

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

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Surge-Protective Devices Committee
of the
IEEE Power Engineering Society

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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

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Section 4 Working Group 3.4.14
Appendix C..... Working Group 3.4.16

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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.

¹The 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 μ s and 8/20 μ s 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 μ s 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 μ s/km of distance from the station to the backflash location. Fronts in the range of 0.5–4.0 μ s have been used. The tail of the surge is typically between 10 μ s and 20 μ s, 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 μ s longer than those for a backflash and the tails average about 90 μ s.

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

²The “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 μ s is 8–12% higher than that occurring for a standard 8/20 μ s lightning current wave. The voltage occurring for a current cresting in 45–60 μ s is 2–4% lower than that for the 8/20 μ s 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-

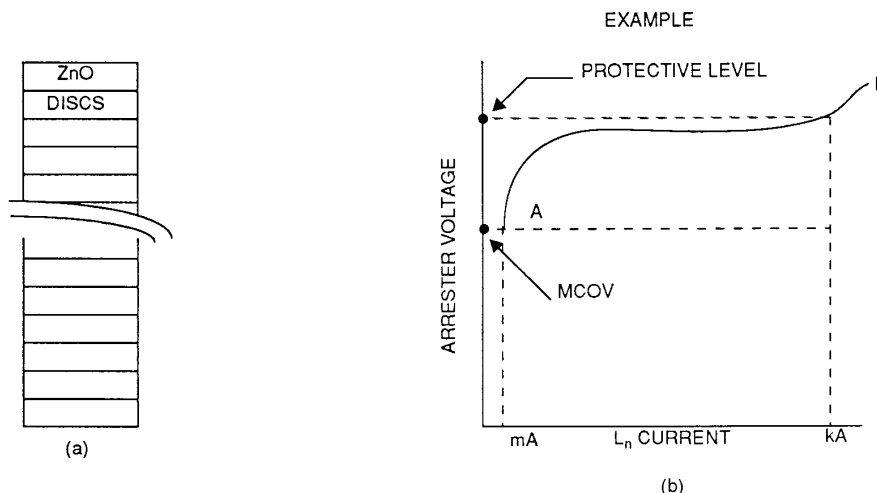


Fig 1
Gapless Metal-Oxide Surge Arrester

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-

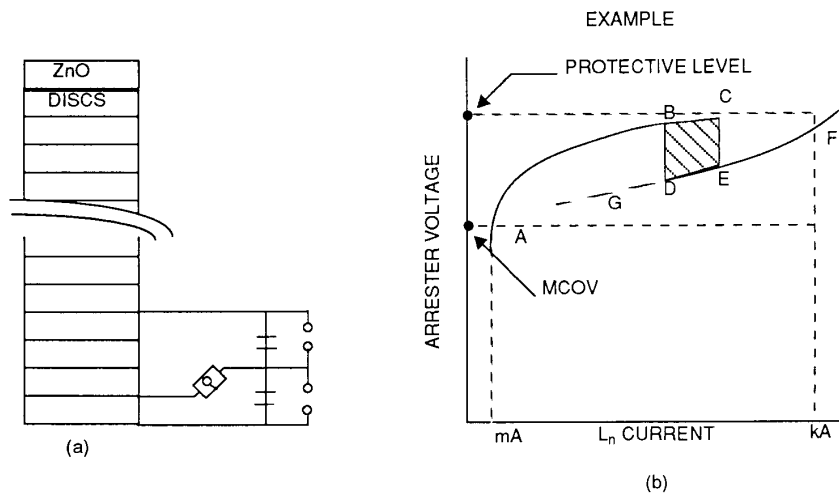


Fig 2
Shunt-Gapped Metal-Oxide Surge Arrester

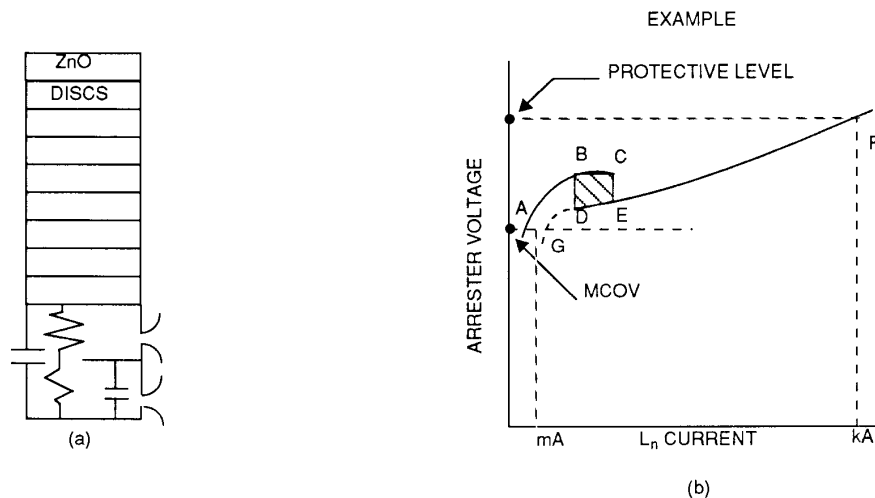


Fig 3
Series-Gapped Metal-Oxide Surge Arrester

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 $-40\text{ }^{\circ}\text{C}$ and $40\text{ }^{\circ}\text{C}$, in temporary maximum air temperatures due to external heat sources near the arrester that do not exceed $60\text{ }^{\circ}\text{C}$, 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.

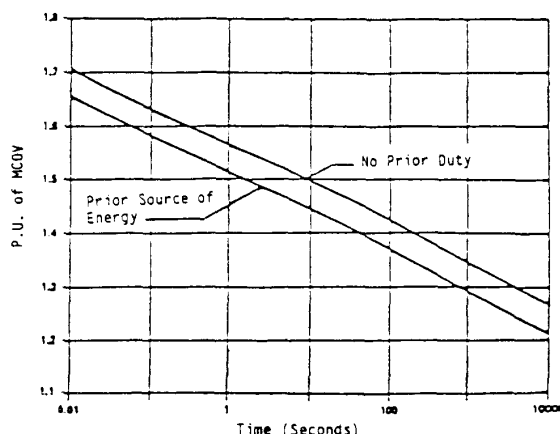


Fig 4
Typical 60 Hz Temporary Overvoltage Capability Curve

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 μ s 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 μ s 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 μ s; 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 μ s, 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 μ s 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 μ s 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 over-voltages and with the characteristics of surge-protective devices.”

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

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

“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.

$$PR_{L1} = \frac{CWW}{FOW}$$

$$PR_{L2} = \frac{BIL}{LPL}$$

$$PR_S = \frac{BSL}{SPL}$$

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

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 μ s FOW Discharge Voltage (DV) (NOTE 1)	8/20 μ s 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									
4.37-1.69	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 μ s. Protective level is maximum DV for a 10 kA impulse current wave on arrester duty cycle rating through 31.2 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 μ s to 60 μ s) 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

- | | |
|--|--|
| <p>1. Select surge arrester (see 3.3)</p> <p>1.1 MCOV $\geq$ Maximum Line-to-Neutral Voltage</p> <p>1.2 TOV Capability $\geq$ System TOV</p> <p>1.3 Switching Impulse Energy Capability $\geq$ that produced by the system</p> <p>1.4 Arrester Class:</p> <p>(1) Available ratings</p> <p>(2) Pressure relief</p> <p>(3) Durability</p> <p>2. Determine protective characteristics (see 3.4)</p> <p>2.1 Lightning Impulse Protective Level, LPL</p> <p>2.2 Front-of Wave Protection Level, FOW</p> <p>2.3 Switching Impulse Protective Level, SPL</p> <p>3. Locate surge arrester (see 3.5)</p> <p>As close as possible to equipment to be protected</p> <p>4. Select Insulation Strength (see 3.6)</p> <p>See equipment standards for BILs and BSLs and for CWW</p> <p>5. Determine voltage at equipment terminals (see 3.5)</p> <p>Arrester lead length and transformer-to-arrester separation distance effects can be determined per Appendix C</p> <p>6. Evaluate coordination (see 3.7)</p> <p>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:</p> <p>$PR_{L1} = CWW/FOW \geq 1.2$</p> <p>$PR_{L2} = BIL/LPL \geq 1.2$</p> <p>$PR_S = BSL/SPL \geq 1.15$</p> <p>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.</p> | <p>6.2 If the voltage at the equipment terminals, V_T, is calculated per Appendix C, the protective ratios are as follows:</p> <p>If the time-to-crest of the arrester voltage is equal to or less than 2 μs:</p> <p>(1) $PR_{L1} = CWW/V_T \geq 1.15$</p> <p>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.</p> <p>(2) Otherwise</p> <p>$PR_{L2} = BIL/V_T \geq 1.15$</p> <p>(3) For switching impulse, as in step 6.1</p> <p>$PR_S = BSL/SPL \geq 1.15$</p> <p>For acceptable coordination, the PRs should be equal to or greater than 1.15.</p> <p>7. Evaluate alternates (see 3.8)</p> <p>If acceptable coordination cannot be achieved, evaluate the following measures:</p> <p>(1) Increase BIL and BSL</p> <p>(2) Decrease arrester separation distance</p> <p>(3) Add additional arresters</p> <p>(4) Use arrester with lower protective characteristics</p> |
|--|--|

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

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

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:

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

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.