

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**

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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 of various applications are provided. In many cases, the prescribed steps are adequate. More complex and special solutions 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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Introduction

(This introduction is not part of IEEE Std C62.22-1997, IEEE Guide for the Application of Metal-Oxide Surge Arresters for Alternating-Current Systems.)

This guide presents the suggested application methods for using metal-oxide surge arresters when applied to ac power systems. This guide was written for arresters with and without gaps. Soon to be published IEC 99-5 is a similar standard used in the international community for arresters without gaps.

Material for this guide has been developed over many years. This edition has been compiled by Working Group 3.4.14 of the Application of Surge Protective Devices (ASPD) Subcommittee, Surge Protective Devices (SPD) Committee.

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

1. Scope

This guide covers the application of metal-oxide surge arresters (see IEEE Std C62.11-1993) 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.

This application guide does not cover the application of low-voltage surge protective devices below 1000 V ac. However, it references these devices when applied to the secondary of a transformer since they are part of the transformer protection.

The subject is broad, with many ramifications, and it requires a volume of considerable bulk to explain all possible cases in detail. Clause 5 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 Clause 6 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.

2. 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.

ANSI C62.22-1987, American National Standard Guide for the Application of Gapped Silicon-Carbide Surge Arresters for AC Systems.¹

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

IEC 34-15 (1995-01), Rotating Electrical Machines—Part 15: Impulse Voltage Withstand Levels of Rotating A.C. Machines with Form Wound Stator Coils (draft revision).²

IEEE Std 18-1992, IEEE Standard for Shunt Power Capacitors.

IEEE Std 100-1996, The IEEE Standard Dictionary of Electrical and Electronics Terms, Sixth Edition.³

IEEE Std 824-1994, IEEE Standard for Series Capacitors in Power Systems.

IEEE Std 998-1996, IEEE Guide for Direct Lightning Stroke Shielding of Substations.

IEEE Std 1036-1992, IEEE Guide for Application of Shunt Power Capacitors.

IEEE Std 1313.1-1996, IEEE Standard for Insulation Coordination—Definitions, Principles, and Rules.

IEEE Std C37.04-1979 (Reaff 1989), IEEE Standard Rating Structure for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis (DoD).

IEEE Std C37.015-1993, IEEE Application Guide for Shunt Reactor Switching.

IEEE Std C57.12.00-1993, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers.

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.⁴

IEEE Std C57.13-1993, IEEE Standard Requirements for Instrument Transformers.

IEEE Std C57.21-1990 (Reaff 1995), IEEE Standard Requirements, Terminology, and Test Code for Shunt Reactors Rated Over 500 kVA.

IEEE Std C62.1-1989 (Reaff 1994), IEEE Standard for Gapped Silicon-Carbide Surge Arresters for AC Power Circuits.

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

²IEC publications are available from IEC Sales Department, Case Postale 131, 3, rue de Varembé, CH-1211, Genève 20, Switzerland/Suisse. IEC publications are also available in the United States from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

³IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

⁴IEEE Std C57.12.01-1989 has been withdrawn; however, copies can be obtained from Global Engineering, 15 Inverness Way East, Englewood, CO 80112-5704, USA, tel. (303) 792-2181.

IEEE Std C62.11-1993, IEEE Standard for Metal-Oxide Surge Arresters for Alternating Current Power Circuits.

IEEE Std C62.92.1-1987 (Reaff 1993), IEEE Guide for the Application of Neutral Grounding in Electrical Utility Systems, Part I—Introduction.

IEEE Std C62.92.4-1991 (Reaff 1996), IEEE Guide for the Application of Neutral Grounding in Electric Utility Systems, Part IV—Distribution.

IEEE Std C62.92.5-1992 (Reaff 1997), IEEE Guide for the Application of Neutral Grounding in Electric Utility Systems, Part V—Transmission Systems and Subtransmission Systems.

NEMA MG 1-1993, Motors and Generators.⁵

3. Definitions and acronyms

3.1 Definitions

For the purposes of this guide, the following terms and definitions apply. IEEE Std 100-1996, The IEEE Standard Dictionary of Electrical and Electronics Terms, should be referenced for terms not defined in this clause.

3.1.1 arrester: *See:* surge arrester.

3.1.2 arrester discharge current: The current that flows through an arrester resulting from an impinging surge.

3.1.3 arrester discharge voltage: The voltage that appears across the terminals of an arrester during the passage of discharge current.

3.1.4 arrester duty cycle rating: The designated maximum permissible root-mean-square (rms) value of power-frequency voltage between its line and ground terminals at which it is designed to perform its duty cycle.

3.1.5 basic lightning impulse insulation level (BIL): The electrical strength of insulation expressed in terms of the crest value of a standard lightning impulse under standard atmospheric conditions. BIL may be expressed as either statistical or conventional.

3.1.6 basic switching impulse insulation level (BSL): The electrical strength of insulation expressed in terms of the crest value of a standard switching impulse. BSL may be expressed as either statistical or conventional.

3.1.7 coefficient of grounding (COG): The ratio, ELG/ELL (expressed as a percentage), of the highest root-mean-square (rms) line-to-ground power-frequency voltage ELG 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 ELL that would be obtained at the selected location with the fault removed.

⁵NEMA publications are available from the National Electrical Manufacturers Association, 1300 N. 17th St., Ste. 1847, Rosslyn, VA 22209, USA.

3.1.8 conventional BIL: The crest value of a standard lightning impulse for which the insulation shall not exhibit disruptive discharge when subjected to a specific number of applications of this impulse under specified conditions, applicable specifically to nonself-restoring insulations.

3.1.9 conventional BSL: The crest value of a standard switching impulse for which the insulation does not exhibit disruptive discharge when subjected to a specific number of impulses under specified conditions, applicable to nonself-restoring insulations.

3.1.10 conventional withstand voltage: The voltage that an insulation is capable of withstanding with a 0% probability of failure.

3.1.11 coordination of insulation: The selection of insulation strength consistent with expected overvoltages to obtain an acceptable risk of failure.

3.1.12 crest value: (of an impulse) The maximum value that an impulse attains. *Synonym:* **peak value.**

3.1.13 critical flashover voltage (CFO): The amplitude of voltage of a given waveshape that, under specified conditions, causes flashover through the surrounding medium on 50% of the voltage applications.

3.1.14 deadfront type arrester: An arrester assembled in a shielded housing providing system insulation and conductive ground shield, intended to be installed in an enclosure for the protection of underground and padmounted distribution equipment and circuits.

3.1.15 disruptive discharge: The sudden and large increase in current through an insulating medium due to the complete failure of the medium under electrical stress.

3.1.16 distribution arrester:

(A) **heavy duty class:** An arrester most often used to protect overhead distribution systems exposed to severe lightning currents.

(B) **light duty class:** An arrester generally installed on and used to protect underground distribution systems where the major portion of the lightning stroke current is discharged by an arrester located at the overhead line/cable junction.

(C) **normal duty class:** An arrester generally used to protect overhead distribution systems exposed to normal lightning currents.

3.1.17 ferroresonance: Can also occur between the capacitance to ground of an ungrounded circuit and voltage transformers with primary windings that are grounded. This phenomenon is also possible in gas-insulated systems.

3.1.18 flashover: A disruptive discharge around or over the surface of a solid or liquid insulator.

3.1.19 impulse: A surge of unidirectional polarity.

3.1.20 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.

3.1.21 lightning overvoltage: The crest voltage appearing across an arrester or insulation caused by a lightning surge.

3.1.22 lightning surge: A transient electric disturbance in an electric circuit caused by lightning.

3.1.23 liquid-immersed type arrester: An arrester designed for use immersed in an insulating liquid.

3.1.24 maximum continuous operating voltage rating (MCOV): The maximum designated root-mean-square (rms) value of power frequency voltage that may be applied continuously between the terminals of the arrester.

3.1.25 metal-oxide surge arrester (MOSA): A surge arrester utilizing valve elements fabricated from non-linear resistance metal-oxide materials.

3.1.26 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.

3.1.27 nominal system voltage: A nominal value assigned to designate a system of a given voltage class.

3.1.28 nonself-restoring insulation: An insulation that loses its insulating properties or does not recover them completely after a disruptive discharge caused by the application of a test voltage; insulation of this kind is generally, but not necessarily, internal insulation.

3.1.29 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).

3.1.30 peak value: *See crest value.*

3.1.31 riser pole type arrester: An arrester for pole mounting most often used to protect underground distribution cable and equipment.

3.1.32 self-restoring insulation: Insulation that completely recovers its insulating properties after a disruptive discharge caused by the application of an overvoltage; insulation of this kind is generally, but not necessarily, external insulation.

3.1.33 series gap: 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.

3.1.34 standard lightning impulse: The wave shape of the standard impulse used is 1.2/50 μs (when not in conflict with products standards).

3.1.35 standard switching impulses: The wave shapes of standard impulse tests depend on equipment being tested:

- a) For air insulation and switchgear: 250/2500 μs
- b) For transformer products: 100/1000 μs
- c) For arrester sparkover tests:
 - 1) 30–60/90–180 μs
 - 2) 50–300/400–900 μs
 - 3) 1000–2000/3000–6000 μs (The tail duration is not critical)

3.1.36 statistical BIL: The crest values of a standard lightning impulse for which the insulation exhibits a 90% probability of withstand (or a 10% probability of failure) under specified conditions, applicable specifically to self-restoring insulations.

3.1.37 statistical BSL: The crest value of a standard switching impulse for which the insulation exhibits a 90% probability of withstand (or a 10% probability of failure), under specified conditions, applicable to self-restoring insulations.

3.1.38 statistical withstand voltage: The voltage that an insulation is capable of withstanding with a given probability of failure, corresponding to a specified probability of failure (e.g., 10%, 0.1%).

3.1.39 surge: A transient wave of current, potential, or power in an electric circuit.

3.1.40 surge arrester: A protective device for limiting surge voltages on equipment by discharging or bypassing surge current; it limits the flow of power follow current to ground, and is capable of repeating these functions as specified.

3.1.41 switching overvoltage: Any combination of switching surge(s) and temporary overvoltage(s) associated with a single switching episode.

3.1.42 switching surge: A heavily damped transient electrical disturbance associated with switching. System insulation flashover may precede or follow the switching in some cases but not all.

3.1.43 system voltage: The root-mean-square (rms) phase-to-phase power frequency voltage on a three-phase alternating-current electric system.

3.1.44 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.

3.1.45 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.

3.1.46 unit operation: Discharge of a surge through an arrester while the arrester is energized.

3.1.47 valve arrester: An arrester that includes one or more valve elements.

3.1.48 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.

3.1.49 virtual duration of wave front: (of an impulse) The virtual value for the duration of the wave front is as follows:

- a) 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.
- b) 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.
- c) For current waves, 1.25 times the time for the current to increase from 10% to 90% of crest value.

3.1.50 virtual zero point: (of an impulse) The intersection with 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.

3.1.51 wave front: (of an impulse) That part of an impulse that occurs prior to the crest value.

3.1.52 wave shape: (of an impulse test wave) The graph of an impulse test wave as a function of time.

3.1.53 wave shape designation: (of an impulse)

- a) 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. 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 and 8/20 waves.

- b) 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 $75 \text{ A} \times 2000 \text{ } \mu\text{s}$ wave.

3.1.54 wave tail: (of an impulse) That part between the crest value and the end of the impulse.

3.1.55 withstand voltage: The voltage that an insulation is capable of withstanding with a given probability of failure. In terms of insulation, this is expressed as either conventional withstand voltage or statistical withstand voltage.

4. General considerations

4.1 Overvoltages

Overvoltages in power systems may be generated by external events, such as lightning; by internal events, such as switching and faults; by internal conditions including faults, ferroresonance, load rejection, loss of ground, etc.; or by any combination of the above. 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.

4.1.1 Lightning currents and overvoltages

Lightning surge voltages that arrive at the line entrance of a station are caused either by:

- a) 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
- b) A lightning flash terminating on the phase conductor (denoted as a shielding failure).

The lightning surge voltage magnitudes and wave shapes 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. This represents a reasonable worst-case condition. The steepness of the incoming surge (rate of rise) is dependent on the distance between the station and the backflash location. The steepness decreases approximately as an inverse function of this distance, d , and ranges from about $700/d \text{ kV}/\mu\text{s}$ for a single phase conductor to about $1700/d \text{ kV}/\mu\text{s}$ for a 3- to 4-conductor bundle where d is in km. Steepnesses in the range of 500 to 2000 $\text{kV}/\mu\text{s}$ are typically encountered. The tail of the incoming surge described is generally in the range of 10 to 20 μs .

Lightning surge crest voltages caused by shielding failures generally do not exceed the negative polarity CFO of the line. The wave fronts and tails at the location of the shielding failure are equal to those of the lightning stroke current. Therefore, the steepness of the incoming surge at the station is less than those from a backflash while the tail is longer, an average time to half value of about 92 μs .

For lines that are effectively shielded, for the same reliability criterion, the surge voltages caused by a backflash are usually more severe. That is, they have greater steepness and greater crest voltage, and therefore are the only ones generally considered for analysis of station protection.

4.1.2 Switching overvoltages

Switching overvoltages occur on all systems (AIEE Committee Report [B1]⁶, IEEE Committee Report [B61], and IEEE Committee Report [B62]) and usually result from a circuit-breaker operation or the occurrence of a fault. 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 energizing.

On extra high-voltage (EHV) systems, it is 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 system study. Arresters of higher energy capability or parallel arresters may be required (see 5.11).

4.1.3 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. 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 4.2.3).

When detailed system studies or detailed calculations are unavailable, as a minimum the overvoltages due to line-to-ground faults should be addressed. Single line-to-ground faults are the most common type of system disturbance. The magnitudes of these overvoltages are related to system grounding and can be estimated by the “coefficient of grounding” (COG) as outlined in 5.3.2.1. 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 (Clarke [B25]).

4.2 Metal-oxide arresters

4.2.1 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.

⁶The numbers in brackets correspond to those of the bibliography in annex D.

4.2.1.1 Gapless arresters

Gapless arresters utilize a single stacked column or two or more parallel columns of metal-oxide valve elements, as schematically shown in Figure 1(a). A typical volt-ampere characteristic for such an arrester is illustrated in Figure 1(b). Above the knee of the volt-ampere 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 metal-oxide 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 the valve element 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 maximum continuous operating voltage (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 volt-ampere characteristic. As the surge current decreases, the discharge voltage will decrease back toward the pre-surge level.

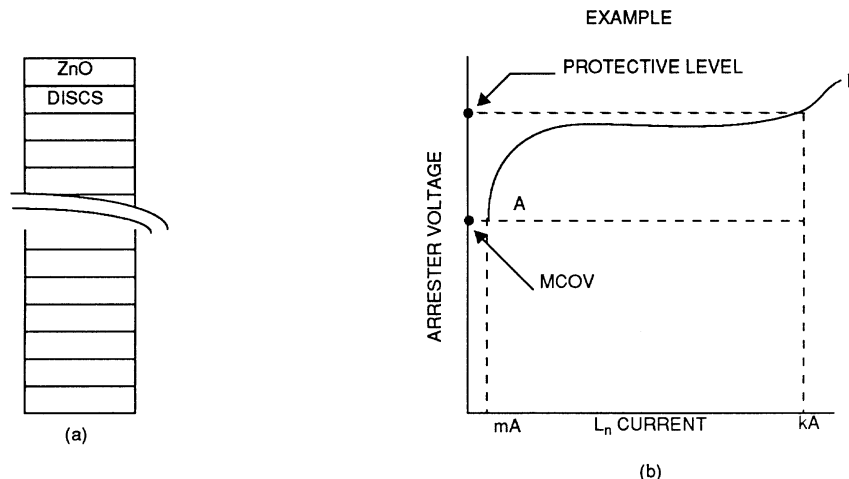


Figure 1—Gapless metal-oxide surge arrester

4.2.1.2 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 Figure 2(a). A typical volt-ampere characteristic of such an arrester is illustrated in Figure 2(b). On arrival of a surge, the arrester voltage initially increases with increasing surge-current magnitude according to the volt-ampere characteristics A-B. When the surge current magnitude reaches 250–500 A (range B to C on volt-ampere characteristic), sparkover of a gap electrically connected in parallel with a few metal-oxide valve elements results in a shunting of the surge current around these valve elements, 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.

4.2.1.3 Series-gapped arresters

Another approach to obtain reduced protective levels is to use fewer valve elements in conjunction with series-connected spark gaps, as depicted in Figure 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 elements. A typical volt-ampere characteristic is illustrated in Figure 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 elements 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..

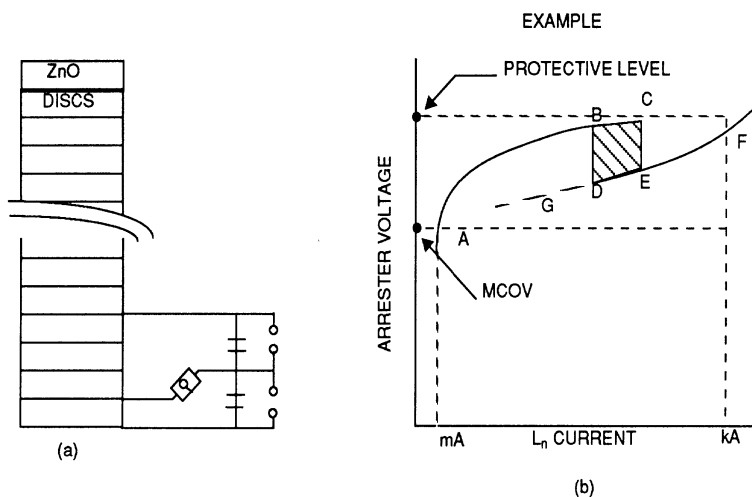


Figure 2—Shunt-gapped metal-oxide surge arrester

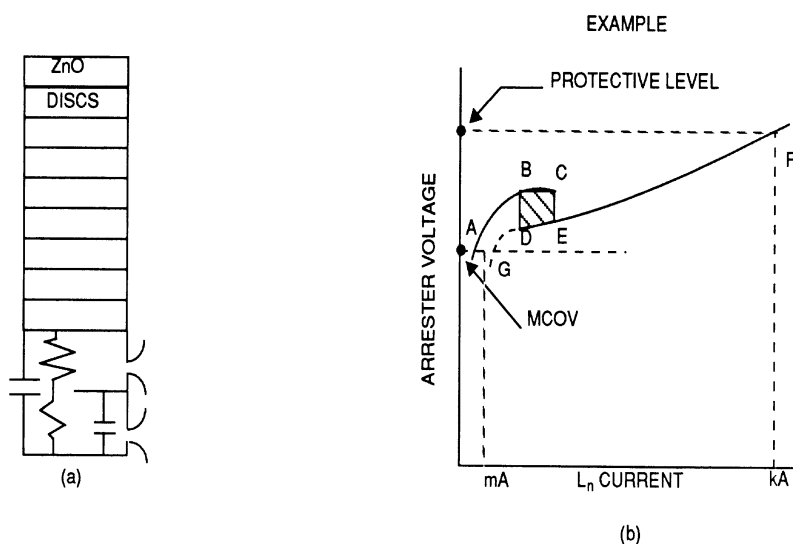


Figure 3—Series-gapped metal-oxide surge arrester

4.2.1.4 Test procedures

IEEE Std C62.11-1993 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 manner, irrespective of whether the levels are limited by sparkover or by discharge voltage (see 4.3).

4.2.1.5 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 been standardized at the time this guide was prepared.

4.2.1.6 Unusual conditions

In addition to operation beyond the limits of 4.2.1.5, exposure to damaging fumes, vapors, steam, salt spray, or excessive amounts of contamination may require special consideration. Arresters should not be installed where they may be subjected to excessive mechanical stresses or to abnormal vibrations or shocks.

4.2.2 Standard voltage ratings

The present metal-oxide design standard, IEEE Std C62.11-1993, specifies a dual voltage rating for each arrester. The conventional duty-cycle voltage rating (see 3.8) now has a corresponding MCOV rating (see 3.27). Refer to Table 1 of IEEE Std C62.11-1993.

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.

4.2.3 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. All manufacturers publish information on overvoltage capability. A typical 60 Hz temporary overvoltage capability curve is shown in Figure 5 and the test to confirm this capability is specified in IEEE Std C62.11-1993.

4.2.4 Energy handling capability

When metal-oxide arresters are energized, valve elements of the arrester will absorb energy that results in a temperature increase of the valve elements. Under normal operating conditions (i.e., absence of overvoltage) there is a balance between the heat generated by the valve elements and the heat dissipated by the arrester through conduction, convection, and radiation such that a stable operating condition is maintained. Overvoltage events disturb this stable condition by causing the valve elements to absorb increased levels of energy for the time the overvoltage exceeds the normal operating voltage. The subsequent response of the arrester depends greatly on the magnitude and rate of energy input and on the specific design of the arrester.

For simple applications where overvoltages are well defined, the resulting energy absorbed by the arrester can be determined by calculation (minimum characteristics should be used). For complex situations, computer simulation studies using programs such as Electromagnetic Transients Program (EMTP) may be required. These studies require knowledge of the arrester minimum and maximum voltage-current character-

istics, usually available from the arrester manufacturer, for modeling in EMTP. Both the minimum as well as the maximum characteristics shall be used in order to calculate the actual energy and protective levels respectively.

If the temperature rise of the valve elements due to energy absorption is too high, the arrester can be driven into a state of thermal runaway, a condition in which heat generated exceeds heat dissipated, resulting in further increase in valve element temperature. If the temperature of a valve element reaches a high enough level, damage to the valve elements can occur, leading to an electrical breakdown and failure of the arrester.

If the energy density is sufficiently high or if the distribution of energy density within the valve element is non-uniform to cause locally high temperature gradients, thermomechanical damage in the form of valve element cracking or puncture may occur. This is possible even if the overall temperature rise of the valve elements would not have been high enough to drive the arrester into thermal runaway.

The energy that an arrester can absorb during an overvoltage event without impairing the arrester's ability to serve the intended function following the event is usually called "energy handling capability" or "energy withstand capability." This capability is often expressed in terms of kilojoules per kV of arrester MCOV or per kV of duty-cycle rating. Because it is dependent on the specific form (magnitude, waveshape and duration) of the overvoltage, the energy handling capability cannot be expressed by a single value of kJ/kV. Manufacturers typically publish some information on energy handling capability, but it should be recognized that, at present, there are no standardized tests for determination of arrester's energy handling capability. Users are advised to consult with manufacturers on appropriate use of information provided. Additional information on metal-oxide valve element energy handling capability is given in IEEE Working Group Report [B69] and Ringler et al., [B115].

4.3 Protective levels

The protective level of an arrester is the maximum crest voltage that appears across the arrester 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.

4.3.1 Classification current

Table 3 in IEEE Std C62.11-1993 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 C62.11-1993 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 5.4.2 and 5.4.3). IEEE Std C62.11-1993 requires that certain tests, including discharge voltage measurements, be made at the specified classification current magnitude.

4.3.2 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 C62.11-1993 specifies that tests should be made with 8/20 μ s currents of 1500 A, 3000 A, 5000 A, 10 000 A, and 20 000 A. If the arrester lightning impulse classification current shown in Table 3 of IEEE Std C62.11-1993 is not one of these, an additional test must be made at the classification current given for the particular arrester class.

4.3.3 Front-of-wave protective level (FOW)

FOW protective level for metal-oxide arresters is the higher of

- a) 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
- b) Gap sparkover for specified rates-of-rise of wave shapes in IEEE Std C62.11-1993.

4.3.4 Switching impulse protective level (SPL)

SPL is the higher of either:

- a) 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
- b) Gap sparkover voltage on similar wave shapes.

The switching impulse classifying currents of Table 4 of IEEE Std C62.11-1993 for a two line substation 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 C62.11-1993. 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.

4.4 Insulation withstand

Insulation strength is expressed in terms of conventional or statistical BILs and BSLs. The withstand voltages of interest in arrester applications are taken from the list of preferred BIL and BSL values in IEEE Std 1313.1-1993.

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

- a) *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.
- b) *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.
- c) *Basic Switching Impulse Insulation Level (BSL)*: The test impulse depends on the type of equipment.

Transmission and distribution line insulation strength is usually statistically described by a critical flashover voltage (CFO) at which the insulation exhibits a 50% probability of flashover and by a standard deviation σ which is approximately 5% of the CFO.

The insulation strength of apparatus within a station is expressed in terms of a BIL, a chopped-wave voltage, and for higher system voltages, a BSL. As noted from the definitions, the BIL and BSL may be either conventional or for statistical BILs and BSLs. The statistical BIL (or BSL) is equal to $CFO - 1.28 \sigma$.

4.5 Separation effects

The voltage at the protected insulation will usually be higher than at the arrester terminals due to oscillations on connecting leads (Witzke and Bliss [B133]). This rise in voltage is called a separation effect.

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 Annex 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 5.5.

4.6 Insulation coordination

Insulation coordination is defined in IEEE Std 1313.1-1996 and in this guide as “the selection of insulation strength consistent with expected overvoltages to obtain an acceptable risk of failure.”

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.

Three protective ratios are in common use, comparing protective levels with corresponding insulation withstands.

$$PR_{L1} = \frac{CWW}{FOW} \quad (\text{Acceptable ratio is 1.15})$$

$$PR_{L2} = \frac{BIL}{LPL} \quad (\text{Acceptable ratio is 1.15})$$

$$PR_S = \frac{BSL}{SPL} \quad (\text{Acceptable ratio is 1.2})$$

The protective margin (PM) in percent is defined as: $PM = (PR - 1)100$. PR and PM applications are covered in Clauses 5 and 6.

A graphical approach to insulation coordination is also discussed in 5.7.

5. Protection of transmission systems

5.1 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 5.2 and elaborated upon in 5.3 through 5.8.

Arrester applications for transformer or other series windings, unloaded windings, and ungrounded neutrals are discussed in 5.9.

Where a lower chopped-wave insulation level is specified in equipment such as dry-type transformers, the protection procedures are covered in 5.10.

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

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

5.2 Step-by-step procedures

A summary of the steps required to select arresters is provided in Figure 4.

1. Select surge arrester
 - 1.1 $\text{MCOV} \geq \text{Maximum Phase-to-Neutral Voltage}$ (see 5.3.1)
 - 1.2 $\text{TOV Capability} \geq \text{System TOV}$ (see 5.3.2)
 - 1.3 $\text{Switching Impulse Energy Capability} \geq \text{that produced by the system}$ (see 5.3.3)
 - 1.4 Arrester Class:

(1) Available ratings

(2) Pressure relief

(3) Durability

}

(see Table 1)
2. Determine protective characteristics (see 5.4.1)
 - 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 5.5)
As close as possible to equipment to be protected
4. Determine voltage at equipment terminals (see 5.5)
Arrester lead length and transformer-to-arrester separation distance effects can be determined per Annex C
5. Select Insulation Strength (see 5.6)
See equipment standards for BILs, BSLs and CWWs
6. Evaluate coordination (see 5.7)
 - 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:

$$\text{PR}_L = \text{CWW}/\text{FOW}$$

$$\text{PR}_{L2} = \text{BIL}/\text{LPL}$$

$$\text{PR}_S = \text{BSL}/\text{SPL}$$

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 Annex C, the protective ratios are as follows:

If the time-to-crest of the arrester voltage is equal to or less than $2 \mu\text{s}$:

$$\text{PR}_{L1} = \text{CWW}/V_T$$

$$\text{PM}_{L1} = (\text{PR}_{L1} - 1) 100 (\%)$$

If CWW does not exist or the time-to-crest of the arrester voltage is greater than $2 \mu\text{s}$:

$$\text{PR}_{L2} = \text{BIL}/V_T$$

$$\text{PM}_{L2} = (\text{PR}_{L2} - 1) 100 (\%)$$

Also

$$\text{PR}_S = \text{BSL}/\text{SPL}$$

$$\text{PM}_S = (\text{PR}_S - 1) 100 (\%)$$

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 $\text{PM}_S \geq 15$).
7. Evaluate alternates (see 5.8)

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

Figure 4—Summary of procedures for arresters selection and insulation coordination

Table 1—Typical station and intermediate class arrester characteristics

Station class									
Steady state operation: system voltage and arrester ratings				Protective levels: range of industry maxima per unit of MCOV			Durability characteristics: IEEE Std C62.11-1993		
Max system voltage L-L kV-rms ^a	Max system voltage L-G kV-rms ^a	Min MCOV rating kV-rms	Duty cycle ratings kV-rms	0.5 μ s FOW protective level ^b	8/20 μ s protective level ^b	Switching surge protective level ^c	High current withstand crest amperes	Trans. line discharge miles	Pressure relief kA rms (symmetrical) ^d
4.37	2.52	2.55	3	2.32–2.48	2.10–2.20	1.70–1.85	65 000	150	40–80
8.73	5.04	5.1	6–9	2.33–2.48	1.97–2.23	1.70–1.85	65 000	150	40–80
13.1	7.56	7.65	9–12	2.33–2.48	1.97–2.23	1.70–1.85	65 000	150	40–80
13.9	8.00	8.4	10–15	2.33–2.48	1.97–2.23	1.70–1.85	65 000	150	40–80
14.5	8.37	8.4	10–15	2.33–2.48	1.97–2.23	1.70–1.85	65 000	150	40–80
26.2	15.1	15.3	18–27	2.33–2.48	1.97–2.23	1.70–1.85	65 000	150	40–80
36.2	20.9	22	27–36	2.43–2.48	1.97–2.23	1.70–1.85	65 000	150	40–80
48.3	27.8	29	36–48	2.43–2.48	1.97–2.23	1.70–1.85	65 000	150	40–80
72.5	41.8	42	54–72	2.19–2.40	1.97–2.18	1.64–1.84	65 000	150	40–80
121	69.8	70	90–120	2.19–2.40	1.97–2.18	1.64–1.84	65 000	150	40–80
145	83.7	84	108–144	2.19–2.39	1.97–2.17	1.64–1.84	65 000	150	40–80
169	97.5	98	120–172	2.19–2.39	1.97–2.17	1.64–1.84	65 000	175	40–80
242	139	140	172–240	2.19–2.36	1.97–2.15	1.64–1.84	65 000	175	40–80
362	209	209	258–312	2.19–2.36	1.97–2.15	1.71–1.85	65 000	200	40–80
550	317	318	396–564	2.01–2.47	2.01–2.25	1.71–1.85	65 000	200	40–80
800	461	462	576–612	2.01–2.47	2.01–2.25	1.71–1.85	65 000	200	40–80
Intermediate class									
4.37–145	2.52–83.72	2.8–84	3–144	2.38–2.85	2.28–2.55	1.71–1.85	65 000	100	16.1 ^d

^aVoltage range A, ANSI C84.1-1989^bEquivalent front-of-wave protective level producing a voltage wave cresting in 0.5 μ s. Protective level is maximum discharge voltage (DV) for 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 C62.11-1993.^cSwitching 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 C62.11-1993.^dTest values for arresters with porcelain tops have not been standardized. Pressure relief classification is in 5 kA steps.

The following sequence is used:

- a) Select an arrester and determine its protective characteristics.
- b) Select (or determine) the insulation withstand.
- c) 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. Typical characteristics of station class and intermediate class arresters are given in Table 1. Distribution class arresters are sometimes used in stations, and typical characteristics of such arresters may be found in Table 6. Protective levels are given in per-unit values of crest arrester MCOV rating. 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 C62.11-1993.

5.3 Arrester selection

For a given application, the selection of an appropriate arrester (Figure 4, Item 1) 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, 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 Clause 6) 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.

5.3.1 Maximum continuous operating voltage (MCOV)

For each arrester location, arrester MCOV must 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 to a delta-connected system with a fault on one phase, is exposed to phase-to-phase voltage.

5.3.2 Temporary overvoltage capability (TOV)

In addition to considerations affecting the selection of arrester MCOV, the user must also select the arrester to withstand the temporary overvoltages in the system at the arrester location. The basic requirement is that the power frequency voltage versus time characteristic of the arrester should be higher than the temporary overvoltage (TOV) amplitude versus duration characteristic of the system for all times of concern.

Figure 5 is a typical generic TOV curve for Station and Intermediate Class Arresters. The upper curve shows the time the arrester withstands given overvoltages and subsequently thermally recovers when MCOV is applied. The lower curve is similar to upper, but applies to a condition where the arrester has absorbed prior energy from two transmission line discharges. For Station and Intermediate Class arresters, the test procedure is described in IEEE Std C62.11-1993 and each manufacturer may publish different test results. Figure 5 is shown for illustrative purposes only. For applications, TOV data should be obtained from the manufacturers.

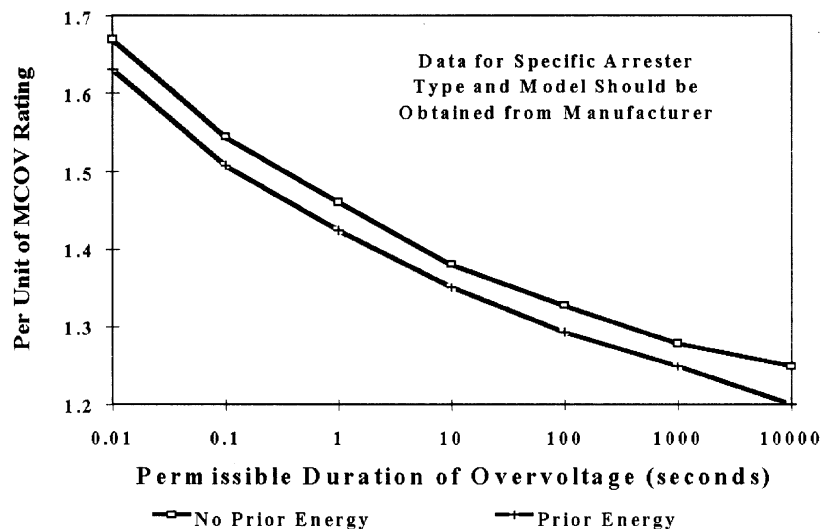


Figure 5—Example of typical arrester TOV data (do not use for application)

The selected arrester must have both MCOV and temporary overvoltage capability appropriate for the operating system. Sometimes the MCOV is decisive and sometimes TOV considerations are decisive.

A change in relay setting, or use of faster breakers may sometimes allow use of arresters based on MCOV when TOV would otherwise have been decisive.

5.3.2.1 Fault conditions

5.3.2.1.1 Overvoltage amplitude considerations

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

The numbers adjacent to each of the curves of Annex B are the coefficients of grounding in percent. 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 Figure 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 (AIEE Committee Report [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.

NOTE—Annex A of IEEE Std C62.92.1-1987 contains additional information for determining coefficients of grounding, more thoroughly addressing this subject.

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 at 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 (R_f) the definitions of k above would have to be modified as follows: For SLG fault: $k = \frac{R_0 + R_f + jX_0}{R_1 + R_f + jX_0}$ For DLG fault: $k = \frac{R_0 + 2R_f + jX_0}{R_1 + 2R_f + jX_1}$ where $R_f = \text{Fault resistance}$
--	---

Figure 6—COG calculations

5.3.2.1.2 Overvoltage duration considerations

The duration of overvoltages from line-to-ground faults depends on the adopted short-circuit relaying protection. In the absence of other information the following typical values may be used:

Grounded neutral systems:	TOV duration
Line protection	0.2 s
Back-up protection	1 s
Resonant grounded or isolated neutral systems:	
Without ground fault clearing	3 h
With ground fault clearing	4 s

5.3.2.2 Load rejection

After disconnection of loads, the voltage rises at the source side of the operating circuit breaker. The amplitude of the overvoltage depends on the disconnected load and on the short circuit power of the feeding substation. The temporary overvoltages can have particularly high amplitudes after full load rejection at generator transformers due to magnetizing and overspeed conditions. The amplitudes of load rejection overvoltages are usually not constant during their durations. Accurate calculations have to consider many parameters.

As a guidance the following typical values of such overvoltages may be used:

- In moderately extended systems, a full load rejection can give rise to phase-to-ground overvoltages with amplitude usually below 1.2 p.u. The overvoltage duration depends on the operation of voltage-control equipment and may be up to several minutes.

- In extended systems, after a full load rejection, the phase-to-ground overvoltages may reach 1.5 p.u. or even more when Ferranti or resonance effects occur. Their durations may be in the order of some seconds.
- Where load is rejected from the load side of a generator step-up transformer, the temporary overvoltages may reach amplitudes up to 1.4 p.u. for turbo generators and up to 1.5 p.u. for hydro generators. The duration is approximately 3 s.
- When the time dependence of the amplitudes is known, a suitable representation of the overvoltage is the maximum amplitude with a duration equal to the time that the amplitudes exceed 90% of this value.

Other causes of temporary overvoltages need consideration. In some cases the following:

- a) Resonance effects, e.g., when charging long unloaded lines or when resonances exist between systems. Temporary overvoltages due to ferroresonance should be considered and are addressed in 6.4.4. Temporary overvoltages due to ferroresonance should not form the basis for the surge arrester selection and should be eliminated.
- b) Voltage rise along long lines (Ferranti effect).
- c) Harmonic overvoltages, e.g., when switching transformers.
- d) Accidental contact with conductors of higher system voltage.
- e) Backfeed through interconnected transformer windings, e.g., dual transformer station with common secondary bus during fault clearing or single-phase switched three-phase transformer with an unbalanced secondary load.
- f) Loss of system grounding.

Sequences of causes of temporary overvoltages, e.g., load rejection caused by a ground fault, need consideration when the overvoltages due to the load rejection are due to the ground fault with comparable severity. In such cases, however, the amount of rejected load dependent on the fault location and the arrester location has to be carefully examined.

Combination of causes such as ground faults caused by load rejection may result in higher temporary overvoltage values than the single events. When such combinations are considered sufficiently probable, the overvoltage factors for each cause have to be multiplied, taking into account the actual system configuration.

5.3.3 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:

$$J = D_L E_A I_A / v \quad (1)$$

where

E_A is arrester switching impulse discharge voltage (in kilovolts) for I_A ,
 I_A is switching impulse current (in kiloamperes),
 D_L is line length (in miles or kilometers), and
 v is the speed of light (300 km/ms) or 186 000 mi/s.

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

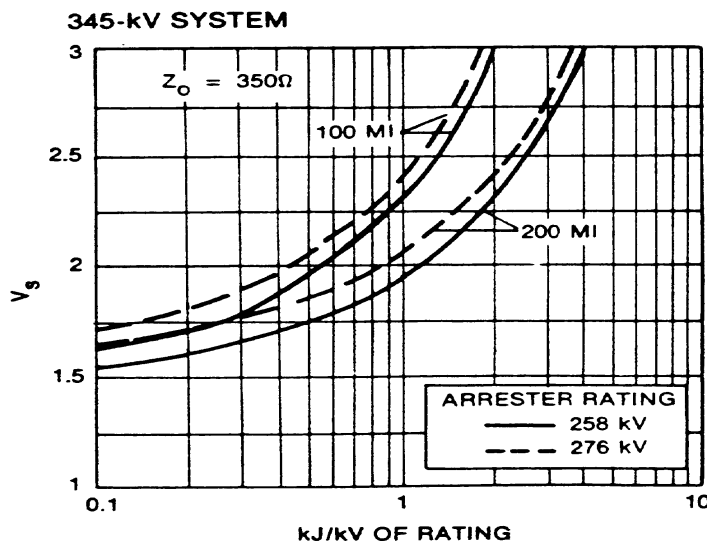
$$I_A = (E_S - E_A) / Z \quad (2)$$

where

E_S is prospective switching surge voltage (in kilovolts) and
 Z is 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 equations (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 Figure 7 for a 209 kV MCOV rated arrester (258 kV duty cycle rating) on a 345 kV, 100 mi 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-unit of 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—In Figure 7, V_s is prospective voltage in per unit of peak line-to-ground system voltage.

Figure 7—Typical curve for a prospective switching surge voltage versus arrester discharge energy for a 345 kV line

5.3.4 Tentative selection of arrester voltage rating

The arrester voltage rating should be tentatively selected on the basis of MCOV (5.3.1), TOV (5.3.2), and switching surge durability (5.3.3).

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

- a) *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 5.3.2.1 are likely to be exceeded frequently, increasing the probability of arrester operations during such conditions, it may be necessary to use an arrester with a higher voltage rating. Other causes of TOV as listed in 5.3.2.2 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.
- b) *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.

5.3.5 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:

- a) Available voltage ratings
- b) Pressure relief current limits, which should not be exceeded by the system's available short-circuit current and duration at the arrester location
- c) 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.

5.4 Protective levels of arrester (Figure 4, Item 2)

5.4.1 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 Subclauses 8.3 and 8.4 of IEEE Std C62.11-1993. The following protective levels should be considered:

- a) *FWO:* The higher value of FWO sparkover or arrester discharge voltage cresting in 0.5 μ s at the classifying current.
- b) *LPL:* The higher value of lightning impulse sparkover for a 1.2/50 lightning impulse or arrester discharge voltage that results from an 8/20 current wave. The appropriate current magnitude is determined by the system voltage per Table 2.
- c) *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 μ s to 60 μ s. The appropriate current magnitude is based on the system voltage as contained in 5.4.3.

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	10
145	10
242	10
362	10
550	15
800	20

5.4.2 Arrester coordinating currents for lightning surges

5.4.2.1 Factors that affect the selection of discharge currents for determining 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 the following:

- The importance and degree of protection desired. Basing protective levels on higher current magnitudes and rates-of-rise increases the reliability of protection.
- 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.
- The probability of occurrence of the higher stroke currents. The magnitude of lightning currents vary over a wide range of values (Orville, Henderson, and Pyle [B105]). Lines in areas of high keraunic levels have an increased chance of being struck by lightning with high-current magnitudes (see Annex A).
- 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.

5.4.2.2 Recommended arrester coordinating currents for lightning surges

The appropriate coordinating current for lightning surges depends strongly on the effectiveness of line shielding.

5.4.2.2.1 Recommended currents for shielded stations with completely shielded lines

The lightning performance of shielded lines is based on the shielding failure and back-flashover rates of the lines. 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 back-flashovers will be the predominant mechanism of

line insulation flashover. In either event, the magnitude of the arrester discharge current can be estimated from:

$$I = I_c = 3.84(E_{CFO} - E_C)/Z_0 \quad (3)$$

where

- I is arrester discharge current (in kiloamperes),
- I_C is arrester coordinating current (in kiloamperes),
- E_{CFO} is positive CFO of line insulation (in kilovolts),
- E_C is arrester discharge voltage (in kilovolts) for the estimated value of the coordinating current (see Table 2),
- Z_0 is single-phase surge impedance of line (in ohms), and
- 3.84 is the correction factor based on system studies. The increase in current is due to transformer capacitance.

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.

5.4.2.2.2 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 the following:

- a) The ground flash density
- b) The probability of strokes to the line exceeding a selected value
- c) The percentage of total stroke current that discharges through the arrester

Items (a) and (b) can be evaluated using the methods of Brown and Thunander [B18] or from the ground flash density maps published by EPRI (Orville, Henderson, and Pyle [B105]). Conservative guidelines for (c) are contained in the following table (from Schei and Huse [B117]).

Table 3—Guidelines for total stroke discharge current

Distance line shielding extends from station	Percentage of stroke current discharged through arrester
1.5 mi (2.4 km)	25
1.0 mi (1.6 km)	35
0.5 mi (0.8 km)	50

5.4.2.2.3 Discharge currents in stations where lines are not shielded

Completely unshielded lines usually are limited to either

- a) Lower voltage lines, (i.e., 34.5 kV and below); and/or
- b) 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.

5.4.3 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 C62.11-1993) are listed in the following table:

Table 4—Recommended switching surge coordinating currents

Maximum system voltage (kV)	Station class (A crest)	Intermediate class (A crest)
3–150	500	500
151–325	1000	—
326–900	2000	—

5.4.4 Surge transfer through transformers

When a transformer and connected transmission line are switched together, the low side arrester may operate, causing it to discharge the energy transferred through the transformer from the higher-voltage line. There is a possibility of overstressing an arrester on the low side of a transformer due to this surge transfer. Measures must be taken to ensure that the high-side arrester operates to absorb the majority of the surge energy. This can be accomplished by coordinating the switching surge discharge voltages of the high- and low-side arresters.

The probability of failure of the low-side arrester can be reduced by selecting a low-side arrester with a higher relative switching surge protective level (SPL) than the arrester on the high side, taking the transformer turns ratio into consideration. For example:

$$SPL_{LV} > N(SPL_{HV})$$