40]. The protective level between the riser-pole and the midcircuit arrester will be the greater of the protective level of the riser-pole arrester or the discharge voltage of the reflection-point arrester. The protective level in the cable between the reflection-point arrester and the midcircuit arrester is as in the previous example. Equipment connected between the reflection-point arrester and the midcircuit arrester may need individual arrester protection.

The most effective protection method is to install arresters at the riser pole, open point, and at each underground equipment location. The voltage on each piece of equipment will be held to the low-current discharge voltage of its arrester, and only the section of cable between the open point and the first upstream arrester will see a higher surge voltage.

The surge energy, or duty, discharged by an arrester installed on an underground system is controlled by the exposure of the arrester at the riser pole and is usually a small fraction of the energy discharged by the riser-pole arrester. For arresters with identical discharge voltage characteristics, the arrester in the cable system will discharge only about 20% of the total surge current [B46]. The use of arresters at the riser pole with lower discharge voltage, riser-pole type (see the note for Table 6) or intermediate class, will further reduce the magnitude of surge current discharged by the underground arresters by themselves discharging a larger proportion of the surge current.

When control of transients to lower values is desired to prolong cable life, arresters with lower discharge voltage characteristics, or possibly elbow or liquid-immersed arresters, can be used. Although not yet proven effective, it has been done when "treeing" has been suspected of decreasing cable life.

Arresters installed directly on underground equipment may be either elbow arresters (for dead front equipment) or base- or bracket-mounted arresters (if equipment has mounting provisions). Also, liquid-immersed arresters are available mounted inside the transformers.

4.8.5 Contaminated Atmospheres. Surveys [B30] have shown that failures of gapped silicon-carbide arresters due to operation in contaminated atmospheres are quite rare. Because metal-oxide distribution arresters are usually constructed without internal gaps, internally induced failures of these arresters due to external contamination should not be a factor. However, external failure (flashover) of the arrester housing may occur from the combined effect of

(1) Accumulation of contaminants on the arrester and
(2) Conditions of wet snow, frost, light rain, or fog

The usual solution is periodic cleaning of the porcelain housing. In a few cases, application of nonconducting, nontracking, water-repellent greases to the insulating surfaces has been used. Overinsulating the arrester housings has also been used effectively to reduce the effects of external contamination.

4.9 Isolation

4.9.1 Disconnectors and External Gaps. Distribution arresters are sometimes furnished with external gaps that are placed between the line lead and the arrester terminal. Other arresters may be provided with disconnectors, which are usually mounted on the ground terminal of the arrester and connected between the ground terminal and the ground lead. The purpose of both devices is to isolate a failed arrester from the distribution system. In each case, a system fuse, recloser, or circuit breaker may operate to clear the fault if the arrester fails.

In the case of an arrester equipped with an external isolating gap, a failed, but intact, arrester remains connected to the system and continues to provide some measure of protection for the transformer on subsequent lightning surges. However, detection of a failed arrester from ground level may be difficult, but close inspection will usually reveal a burn mark or bubble of metal on the arcing horn from the passage of an abnormally high power-frequency current.

In the case of an arrester equipped with a disconnector, operation of the disconnector physically separates the arrester ground connection from the failed arrester and thus gives a visual indication of failure. Surge protection for the transformer is no longer provided. Care has to be taken to provide enough clearance to ensure that the separated ground lead is not thrown into an energized conductor. The ground lead should be flexible enough to allow the disconnector to separate from the arrester.

4.9.2 Current-Limiting Fuses. Current-limiting fuses are used to protect and isolate faulted distribution equipment as well as some single- and three-phase laterals. The principal advantage of these fuses is their ability to limit the let-through fault current (fault energy).

Since some current-limiting fuses can generate high arc voltage with peak magnitudes exceeding system voltage, care has to be exercised to ensure proper coordination between the fuse and the source side arrester. Although experience with these applications for metal-oxide arresters is limited, distribution arrester damage as a result of current-limiting fuse operation has not been an application problem. In the event that arrester damage does occur, an arrester with a higher MCOV rating than would normally be applied could be required, i.e., conduction would start at higher arc voltages, reducing the number of arrester operations and, therefore, reducing the duty on the arrester. Should conduction occur, the energy (joules/kilovolts of rating) dissipated by the arrester, would be reduced.

Additional information on the effects of current-limiting fuses can be found in [B28], [B38], and [B45].

5. References

This guide shall be used in conjunction with the following publications. When the following standards are superseded by an approved revision, the revision shall apply.

[1] ANSI C84.1-1989, American National Standard for Electric Power Systems and Equipment—Voltage Ratings (60 Hz).[1]

[2] ANSI C92.1-1982, American National Standard for Power Systems—Insulation Coordination.

[3] IEEE Std C37.04-1979 (Reaff. 1988), IEEE Standard Rating Structure for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis (ANSI).[2]

[4] IEEE Std C57.12.00-1987, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers (ANSI).

[5] IEEE Std C57.12.01-1989, IEEE Standard General Requirements for Dry-Type Distribution and Power Transformers Including Those With Solid Cast and/or Resin-Encapsulated Windings.

[6] IEEE Std C57.13-1978 (Reaff. 1986), IEEE Standard Requirements for Instrument Transformers (ANSI).

[7] IEEE Std C57.21-1990, IEEE Standard Requirements, Terminology, and Test Code for Shunt Reactors Rated Over 500 kVA (ANSI).

[8] IEEE Std C62.1-1989, IEEE Standard for Gapped Silicon-Carbide Surge Arresters for AC Power Circuits.

[9] IEEE Std C62.11-1987, IEEE Standard for Metal-Oxide Surge Arresters for AC Power Circuits (ANSI).

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[1] ANSI publications are available from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

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

[10] IEEE Std C62.92-1987, IEEE Guide for the Application of Neutral Grounding in Electrical Utility Systems, Part I—Introduction (ANSI).

[11] IEEE Std 100-1988, IEEE Standard Dictionary of Electrical and Electronics Terms—Fourth Edition (ANSI).

Appendixes

(These appendixes are not a part of IEEE Std C62.22-1991, IEEE Guide for the Application of Metal-Oxide Surge Arresters for Alternating-Current Systems, but are included for information only.)

Appendix A

Lightning Flashes, Lightning Stroke Currents, Traveling Waves, and Station Shielding

A1. Lightning Flashes and Strokes

A lightning flash is composed of one or more lightning strokes, each flash having three strokes on the average. In general, the first stroke has a higher current but the rate of rise is less steep than subsequent strokes. To determine the incoming surge voltage to a station for analyzing protection of station equipment, usually only the surge voltages caused by the first stroke are considered. However, to determine the energy discharged by an arrester, subsequent strokes should also be considered.

As shown in [B3] and [B6], the lightning stroke parameters for negative downward strokes are considered to be approximated by Log-Normal distribution, whose probability density function is

$$f(x) = \frac{1}{xB\sqrt{2\pi}}e^{-\frac{1}{2}\left[\frac{\ln\frac{x}{M}}{B}\right]^{2}} \qquad \text{(Eq A1)}$$

where

$f(x)$ = Probability density function
M = Median value of distribution
B = Logarithmic standard deviation

The measurements of Berger [B6] show the following values of M and B for first and subsequent strokes:

Table A1
First Stroke Statistics

Parameter	M	B	P
Crest Current (kA)	31.1	0.48	0.38
Maximum Steepness (kA/μs)	24.4	0.60	
Front (μs)	1.28	0.61	
Tail (μs)	77.5	0.58	

Table A2
Subsequent Stroke Statistics

Parameter	M	B	P
Crest Current (kA)	12.3	0.53	0.56
Maximum Steepness (kA/μs)	39.9	0.85	
Front (μs)	0.31	0.71	
Tail (μs)	30.2	0.93	

As noted, the steepness and crest current are correlated; the correlation coefficient is denoted by P. The front is derived on a statistical basis from the other two quantities and the correlation coefficient.

The first-stroke crest current data in the above table obtained by Berger was combined with other data. The resultant distribution is piecewise Log-Normal whose parameters are:

Range	M	B
20 kA and below	61	1.33
20 kA and above	33.3	0.605

The distribution may also be approximated [B2] by the equation:

$$P(I_S) = \frac{100}{1 + \left[\frac{I_S}{31}\right]^{2.6}} \qquad \text{(Eq A2)}$$

where

$P(I_S)$ = Probability of peak current that is equal to or exceeds I_S (in percent)
I_S = Peak first-stroke current (in kiloamperes)

The lightning severity within a specific area is generally specified by the ground flash density, N_g, in flashes per kilometer squared. However, at present within the United States, data on the average N_g are not generally available, and the lightning severity has to be based on the annual keraunic level or the number of thunderstorm days per year, T_d. In the United States, these levels vary from five or less on the West Coast to greater than 100 in Florida, with an average between 35 and 40 [B31]. The value of N_g may be approximated from T_d by the equation:

$$N_g = 0.04 T_d^{1.25} \qquad \text{(Eq A3)}$$

where both N_g and T_d are average yearly values [B16]. The coefficients of variation of both N_g and T_d are large, about 60% for low values of T_d and about 30% for high values of T_d [B22]. (An exponent of 1.35 for this equation appears in [B31]. (The 1.25 exponent has since been accepted and approved by the developers of [B31].)

A2. Arrester Currents Due to Lightning Strokes

As a general rule, arrester currents due to lightning strokes are less than the current in the stroke itself. In the case of direct strokes to lines, traveling waves are set up in opposite directions from the point of contact. Flashover of line insulation provides a parallel path to ground through which a portion of the stroke is diverted from the arrester. In the case of strokes to more than one conductor or flashovers between conductors, two or more surge arresters may operate and share the current. Only in the case of a direct stroke very near to the terminal of the arrester, with no flashover occurring before arrester operation, is the arrester called upon to discharge most of the lightning stroke current. The probability of such an occurrence can be significantly reduced by the use of shielding. Evaluation of arrester currents is discussed in 3.4.2.

A3. Line Shielding

Overhead lines may be protected against direct lightning strokes to the conductors by the use of shield (overhead ground) wires, which are positioned to intercept lightning strokes and to direct the stroke current to ground via metallic tower or pole structures. Where wood pole structures axe used, low-impedance conductors are used to connect the shield wires to ground.

Almost all direct strokes to line conductors are eliminated by the use of shield wires. When such a direct stroke (shielding failure) does occur, line flashover is almost certain. When a lightning stroke terminates on a shield wire, the stroke current is diverted to ground through the structure-connecting conductors. The impedance of the current path together with ground resistance results in a voltage at the top of the line structure, a portion of which is coupled to the phase conductor. The difference between the phase conductor potential and structure top potential is impressed directly across line insulation and may result in flashover. This type of flashover is called a backflash. The incidence of backflashes is controlled by selection of a proper insulation level; by keeping the structure ground resistance at an acceptably low value; and by providing adequate clearance from conductor to structure ground, conductor to shield wire, and conductor to conductor.

A4. Station Shielding

Procedures analogous to those used for shielding lines may also be used for shielding stations. Shielding methods include overhead ground wires, metallic masts without ground wires, and lightning rods supported from the station structure. These methods may be used in many combinations.

A5. Uses of Shielding in Station Protection Applications

The purpose of shielding in station applications is to reduce the risk of insulation failure to an acceptable level. In certain applications, this may be achieved by shielding the station alone. In other cases, it may be necessary to shield all incoming lines to the station. As pointed out in A6, shielding of the lines for a relatively short distance from the station may be all that is required for station protection.

With well-designed shielding, insulation, and grounding systems, the probability of direct strokes to phase conductors is reduced to a low level and the voltages across insulation in the event of strokes to the shielding system are reduced below flashover levels. As a result, arrester discharge currents are reduced, thereby permitting the arrester to provide better protection to equipment insulation (see 3.4.2).

A6. Traveling Waves

Lightning strokes to lines, as well as switching operations, set up traveling waves that move along the line [B7]. Crest voltage can double when the wave arrives at the terminals of an open line switch or circuit breaker. A reflected voltage approaching double the incident wave occurs at line-terminating transformers.

As a wave initiated by lightning moves along a line, the crest is reduced and time to crest is increased [B54]. Effective shielding of a line for as little as one-half mile (800 m) from the station can reduce a high percentage of incoming surges to a tolerable level [B7].

Appendix B
COG for Various Conditions

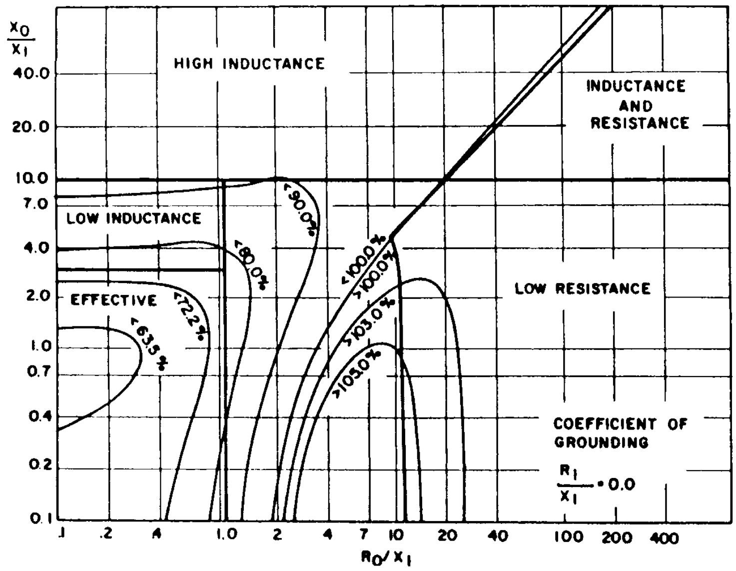

Fig B1
Coefficients of Grounding for $R_1/X_1 = 0$

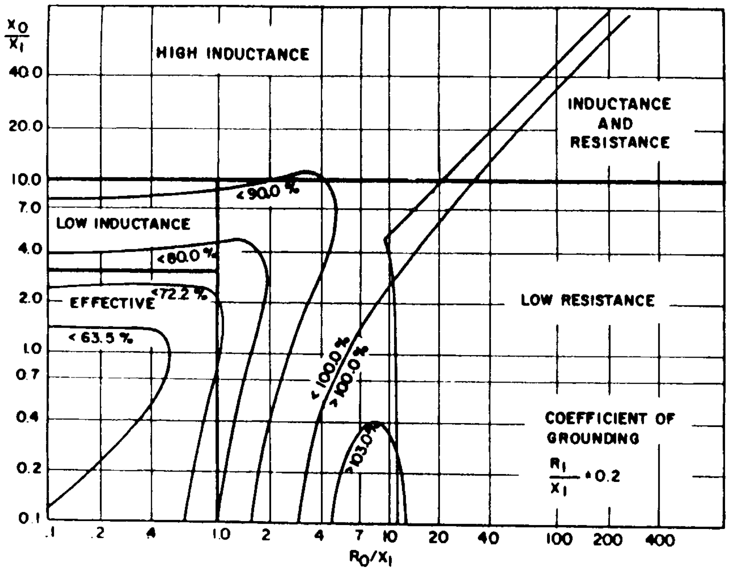

Fig B2
Coefficients of Grounding for $R_1/X_1 = 0.2$

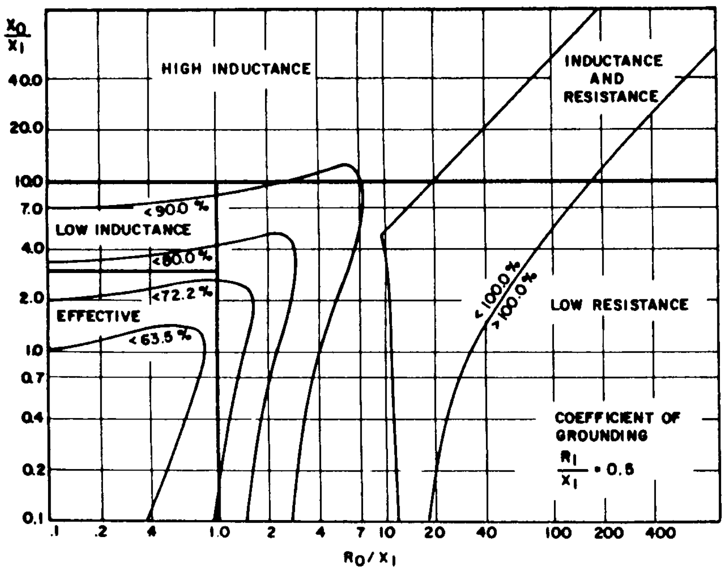

Fig B3
Coefficients of Grounding for $R_1/X_1 = 0.5$

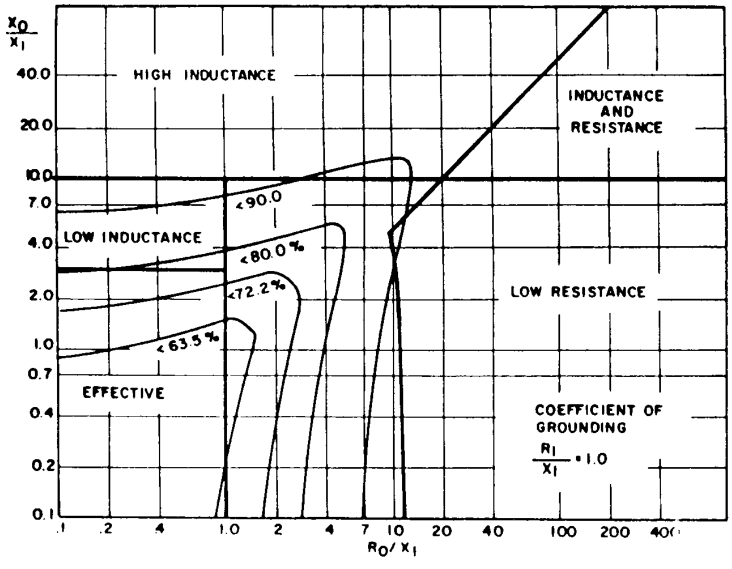

Fig B4
Coefficients of Grounding for $R_1/X_1 = 1$

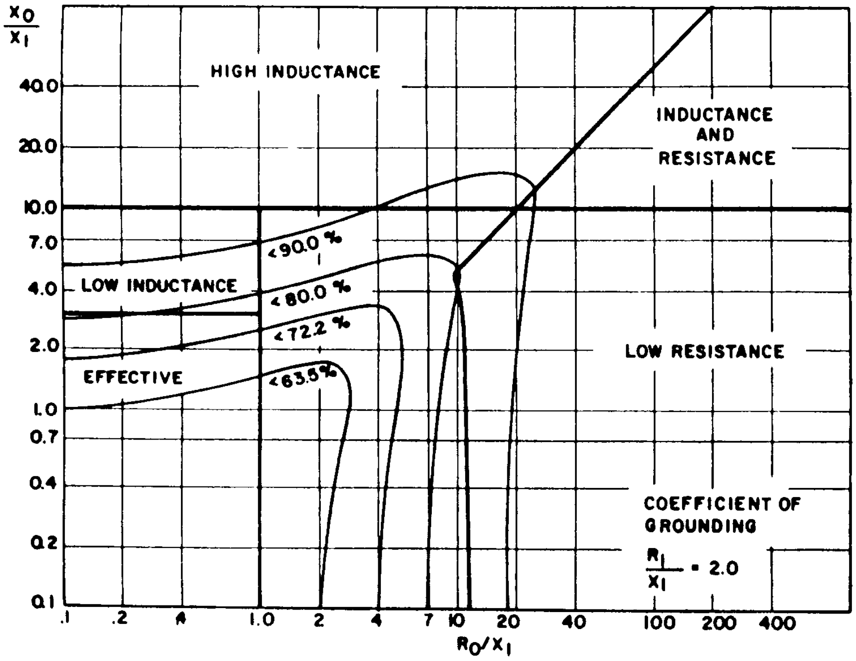

Fig B5
Coefficients of Grounding for $R_1/X_1 = 2$

NOTE: Parameter values given against Figs B1 through B5 indicate limiting values of COG (see D1.3.3) within the area circumscribed by the curve. Definitions of grounding class or means are indicated in each area. All impedance values have to be on the same kilovoltampere base or in ohms on the same voltage base.

R_0 = Zero-sequence resistance
R_1 = Positive-sequence resistance
R_2 = Negative-sequence resistance
X_0 = Zero-sequence inductive reactance
X_1 = Positive-sequence inductive reactance
X_2 = Negative-sequence inductive reactance
X_1 = X_2

All these quantities are components of the system impedance as seen from the point of fault. See 3.3.2.1.
The effect of fault resistance was taken into account. The resistance that gives the maximum voltage to ground was the value used.
The COG for other values of $Z_1 = Z_2$, can be calculated using the equations in Fig 6. The curves of the figures in Appendix B are from IEEE Std C62.92-1987 [10]. For assumptions in producing these curves, see IEEE Std C62.92-1987 [10].

Appendix C
Calculations of Surge Arrester Separation Distances

C1. Purpose

The purpose of this appendix is to provide a relatively simple method for calculating maximum allowable separation distances between surge arresters and equipment to be protected.

C2. Introduction

The most effective location for any surge arrester is at the terminals of the equipment to be protected. For a variety of reasons, surge arresters have to sometimes be located some distance away from the equipment, or sometimes one set of surge arresters may be used to protect more than one piece of equipment.

Locating a surge arrester remote from the equipment to be protected reduces the protective margin. Depending on a number of factors, the transient voltage at the equipment can easily be more than twice the surge arrester protective level. An analysis has to be made to determine how far a surge arrester can be located away from the equipment and still provide adequate protection.

C3. Study Method

This appendix provides a simplified procedure for calculating acceptable separation distances for simple substation configurations. The procedure is illustrated in this appendix using two examples:

(1) A substation consisting of a single overhead line terminated with a single transformer
(2) A multiline two-transformer substation

A reduction process is used in the second example to derive a single-line single-transformer substation that can be analyzed as shown in the first example.

The procedure uses the curve shown in Fig C8, which was generated from studies using the Electromagnetic Transients Program (EMTP). Eq C1 represents the curve plotted in Fig C8 and may be used instead. All the computer studies were made on single-line single-transformer substations with system voltages ranging from 69 kV to 765 kV.

The curve on Fig C8 is an average curve using the results from EMTP studies as indicated above. The curve includes the effect of the power frequency voltage and is valid for separation distances not exceeding 300 ft (91 m). Transformer surge capacitance values of 1000 pF to 5000 pF do not materially affect the separation effects.

Special studies are required for complex substations using analytical tools such as the EMTP. It is not the intent of this appendix to provide guidance in selecting cases for study or in interpreting the results obtained when using the EMTP or other analytical tools.

C4. Definitions of Symbols

The symbols used to calculate surge arrester separation distances are defined as follows:

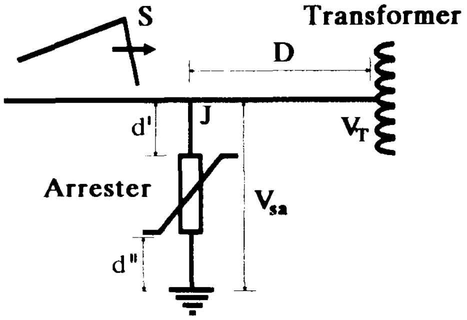

Fig C1
Definition of Symbols

BIL = Basic Lightning Impulse Insulation Level of the transformer (in kilovolts)
C = Surge propagation rate in overhead conductors (in feet per microsecond or meters per microsecond)
CWW = Chopped Wave Withstand of transformers (in kilovolts) (1.10 x BIL) (ANSI C57.12.00-1987 [4], Table 5)
d' = Conductor length between junction J and surge arrester terminal (in feet or meters)
d" = Conductor length between surge arrester and ground (in feet or meters)
d = Total surge arrester lead, d' + d" (in feet or meters)
D = Maximum allowable separation distance between junction J and transformer terminal (in feet or meters)
di/dt = Rate of rise of surge current = 2(S)/Z (in kiloamperes per microsecond)
J = Common point among transformer lead, surge arrester lead, and surged line
L = Inductance of surge arrester lead d (in microhenries) (Assume 0.4 μH/ft or 1.3 μH/m)
N = Number of transmission lines, including the surged line
S' = Rate of rise of incoming surge on the transmission line (kV/μs) (Use 11 kV/μs per kV MCOV rating to a maximum of 2000 kV/μs—IEEE Std C62.11-1987 [9])
S = Rate of rise of incoming surge at junction J (in kilovolts per microsecond)
V_a = Surge arrester FOW protective level at 0.5 μs (in kilovolts) (See Table 1)
V_{sa} = Voltage across the surge arrester, from junction J to ground (in kilovolts)
V_T = Maximum voltage stress allowable at the transformer (in kilovolts):
V_T = CWW/1.15 if time to crest voltage is less than 2 μs
V_T = BIL/1.15 if time to crest voltage is more than 2 μs
This assumes a 15% protective margin (See Fig 5)
Z = Surge impedance of transmission line (in ohms) (Refer to Table 5 in IEEE Std C62.11-1987 [9])

C5. Single-Line Single-Transformer Substation, Example 1

Refer to Fig C1. Parameters in this example for a 115 kV system are as follows:

BIL = 350 kV
C = 984 ft/μs (300 m/μs)

d = d' + d'' = 25 ft (7.6 m)
S' = 11 x MCOV rating = 11 x 70 = 770 kV/μs
S = S' in this example
V_a = 226 kV for MCOV = 70 kV
Time to crest voltage: (226/770) < 2 μs
Use V_T = CWW/1.15
Z = 450 Ω

Calculate the following:

CWW = 1.1 x BIL= 1.1 x 350 = 385 kV
di/dt = 2 S/Z = 2(770) /450 = 3.42 kA/μs
L = (d' + d'') 0.4 μH/ft = 25 x 0.4 = 10 μH
(d' + d'') 1.3 μH/m = 7.6 x 1.3 = 10 μH
V_{sa} = V_a + L(di/dt) = 226 + 10(3.42) = 260 kV
V_T = CWW/1.15 = 385/1.15 = 335 kV
V_T/V_{sa} = 335/260 = 1.29

The abscissa value corresponding to $V_T/V_{sa} = 1.29$ on the curve of Fig C8 is $D(S)/(C \times V_{sa}) = 0.068$.

Solving for: $D = 0.068(C \times V_{sa}) /(S)$
$= 0.068(984 \times 260)/770$ = 23 ft (7 m)

This is the maximum allowable distance between the surge arrester and the transformer.

C5.1 Calculated Allowable Separation Distances. Allowable separation distances have been calculated using the above procedure for system voltages from 69 kV through 765 kV based on the following:

— Typical values of BILs
— Station class surge arresters
— Minimum MCOV ratings
— Maximum value for the 0.5 μs FOW protective level from Table 1

The allowable separation distances are given in Table 4.

C6. Multiline Two-Transformer Substation

Fig C2 shows a substation with three transmission lines, two transformers, and one set of surge arresters. Allowable surge arrester separation distances should be calculated for each transformer, assuming the incoming surge on each of the three lines, to determine the surge-protection adequacy of both transformers with one set of surge arresters.

To use the method of this appendix, the multiline two-transformer substation of Fig C2 has to be reduced to a single-line single-transformer substation similar to that of Fig C1. The following procedure shows the reduction method. The procedure should be repeated for each transformer, while assuming the incoming surge to travel on each line separately. Line-out conditions may also be investigated to identify the most severe case.

C6.1 Step-by-Step Procedure for Reduction Process

Step 1: Remove the transformer not being considered and identify the transmission line with the incoming surge.

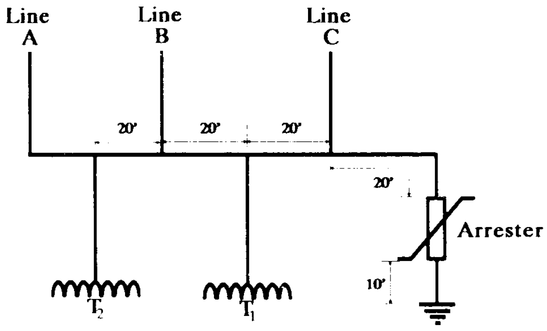

Fig C2
An Example of a Multiline Two-Transformer Substation

Step 2: (a) Identify junction J, which is the common point among the transformer lead, surge arrester lead, and the surged line.
(b) Identify the separation distance D as the connection between junction J and the transformer terminal that would include the bus-bar length, if applicable.
(c) Identify the surge arrester lead d' as the connection between junction J and the surge arrester that would include the bus-bar length, if applicable.

Step 3: Remove all lines connected to d' (connection between junction J and surge arrester).

Step 4: The rate of voltage rise at junction J is S = (S') x 3/(N + 2), where N equals the total number of lines (including the surged line) remaining after Step 3.

The multiline two-transformer substation has been reduced, and the maximum allowable separation distance, D, can be calculated using the procedure used in Section C5.

C6.2 Multiline Two-Transformer Substation—Example 2. Refer to Figs C2 and C3. Parameters used in this example for a 138 kV system follow:

BIL = 450 kV
C = 984 ft/μs (300 m/μs)
d' = 40 ft (12 m)
d" = 10 ft (3 m)
S' = 11 x MCOV rating = 11 x 84 = 924 kV/μs
V_a = 273 kV for MCOV = 84 kV
Time to crest voltage: (273/924) < 2 μs
Use V_T = CWW/1.15
Z = 450 Ω

C6.2.1 Reduction of Fig C2—Incoming Surge on Line A

Step 1: Remove transformer not being considered, T2 in this case, and assume the incoming surge is on Line A. See Fig C3.

Step 2: (a) Identify junction J, where the dashed lines meet in Fig C3.
(b) Identify the separation distance D, and
(c) Identify the surge arrester lead d'; d' = 40 ft (12 m) in this example (See Fig C2), and d = d' + d" = 40 + 10 = 50 ft (12 + 3 = 15 m).

Step 3: Remove all lines connected to d'; Line C in this case.

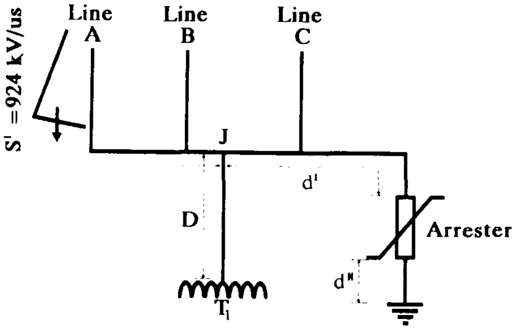

Fig C3
Example 2—Multiline Two-Transformer Substation With an Incoming Surge on Line A—Transformer T2 Not Being Considered Is Removed

Step 4: Calculate the voltage rate of rise at junction J.

S = (S') x 3/(N + 2); N = 2 (see Fig C4)

= (924) x 3/(2 + 2) = 693 kv/μs (see Fig C4)

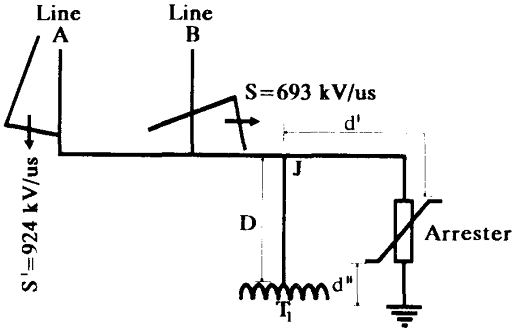

Fig C4
Example 2—Multiline Two-Transformer Substation With an Incoming Surge on Line A—All Lines Connected to d' Are Removed

The reduced single-line single-transformer substation to be analyzed is shown in Fig C5. Calculate the following:

CWW = 1.1 x BIL = 1.1 x 450 = 495 kV

di/dt = 2(S)/Z = 2(693)/450 = 3.08 kA/μs

L = (d' + d") 0.4 μH/ft = (50)0.4 = 20 μH

[(d' + d") 1.3 μH/m = (15)1.3 = 20 μH]

V_{sa} = V_a + L(di/dt) = 273 + 20(3.08) = 335 kV

V_T = CWW/1.15 = 495/1.15 = 430 kV

V_T/V_{sa} = 430/335 = 1.28

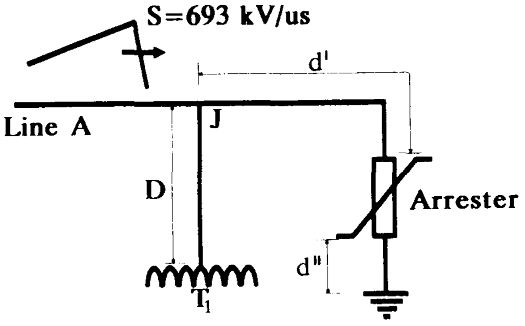

Fig C5
Example 2—Multiline Two-Transformer Substation With an Incoming Surge on Line A—Simplified to a Single-Line Single-Transformer Substation

The abscissa value corresponding to $V_T/V_{sa} = 1.28$ on the curve of Fig C8 is $D(S)/(C \times V_{sa}) = 0.066$.

$$\text{Solving for } D = 0.066\,(C \times V_{sa})/(S)$$
$$= 0.066\,(984 \times 335)/(693) = 31 \text{ ft } (9.4 \text{ m})$$

This is the maximum allowable distance between the surge arrester and the T1 transformer if Line A is the surged line.

Repeat the procedure with the incoming surge on each of the other lines. C6.2.2 shows the incoming surge on Line C.

C6.2.2 Reduction of Fig C2—Incoming Surge on Line C

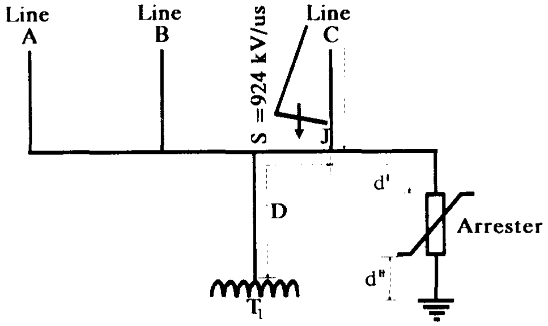

Fig C6
Example 2—Multiline Two-Transformer Substation With an Incoming Surge on Line C—Transformer T2 Not Being Considered Is Removed

Step 1: Remove transformer not being considered, T2 in this case, and assume the incoming surge is on Line C. See Fig C6.

Step 2: (a) Identify junction J, where the dashed lines meet in Fig C6.

(b) Identify the separation distance D, and

(c) Identify the surge arrester lead d'; d' = 20 ft (6 m) in this example (see Fig C2), and d = d' + d" = 20 + 10 = 30 ft (6 + 3 = 9 m).

Step 3: Remove all lines connected to d'; none in this case.

Step 4: Calculate the voltage rate of rise at junction J.

S = (S') x 3/(N + 2); N = 3 (see Fig C6)
= (924) x 3/(3+2)
= 554 kV/μs

The reduced single-line single-transformer substation to be analyzed is shown in Fig C7.

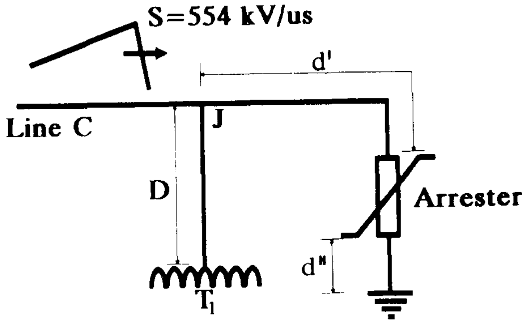

Fig C7
Example 2—Multiline Two-Transformer Substation With an Incoming Surge on Line C—Reduced to a Single-Line Single-Transformer Case

Calculate the following:

CWW = 1.1 x BIL = 1.1 x 450 = 495 kV
di/dt = 2(S)/Z = 2(554)/450 = 2.46 kA/μs
d = d' + d" = 30 ft (9 m)
L = (d' + d") 0.4 μH/ft = (30)(0.4) = 12 μH
[(d' + d") 1.3 μH/m = (9)(1.3) = 12 μH]
V_{sa} = V_a + L(di/dt) = 273 + 12(2.46) = 302 kV
V_T = CWW/1.15 = 495/1.15 = 430 kV
V_T/V_{sa} = 430/302 = 1.42

The abscissa value corresponding to $V_T/V_{sa} = 1.42$ on the curve of Fig C8 is D (S)/(C x V_{sa}) = 0.108.

Solve for: D = 0.108(984 x 302)/(554) = 58 ft (17.7 m)

An incoming surge on Line A is more critical than one on Line C (D = 31 ft versus 58 ft or 9.4 m versus 17.7 m).

Repeat the procedure with the incoming surge on Line B, and determine the maximum allowable separation distance D for transformer T1.

A similar procedure should be followed to determine the maximum allowable separation distance D for transformer T2.

C7. Equation Representation for Fig C8

The following equation may be used to calculate the maximum allowable separation distance (*D*). The equation closely approximates the curve in Fig C8.

$$D \le \left[\frac{0.385\,(CV_{sa})}{S}\right] \times \left[\frac{0.957BIL - V_{sa}}{2.92V_{sa} - 0.957BIL}\right] \qquad \text{(Eq C1)}$$

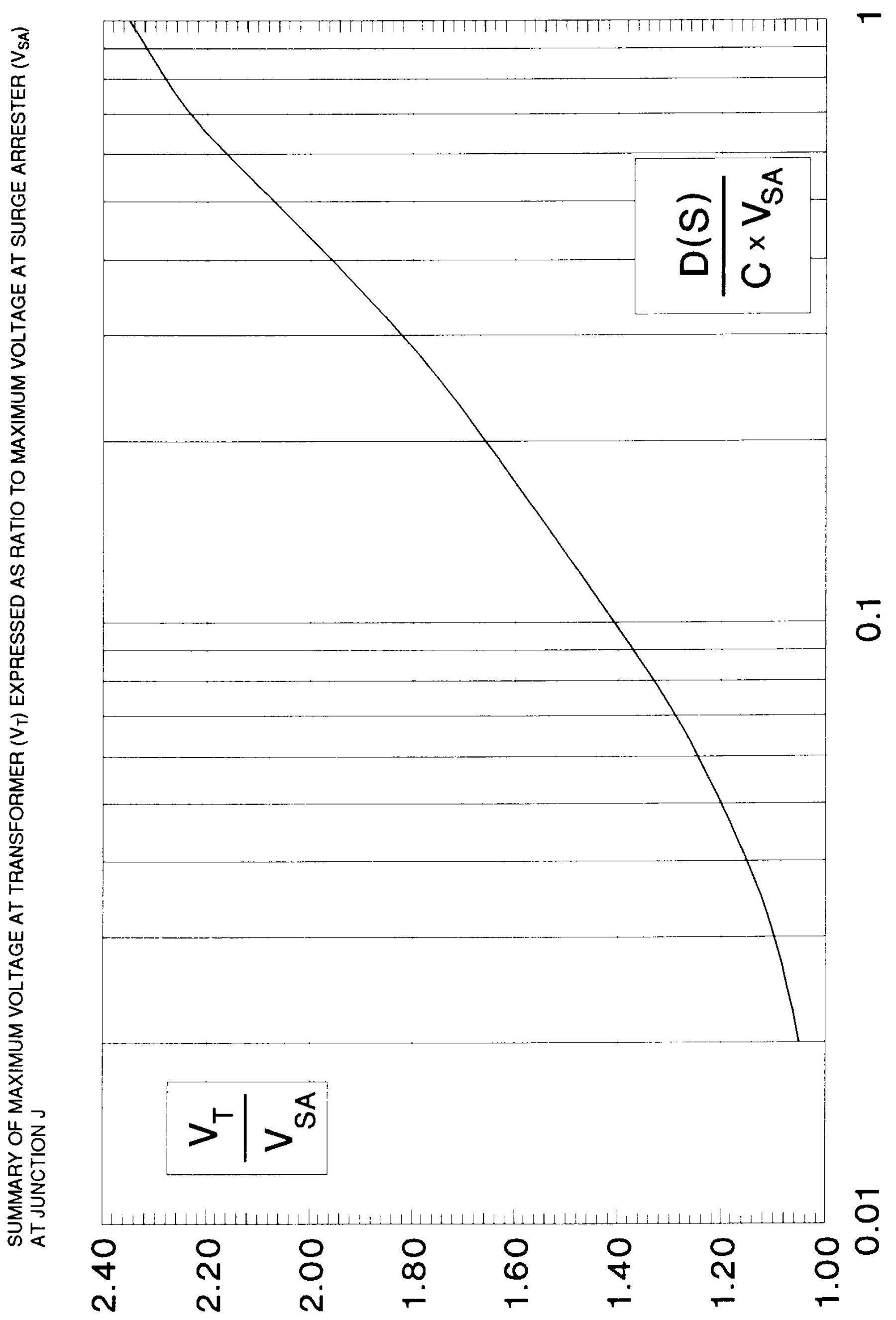

Fig C8
Curve for Graphical Determination of Acceptable Separation Distance

Appendix D
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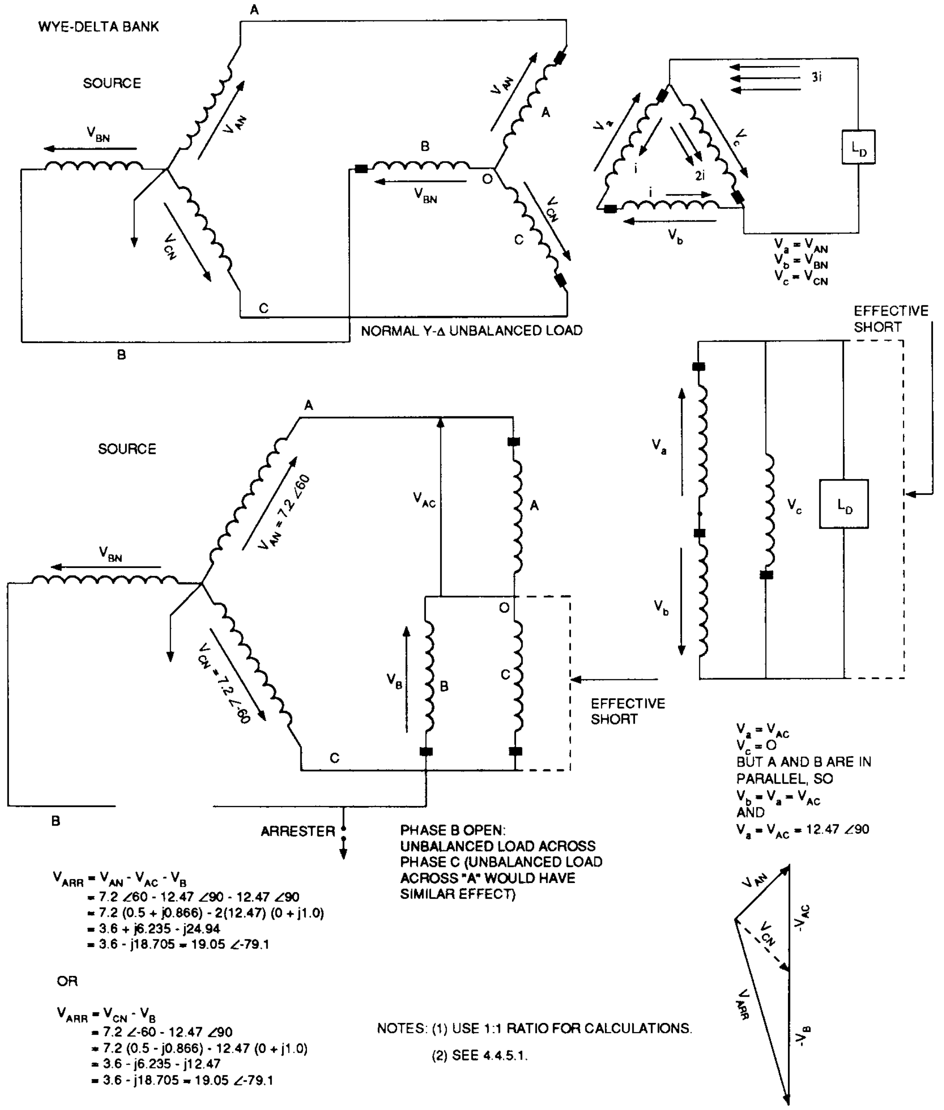
Appendix E
Distribution System Overvoltage Line Diagrams



$V_a = V_{AC}$
$V_c = O$
BUT A AND B ARE IN PARALLEL, SO
$V_b = V_a = V_{AC}$
AND
$V_a = V_{AC} = 12.47 \angle 90$

PHASE B OPEN:
UNBALANCED LOAD ACROSS PHASE C (UNBALANCED LOAD ACROSS "A" WOULD HAVE SIMILAR EFFECT)

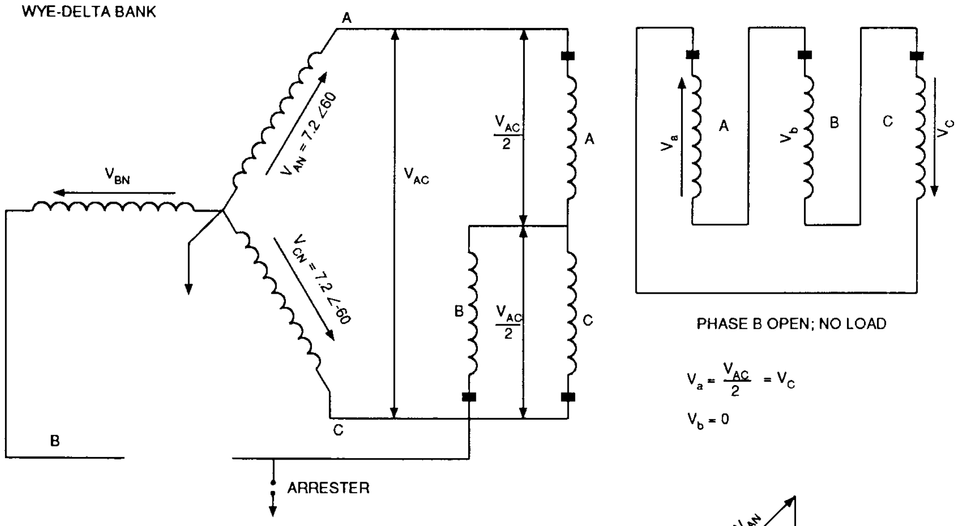
$$
\begin{aligned}
V_{ARR} &= V_{AN} - V_{AC} - V_B \\
&= 7.2 \angle 60 - 12.47 \angle 90 - 12.47 \angle 90 \\
&= 7.2\,(0.5 + j0.866) - 2(12.47)\,(0 + j1.0) \\
&= 3.6 + j6.235 - j24.94 \\
&= 3.6 - j18.705 = 19.05 \angle -79.1
\end{aligned}
$$

OR

$$
\begin{aligned}
V_{ARR} &= V_{CN} - V_B \\
&= 7.2 \angle -60 - 12.47 \angle 90 \\
&= 7.2\,(0.5 - j0.866) - 12.47\,(0 + j1.0) \\
&= 3.6 - j6.235 - j12.47 \\
&= 3.6 - j18.705 = 19.05 \angle -79.1
\end{aligned}
$$

NOTES: (1) USE 1:1 RATIO FOR CALCULATIONS.
(2) SEE 4.4.5.1.

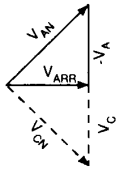
Fig E1
Shorted Secondary



PHASE B OPEN; NO LOAD

$V_a = \frac{V_{AC}}{2} = V_C$

$V_b = 0$



$$\begin{aligned} V_{ARR} &= V_{AN} - V_A \\ &= 7.2 \angle 60 - \frac{12.47}{2} \angle 90 \\ &= 7.2\,(0.5 + j0.866) - 6.235\,(0 + j1) \\ &= 3.6 + j6.235 - j6.235 \\ &= 3.6 \angle 0 \end{aligned}$$

OR

$$\begin{aligned} V_{ARR} &= V_{CN} + V_C \\ &= 7.2 \angle -60 + \frac{12.47}{2} \angle 90 \\ &= 7.2\,(0.5 - j0.866) + 6.235\,(0 + j1) \\ &= 3.6 - j6.235 + j6.235 \\ &= 3.6 \angle 0 \end{aligned}$$

NOTES: (1) USE 1:1 RATIO FOR CALCULATIONS.

(2) UNBALANCED LOAD ACROSS "B" ONLY WOULD NOT ALTER THE ABOVE RESULTS.

(3) SEE 4.4.5.1.

Fig E2
Open Primary

Appendix F
Dual Transformer Station

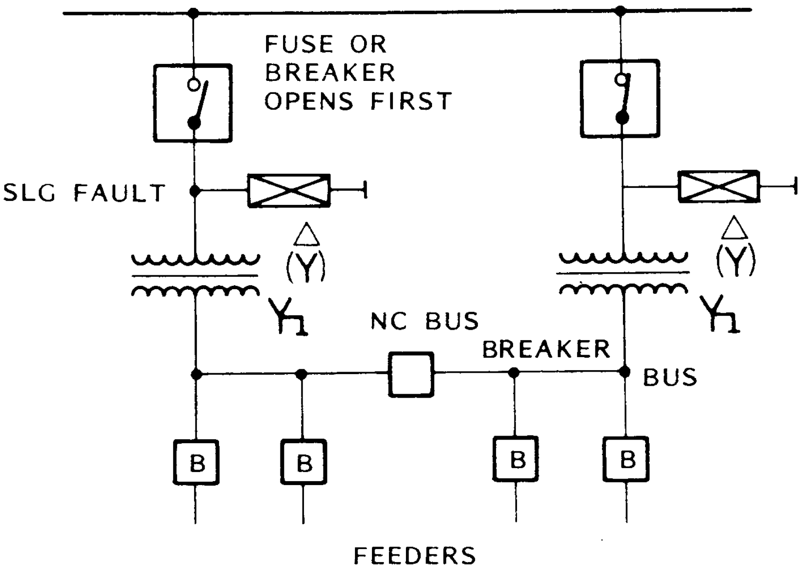


Fig F1
Dual Transformer Station