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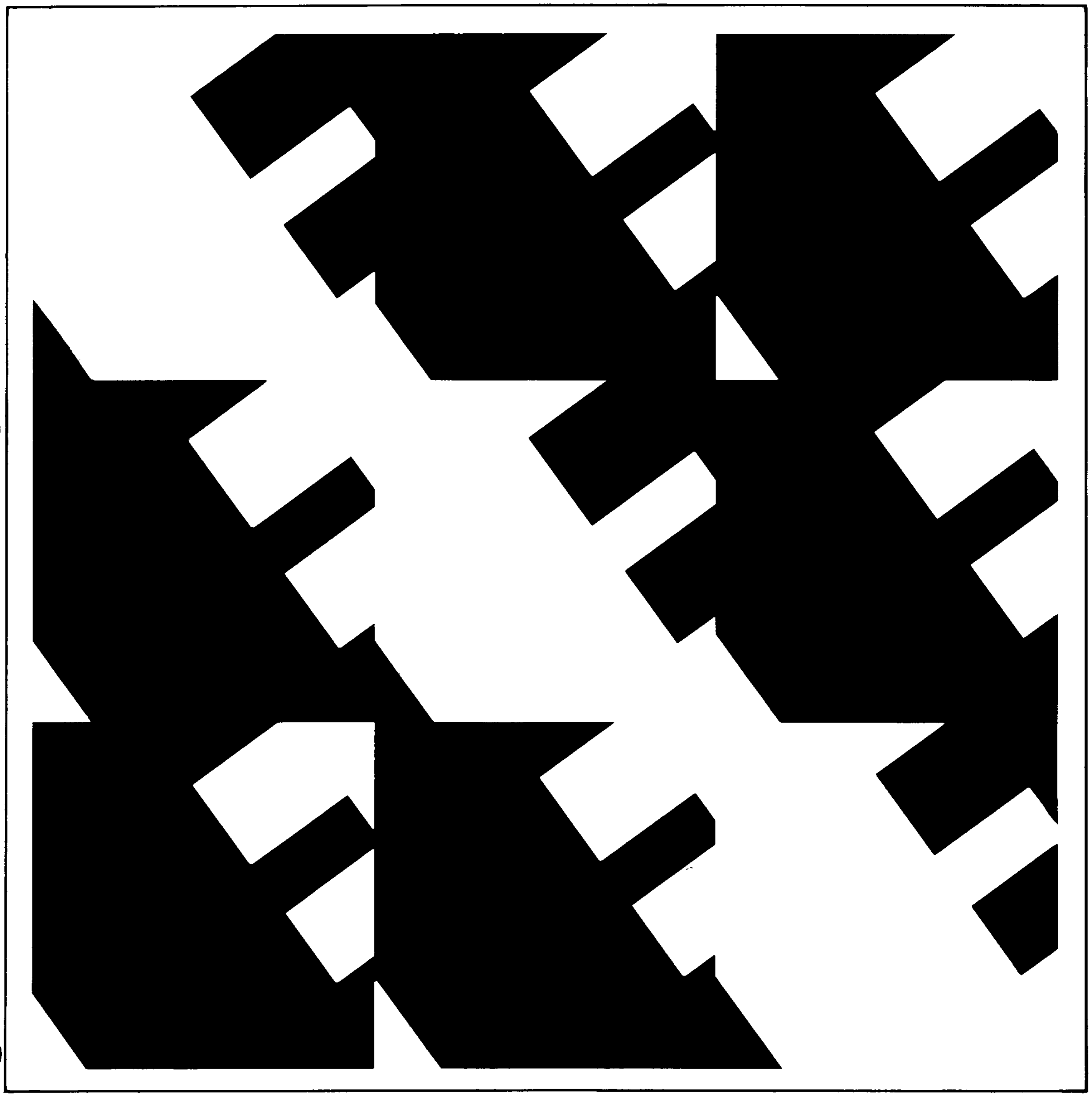
IEEE Guide for the Application of Gapped Silicon-Carbide Surge Arresters for Alternating Current Systems



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IEEE Guide for the Application of Gapped Silicon-Carbide Surge Arresters for Alternating Current Systems

Sponsor

**Surge Protective Devices Committee
of the
IEEE Power Engineering Society**

Approved March 12, 1987

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American National Standards Institute

**The Institute of Electrical and Electronics Engineers, Inc
345 East 47th Street, New York, NY 10017, USA**

Foreword

(This Foreword is not a part of ANSI/IEEE Std C.62.2-1987 IEEE Guide for the Application of Gapped Silicon-Carbide Surge Arresters for Alternating Current Systems).

This guide supplements ANSI/IEEE Std C62.1-1984, American National Standard for Surge Arresters for Alternating Current Power Circuits, to assist users in the selection and application of surge arresters.

This document is a revision of ANSI C62.2-1981. Revisions include:

1) A modification in the title of the guide, substituting "Gapped Silicon-Carbide" for "Valve-Type," to distinguish it from a guide for the application of metal-oxide surge arresters.

2) A new section 3.12, "Protection of Gas-Insulated Substations," has been added.

3) Sections 2.1.1, 3.10, 4.7, and 4.10 have been rewritten.

4) Appendix A has been updated, as well as Tables 1 and 6, which has been renumbered as Table 7 and modified to include the Heavy Duty Distribution Surge Arrester.

5) Definitions D4.4 and D4.5 have been revised and renumbered D5.3 and D5.4 respectively (the original D4.3 was deleted).

6) New references were added, consistent with new and revised sections.

7) A new Appendix E, "Coefficent of grounding (COG) Calculations," has been added.

8) A new Appendix F, "Arrester Stroke Currents—Arresters Connected to Distribution Lines," has been added.

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IEEE Guide for the Application of Gapped Silicon-Carbide Surge Arresters for Alternating-Current Systems

1. Scope and References

1.1 Scope. This standard covers the application of gapped silicon-carbide surge arresters (see ANSI/IEEE Std C62.1-1984 [1])[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, thereby jeopardizing 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 a broad one with many ramifications, and it would require a volume of considerable bulk to explain all possible cases in detail. Section 3 of this standard 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 distribution systems, both open-wire and spacer cable; underground system cables; all distribution transformers; and other electric distribution equipment.

Step-by-step directions toward proper solutions for various applications are provided. For many cases the prescribed steps are adequate. Complex situations or 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]The numbers in brackets correspond to those of the references listed in 1.2; numbers in brackets preceeded by letters correspond to numbers in the reference sections of the Appendixes.

1.2 References. When American National Standards referred to in this document are superseded by a revision approved by the American National Standards Institute, Inc, the revision shall apply:

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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 initiated or generated. The magnitude of these overvoltages can be above maximum permissible levels and, therefore, must be reduced and protected against if damage to equipment and 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 by (1) a lightning flash terminating on the overhead shield wire with a subsequent flashover to the phase conductor (denoted as a "backflash"), by (2) a lightning flash terminating on the phase conductor (denoted as a "shielding failure"), or by (3) induced surges.

The lightning surge voltage magnitude and wave shape at the line entrance of a station are functions of the following:

(1) Magnitude and wave shape of lightning stroke current.
(2) Distance of the stroke from the line (induced stroke).
(3) Tower, steel pole, or power ground lead surge impedance.
(4) Line surge impedance.
(5) Tower footing or pole ground resistance.
(6) Lightning impulse critical flashover voltage 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 critical flashover voltage (CFO), which represents a reasonable worst condition. The wavefront or time-to-crest is dependent on the distance between the station and location of the backflash. The front is approximately 1 μs/km of distance from the station to the backflash location. Fronts in the range of 0.5 to 4.0 μs have been used. The tail of the surge is between 10 and 20 μs, depending on the tower footing resistance. (Larger footing resistances produce longer 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 0.3 to 0.1 μs longer than those for a backflash, and the tails average about 90 μs.

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

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

As shown in references [2] and [3], the lightning stroke parameters for negative downward strokes are considered to be approximated by a Log-Normal distribution whose probability density function is:

$$f(x) = \frac{1}{\sqrt{2\pi}\,\beta x}\, e^{-1/2\left[\frac{\ln x/M}{\beta}\right]^2}$$

where M is the median and β is logarithmic standard deviation.

The measurements of Berger, Anderson, and Kroninger [3] presented in Table 1 show the following value of M and β for the crest current, maximum steepness, and time-to-half value. Also listed are the 5% and 95% values. The maximum steepness and crest currents are correlated; the correlation coefficient is denoted by ρ. The minimum linear front is derived from the parameters for the maximum steepness, the crest current, and the correlation coefficient. The minimum linear front is sometimes used to aproximate the concave upward front typical of the negative downward flash [4]. The front is a statistic derived from the other two quantities and the correlation coefficient.

The first stroke crest current data in Table 1 obtained by Berger et al [3] was combined with

Table 1
Lightning Stroke Current Data

	First Stroke % Exceeding the Value					Subsequent Strokes % Exceeding the Value				
Parameter	95%	50% (*M*)	5%	β	ρ	95%	50% (M)	5%	β	ρ
Crest Current, kA	14	31.1	69	0.48	0.38	5	12.3	29	0.53	0.56
Maximum Steepness, kA/μs	9	24.3	65	0.60	0.38	10	39.9	162	0.85	0.56
Minimum Linear Front, μs	0.5	1.28	3.5	0.61	—	0.1	0.31	1.0	0.71	—
Time-to-Half Value, μs	30	77.5	200	0.58	—	7	30.2	140	0.93	—

other data. The resultant distribution is piecewise Log-Normal with parameters as follows:

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

The distribution may also be approximated [5] by the equation:

$$P(I) = \left[1 + \left(\frac{I}{31}\right)^{2.6}\right]^{-1}$$

where $P(I)$ is the probability that the crest current will equal or exceed I (kA).

The lightning severity within a specific area is generally specified by the ground flash density, Ng, in flashes per km^2. However, at present within the USA, data on the average Ng is not generally available, and the lightning severity must be based on the annual keraunic level, or the number of thunderstorm days per year, T_d. In the USA, these levels vary from five or less on the West Coast to greater than 100 in Florida, with an average between 35 and 40 [4]. The value of Ng may be approximated from T_d by the equation:

$$Ng = 0.04\, T_d^a$$

where both Ng and T_d are average yearly values.[3] The coefficient of variation of both Ng and T_d are large, about 60% for low values of T_d and about 30% for high values of T_d [7].

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

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

It has been found feasible to eliminate all except a small percentage of direct strokes to line conductors by the use of shield wires. When such a direct stroke (shielding failure) does occur, line flashover is almost certain. When a lightning stroke terminates on a shield wire, the stroke current is diverted to ground through the structure-connecting conductors. The impedance of the current path together with ground resistance results in a voltage at the top of the line structure, a portion of which is coupled to the phase conductor. The

[3]The exponent "a" for T_d is empirical—1.25 is used in [6], 1.35 in [4].

difference between the phase conductor potential and structure top potential is impressed directly across line insulation and may result in flashover. This type of flashover is called a backflash. The incidence of backflashes is controlled by selection of a proper insulation level, by keeping the structure ground resistance to an acceptably low value, and by providing adequate clearance from conductor to structure ground, conductor to shield wire, and conductor to conductor.

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

2.1.1.4 Uses of Shielding in Station Protection Applications. The purpose of shielding in station applications is to reduce the risk of insulation failure to an acceptable level. In certain applications this may be achieved by shielding the station alone. In other cases it may be necessary to shield all incoming lines to the station. As pointed out in 2.1.1.5, shielding of the lines for a relatively short distance from the station is all that is required as far as station protection is concerned.

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

2.1.1.5 Traveling Waves. Lightning strokes to lines as well as switching operations set up traveling waves (Appendix D) which move along the line [8]. Crest voltage will double when the wave arrives at the terminals of an open line switch or circuit breaker. Voltage approaching double occurs at line-terminating transformers.

As a wave initiated by lightning moves along a line, the crest is reduced, and time to crest is increased [9]. Effective shielding of a line for as little as one-half mile (800 m) from the station can reduce a high percentage of incoming surges to a tolerable level [8].

2.1.2 Switching Overvoltages. Overvoltages due to switching occur on all systems [10, 11, 12] and must be considered in the selection of arrester ratings. Switching surge protective levels (see 2.3) are usually not important for systems operating at 100 kV and below (and rarely for systems up to 230 kV), because insulation designed to withstand lightning overvoltages will usually withstand stresses caused by switching. On systems operating above 100 kV, switching surges should be considered. Switching overvoltages become the determining factor in insulation coordination (see 2.6) on EHV systems [10]. Refer to Appendix B for a discussion of switching overvoltages and their effect on arresters.

2.1.2.1 Components of Switching Overvoltages. A switching overvoltage may consist of a switching surge, a temporary overvoltage (TOV), or a combination of both. Normally, the surge occurs at the beginning of a switching overvoltage initiated by operation of a switching device. However, surges may be superimposed on a preexisting TOV by operation of another switching device, protective gap, or by insulation flashover. Arresters may be used to limit switching surges. The major importance of maximum TOV is that its value is used to determine acceptable arrester ratings (see 3.3.1).

Switching surges are heavily damped oscillatory transients, which can be limited by an arrester capable of successful operations on successive peaks. The arrester must be able to reseal against any TOV that may follow the initial transient.

Temporary overvoltages are defined as oscillatory overvoltages of relatively long duration that are undamped or only slightly damped. A common source of TOV is neutral shift due to line-to-ground faults. This and other causes of TOV are discussed in 3.3.

2.2 Valve Arresters

2.2.1 Design. Conventional valve-type arresters consist of gap sections and silicon-carbide valve elements installed in a suitable housing. Gap sections are designed to withstand normal voltage and to sparkover at a predetermined level to allow current to flow through the valve elements. Valve elements are resistors that, because of their nonlinear current-voltage characteristics, limit the voltage across the arrester terminals during the flow of discharge current and contribute to the limitation of follow current at normal power-frequency voltage. If the voltage applied to the arrester is equal to or less than its reseal voltage rating, the gap will interrupt the follow current within one half of a cycle. Otherwise, the gaps may fail to reseal and arrester failure will occur. Arrester protective characteristics (sparkover and discharge voltage) increase as a function of rating for a given arrester design as does reseal voltage rating. An iterative process (see Fig 1 on page 19) is used to reconcile the conflicting demands of reseal capability and protective levels.

2.2.1.1 Usual Operating Conditions. Arresters are designed to operate properly at an ambient temperature not exceeding 40 °C and at altitudes of 1 800 m (6000 ft) or below. Power system frequency should be between 48 and 62 Hz (see ANSI/IEEE C62.1-1984 [1]).

2.2.1.2 Unusual Conditions. In addition to operation beyond the limits of 2.2.1.1, exposure to damaging fumes or vapors, steam, dripping water, or salt spray require special consideration. Arresters must not be installed so that mechanical stresses are excessive.

Arresters should not be subjected to abnormal vibrations or shocks. Manufacturer's recommended clearances must be maintained between the arresters and nearby conducting objects.

2.2.2 Lightning Impulse Sparkover. Such sparkovers are obtained by applying 1.2/50 μs impulses. For impulses below a certain crest value, no arrester sparkover occurs and a "full-wave" crest voltage is impressed on the protected insulation, which must be designed to withstand such impulses. If the crest is increased to "let-through voltage" level (LT) (refer to D6.7.1 in Appendix D), sparkovers may occur occasionally, with times to sparkover of 3 μs or more. In such cases, a chopped impulse followed by a discharge voltage (*IR*) is let through to the insulation. It is to be expected, therefore, that the insulation must be able to withstand either the discharge voltage or an unmodified surge at let-through level. A BIL (see 2.4) at least 20% greater than let-through would be required (see 3.7.1.1). As crest values of 1.2/50 μs test impulses are increased above let-through, and sparkover occurs at successively shorter times and higher voltages until the impulse is chopped before the prospective crest of the impulse can be reached. Such operations are called "front-of-wave" sparkovers (FOW). Most types of insulation can withstand higher crest impulse levels associated with front-of-wave sparkover because of the shorter duration of the impulse voltage. For this reason, FOW sparkover is usually coordinated with chopped-wave withstand (see 3.6.1).

A sparkover characteristic curve similar to that of Fig 3 on page 28 can be obtained by test. Maximum sparkovers for given times to sparkover are shown. A band of data points are obtained by making tests with impulses with front times ranging from 1 to 2000 μs (see 2.2.4). The curve is drawn through or above the maximum sparkover points, as shown in ANSI/IEEE Std C62.1-1984 [1].

2.2.3 Lightning Impulse Discharge Voltage (*IR*). It is recognized that discharge voltages for surge arresters should be based upon discharge currents having wave shapes and magnitudes that represent those to which the arresters will be subjected in service and that data on the lightning impulse strength level of apparatus to be protected by arresters should be coordinated with the corresponding arrester discharge voltage wave shapes.

The discharge voltage wave shape of nonlinear valve resistors typically has a shorter front and longer tail than the discharge current wave. The discharge voltage resulting from a discharge current having a standard 8/20 μs wave shape approximates the standard 1.2/50 μs impulse reasonably well for current magnitudes between 5 kA and 20 kA.

2.2.4 Switching Impulse Sparkover and Discharge Voltage. Values of switching impulse sparkover and discharge voltages are determined by applying test impulses with fronts ranging from 30 to 2000 μs. On certain arrester designs, switching impulse discharge levels may exceed sparkover.

2.2.5 Reseal. A rule of long standing has been that the voltage rating of the arrester must be at least equal to the maximum expected temporary overvoltage (TOV) in order to reseal following an operation. The TOV was determined primarily by the line-to-ground 60-Hz voltages on the unfaulted phases caused by a line-to-ground fault on the remaining phase.

Arresters, particularly in the station class, have been available with capability of operating and resealing at voltages above rated voltage. The use of such arresters becomes important in applications on systems operating at 300 kV and above. Refer to Appendix B.

2.3 Protective Levels. The protective level of an arrester is the maximum crest value of voltage that appears across its terminals under specified conditions of operation.

2.3.1 Sparkover Levels. There are three sparkover protective levels corresponding to three points on the sparkover curve (see 2.2.2):

(1) Front-of-wave sparkover (FOW), which is the maximum sparkover on a linearly rising impulse front. The rate of rise of the front increases with arrester rating (see Appendix A).

(2) Let-through (1.2/50 μs) (LT) sparkover (see 2.2.2 and D6.7.1).

(3) Switching surge sparkover, which is the maximum sparkover at a time to sparkover greater than 30 μs for impulses having times to crest between 30 and 2000 μs.

2.3.2 Discharge Voltage Levels. There are two discharge protective levels, lightning and switching.

(1) Lightning discharge voltage levels (*IR*) are established by tests using 8/20-μs current impulses (see ANSI/IEEE Std C62.1-1984 [1]). The particular *IR* must always be identified by the crest magnitude of the test current used to establish it.

NOTE: The greater of LT or *IR* (at a specified current) is the lightning protective level (LPL).

(2) Switching impulse discharge voltage level is established by tests as described in ANSI/IEEE Std C62.1-1984 [1]. The greater of either the switching surge sparkover or the switching impulse discharge voltage is the switching surge protective level (SSP).

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 BILs and BSLs in ANSI C92.1-1982 [13].

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

(1) Chopped Wave (CWW). Tests are made with a 1.2/50-μs impulse chopped by the action of a rod gap in a minimum time as specified in the appropriate product standard.

(2) Basic Lightning Impulse Insulation Level (BIL). Tests are made with full-wave 1.2/50-μs impulses as specified in the appropriate equipment standard.

(3) Basic Switching Impulse Insulation Level (BSL). The test impulse depends on the type of equipment.

2.5 Separation Effects. The voltage at the protected insulation will always be higher than at the arrester terminals due to oscillations on connecting leads [14]. This rise in voltage is called separation effect (SE).

Separation effects increase with increasing rate of rise of the incoming surge and with increasing distances between the arrester and protected equipment. (Separation effect may be significant when the protective ratio, as defined in 2.6, is less than 1.15.) 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 never be considered in applying the fundamental protective ratio formula to switching surge withstand (BSL).

Other considerations in locating arresters are discussed in 3.5 and 4.5.

2.6 Insulation Coordination. Insulation coordination is defined in ANSI C92.1-1982 [13] as "the process of correlating the insulation strengths of electrical equipment with expected overvoltages and with the characteristics of surge protective devices."

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

$$\frac{\text{insulation withstand level}}{\text{voltage at protected equipment}}$$

"Voltage at protected equipment" includes separation effect, if significant. If not, it is equal to arrester protective level, plus the line and ground lead voltages.

There are three protective ratios in common use, which compare protective levels with corresponding insulation withstands:

$$\frac{\text{Chopped-Wave Withstand (CWW)}}{\text{Front-of-Wave Sparkover (FOW)}}$$

$$\frac{\text{Basic Impulse Insulation Withstand (BIL)}}{\text{Lightning Protective Level (LPL)}}$$

$$\frac{\text{Switching Impulse Insulation Withstand (BSL)}}{\text{Switching Surge Protective Level (SSP)}}$$

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 full-wave level. 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 3.7.

Applications such as transformer series windings, nonloaded windings, and ungrounded neutrals are discussed in 3.8.

Where a lower chopped-wave insulation level is specified in equipment such as dry-type transformers, the protection procedures are covered in 3.9.

Systems operating at voltage levels above 242 kV to less than 1000 kV are referred to as extra-high-voltage (EHV) systems; see ANSI C92.1-1982 [13]. For EHV applications, special considerations are necessary. These are discussed in Appendix B.

It is to be emphasized that basic to the application theory presented by this guide are the presumptions (1) that surge arrester ground terminals are interconnected with the grounded parts of the protected equipment, and (2) that both line and ground connections are as short as practical.

3.2 Step-by-Step Procedures and Generalized Arrester Characteristics. Figure 1 and Table 2 are designed for ready reference in arrester application.

3.2.1 Selection of Arresters. Figure 1 provides a summary of the steps required to select arresters. The following sequence is used:

(1) Select arrester and determine its protective characteristics.

(2) Select (or determine) insulation withstand.

(3) Evaluate insulation coordination.

Other sequences are 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 Arrester Characteristics. Table 2 summarizes information applicable to station class and intermediate class arresters. Distribution class arresters are sometimes used in stations. A table containing information applicable to distribution arresters may be found in Section 4.

Protective levels are given in per-unit values of crest arrester rating. As explained in Table 2, per-unit values may be converted to kilovolts and used in preliminary selection of arresters. Values in the numbered columns under "Durability Characteristics" are specific requirements for the range of ratings shown; see ANSI/IEEE C62.1-1984. Additional application information is found in notes numbered to correspond with the columns.

3.3 Arrester Selection. As indicated in Fig 1, arrester selection involves the choice of a voltage rating and a class. Voltage rating is an index of the highest permissible temporary overvoltage (TOV) at the arrester terminals (see 3.3.1).

Voltage ratings alone or in conjunction with class designations are used to specify test values and procedures, as described in ANSI/IEEE C62.1-1984 [1]. The class designations are station, intermediate, distribution, and secondary.

Station arresters are designed for heavy-duty applications. They have the greatest range of ratings (see Table 2), the best protective characteristics, and the greatest durability. Intermediate arresters are designed for moderate duty and only for applications at 138 kV and below. Distribution arresters (see Table 7) 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. Secondary arresters are available for application to systems operating at less than 1000 V (see Table A4 in Appendix A).

3.3.1 Determining the Maximum Temporary Overvoltage (TOV). An arrester must be capable of resealing against the maximum anticipated TOV. The most common source of

I. Tentatively select arrester (see 3.3)

(1) Determine maximum temporary overvoltage (TOV) (see 3.3.1).

(a) Calculate using R_0/X_1 vs X_0/X_1 curves (Fig. 2) or calculations (see 3.3.1.1).

(b) Evaluate effect of load rejection, switching, resonance, saturation, and possible loss of system, ground source (see 3.3.1.1 and 3.3.1.2).

(c) Check for chance of frequent system operation at voltages above "maximum system" level (see D7.2 of Appendix D), abnormal frequency, or disconnection of ground source (see 3.3.2.2).

RULE: Voltage ratings are usually equal to or greater than TOV (see 3.3.2).

(2) Select arrester class (see 3.3.3). Consider:

(a) Pressure relief rating equal to or greater than system fault.

(b) Lightning surge duty.

(c) Switching surge duty (station and intermediate only).

(d) Reliability requirements.

RULE: Class must be available in voltage rating selected and must meet durability and system reliability requirements.

II. Determine protection characteristics of selected arrester (see 3.4)

RULE: Use manufacturer's data for arrester selected where available.

(1) Use Table 2 or Appendix A for general studies. For selection of lightning discharge currents, see 3.4.2.

(2) Establish three standard arrester protective levels (see 3.7):

(a) Front-of-wave sparkover (FOW).

(b) The greater of 1.2/50-µs sparkover (LT) or lightning discharge voltage at selected current (LPL); see 3.4.1.

(c) The greater of switching surge sparkover or discharge voltage (SSP); see 3.4.1.

(3) Use in VI(1) or VI(2), as applicable.

III. Locate arresters with respect to equipment

(1) Nonshielded incoming lines. Locate arresters as close as possible to transformers. Consider use of line entrance gaps or arresters (see 3.5.1).

(2) Shielded incoming lines. Locate arresters to provide optimum protection to all equipment (see 3.5.2).

IV. Determine voltage at protected equipment

The voltage at protected equipment will be greater than that at the arrester (separation effect).

(1) If the sum of the arrester lead length L and transformer lead length S is not greater than the values in Table 5, separation effect can be ignored.

(2) Otherwise, evaluate voltage at equipment in accordance with Appendix C.

V. Determine insulation withstand voltages (see 3.6)

(1) Basic lightning impulse insulation levels (BIL) are established for most types of equipment either by voltage or by special test.

(2) Chopped-wave withstand voltages (CWW) for oil-filled transformers are 1.1 to 1.15 times BIL (see 3.6.1). WARNING: Even lower ratios apply to dry-type insulation at short times (see 3.9).

(3) Basic switching impulse insulation levels (BSL) are 0.75–0.9 times BIL for transformers and 0.63–0.69 times BIL for breakers 362–765 kV.

VI. Evaluate coordination (see 3.7)

(1) When separation effect (see IV in this figure) can be disregarded, each of the following criteria must be met:

PR(1):	CWW/FOW $\geq$ 1.2
PR(2):	BIL/LPL $\geq$ 1.2
PR(3):	BSL/SSP $\geq$ 1.15

Alternatively, coordination curves can be used (see 3.7.3.1).

(2) If separation effects cannot be disregarded:

(a) Find voltage at equipment, E_i, using methods of Appendix C. Where front is such that sparkover occurs in $\leq$ 2 µs, base E_i on FOW sparkover and use formula PR(1S) in (b) below. Otherwise, base E_i on LPL in accordance with II(2b) above, and use formula PR(2S) in (b) below.

(b) All of the following criteria must be met:

PR(1S):	CWW/$E_i \geq$ 1.15
PR(2S):	BIL/$E_i \geq$ 1.15 or
PR(3S):	BSL/SSP $\geq$ 1.15

(3) If criteria of VI(1) or VI(2b), as applicable, cannot be met (see 3.7.3):

(a) Use arrester with lower lightning or switching surge protective levels.

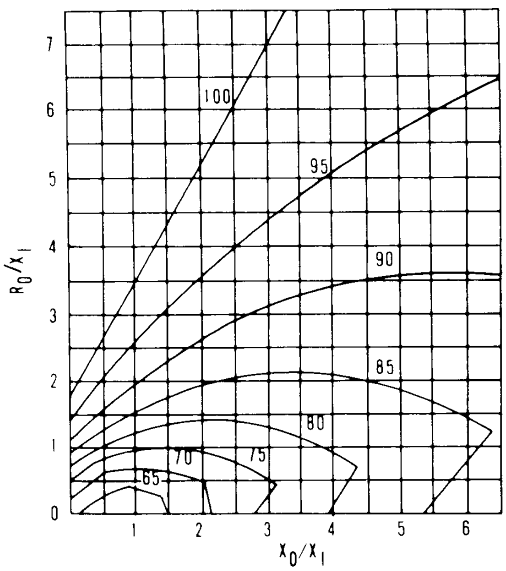
(b) Change arrester location to reduce separation.

(c) Use higher withstand voltage.

(d) Improve shielding.

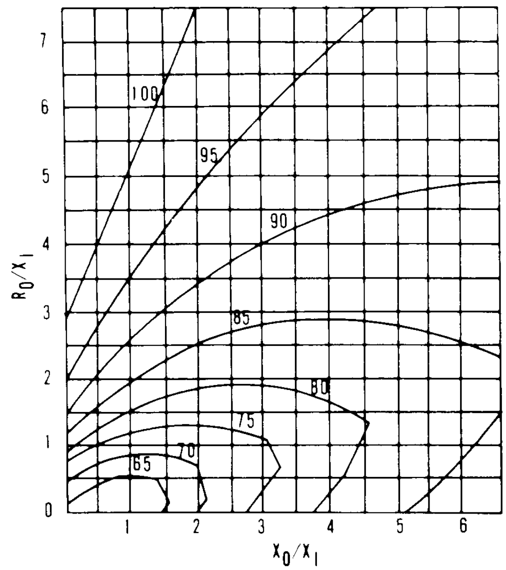
(e) Add arresters.

Fig 1
Summary of Step-by-Step Procedures for Arrester Selection and Insulation Coordination



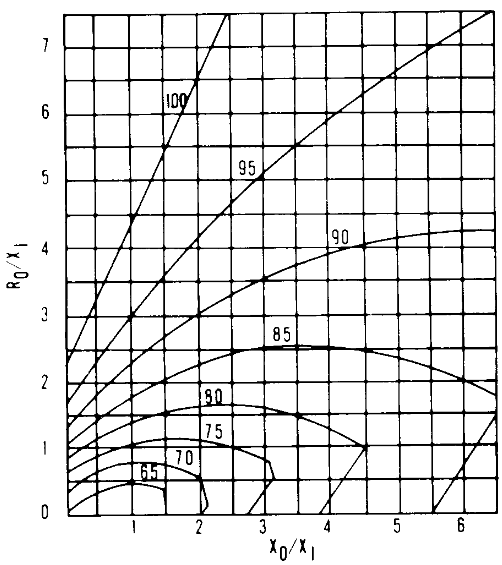
Voltage conditions neglecting positive- and negative-sequence resistance: $R_1 = R_2 = 0$

(a)



Voltage conditions for $R_1 = R_1 = 0.1X_2$

(b)



Voltage conditions for $R_1 = R_1 = 0.1X_1$

(c)

NOTE: Numbers on curves indicate coefficient of grounding (see D2.3.3) for any type of fault for points on the curve defined by coordinate values listed along the axes. All impedence values must be on the same kVA base or in ohms on the same voltage base.

R_0 = zero-sequence resistance
R_1 = positive-sequence resistance
R_2 = negative-sequence resistance
X_0 = zero-sequence inductive reactance
X_1 = positive-sequence inductive reactance
X_2 = negative-sequence inductive reactance
$X_1 = X_2$

All these quantities are components of the system impedance as seen from the point of fault. See 3.3.1.1.

The effect of fault resistance was taken into account. The resistance that gives the maximum voltage to ground was the value used. The discontinuity of the curves is caused by the effect of fault resistance.

The coefficient of grounding for other values $R_1 = R_2$ ($Z_1 = Z_2$) can be calculated using the equations shown in Appendix E.

Fig 2
Coefficients of Grounding for Various System Conditions

Table 2
Station and Intermediate Arrester Characteristics

		Protective Levels* Per-Unit Crest Arrester Rating				Durability Characteristics†			
						(1)	(2)	(3)	(4)
Ratings (kV rms)	Range of Application Nominal System Voltage (kV)	Front-of-Wave Sparkover	1.2/50 µs Sparkover	Switching Surge Sparkover	Discharge Voltage, 10 kA, 8/20 µs Wave	Duty Cycle Initiating Surge (crest amperes)	Transmission Line Discharge (miles)	High Current Withstand (crest amperes)	Pressure Relief (rms symmetrical amperes)
Station Class									
3–9	2.2–12.47	2.24–4.24	1.89–3.30	Test	1.57–1.77	10000	150	65000	65000 25000
12–15	13.2–18	2.12–2.83	1.89–2.42	not	1.57–1.70	10000	150	65000	65000 25000
21–48	18–46	2.09–2.56	1.80–2.29	required	1.56–1.70	10000	150	65000	40000 25000
60–120	69–138	1.99–2.24	1.60–1.94	1.60–1.80	1.56–1.69	10000	150	65000	40000 25000
144–240	161–287	1.83–2.22	1.57–1.70	1.57–1.61	1.56–1.79	10000	175	65000	40000 25000
258–312	345	2.06–2.17	1.56–1.70	1.57–1.61	1.56–1.58	10000	200	65000	40000 25000
372 or higher	500 or higher	1.94–2.10	1.65–1.70	1.44–1.58	1.54–1.60	10000	200	65000	40000‡ 25000
Intermediate Class									
3–6	2.4–7.2	2.47–2.83	2.24–2.83	Test not	1.77–2.36	5000	100	65000	16100
9–48	7.2–46	2.10–2.59	1.78–2.51	required	1.77–2.19	5000	100	65000	16100
60–120	69–138	1.76–2.26	1.63–1.84	2.06–2.43	1.77–2.02	5000	100	65000	16100

*The per-unit values shown are maximum industry values from tables in Appendix A. For specific values, consult manufacturer's literature. Protective level (kV) = per-unit level x rating x $\sqrt{2}$. For example, range of FOW sparkover for a 258-kV arrester is (2.06 to 2.17) x 258 x $\sqrt{2}$ = 752 to 792 kV.

†This refers to the ability of the arrester to protect itself against the stresses resulting from the following:

(1) Power-follow current.

(2) The number of line miles an arrester can discharge, which is a measure of its ability to handle switching surges (see Appendix B). The general relationship (for overhead lines only) is: $D = (D_L)(Z/Z_L)(E_L/S)^2$ where D = line miles, Z = line surge impedance. S = switching overvoltage/(system maximum line-to-ground peak voltage). For D_L, Z_L, see ANSI/IEEE C62.1-1984 [1]. The use of this formula is valid only for values of D, Z, and S within about 25 % of the Values D_L, Z_L, and E_L, as listed in ANSI/IEEE C62.1-1984 [1]. Underground lines may require special attention because of their low surge impedance [34, 35].

(3) Severe lightning disharges.

(4) Maximum permissible protective bus faults.

‡For applications requiring currents above 40 kA, ratings of 45, 50, 55, or 60 kA shall be used.

TOV is voltage rise on unfaulted phases during a line-to-ground fault.

In many cases only TOV due to line-to-ground faults must be considered. However, there are other sources of TOV and operating conditions that affect arrester operation, as discussed in 3.3.1.1, 3.3.1.2, and 3.3.2.

3.3.1.1 Fault Conditions. The curves of Fig 2 may be used to quickly determine temporary overvoltages during fault conditions on applications involving short lines operating at voltages through 242 kV. The numbers adjacent to each of the curves in Fig 2 are the coefficients of grounding in percent (see D2.3.3 of Appendix D). 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 using equivalent system impedances as seen from the fault location. The effect of shunt reactors, shunt and series capacitances, and distributed line capacitances must be included in the calculations where significant. This applies particularly to applications involving long lines and EHV lines [10]. Where the shunt capacitance of lines is large, there may be additional voltage rises due to line charging currents, harmonics due to transformer saturation, and (less frequently) resonance effects.[4]

3.3.1.2 Other Causes of Temporary Overvoltage.[4] Other causes of TOV include:

(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.

3.3.2 Choosing the Tentative Arrester Voltage Rating. Choose the tentative arrester voltage rating based on the maximum phase-to-ground temporary overvoltage determined as indicated in 3.3.1. This voltage rating should be chosen at least equal[5] to the maximum phase-to-ground temporary overvoltage in order to interrupt the power follow current. It is recommended that an arrester voltage rating at least 25% higher than the maximum operating phase-to-ground voltage be selected for stations when possible. Use of an arrester with too low a voltage rating may result in an excessive failure rate of the arresters in service.

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

3.3.2.1 Abnormal System Operating Voltages. The selection of arrester voltage ratings based on maximum system voltages assumes that, in service, the maximum system voltage is exceeded only under abnormal operating conditions, and that the probability of a coincidental arrester operation is very small. However, if maximum system voltages used in determining temporary overvoltages, as in 3.3.1.1, 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 3.3.1.2, require consideration on an individual basis; no general rules are applicable.

3.3.2.2 Abnormal System Frequency. Normal system frequency less than 48 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.

If any grounding source could be disconnected by sectionalizing, check the effect on the coefficient of grounding and the arrester rating.

3.3.3 Choosing the Proper Class of Arrester. Choose the proper class of arrester based on the protective characteristics summarized in Table 2 and the following:

(1) Available voltage ratings.

(2) Pressure relief current limits, which should not be exceeded by the system's available short-circuit current at the arrester location.

(3) Durability characteristics (see Table 2) that are adequate for system requirements.

---

[4] Voltages experienced during listed conditions are determined by system operating experience and analog or digital computer studies.

[5] Some arresters are capable of limited operation at TOV above rating. Consult manufacturer if a low rating is necessary to protect insulation with unusually low withstand levels [15, 16].

The class of arrester selected may be influenced by the size and importance of the station or equipment to be protected. For example, station class arresters should be used on large substations. Since the maximum intermediate rating is 120 kV, station arresters must be used when system operating voltages are greater than 144 kV. Intermediate class arresters may be used on smaller substations and on subtransmission lines and cable terminal poles at 138 kV and below. Distribution class arresters might be used in small distribution substations to protect distribution voltage buses.

3.4 Protective Levels of Arresters

3.4.1 Determining Protective Levels. Protective levels are determined by either sparkover or discharge voltages of the arrester under consideration. The following protective levels are used:

(1) Front-of-wave sparkover (FOW)
(2) 1.2/50-μs sparkover ("let through")
(3) Switching surge sparkover
(4) Discharge voltage, 8/20-μs impulse (at specified current)
(5) Switching impulse discharge voltage

NOTE: Manufacturers' literature is always the best source. For approximate values, consult Fig 2, Table 7, and Appendix A. See also 2.3.1 and 2.3.2.

For combined protective levels the following levels apply:

(1) The greater of 1.2/50 μs sparkover (let-through) or lightning discharge voltage (8/20 μs) at specified level is the lightning protective level (LPL).
(2) The greater of switching surge sparkover or switching discharge voltage is the switching surge protective level (SSP).

3.4.2 Estimating the Magnitude of Arrester Discharge Current. The magnitude of arrester current is a function of stroke current, ground resistance at the point of stroke, distance from the arrester to point of stroke, surge impedance of the line, number and location of line flashovers, flashover characteristic of line insulation, and arrester discharge voltage. The following formula has been previously recommended for use in determining the magnitude of surge currents:

$$i_a = \frac{2e_o - e_a}{Z}$$

where

i_a = discharge current, crest amperes

e_o = 1.2 x line insulation level (critical flashover 1.2/50-μs wave), crest volts

Z = line surge impedance, ohms

e_a = arrester discharge voltage, crest volts

In some studies, however, this formula has been found to apply directly (a) only when the flashover occurs a considerable distance from the station, or (b) when the line is struck without an ensuing flashover. Otherwise, the fraction of total stroke current discharged through the arrester can vary considerably depending upon the parameters involved [17].

A practical situation where the probability of flashover is reduced to a very low level occurs where all lines are completely shielded over their entire length. For this case, the foregoing formula is applicable, but it is more conservative to allow for the occasional shielding failure and to use the values recommended in 3.4.3.1. Other considerations must be taken into account for cases where lines are not completely shielded (see 3.4.3.2).

3.4.3 Basis for the Selection of Discharge Currents to Determine Discharge Voltage. The selection of discharge current should depend upon the following:

(1) The importance of the installation. Selected discharge current can be increased to dictate selection of arresters with a lower protective level, if desired.

(2) The line insulation. Where fully insulated wood pole lines are used, an arrester is likely to be subjected to much higher surge current than one connected to a higher voltage line with grounded crossarms, unless the stroke occurs so close to the arrester that the impedance and insulation of the line cannot influence the surge.

(3) The probability of the occurrence of the higher currents. This problem is related to the number of days in the year in which thunderstorms occur in the locality, their severity, the nature of the terrain, the design of the line, and the shielding of the line and terminal equipment.

3.4.3.1 Recommended Currents for Shielded Stations with Completely Shielded Lines. Table 3 gives values that have been found to be satisfactory in most situations.

3.4.3.2 Discharge Currents Where Lines Are Shielded for a Short Distance Adjacent to 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 (a) strokes per unit area per mile, (b) probability of strokes to line exceeding a selected value, and (c) percentage of total stroke current that discharges through the arrester. Items (a) and (b) can be evaluated using the methods of Brown and Thunander [18]. It will be found conservative to use the following table [17] for item (c):

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

3.4.3.3 Discharge Currents in Stations Where Lines Are Not Shielded. As discussed in 2.1.1.1, arrester currents due to lightning strokes are generally less than stroke currents. Despite the fact that stations with nonshielded lines can be subjected to extremely high rates of rise from incoming surges and to high currents resulting from flashovers close to the arrester, the effect of station bus, line arrangement, and equipment is such that the arrester current is significantly less than the stroke currents discussed in 2.1.1. In general, the discharge level for stations with unshielded lines should not be less than 20 000 A. In severe thunderstorm areas (ie, keraunic level 40 or above), higher levels may be desirable.

3.5 Locating Arresters and Determining Voltage at Protected Equipment. A major determining factor in locating arresters is the shielding (if any) provided (see 2.1.1.3 and 2.1.1.4). It is usually feasible to provide shielding for the substation proper even though the associated lines are unshielded. This will reduce or eliminate direct lightning strokes to the station with accompanying steep fronts and extreme magnitudes.

However, it should be recognized that the majority of strokes will be to the lines, which will create surges that travel along the line and into the station [8]. If the lines are shielded, the surges entering the station are much less severe than those from unshielded lines. Consequently, arrester protective levels are lower.

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

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

3.5.1.1 Single Unshielded Incoming Overhead Line. An arrester with a single unshielded incoming overhead line should be located as near as possible to the terminals of the equipment (usually a tranformer) to be protected.

3.5.1.2 Multiple Unshielded Overhead Lines. When several unshielded incoming overhead lines meet in the station, the incoming overvoltage waves are reduced by reflection. However, consideration should be given to the case where one or more of the lines are disconnected by switching. When one or more circuit breakers or disconnecting switches are open in such a station, the corresponding line entrances or certain parts of the station may be left without protection from the arresters at the transformers. Lightning flashover of insulation on a de-energized line is unlikely to cause damage, but other insulation in equipment such as circuit breakers, potential transformers, and current transformers connected on the line side might be damaged. If such cases are recognized to require additional protection, valve-type arresters or gaps can be installed at the respective line entrances.

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

Table 3
Recommended Currents for Determining Discharge Voltages in Shielded Stations with Shielded Incoming Lines

Maximum System Voltage (kV)	Discharge Current (amperes)
15	—*
36.5	—*
72.5	5000
121	5000
145	5000
242	10000
362	10000
550	15000
800	20000

*Generally unshielded lines.

3.5.2.1 Single Shielded Incoming Overhead Lines. With a single shielded incoming overhead line assume that one set of arresters is located at a point that provides optimum protection to all equipment but gives preference to the transformer.

Determine the maximum impulse voltage at the protected insulation for the assumed arrester location using the method of Appendix C. Where separation is not significant (see 3.7.1.3), this will not be necessary.

3.5.2.2 Multiple Shielded Overhead Lines. With multiple shielded incoming overhead lines (associated with large installations with transformers, switchgear, and measuring equipment) assume that the arresters are at the most practical locations.

The methods described in 3.7.1.3 and Appendix C can be used to determine maximum impulse voltage for some cases. More important installations may justify a detailed digital or analog transient study. Such studies and interpretation of their results are outside the scope of this standard.

Consideration must be given in the calculations to the possibility that the station may become sectionalized or that lines may be disconnected during service. Under all circumstances, it must be possible to maintain proper protective ratios for both lightning and switching surges as given in 3.7.1.1 [19].

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

3.5.3.1 Arresters at Cable-Connected Equipment. If arresters can be installed at the equipment, a procedure analogous to that outlined in 3.5.2 is followed. However, the method of 3.7.1.3 and Appendix C are not applicable [20–22].

Any arresters installed at the protected equipment should be connected to the equipment ground and the station ground with the shortest possible lead.

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

The following procedure shall be used:

(1) Determine the length of the cable connection.

(2) Determine the maximum impulse voltage at the protected equipment, using procedures and recommendations from either Witske and Bliss [20] or Powell [23].

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

3.6 Determining Insulation Strength. Chopped-wave (CWW), full-wave (BIL), and switching surge withstand (BSL) levels vary depending upon both equipment type and nature of insulation.

3.6.1 Transient Impulse Strength for Equipment Insulation Other Than Air. The effect of the duration of transient surges on insulation withstand strength has not been standardized for all types of equipment. Requirements for mineral oil-immersed distribution transformers, power transformers, instrument transformers, and shunt reactors are given in

Table 4
Factors for Estimating Withstand Voltages of Mineral Oil Immersed Equipment

Impulse Duration	Withstand Voltage	Equipment
Front of wave (0.5 μs)*	1.3 to 1.5 x BIL	Transformers reactors
Chopped wave (2 μs)*	1.29 x BIL	Breakers, 15.5 kV and above
Chopped wave (3 μs)*	1.1 to 1.15 x BIL	Transformers reactors
	1.15 x BIL	Breakers, 15.5 kV and above
Switching surge (100 x (†) μs)	0.83 x BIL	Transformers reactors
Switching surge (250 x 2500 μs)	0.63 to 0.69 x BIL	Breakers, 362-800 kV‡

*Time to chop.
†Time above 90% of crest ≥ 200 μs. Time to first voltage zero ≥ 1000 μs.
‡Includes air blast and SF_6 breakers.

ANSI/IEEE Std C57.13-1978 (R1986) [24], ANSI/IEEE C57.21-1981 [25], ANSI/IEEE Std C57.12.00-1987 [26], and ANSI/IEEE Std C57.12.90-1987 [27]. For information on circuit interrupting devices, see ANSI/IEEE Std C37.04-1979 (R1988) [28], ANSI C37.06-1987 [29], ANSI C37.0781-1972 [30], and ANSI/IEEE C37.074-1972 (R1978) [31]. For rating structure and standard schedules of preferred ratings and related required capabilities for ac high-voltage circuit breakers see ANSI C37.0781-1972 [30] and ANSI/IEEE C37.074-1972 (R1978) [31]. (See Appendix B for switching effects and classifications.)

The switching surge strength is particularly important when the impulse insulation withstand strength is reduced, since the selection of the proper surge arrester may be influenced more by switching surge levels than by lightning voltages. For information on switching surge test wave shapes and values for circuit breakers, transformers, and shunt reactors, see ANSI/IEEE Std C37.04-1979 (R1988) [28], ANSI/IEEE Std C57.12.90-1987 [27], and ANSI/IEEE C57.21-1981 [25], respectively.

The approximate factors given in Table 4 can be used to estimate the withstand voltages of mineral oil-immersed equipment, such as transformers, shunt reactors, and circuit breakers, but if the front-of-wave factor must be used in an insulation coordination plan, it should be checked with the equipment manufacturer.

3.6.2 Impulse Withstand Strength for Air Insulation. Refer to ANSI C37.20-1974 [32]. Table 5 of ANSI/IEEE Std C57.12.00-1987 [26] can also be consulted. Values for specific apparatus can be obtained from the manufacturer. Protection for this equipment should be based on limiting the surge voltages at the equipment, including the appropriate protective margin to the TIL values in the above-mentioned standards.

Porcelain insulation used in station support insulators has a volt–time characteristic similar to a rod gap with greater increases at shorter times than the values given in Table 4.

3.7 Evaluating Insulation Coordination. Insulation coordination is evaluated on the basis of the margin between insulation withstand and protective level, including separation effect (SE), if significant [19].

Significant separation occurs in configurations in which the crest of the voltage at protected insulation exceeds the arrester protective level sufficiently to reduce protective margins or ratios to unacceptable levels (see 3.7.1.1 and 3.7.1.2). Separation effect should be evaluated using the methods of Appendix C when the sum of arrester lead length L and transformer lead length S is greater than tabulated values given in Table 5. This rule applies to both station-type and intermediate-type arresters.

Two general procedures are used for insulation coordination: the three-point method, and the coordination curve comparison method.

3.7.1 Three-Point Method. In this method, chopped-wave withstand (CWW), BIL, and switching-surge withstand (BSL) are compared with the corresponding protective levels. The basic assumption is made that the insulation will be protected over the entire range of lightning and switching impulses that can occur in service, provided the margin is adequate at the three points. The smaller margins specified for cases where separation effects are evaluated are permissible [19], because part of the standard margin (see 2.6) includes an allowance for separation. Furthermore, the methods of evaluating separation effects described in Appendix C tend to give conservative results.

Table 5
Maximum Allowable Separation

	Number of Lines*							
	1		2		3		4	
	Allowable Separation, D†							
PR(1)‡	(feet)	(meters)	(feet)	(meters)	(feet)	(meters)	(feet)	(meters)
1.2	10	3	14	4.3	18	5.5	22	6.7
1.4	14	4.3	20	6.1	26	7.9	32	9.8
1.6	20	6.1	29	8.8	39	12	50	15
1.8	30	9.1	46	14	64	20	84	26
1.9	37	11.3	61	19	88	27	118	40
2.0	49	14.9	84	26	130	40	187	60
2.1	68	20.7	132	40	234	71	397	121

*After Rules 2 and 3 (see C3.2 in Appendix C) have been applied.

†D = arrester lead length L + transformer lead length S (where L and S are measured from their junction with the path of the incoming surge; see Fig C1 in Appendix C).

‡This table is based on the use of CWW = 1.15 BIL. If surge front is reduced by the multiple-line effect (see Rule 5, C3.2) such that sparkover occurs after 2 μs, the table should not be used.

NOTE: Table separations are calculated using an incoming surge with a rate of rise of 8.33 crest kV/μs/kV (rms) of arrester rating. For other rates of rise, use the methods of Appendix C.

Five standard protective ratios (PR) and protective margins (PM) are identified as follows:[6]

(1) Where separation is not significant:

PR(1) = CWW/FOW PM(1) = [PR(1) − 1] 100
PR(2) = BIL/LPL PM(2) = [PR(2) − 1] 100
PR(3) = BSL/SSP PM(3) = [PR(3) − 1] 100

(2) Where there is significant separation (refer to 3.7.1.3):

PR(1S) = CWW/E_i PM(1S) = [PR(1S) − 1] 100
PR(2S) = BIL/E_i PM(2S) = [PR(2S) − 1] 100
PR(3) = BSL/SSP PM(3) = [PR(3) − 1] 100

3.7.1.1 Protective Ratio Limits for Coordination. The PR limits for coordination are as follows:

PR(1) ≥ 1.2 PR(1S) ≥ 1.15
PR(2) ≥ 1.2 PR(2S) ≥ 1.15
PR(3) ≥ 1.15

3.7.1.2 Protective Margin Limits for Coordination. The PM limits for coordination are as follows:

PM(1) ≥ 20 PM(1S) ≥ 15
PM(2) ≥ 20 PM(2S) ≥ 15
PM(3) ≥ 15 PM(3) ≥ 15

[6]CWW, chopped-wave withstand (see 2.4)
BIL, basic impulse insulation level (see 2.4)
BSL, basic switching impulse insulation level (see 2.4)
FOW, front-of-wave arrester sparkover (see 2.3.1)
LPL, lightning protective level (see 2.3.1 and 2.3.2)
SSP, switching surge protective level (see 2.3.1 and 2.3.2)
E_i, voltage at transformer (see 3.7.1.3 and Appendix C)

3.7.1.3 Significant Separation. As discussed in 2.5 and 2.6, separation effects may become significant when the protective ratio (see 2.6) is less than 1.15. Table 5 gives the maximum separation that can be used without violating the 1.15 minimum limit for PR(1S) as defined in 3.7.1.1.

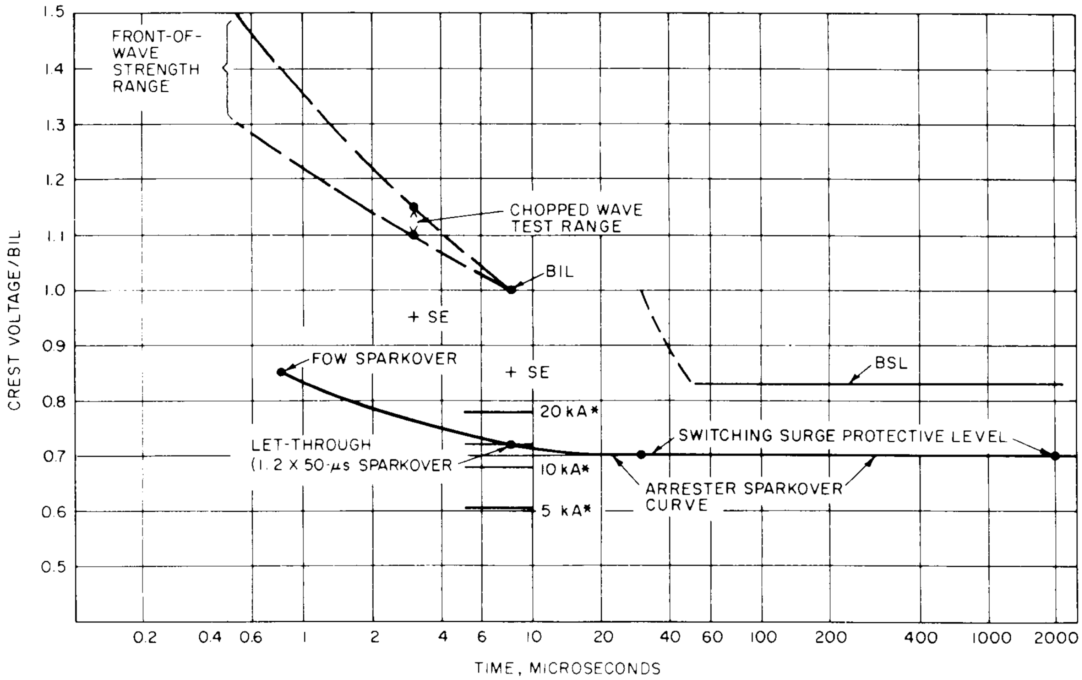
CAUTION: If the third footnote to Table 5 applies, use the detailed method of Appendix C, since the table may not be valid.

3.7.1.4 Satisfactory Performance. Insulation coordination is considered satisfactory when all of the criteria of 3.7.1.1 or 3.7.1.2 (as applicable) are met.

3.7.2 Coordination Curve Comparison Method [10]. It should be recognized that data from the four (at most) generally available insulation tests can be used to develop only an approximate insulation volt–time curve. A curve plotted in accordance with the instructions given in the notes for Fig 3 is no more than a graphical interpretation of the test results presented in a highly conventionalized manner as an aid to insulation coordination. It is not a true volt–time curve for the transformer. On the other hand, the arrester-sparkover curve is an accurate representation of an arrester's response to impulses.

Evaluation of insulation coordination by the curve method is made in accordance with Note 3 to Fig 3.

3.7.3 When Coordination Cannot Be Achieved. If coordination cannot be achieved with the arrester tentatively selected in 3.3, it



*Discharge level for an 8 × 20-μs test wave.

NOTES: (1) For the transformer curve, plot four points for the following withstand voltages as obtained from the manufacturer or standards: (a) front of wave (if available), (b) chopped wave, (c) full wave (BIL) at about 8 μs, and (d) switching surge at about 300 μs. Connect the points with a dotted or dashed line showing disjointed curves at the chopped-wave point extending the full-wave voltage as a straight line from about 8 to 50 μs and the switching surge withstand voltage as a straight line extending from approximately 50 to 2000 μs and passing through the plotted 300-μs point. It is not possible to interpolate exactly between points on the curve. Good experience has been obtained with the assumptions implicit in the preceding rules: (a) The full BIL strength will apply for front times between 8 and 50 μs. (b) Minimum switching surge withstand occurs between 50 and 2000 μs.

(2) For the arrester curve, approximate the sparkover curve as follows: (a) Plot three points for the following published sparkover voltages for the specific arresters to be installed: front of wave, 1.2/50-μs sparkover (at 8 μs), and switching surge protective level as a straight line from about 30 to 2000 μs. Connect the points with a curve of approximately the shape shown. If a manufacturer's voltage-time sparkover curve is available, it may be used instead of the approximation. (b) Draw a ladder of lines, each extending from 5 μs to 10 μs at levels corresponding to 5 kA, 10 kA, and 20 kA discharge voltage. Add a similar line passing through the 1.2/50-μs sparkover.

(3) To use the curve:

(a) Locate the point between 0.5 and 50 μs where the separation between withstand and arrester curve(s) is minimum. (Treat 1.2/50-μs sparkover and selected discharge kA lines as separate curves.) Calculate PM = [(withstand voltage)/(arrester voltage) - 1] x 100. PM must be ≥ 20 at this point. When separation effect has been evaluated, PM must be ≥ 15%.
(b) Make a similar check between 50 and 2000 μs. PM must be ≥ 15%.
(c) If separation is significant (see 3.7.1.3), evaluate voltage at protected equipment (Appendix C). Plot point at 3 μs if sparkover occurs in less than 2 μs; otherwise, plot at 8 μs.

Fig 3
Typical Voltage-Time Curve for Coordination of Arrester Protective Levels with Insulation Withstand Strength for Liquid-Filled Transformers

becomes necessary to consider alternative measures, such as the following:

(1) Selecting an arrester with a lower lightning or switching-surge protective level. This may involve a different class, design, or voltage rating. An arrester with a lower voltage rating than that indicated by consideration of 3.2.2 increases the risk of arrester failures that result from the inability of the arrester gaps to reseal against a voltage exceeding arrester rating.

(2) Changing the location of the arrester to reduce the separation distance or arrester lead length, or both.

(3) Increasing the insulation level of the equipment to be protected.

(4) Improving the shielding.

(5) Installing an additional set of arresters at a different point in the station.

3.8 Transformer Series Windings, Nonloaded Windings, and Ungrounded Neutrals

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

NOTE: This arrangement may change sparkover. Consult manufacturer on effect of nonstandard mounting.

3.8.1.1 Selection of Arrester. Select the class of arrester as recommended in 3.3.3. Select the voltage rating of arrester that is equal to or greater than the maximum power-frequency voltage that will appear across the series winding under fault conditions.

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

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

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

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

In selecting an arrester rating for protection of a neutral terminal, the general considerations of 3.3.1 and 3.3.1.2(1) are particularly applicable. The curves of Fig 2 cannot be used. The required overvoltage at the neutral is equal to system zero-sequence voltage during faults involving ground. Calculations using the method of symmetrical components are straightforward [33].

Care must be taken to use the BIL of the neutral (which is not necessarily as great as the transformer line terminal BIL) in determining required arrester protective level. A protective level PR(2) = BIL (neutral)/IR ≥ 1.2 is required; see 3.7. Discharge voltage *IR* at 3 kA is used to determine this PR.

3.9 Protection of Dry-Type Insulation.

The dry-type insulated equipment covered by this subsection includes such apparatus as dry-type transformers, which may have full-wave impulse withstand insulation strengths lower than liquid-immersed equipment of the same voltage rating. Generally, the impulse withstand strengths with waves of short duration are considered to be the same, or nearly the same, as the full-wave impulse withstand strength, as given for dry-type transformers in Table 5 of ANSI/IEEE Std C57.12.00-1987 [26]. Check the manufacturer of the equipment for specific values.

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

(1) Apply the information in 3.3 for selection of the arrester in rating and class.

(2) Determine the minimum permissible full-wave impulse insulation strength (BIL) of the transformer by multiplying the front-of-wave impulse sparkover protective level of the arresters by 1.2. (It is assumed that FOW is greater than *IR*. Refer to 3.4.)

(3) For cable-connected dry-type transformers refer to 3.5.3.

3.10 Protection of Shunt Capacitor Banks and Large-Capacitance Cables

3.10.1 Arrester Protection. Arrester protection is recommended for delta, ungrounded-wye, most solidly grounded-wye, and most switched banks regardless of connection.

Delta and ungrounded-wye capacitor banks have very small values of capacitance to ground, and a lightning surge on one phase will tend to charge the other phases through the phase-to-phase capacitance. Therefore, lightning surges can be hazardous and these banks should be protected. Grounded-wye banks have their full capacitance from line to ground and tend to reduce the magnitude of surge voltages reaching their terminals. In some instances, these banks are self-protecting. This is not always the case, however, and thus arresters should be considered for each capacitor bank application.

Severe duty is imposed on arresters adjacent to shunt capacitor banks due to high energy discharges during bank switching, regardless of whether the arresters were installed for protection of the capacitor or other equipment. Of particular concern is prestriking or restriking of the switching device during switching operations. For switched capacitors, surge arresters are recommended near the switching device on the capacitor side of the switch. The arrester manufacturer should be consulted for aid in selecting arresters suitable for the duty.

3.10.2 Duty on Arresters. Duty on arresters connected to terminals of large capacitance cables is similar to that caused by shunt capacitor switching [34, 35] see 3.5.3.

3.11 Protection of Rotating Machines. At present a guide for the protection of rotating machines is in preparation (ANSI/IEEE Std C62.21). This section will not be applicable when the new guide becomes available.

3.11.1 Machines Connected to Overhead Lines Directly or Through a Short Length of Cable. For machines connected to overhead lines, either directly or through a short length of cable, perform the following [36–38]:

(1) Install as close as practical to the machine terminals, between phase and ground, surge protective capacitors to reduce the slope of the wave front and arresters to limit the magnitude of the incoming surge. Also, connect arresters on the overhead lines ahead of the machine location or at an overhead line-cable junction point. Capacitors may not be required for installations involving machines with single-turn coils where there is no turn-to-turn stress.

(2) Select the capacitors on the basis of machine voltage rating and connection in accordance with manufacturer's recommendations.

(3) Determine the minimum permissible BIL of the insulation by multiplying the lightning impulse protective level (LPL) of the arrester by 1.2 (see 3.7.1).

(4) Select the voltage rating and class of arrester as directed in 3.3.3.

3.11.2 Machines Connected to Overhead Lines Through Transformers. For machines connected to overhead lines through transformers [39–42] protection as described in 3.11.1 may not be required, or the capacitors may possibly be omitted [43, 44]. It is possible to make an investigation of resultant surge voltages using a recurrent surge generator. However, it is suggested that Dillard and Hileman [43] and Abetti, Johnson, and Schultz [44] be reviewed before proceeding to perform such tests.

When arresters are definitely to be installed at the machine terminals, follow the procedure in 3.11.1.

3.12 Protection of Gas-Insulated Substations. Because all insulation within a gas-insulated substation (GIS) must be considered non-self restoring, surge protection should be provided and must be coordinated with all elements of the station. The most critical protective case for the line entrance arrester is coordination with a GIS open switch or circuit breaker and a steep-front incoming lightning surge. Two approaches have been taken in the arrester protection of existing stations connected to overhead lines: (1) conventional arresters at the line entrance, and (2) special gas-insulated surge arresters at more ideal protective locations within the GIS.

The dominant design criterion in the insulation coordination and surge protection of a GIS is related to lightning overvoltages. Most estimates of the increase (turnup) of GIS insulation strength for waves with short front times down to approximately a microsecond range from none at all to very modest. Steep-front reflections from surge impedance discontinuities within the GIS—most notably an open switch—can lead to significant differences between surge arrester protective level and surge voltage magnitude at substation locations remote from the arrester.

Other than a simple gas-insulated bus, insulation coordination of a GIS requires the use of sophisticated analytical tools to study the internal reflected waves that can occur during different operating configurations. Numerous papers have been published that address several studies. Some other significant findings derived from studies are given below:

(1) The steepest wave front (close-in surge) in general leads to the highest GIS voltage. However, in some cases lower steepness may result in higher voltages.

(2) Wave front rise time is a more significant parameter than simple magnitude of incoming surge.

(3) Increased station capacitance, eg, CCVT's, and its location can have a significant effect on reducing overvoltages.

(4) Cable entries limit the rate-of-rise of entering surges.

(5) With a cable entry and an arrester at the junction with the GIS, the overvoltage within the GIS will increase as the length of the GIS increases, but the overvoltage within the GIS will decrease as the length of the cable increases.

(6) With only one arrester, maximum surge voltage increases with distance from the arrester.

(7) Open switches or circuit breakers in the GIS are potential points of highest overvoltage levels.

For additional information on the effects of these factors and additional details on the application of current-limiting gapped arresters for protection of GIS, see references [45] through [49].

4. Protection of Distribution Systems

4.1 Introduction. This section covers the application of valve-type surge arresters to safeguard electrical distribution equipment and lines against the hazards of abnormally high voltage surges, particularly those caused by lightning. Although the basic principles of arrester selection and application as outlined in Section 3 also apply to distribution arresters, there are specific differences that require special consideration. Protective and durability characteristics of distribution arresters meeting specifications of ANSI/IEEE Std C62.1-1984 [1] are listed in Table 7. Further information is given in Appendix A.

Distribution lines are generally not shielded and therefore are particularly susceptible to direct lightning strokes [18]. The transient overvoltages developed by lightning are of greater concern than those caused by switching of distribution systems. Insulation coordination based on lightning surge voltages and current discharge voltages is thus the major consideration for distribution systems.

The duty imposed on arresters connected to distribution lines can be severe because of lightning current discharge requirements. Other potential causes of severe arrester duty occur when arresters are used to protect grounded-wye capacitor banks (see 4.7) or when arresters are subjected to ferroresonant overvoltages (see 4.12).

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

4.2 General Procedure. The general procedure for selecting a distribution arrester is to determine the proper arrester rating that can be used for all similar locations on the distribution system to be protected. This is usually done based on past experience, but can be calculated based on the maximum phase-to-ground voltage that can occur on unfaulted phases during single phase-to-ground faults. Voltage rating selection is discussed in 4.3.

Insulation coordination is discussed in 4.4. For system voltages up to 15 kV, insulation coordination for overhead connected equipment has not been rigorously studied because the protective margin (PM) between standard equipment basic lightning impulse insulation level (BIL) and the protective characteristics of modern distribution arresters is substantially in excess of 20% in usual applications. However, in recent years distribution systems at 25 kV and greater have been placed in service by conversion of some existing subtransmission lines and by new construction. Insulation coordination becomes a primary consideration for higher-voltage systems (particularly when reduced BIL values are used), for line protection (see 4.6), and for protection of underground distribution systems (see 4.10).

4.2.1 Installation practices jeopardizing insulation coordination.

(1) Long lead wires between line and arrester line terminal and between arrester ground terminal and ground (see 4.5.1).

(2) Large separation distances between the arrester and the protected equipment (see 4.5.2).

(3) Failure to interconnect the arrester and equipment ground terminals (see 4.5.4).

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

(1) Arrester protection of shunt capacitor banks (see 4.7).
(2) Arrester protection of switches, reclosers, etc (see 4.8).
(3) Arrester protection of voltage regulators (see 4.9).
(4) Arrester protection of underground circuits (see 4.10).
(5) Arrester application in contaminated atmospheres (see 4.11).

4.3 Selection of Arrester Ratings. Systems to be protected by distribution arresters are (1) delta connected, (2) three-wire wye unigrounded at the source, or (3) four-wire multiground wye. Construction includes open wire, spacer cable, and underground.

Voltage ratings of arresters usually applied to distribution systems are listed in Table 6. General characteristics of distribution arresters are shown in Tables 7a and 7b.

4.3.1 Delta Systems. The arrester rating should be equal to or greater than the maximum phase-to-phase voltage.

4.3.2 Three-Wire Unigrounded Wye Systems (Grounded at Source Only). In lieu of calculations to determine phase-to-ground voltages during single line-to-ground faults, it is generally acceptable to use an arrester rating at least equal to 80% of the maximum phase-to-phase voltage with no fault on the system. (The 80% rule is usually not applicable when these unigrounded systems are grounded through an impedance. In these cases the voltage on the unfaulted phases must be calculated to determine arrester rating).

On systems where it is possible to backfeed a portion of the circuit through devices such as transformers or capacitors connected to the circuit after a phase has been interrupted, the arrester rating should be at least equal to the maximum phase-to-phase voltage.

4.3.3 Four-Wire Multigrounded Wye Systems (Including Spacer-Cable Circuits). Since most distribution systems are of the four-wire multigrounded wye type, arrester ratings used have been established by many years of operating experience.

This long-term experience is not available for the higher-voltage distribution systems being installed or for spacer-cable circuits, and a method for establishing arrester ratings is required. In a generally accepted method [50], the nominal phase-to-ground operating voltage of the system is multiplied by:

(1) 1.25 for four-wire multigrounded wye open-wire circuits;

(2) 1.50 for spacer cable circuits.

These multiplying factors take into account voltage regulation and the effect of connected distribution transformers magnetizing reactance. For open-wire systems having operating voltages not listed in Table 6, the 1.25 factor is recommended to determine arrester rating; for spacer-cable circuits, the 1.5 factor can be used as a guide, but it is recognized that this results in conservative minimum arrester ratings.

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

$$PM(1) = (CWW/FOW - 1)100$$
$$PM(2) = (BIL/IR - 1)100$$

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

The general rule is that PM(1) and PM(2) must both be at least 20%. However, experience with surge protection of distribution systems (15 kV and less) has been gained with protective margins greatly in excess of 20%. By connecting distribution arresters directly across overhead equipment insulation, separation effects (SE) are minimized and consideration of PM(1) can usually be neglected. However, PM(1) must be considered when arresters are used for line protection (see 4.6), underground systems protection (see 4.10), or dry-type insulation protection. A PM(1) of at least 20% is recommended for dry-type insulation.

The discharge voltage of an arrester is greater for less frequent high crest lightning surges and increases with higher rates of rise of lightning current [51]. It is the usual practice to select a reference value of discharge current that will be exceeded infrequently. The discharge voltage at this reference level is used to calculate PM(2). Obviously, the selection of a higher reference level for any given arrester will result in a smaller PM(2).

There is no universally accepted surge current level on which to base insulation coordination, although currents in the 10–20 kA range are often used. [The range of arrester discharge voltage values at 10 kA (8/20-μs wave) is shown in column 5 of Table 7a.] Reference currents above 20 kA can be considered to take into account lightning currents with faster rates of rise than the standard test waves used to make discharge voltage measurements [51] or where severe lightning is common. (Arrester discharge voltage values can be obtained from the manufacturer for currents greater than 20 kA.) Strict application of the 20% margin rule will then favor the use of arresters with low discharge voltages. PM(2) does not include an allowance for voltage developed across arrester connecting lead wires (see 4.5.1). The arrester discharge voltage characteristic to be used for insulation coordination purposes is the total of the arrester discharge voltage plus the connecting lead wire voltage. Maintaining lead wires as short as possible is particularly important when protecting underground systems (see 4.10).

4.5 Arrester Connections

4.5.1 Effect of Connecting Lead Wires. Lightning currents discharging through the inductance of connecting wires produce a voltage that adds to the arrester discharge voltage. The total length of these wires is measured from the point at which the arrester line connection is made to the line to the point at which interconnection is made to the protected equipment ground (minus the length of the arrester). A commonly accepted voltage value to be added to the arrester discharge voltage is 1.6 kV/ft of lead wire [52]. Based on tests, this voltage develops from a 20 kA discharge current (4 x 10 μs wave) for lead lengths under 5 ft [53] Although the lead wire voltage developed at insulation coordination levels of 10 and 20 kA (8/20-μs wave) are approximately one-fourth and one-half the value of 1.6 kV ft [53] , it is important to keep lead lengths as short as possible. Higher lightning currents, faster rising current waves, and long lead lengths produce substantially higher voltages. Excessive lead wire lengths can eliminate the safety factor allowed for by the protective margin PM(2).

4.5.2 Effect of Separation Distance. Distribution arresters are often used to protect a single piece of equipment and, therefore, should be connected as close as possible to the equipment. This reduces separation effects (see Section 2 and Appendix C). Arresters used to protect equipment should not be installed on separate poles (a pole span away from the equipment to be protected), especially where only one arrester is used and the transformer is connected to a line that runs in two directions from the tap point. In effect, surges approaching equipment from the side where no arrester is installed are not limited and may cause equipment failure. Surges approaching from the arrester side are limited by arrester action, but separation effect is very high.

4.5.3 Location of Arresters with Respect to Equipment Fuses. In general, it is a good practice to connect fuses between the arrester and the transformer or other equipment being protected. This minimizes the magnitude of lightning current carried by the fuse during arrester operation and the possibility of fuse damage or blowing. Where fuses must be connected ahead of arresters (for instance, to keep arrester lead wires short when protecting underground cable equipment), it is recommended that the surge withstand characteristics of the fuse be evaluated [55].

4.5.4 Interconnection of Grounds

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

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

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

4.5.5 Clearances of Arresters to Energized Conductors and Equipment and to Grounds. For proper operation, distribution arresters should be installed to maintain clearances listed in Table 8. Regulations or other considerations may dictate larger clearances in exposed locations. Listed clearances are suitable for arresters in metal enclosures.

4.6 Protection of Distribution Circuits. Since grounded shield wires are not often used, distribution arresters are frequently used to protect the lines of these systems from flashover resulting from lightning strikes.

The protection of overhead distribution circuits has been studied, and reports [56, 57] have been made regarding the degree of protection afforded by surge arresters. The reports indicate the number of line flashovers to be expected is a function of arrester spacing, line design, and keraunic level. Arrester ratings employed for circuit protection are the same as those used for equipment protection at the given line-voltage level.

4.7 Protection of Capacitor Banks. Pole-mounted shunt capacitor banks are usually protected by line-to-ground connection of arresters at or near the bank. Connections should be as outlined in 4.5 (refer also to 3.10). The ratings of arresters used are usually the same as used elsewhere on the system.

Arresters used in applications where the capacitor banks are connected grounded-wye should be capable of handling high-energy discharge. These banks can be charged to high voltages by lightning currents. Arresters sparking over as a result of the high voltage must discharge the associated stored energy.

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

If a capacitor bank is capable of being switched, arresters of high energy capability may be required regardless of the circuit configuration. The highest energy transients to which arresters near capacitors are exposed generally result from a restrike of the switching device when the bank is being de-energized. In the case of an ungrounded capacitor bank, a two-phase restrike can cause excessive current to flow in both arresters associated with the restruck phases. Arresters on either side of the switching device can experience high energy switching transients. The arrester manufacturer should be consulted for aid in selecting arresters suitable for the duty.

4.8 Protection of Switches, Reclosers, Etc. Normally, open line switches should be protected by arresters at both sides of the switch, although lightning-induced flashover on a de-energized line side does not generally cause serious damage, due to the absence of power frequency voltage. The case of switches in an underground system is covered in 4.10.

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

The arresters usually have the same ratings as those used in other parts of the system. Connections should follow the outline of 4.5.

4.9 Protection of Series Windings

4.9.1 Voltage Regulators. If voltage regulators are connected to exposed circuits, they should be protected on both line and load sides. Feeder regulators at substations are often

Table 6
Commonly Applied Voltage Ratings of Arresters on Distribution Systems

System Voltage (kV rms)		Usually Applied Arrester Ratings (kV rms)			
Nominal Voltage	Maximum Voltage Range B*	Four-Wire Multigrounded Neutral Wye	Three-Wire Unigrounded Neutral Wye	Delta and Ungrounded Wye	Spacer-Cable Circuits†
2400	2540			3	
4160Y/2400	4400Y/2540	3	6		3
4160	4400			6	
4800	5080			6	
6900	7260			9 or 9/10	
8320Y/4800	8800Y/5080	6	9 or 9/10		6
12 000Y/6930	12 700Y/7330	9 or 9/10	9/10 or 10		9/10 or 10
12 470Y/7200	13 200Y/7620	9 or 9/10	12		9/10 or 10
13 200Y/7620	13 970Y/8070	9/10 or 10	12		9/10 or 10
13 800Y/7970	14 520Y/8380	9/10, 10, or 12	12		12
13 800	14 520			15	
20 780Y/12 000	22 000Y/12 700	15	18		18
22 860Y/13 200	24 200Y/13 970	18	21		21
23 000	24 340			25	
24 940Y/14 400	26 400Y/15 240	18	21		21
34 500Y/19 920	36 510Y/2180	25 or 27	30		30
34 500	36 510			36‡ or37‡	

*See ANSI C84.1-1982 [54].

†The use of spacer cables at most system voltages has had limited application, reducing the experience factor in establishing arrester ratings usually applied. Where experience is a factor, arrester ratings lower than 1.5 x nominal system line to ground voltage [50] have been used. This is taken into account for the voltage ratings listed.

‡Nonstandard distribution arrester voltage ratings.

Table 7a
Distribution Arrester Protective Characteristics

		Protective Levels Per-Unit Crest Arrester Rating*		
Rating (kV)	Range of Application Maximum System Voltage (kV)	Front-of-Wave Without External Gap (kV)	Sparkover With External Gap (kV)	Discharge With 10 kA 8/20-μs Wave
3	2.6–4.5	3.30–5.89	5.66–8.95	2.71–3.25
6	4.5–7.8	3.18–4.12	5.30–6.71	2.65–3.06
9–12	7.8–14.3	2.83–3.77	4.30–5.97	2.55–3.22
15–21	18–25.8	2.12–3.54	3.70–5.42	2.45–3.09
25–30	38	2.02–3.54		2.36–2.75

*The per-unit values shown are maximum industry values from tables in Appendix A. For specific values, consult manufacturer's literature.

NOTE: Protective level (kV) = per-unit level x rating x$\sqrt{2}$. For example, range of FOW sparkover for a 12-kV arrester is (2.83 to 3.77) x 12$\sqrt{2}$ = 48 to 64 kV.

Table 7b
Distribution Arrester Durability Characteristics*

	(1)	(2)		(3)
Arrester Class	Duty Cycle Initiating Surge (Crest (A))	Low-Current Long-Duration Withstand (Crest (A))	(μs)	High-Current Withstand (Crest (A))
Normal Duty	5000	75	2000	65 000
Heavy Duty	10 000	250	2000	100 000

*This refers to the ability of the arrester to protect itself against the stresses resulting from:

(1) Cumulative power-follow current and surge discharge operations (which also determine the ability to reseal against a voltage equal to the arrester rating).

(2) Long-duration lightning.

(3) Severe lightning discharges.

Table 8
Recommended Minimum Clearances

Arrester Voltage Rating (kV rms)	Surge Arrester Housing Impulse Withstand (kV Crest)*	Recommended Minimum Clearances, Inches (Millimeters)† To Ground(s)	Between Phases
3	45	1-3/4 (45)	2 (51)
6	60	2-3/4 (70)	3-1/4 (83)
9	75	4 (102)	4-3/4 (121)
10	75	4 (102)	4-3/4 (121)
12	85	4-3/4 (121)	5-1/2 (140)
15	95	5-1/2 (140)	6-3/4 (171)
18	125	8 (203)	9 (229)
21	125	8 (203)	9 (229)
25	150	9-1/2 (241)	11 (279)
27	150	9-1/2 (241)	11 (279)
30	150	9-1/2 (241)	11 (279)

*1.2/50 μs full-wave BIL per Table 3 in ANSI/IEEE Std C62.1-1984 [1].

†Clearances measured from metal parts of arrester line terminal and dictated by minimum flashover to maintain BIL in accordance with ANSI/IEEE Std C62.1-1984 [1] and to allow for the bias effect of power frequency voltage between adjacent phases. Air insulation between arrester and wall(s) or between arresters is assumed. Minimum clearance required between bottom stud on arrester and enclosure floor need be only that required to install ground connection and to provide sufficient space for operation of the disconnector if used.

protected by the station arresters on the station bus, but distribution arresters are required on the exposed-line side; however, the most effective protection regardless of regulator location is to install distribution arresters at or near the source and load side terminals with the arrester ground interconnected to the regulator tank.

Serious overvoltages between the terminals of series windings on regulators may develop due to lightning surges on the connected lines. These overvoltages are usually controlled by some form of gap or arrester supplied by the regulator manufacturer.

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

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

4.10 Protection of Equipment on Underground Systems. Most of the problems associated with protection of underground systems result from the practical difficulties involved in locating arresters as close as desired to terminating points or points where substantial changes in surge impedance occur in the underground system. When it is possible to install arresters at equipment locations, application procedures are similar to those used for protection of overhead equipment. When it is not possible to install arresters at individual equipment locations in the underground system, protection is usually provided by arresters located at the junction of the overhead line conductors and the underground system cables. Recently, consideration has been given to installation of arresters on underground transformers on systems 15 kV and above to provide larger protective margins for transformers [21, 22, 58].

For system voltages of 15 kV and below, the use of a distribution surge arrester only at the riser pole generally provides adequate margin for protection of cable-connected equipment. For 25 kV system voltages, distribution arresters are probably not adequate, but adequate protection at the riser pole only may often be obtained by the use of intermediate arresters. Other possibilities are discussed in IEEE Committee Report, Surge Protection of Cable-Connected Equipment on Higher-Voltage Distribution Systems [59]. For 34.5 kV systems, arresters at the riser pole only will not provide adequate protection and use of one or more arresters installed on the cable circuit is necessary.

The voltage held at the riser pole is the arrester sparkover voltage, but after sparkover it is the sum of arrester discharge voltage and the inductive voltage drop in the arrester connecting leads [53]. These voltages propagate into the cable circuit and can approach double their value on the cable and at connected transformers, due to reflections at points such as open switches and terminating transformers. The following rules [52] are directed toward determining the voltages at terminating points, in order to permit the calculation of protective margins:

(1) Assume no attenuation. This assumption becomes conservative for cable lengths greater than 3000 ft [60].

(2) Assume the incident voltages will double at open points and terminating transformers.

(3) Use manufacturer's published maximum front wave sparkover and discharge voltage values consistent with the considerations cited in 3.4 (the discharge voltage at 10 kA has been recommended [52], but 20 kA is conservative for unshielded circuits).

(4) Calculate inductive voltage drop in arrester connecting leads as L (ft) x 1.6 kV/ft (based on linear surge current rise of 4 kA/μs and 0.4 μH/ft of lead).

(5) Compare doubled front-of-wave sparkover voltage with chopped-wave withstand for liquid-filled transformers and with BIL for dry-type transformers and cables. Compare doubled sum of discharge voltage, at assumed current, and connecting lead voltage with transformer and cable BIL. Then, using the recommended protective margin of 20%:

Oil:	$CCW \geq 1.2 \times 2 \times FOW$
Dry:	$BIL \geq 1.2 \times 2 \times FOW$
Both:	$BIL \geq 1.2 \times 2 (IR + V_{lead\ wire})$

For 34.4 kV circuits, the most common protection method is to use an arrester at the riser pole and a second arrester at the remote end of the cable that is a reflection point for the traveling wave. The voltage at the reflection point will be limited to the sparkover voltage of the remote arrester (unless the cable system is very short), since the discharge current in the remote arrester will be low enough that its discharge voltage will not exceed its sparkover value [21, 58]. The voltage at intermediate points in the cable circuit may be higher than the protective level of the arrester at either end. The maximum voltage at intermediate points will be the discharge voltage of the riser-pole arrester plus one half of the sparkover voltage of the reflection point arrester [59].

4.11 Contaminated Atmospheres. Surveys have shown that failures of distribution arresters due to operation in contaminated atmospheres are quite rare. However, such failures may occur from the combined effect of (1) accumulation of contaminants on the arrester, and (2) conditions of wet snow, frost, light rain, or fog. Where contamination failures are suspected, the manufacturer may be able to verify the cause by an inspection of internal arrester parts. The usual solution is periodic cleaning. In a few cases, application of nonconducting, nontracking, water-repellent greases to the insulating surfaces of the arrester has been used.

4.12 Ferroresonance Effects. On multi-grounded wye systems, sustained ferromagnetic nonlinear overvoltages, usually described as ferroresonant overvoltages, most commonly result from opening one or two phases of a circuit serving an ungrounded-wye or delta primary transformer bank, or an ungrounded capacitor bank under light or no-load conditions. Overvoltages are produced by a series equivalent of line capacitance and a saturable magnetic device such as a transformer. The voltages are often of sufficient magnitude and duration to damage or destroy surge arresters.

Ferroresonance effects have been experienced, for example, at system voltages of 14.4/24.9 kV [61] or higher. It has been shown [61] that for usual transformer bank sizes a few miles of overhead line or equivalent cable are required to furnish the necessary capacitance; however, the likelihood of occurrence with shorter line lengths increases with increased system voltage and reduced transformer bank sizes.

Methods of controlling or eliminating ferroresonance effects are discussed in Auer and Schultz [61], Crann and Flickinger [62], and Hopkinson [63].

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

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

In the case of an arrester equipped with a disconnector, operation of the disconnector physically separates the arrester ground connection from the failed arrester and thus gives a visual indication of failure. Care must be taken to provide enough clearance to ensure that the separated ground lead is not thrown into an energized conductor.

NOTE: In certain designs, operation of the disconnector is achieved by the detonation of a small explosive charge when follow current is abnormal. No attempt should be made to unload or disassemble a disconnector.

4.14 Current-Limiting Fuses. Current-limiting fuses are used to protect and isolate faulted single-phase laterals and some three-phase laterals in addition to transformer isolation. Since some current-limiting fuses can generate a high arc voltage with peak magnitudes exceeding system voltage, care must be exercised to ensure proper coordination between the fuse and the arrester.

Although experience with these applications is limited, distribution arrester damage as a result of current-limiting fuse operation has not been an application problem. In the event that arrester damage does occur, an arrester with a higher voltage rating than what would normally be applied would be required. The higher sparkover voltage reduces the chance of sparkover, and the higher discharge voltage reduces the duty on the arrester if sparkover does occur. Additional information on the effects of current-limiting fuses can be found in Kershaw, Huber, and Hassler [64], Olive and Westrom [65], and IEEE Switchgear Committee and Surge Protection Devices Committee Working Group, Coordination of Lightning Arresters and Current-Limiting Fuses [66].

5. Bibliography

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Appendixes

(These Appendixes are not a part of American National Standard Guide for the Application of Gapped Silicon-Carbide Surge Arresters for Alternating-Current Systems, ANSI/IEEE C62.2-1987, but are included for information only.)

Appendix A
Protective Characteristics of Surge Arresters

In lieu of specific data on protective characteristics of available surge arresters, Tables A1 through A6, which are compiled from domestic manufacturers' catalog information, can be used as a guide in general insulation coordination studies. It should be recognized that these data are the range of the maxima listed in manufacturers' catalog information for each type of arrester, resulting in certain apparent inconsistencies in the tables. Therefore, the specific manufacturer's information on the arrester being applied should be used for more accurate insulation coordination. Among the various columns of protective characteristics, the highest or the lowest maximum values of sparkover and discharge voltage are not necessarily related to the same arrester. For example, a particular 12 kV arrester whose front-wave sparkover is identical to the lowest maximum value shown in one of the tables does not necessarily possess the lowest maximum value shown for discharge voltage in the 10 000 A column.

Table A1
Protective Characteristics of Gapped Silicon-Carbide Station Arresters

Voltage Rating of Arrester kV rms)	Impulse Sparkover Voltage: Front-of-Wave Rate of Rise of Test Voltage (kV/μs)	Impulse Sparkover Voltage: Front-of-Wave kV Crest (Range of Maxima)	Impulse Sparkover Voltage: 1.2/50-μs kV Crest (Range of Maxima)	Switching Surge Sparkover Voltage kV Crest (Range of Maxima)	Discharge Voltage for 8/20-μs Discharge Current Wave: kV Crest for 1500 A (Range of Maxima)	kV Crest for 3000 A (Range of Maxima)	kV Crest for 5000 A (Range of Maxima)	kV Crest for 10 000 A (Range of Maxima)	kV Crest for 20 000 A (Range of Maxima)	kV Crest for 40 000 A (Range of Maxima)
3	25	10–18	10–14	–	4.7–6	5.3–6.5	6–7	6.7–7.5	7.7–8.3	–9.2
6	50	19–28	16–23	–	9.3–11	10–12	11.9–13	13.4–14.3	15.3–16.3	–18.5
9	75	28.5–38	24–32	–	13.9–17	16–18	17.8–19	20–21.5	22.9–24.3	–28
12	100	36–48	32–41	–	18.5–22	21.3–24	23.5–25.5	26.7–28.5	30.1–32.1	–37
15	125	45–57	40–51	–	23.1–27.5	26.6–30	29.5–32	33.4–36	38.2–40	–46
21	175	63–76	54–68	–	32.3–38.5	37.2–42	41–45	46.8–50	53.4–55.5	–65
24	200	71–86	62–77	–	36.9–44	42.5–48	47–51	53.4–57	61–63.5	–74
30	250	89–103	77–93	–	46.1–55	53.1–60	59–64	66.9–72	76.3–79	–92.5
36	300	107–118	92–108	–	55.3–66	63.7–72	70.5–76	80–85	91.5–94.5	–111
39	325	115–125	100–114	–	60–71.5	69–78	76.5–82.5	86.5–92	99.1–102	–120
48	400	143–148	122–132	–	73.8–88	84.9–96	94–102	106–114	122–126	–148
60	500	170–190	141–165	136–153	95–109	110–120	118–130	132–143	150–158	–185
72	600	204–226	169–190	163–178	114–131	130–144	141–155	159–170	180–189	–222
90	750	254–275	210–235	203–215	142–163	162–180	176–194	199–213	225–237	–277
96	800	270–295	218–245	218–225	151–174	173–192	188–218	212–227	240–253	–296
108	900	304–325	245–270	245–250	170–196	194–216	212–245	238–256	270–284	–333
120	1000	338–360	272–300	272–275	188–218	216–240	235–272	265–285	300–319	–370
144	1200	400–430	326–346	325–326	226–262	260–288	282–311	318–342	360–379	–444
168	1400	460–525	380–404	380–381	263–305	303–336	329–362	371–399	420–442	–517
180	1500	490–565	400–430	400–410	281–327	324–360	353–388	397–427	450–495	–554
192	1600	520–600	427–460	426–435	300–348	346–384	376–414	424–455	480–505	–591
240	2000	620–735	535–577	533–545	374–436	432–480	470–518	530–570	605–630	–739
258	2000	760–790	575–620	573–585	402–438	465–474	505–515	569–575	650–666	–795
276	2000	805–840	615–664	612–630	429–468	496–507	540–570	609–615	690–714	–850
294	2000	875–885	653–675	653–675	458–472	528–532	576–595	653–653	735–758	–906
312	2000	924–935	690–750	693–710	485–530	562–574	611–620	688–693	780–805	874–961
372	2000	1078–1100	870–890	790–830	562–610	655–680	726–738	809–826	932–955	1136–1145
396	2000	1140–1176	925–950	840–885	599–672	697–726	734–785	861–880	990–1015	1109–1226
420	2000	1200–1250	980–1005	890–940	634–713	739–770	819–830	913–930	1050–1070	1176–1294
444	2000	1265–1320	1035–1055	940–990	670–753	781–814	866–875	965–977	1110–1130	1243–1358
468	2000	1326–1390	1090–1110	992–1045	707–794	823–860	913–930	1018–1040	1170–1200	1310–1441
492	2000	1385–1425	1160–1165	1045–1090	742–830	865–925	958–1000	1070–1115	1232–1290	1500–1515
540	2000	1515–1555	1274–1280	1145–1200	814–890	949–990	1052–1070	1173–1195	1350–1390	1646–1663
576	2000	1616–1665	1359–1380	1225–1285	868–950	1012–1060	1122–1150	1251–1285	1440–1480	1755–1780
612	2000	1700–1765	1440–1480	1300–1370	924–1010	1076–1130	1193–1220	1330–1360	1531–1580	1865–1885
648	2000	1790–1865	1525–1570	1380–1445	977–1070	1138–1190	1261–1290	1407–1440	1619–1670	1974–1996
684	2000	1880–1960	1610–1680	1455–1525	1031–1130	1153–1260	1331–1360	1489–1520	1709–1765	2063–2107

Table A2
Protective Characteristics of Gapped Silicon-Carbide Intermediate Valve Arresters

Voltage Rating of Arrester (kV rms)	Impulse Sparkover Voltage: Front of Wave: Rate of Rise of Test Voltage (kV/μs)	Impulse Sparkover Voltage: Front of Wave: kV Crest (Range of Maxima)	Impulse Sparkover Voltage: 1.2/50-μs kV Crest (Range of Maxima)	Switching Surge Sparkover Voltage kV Crest (Range of Maxima)	Discharge Voltage for 8/20-μs Discharge Current Wave: kV Crest for 1500 A (Range of Maxima)	kV Crest for 3000 A (Range of Maxima)	kV Crest for 5000 A (Range of Maxima)	kV Crest for 10 000 A (Range of Maxima)	kV Crest for 20 000 A (Range of Maxima)
3	25	11–12	11–12	–	5.2–7.5	6–8	6.6–9	7.5–10	8.7–12
6	50	21–21	19–19	–	10.4–13.5	11.9–14	13.2–15.5	15–17.5	17.4–20
9	75	31–33	27.5–32	–	15.6–21	17.9–23	19.8–25	22.5–28	26.1–31
12	100	38–42	35.5–37	–	20.8–27	23.8–29	26.4–32	30–34	34.8–37.5
15	125	47–51	43.5–46.5	–	25.9–34	29.7–36.5	32.9–39.5	37.5–43	43.5–47.5
21	175	67–73	58–64	–	36.3–47.5	41.6–51	46.1–56	52.5–60	60.9–66
24	200	75–78	66–75	–	41.5–54	47.6–58	52.7–64	60–68	69.6–75
30	250	91–97	81–91	–	51.8–68	59.4–73	65.8–79	75–86	87–95
36	300	108–116	95–103	–	62.2–82	71.3–87	79–95	90–102	104–113
39	325	116–126	102–110	–	67.4–91	77.3–97	85.5–106	97.5–114	113–126
48	400	143–154	121–132	–	83–109	95–116	105–127	120–136	139–150
60	500	166–190	147–155	185–206	104–136	119–145	131–159	150–171	174–189
72	600	201–230	171–191	219–245	124–163	143–174	158–191	180–204	209–225
90	750	250–283	223–233	274–304	155–204	178–218	197–239	225–256	261–282
96	800	268–300	236–250	292–323	166–217	190–232	211–254	240–273	278–300
108	900	283–335	258–265	328–362	187–244	214–261	237–286	270–307	313–338
120	1000	299–370	276–295	351–400	207–272	238–290	263–319	300–338	348–380

Table A3
Protective Characteristics of Gapped Silicon-Carbide Distribution Arresters

Voltage Rating of Arrester (kV rms)	Rate of Rise of Test Voltage (kV/μs)	Impulse Sparkover Voltage: Front of Wave, Without External Gap, kV Crest (Range of Maxima)	Impulse Sparkover Voltage: Front of Wave, With External Gap, kV Crest (Range of Maxima)	Impulse Sparkover Voltage: 1.2/50-μs, Without External Gap, kV Crest kV Crest (Range of Maxim)	Impulse Sparkover Voltage: 1.2/50-μs, With External Gap, kV Crest kV Crest (Range of Maxima)	Discharge Voltage for 8/20-μs Discharge Current Wave: kV Crest for 1500 A (Range of Maxima)	kV Crest for 3000 A (Range of Maxima)	kV Crest for 5000 A (Range of Maxima)	kV Crest for 10 000 A (Range of Maxima)	kV Crest for 20 000 A (Range of Maxima)
3	25	14–25	24–38	12–22	24–37	8–10	8.4–11.5	10–12.4	11.5–13.8	13.5–15.7
6	50	27–35	45–57	23–33	35–55	16–20	17–23	20–24	22.5–26	25–30
9	75	39–48	60–76	34–45	48–65	24–30	25–34	29–36.5	32.5–41	36–46
10	83.3	40–48	62–76	35–49	48–67	25–30	27.5–34	29.5–37	32.5–44	36–52
12	100	49–60	73–96	44–57	59–85	32–40	34–46	29.5–48	43–53	49–61.5
15	125	47–75	80–115	49–65	69–100	40–50	42–55	39–60	54–65.5	60–76
18	150	55–90	96–133	58–76	79–118	48–60	51–66	46–72	65–78	71–91
21	175	63–90	110–139	66–78	–123	56–70	59–75	68–80.5	73–90	82–103
27	225	79–102	–	75–98	–	70–80	76–86	82–94	90–105	99–121
30	250	86–114	–	81–100	–	76–89	84–97	91–105	100–116	111–134

Table A4
Protective Characteristics of Gapped Silicon-Carbide Secondary Arresters

Voltage Rating of Arrester (kV rms)	Impulse Sparkover Voltage: Front-of-Wave, Rate of Rise of Test Voltage (kV/μs)	Impulse Sparkover Voltage: Front-of-Wave, kV Crest (Range of Maxima)	Impulse Sparkover Voltage: 1.2/50-μs, kV Crest (Range of Maxima)	Discharge Voltage for 8/20-μs Discharge Current Wave: kV Crest for 1500 A (Range of Maxima)	Discharge Voltage for 8/20-μs Discharge Current Wave: kV Crest for 5000 A (Range of Maxima)
0.175	10	2.3–3.0	2.1–2.5	1.0–1.5	1.4–1.8
0.650	10	2.8–3.8	2.5–3.5	2.2–3.8	2.9–5.0

Table A5
Protective Characteristics of Gapped Silicon-Carbide Distribution Arresters for the Protection of Rotating Machines and Dry-Type Transformers

	Impulse Sparkover Voltage			Discharge Voltage for 8/20-μs Discharge Current Value				
Voltage Rating of Arrester (kV rms)	10 μs to Sparkover (Range of Maxima)	100 kV/μs per 12 kV of Rating (Range of Maxima)	1.2/50-μs Crest (Range of Maxima)	kV Crest for 1500 A (Range of Maxima)	kV Crest for 3000 A (Range of Maxima)	kV Crest for 5000 A (Range of Maxima)	kV Crest for 10 000 A (Range of Maxima)	kV Crest for 20 000 A (Range of Maxima)
3	12-16	11-16	11-16	9-9.5	9.5-10.5	10-11	11-12	12-13.5
4.5	16.5-18	16.5-19	17-18	13.5-15	14.5-17	15-17.5	16.5-19	17.5-21.5
6	22-24	21-24	21-25	14-19	19-21	20-22	22-24	23.5-27
7.5	26-26	26-26.5	26-26.5	22.5-25	24-27	25-29	27-31	29.5-35
9	30-32	32-32	31-32	27-28	29-32	30-33	32.5-36	35-40
12	39-41	39-41	39-41	36-38	38.5-42	40-44	43-48	47-54
15	47-49	46-47	46-49	42-45	46.4-48	50-51	54-55	58.5-62

Table A6
Protective Characteristics of Gapped Silicon-Carbide Station Arresters for the Protection of Rotating Machines and Dry-Type Transformers

	Impulse Sparkover Voltage			Discharge Voltage for 8/20-μs Discharge Current Value				
Voltage Rating of Arrester (kV rms)	10 μs to Sparkover (Range of Maxima)	100 kV/μs per 12 kV of Rating (Range of Maxima)	1.2/50-μs Crest (Range of Maxima)	kV Crest for 1500 A (Range of Maxima)	kV Crest for 3000 A (Range of Maxima)	kV Crest for 5000 A (Range of Maxima)	kV Crest for 10 000 A (Range of Maxima)	kV Crest for 20 000 A (Range of Maxima)
3	10–12	10–13	8–12	4.7–5	5.3–5.8	6–6.4	6.7–7.3	7.7–8.3
4.5	13–14	14–16.5	12.5–15	7–7.5	8–8.7	8.9–9.5	10–10.8	11.5–12.3
6	18–18	19–19	16–18	9.3–10	10.6–11.5	11.9–12.0	13.4–14.3	15.3–16.3
7.5	23–24	24–25	20–23	11.6–12.2	13–14.3	14.8–15.7	16.7–17.7	19–20.3
9	26–28	28.5–30	24–26	13.9–14.6	16–17.1	17.8–18.8	20–21.2	22.9–24.3
12	35–36	36–41	32–36	18.5–19.5	21.3–22.7	23.5–24.9	26.7–28.1	30.1–32.1
15	43–43	45–51	40–43	23.1–24.2	26.6–28.2	29.5–31	33.4–35	38.2–40
16.5	–	–	44–46	–	–	–	–	–
18	48–51	52–60	47–49	27.7–28.9	31.9–33.7	35–37.1	40–41.8	45.8–47.8
19.5	–	–	52–52	–	–	–	–	–
21	54–59	63–70	54–56	32.3–33.7	37.2–39.3	41–43.2	46.8–48.7	53.4–55.5
22.5	–	–	–	–	–	–	–	–
24	62–65	71–78	62–64	36.9–38.5	42.8–44.8	47–49.2	53.4–55.5	61–63.5
25.5	–	–	–	–	–	–	–	–
27	69–73	80–86	69–75	41.5–43.1	47.8–50.3	53–55.3	60–62.5	68.7–71.2

Appendix B

Surge Arrester Applications for EHV Systems

B1. Scope and References

B1.1 Scope. Many of the arrester criteria discussed in Sections 2 and 3 are directly applicable to arresters used for EHV systems where the system voltage, V_{sys}, is greater than 240 kV and less than 1000 kV. There are several requirements, however, that are much more stringent for EHV arrester applications than for lower-voltage installations.

B1.2 References.

[B2] BENKO, I. S., GOLD, S. H., ROTHENBUHLER, W. N., BOCK, L. E., JOHNSON, I. B., and STEVENSON, J. R. Internal Overvoltages and Protective Devices in EHV Compensated Systems—Series Capacitors and Shunt Reactors. *CIGRE Report 33-05*, 1976.

[B3] DIESENDORF, W. Insulation Coordination in H. V. Electric Power Systems. New York: Crane, Russak, 1974.

[B5] BREUER, G. E., HOPKINSON, R. H., JOHNSON, I. B., and SCHULTZ, A. J. Arrester Protection of High Voltage Stations Against Lightning. *AIEE Transactions (Power Apparatus and Systems)*. 1960, 79:414–422.

[B6] IEEE Committee Report. Switching Surges, III—Field and Analyzer Results for Transmission Lines. Past, Present, and Future Trends. *IEEE Transactions on Power Apparatus and Systems*. 1970, PAS-89:173-189.

[B7] AIEE Committee Report. Switching Surges, I—Phase-to-ground voltages. *AIEE Transactions (Power Apparatus and Systems)*. 1961; 80:240–261.

B2. Protection and Rating Selection Considerations.

At extra-high voltages (EHV), switching impulse withstand (BSL) of equipment may be the critical design parameter rather than lightning impulse withstand (BIL). Arresters with known switching protective levels must be used. Desired insulation levels are lower with respect to operating voltages; consequently, lower arrester ratings (0.70–0.75 compared to 0.8–1.00 times V_{sys}) may be required.

B3. Durability Considerations

The arrester selected must be able to withstand the stresses imposed by a variety of transients and temporary overvoltages which are common on EHV systems. These transients occur from a number of causes as discussed in B4.1, B4.2, and B4.3.

In some applications, the arrester must have some or all of the following capabilities:

(1) A known minimum power-frequency sparkover.

(2) Ability to thermally withstand specified temporary overvoltages.

(3) Ability to reseal against specified temporary overvoltages.

(4) Ability to sparkover repetitively and reseal against a specified temporary overvoltage for a specified number of operations.

Arresters with desired capabilities (2), (3), and (4) may have ratings less than temporary overvoltages involved [B1, B2, B3]. Such capabilities have not been standardized and must be discussed with the manufacturers. The nature and magnitude of switching transients may be predicted by analog (TNA) or digital computer studies [B4, B5], field switching tests on various line/equipment configurations, and field or laboratory tests on switching equipment [B6]. System studies or experience are necessary to evaluate surge arrester applications under these conditions. It may be possible to avoid switching operations that produce excessive arrester duty through operating procedures. In some cases, arrester duty can be made acceptable through the choice of a higher arrester rating, but insulation coordination should be reviewed to determine whether the protective margin would be adversely affected by such a change.

B4. Switching Surges that Affect Arrester Application

For purposes of practical arrester application, switching surge voltages can be classified according to required arrester reseal voltage capability, which depends upon the number and severity of possible surge currents discharged by the arrester and the duration of ensuing temporary overvoltages. The classifications are listed and discussed in B4.1 through B4.3. Common types of surges are grouped by these classifications in Fig B1 [B7].

B4.1 Transients Where Several Sparkovers Are Permitted. These transients are usually initiated by inherent switch action and stress the surge arrester through multiple operations. The transients are repetitive in nature and may be of sufficient magnitude to produce sparkover many times. The severe duty on the arrester results from the repeated follow current rather than from the energy in the surge. Heating of the gap and valve block assemblies can be excessive and hence cause arrester failure.

Satisfactory performance of the surge arrester under these conditions is dominated by the capability of the switching device. Arrester problems are best avoided through the use of switching devices that do not prestrike, restrike, or chop excessively. Alternatively, surges may be controlled by performing switching by disconnects only on de-energized systems. Some arresters may perform satisfactorily, but performance is difficult to predict.

B4.2 Transients Where Only One or Two Sparkovers Are Permitted. Operation of circuit breakers or load switches may be accompanied by rapidly decaying switching surges. Transients of this type generally stress the surge arrester through high energy dissipation requirements. This duty can result from discharge of high-magnitude switching surges or multiple discharges of high or intermediate-level surges. The stress on the arresters is severe because, in addition to discharge of the system surge, the arrester must reseal against subsequent temporary overvoltages or normal power-frequency voltage. In some severe applications, the surge arrester must have the ability to reseal above arrester rating [B2, B8, B9].

Satisfactory performance of the arrester in these conditions is typically dominated by system conditions; that is, reclosing surges are generally higher than energizing surges, and energy dissipation from long lines is greater than from short lines. In addition, surge suppression by power circuit breaker preinsertion resistors is commonly used at EHV and generally not at HV. Switching of a transmission line and a transformer may produce more severe temporary overvoltages following the initial surge than switching without a transformer connected. Restriking of circuit breakers on capacitor switching or line dropping will generally produce severe duty on surge arresters.

B4.3 Transients Where Temporary Overvoltages Approach Reseal Capability of the Surge Arrester. Temporary overvoltages that are sustained for more than a few cycles are an important consideration in surge arrester application. These overvoltages should not exceed the arrester's ability to reseal so that multiple operations of the arrester will not occur if the arrester is sparked over by an impulse or spontaneous sparkover of the arrester. Failure to reseal would result in multiple operations with power-follow current and failure of the arrester.

Successful performance of the arresters is based on assurance that the temporary overvoltages will be less than the reseal capability of the surge arrester. Overvoltages can be controlled or influenced by system grounding, system configuration, as well as generator excitation controls in the case of load rejection. Resonance or ferroresonance conditions should be prevented by avoiding system conditions that produce the overvoltage.

I. Surges where several sparkovers are permitted (see B4.1)

(1) Prestriking when energizing capacitive circuits with disconnecting switches

(2) Restriking when deenergizing capacitive circuits with disconnecting switches.

II. Surges where only one or two sparkovers are permitted (see B4.2)

(3) Energizing line or line transformer

(4) Energizing line with shunt compensation

(5) Reclosing on line with trapped charge

(6) Reclosing shunt-compensated line with trapped charge

(7) Energizing, deenergizing, or load dropping of line transformer unit (harmonic overvoltages)

(8) Voltage magnification on closing

(9) Restriking circuit breaker when deenergizing line

(10) Switching capacitor banks or long cables

(11) Chopping inductive current by circuit breakers

III. Surges where temporary overvoltages approach reseal capability of surge arrester (see B4.3)

(12) Clearing line-to-ground faults at one end of line

(13) Clearing overspeeding ac machines

(14) Closing when out of phase

(15) Linear resonance effects

(16) Ferroresonance oscillations

NOTE: This figure lists some switching surges that often require special consideration. The list is not exhaustive [B7].

Fig B1
Causes of Switching Surges that Affect Arrester Applications

Appendix C

Evaluation of Separation Effects in Simple Substations

C1. References.

[C1] IEEE Working Group of the Lightning Protective Devices Subcommittee. Lightning Protection in Multi-Line Stations. *IEEE Transactions on Power Apparatus and Systems.* 1968, PAS-87:1514–1521.

[C2] BREUER, G. E., HOPKINSON, R. H., JOHNSON, I. B., and SCHULTZ, A. J. Arrester Protection of High Voltage Stations Against Lightning. *AIEE Transactions (Power Apparatus and Systems).* 1960. 79:414–422.

[C3] HILEMAN, A. R., GUYKER, W. C., POWELL, R. W., RICHTER, W. A., and DESALVO, J. M. Insulation Coordination in APS 500-kV Stations. *IEEE Transactions on Power Apparatus and Systems.* 1967, PAS-86:655–665.

[C4] MCNULTY, M. B. *A Generalized Study to Determine the Optimum Location of Lightning Arresters in Power Transmission and Subtransmission Stations.* Brooklyn: Polytechnic Institute of Brooklyn, 1966. Thesis.

[C5] WITZKE, R. L., and BLISS, T. J. Coordination of Lightning Arrester Location with Transformer Insulation Level. *AIEE Transactions.* 1950, 69: 964–975.

[C6] AIEE Working Group of the Lightning Protective Devices Subcommittee. Simplified Method for Determining Permissible Separation Between Arresters and Transformers. *AIEE Transactions (Power Apparatus and Systems), Special Supplement.* 1963, 81:33–57.

[C7] LEWIS, W. W. *The Protection of Transmission Systems Against Lightning.* New York: Wiley, 1950.

C2. Study Methods

Detailed analyses of lightning overvoltages in stations are based on model studies. Special studies may be made for specific stations when desired. A number of such studies are reviewed in Lightning Protection in Multi-Line Stations [19], which also contains an extensive bibliography.

Studies of complex stations [C2, C3] are best undertaken by experts who are skilled in the selection of significant cases for study and interpretation of the results obtained. However, the method given in C3, although providing conservative values, may be useful in some cases. If less conservative (ie, more accurate) values are sought, a complete transient analysis technique may be necessary.

In certain multiline two-transformer stations, adequate protection for both transformers can be provided by a single set of arresters. A reduction process [C4] (see C4.1) is used to derive an equivalent "base case" [C5, C6], which can then be analyzed as described in C4.3. Transformer-terminated lines have the same configuration as the "base case" and require no reduction.

C3. Parameters

The following parameters apply to the evaluation of separation effects. Note that c is the common junction of S, L, and the line assumed to have an incoming surge (see Fig C1).

S = combined length of bus and jumper connections between junction c (Fig C1) and the transformer terminals, feet or meters.

L = the combined length of bus and jumper connections between junction c and the ground mat (excluding arrester length), feet or meters.

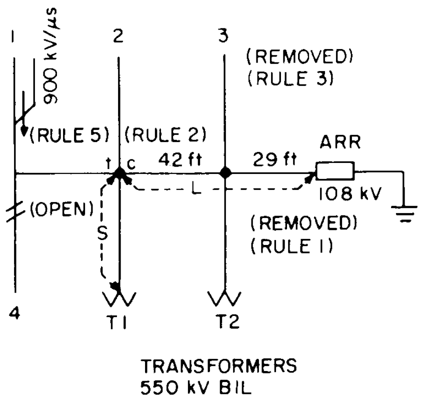
$D = S + L$, feet or meters.

$\bar{D} = \bar{S} + \bar{L}$, per-unit values [C6] see C4.2(1).

R_f = rate of rise of incoming front, kV/µs; apply C4.2, Rule 4, if applicable.

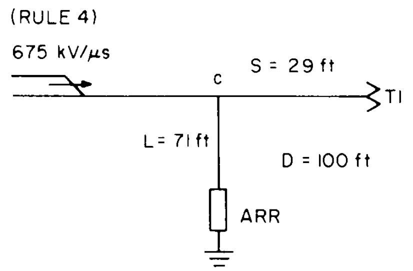
E_f = arrester sparkover on an impulse having a front with rate of rise equal to R_f; this can be determined graphically from the arrester sparkover curve (see Fig C2).

NOTE: Data on measured rates of rise on various systems of 12 kV to 240 kV given in Chapter 5 of Lewis [C7] correlate very well with standard rates of rise used to determine FOW (see 2.3 and Appendix A). In the absence of better data, use test rate of rise for arrester being considered.



Station Configuration Used in 3.3.3, Showing Application of Reduction Rules

(a)



Equivalent Base Case

(b)

Fig C1
Station Configuration and Equivalent Base

E_i = voltage at protected insulation = αE_f.
$\alpha = E_i$, the separation effect (SE).
v = traveling-wave velocity; for conductors in air, 1000 ft/μs when S, L, and D are in feet or 300 m/μs when S, L, and D are in meters.

C4. Calculation Procedure

C4.1 General. The following procedures should be repeated as necessary for various combinations of surged lines, disconnected lines, and different transformers until the most severe cases are identified (see also C4.4):

(1) Reduce station configuration to an equivalent base case if necessary (for multi-line, multitransformer stations, follow the rules given in C4.2).

(2) Check to see whether separation is significant according to Table 5 of the standard. If not, use PR(1) and PR(2) in accordance with 3.7.1(1) and 3.7.1.1 to check insulation coordination.

(3) If separation distance exceeds the Table 5 values, find voltage at protected equipment using the formulas given in C4.3. Evaluate insulation coordination using PR(1S) and PR(2S); see 3.7.1(2) and 3.7.1.3.

C4.2 Reduction of Station Configuration to Base Case. To reduce the station configuration to the base case:

Rule 1. Remove transformer that is not being considered.

Rule 2. Identify junction c (Fig C1) between S, L, and line assumed to have an incoming surge.

Rule 3. Remove all lines connected to L between junction c and the arrester terminal.

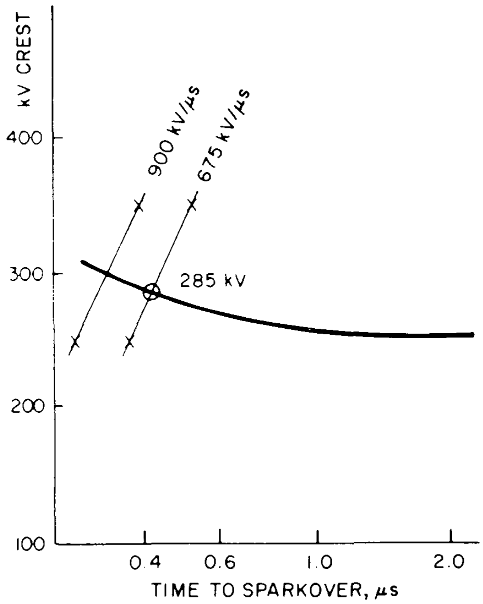
Rule 4. Multiply rate of rise of incoming surge by $3/(n + 2)$, where n is the number of lines (including the surged line) that remain after Rule 3 has been applied.

Rule 5. Identify junction t (Fig C1), the common point between bus connections between transformer 1, transformer 2, and the surged line. If point c, Rule 2, is on the surged line side of point t, the connection is a class B type; see Fig C1(b). Otherwise, the connection is class A. An additional margin is required with class B connections (see C4.3.1).

The use of the foregoing rules is illustrated in Fig C1(a) and (b).

C4.3 Formulas for Base Case Solution. The formulas and procedures used for base case solution are a modification of the methods of [C6]. Equation C2 is the "best-fit" solution for a study involving a large number of values of S, L, and transformer capacitance using the procedures of [C6]. Let

$$\bar{D} = \frac{D(R_f/E_f)}{v} \qquad \text{(Eq C1)}$$



NOTES: (1) Given arrester has an FOW sparkover of 300 kV at 900 kV/μs; see Table A1 of Appendix A.
(2) Calculate two points on rate-of-rise curve, $t_k = E_k/R_f$, k = 1,2.
(3) Desired sparkover is at the intersection of a straight line through these points with the sparkover curve.

Fig C2
Sparkover Curve of 108-kV Station Arrester Showing Method of Determining Sparkover at Various Rates of Rise

Then

$$\alpha_A = \frac{\bar{D}}{0.0125 + 0.476\bar{D}} \quad \text{(Eq C2)}$$

for class A stations,

$$\alpha_B = 1.05\alpha_A \quad \text{(Eq C3)}$$

for class B stations,

$$E_i = \alpha E_f, \text{ where } \alpha = \alpha_A \text{ or } \alpha_B, \quad \text{(Eq C4)}$$

as appropriate.

C4.3.1 Formulas for Maximum Permissible Separation. For class A stations:

(1) Where sparkover occurs at 2 μs or less,

(a) Class A connections: $\alpha_{max} = \dfrac{CWW}{1.15E_f}$

(b) Class B connections: $\alpha_{max} = \dfrac{CWW}{1.21\,E_f}$

(2) Where sparkover occurs after 2 μs,

(a) Class A connections: $\alpha_{max} = \dfrac{BIL}{1.15\text{ LPL}}$

(b) Class B connections: $\alpha_{max} = \dfrac{BIL}{1.21\text{ LPL}}$

(3) Maximum separation allowable:

$$D_{max} = \frac{0.0125\alpha_{max}}{1 - 047\alpha_{max}} \cdot \frac{v}{R_f/E_f} \quad \text{(Eq C5)}$$

C4.4 Example of Calculation of Separation Effects. An example of the application of the rules given in C4.2 to a class A connection is given in Fig C1(a).

(1) Reduction to base case. For the case being considered, line 4 is disconnected and E_i at transformer T1 is desired.

Rule 1. Disconnect T2.

Rule 2. Junction e is identified; S = 29 ft, L = 71 ft.

Rule 3. Line 3 is connected to L; remove.

Rule 4. Two lines remain.

$$R_f = 900 \times \frac{3}{2+2} = 675 \text{ kV/μs}.$$

Rule 5. Junction 1 is coincident with c. The connection is class A.

(2) Check whether separation is likely to be significant.

(a) Selected arrester has FOW = 300 (see Fig C2).

(b) BIL is 550 kV, CWW = 1.15 x 550 = 632.5 (see 3.6.1).

(c) PR(1) = 632.5/300 = 2.11 (see 3.7.1(1)).

(d) From Table 5, allowable separation is 132 ft for two lines. Since D = 29 + 71 = 100 ft, separation is not significant, and the calculation outlined in C4.4(3) would not normally be necessary. As a matter of convenience, however, the method is illustrated in C4.4(3) obtained using the data for the case of Fig C1.

(3) Calculation of E_i

(a) Find E_f for 675 kV/μs, as shown in Fig C2; thus E_f = 285 kV.

(b) From Equation C1, $\bar{D}$ = 100(675/285)/1000 = 0.237.

(c) From Equation C2,

$$\alpha_A = \frac{0.237}{0.0125 + (0.476 \times 0.237)} = 1.89$$

(d) From Eq C4, $E_i = 1.89 \times 285 = 538.65$

(e) From 3.7.1(2), PR(1S) = 632.5/538.65 = 1.17, which is acceptable.

NOTE: Substituting α_{max} = 632.5/(1.15 x 285) = 1.93, in accordance with C4.3.1(1a), into Eq C5 gives α_{max} 125, which checks fairly well with the allowable separation found in C4.4(2d).

C4.5 Table for Allowable Separation. Table 5 was developed by finding the relationship $\beta = E_f$/FOW. A study of the data in Appendix A shows that Test Rate of Rise/FOW averages 2.58 for Tables A1 and A2. A reasonable approximation of β is given by

$$\beta = 1 + 0.07(1 - \rho)(2.58)$$

where

$$\rho = \frac{3}{n + 2} \qquad \text{(see C4.2, Rule 4).}$$

From C4.3.1(1a), α_{max} = CWW/(1.15β x FOW) = PR(1)/1.15β and the values of D in Table 5 are obtained using Equation C5.

Appendix D

Definitions

D1. References

[D1] ANSI/IEEE C62.1-1984, IEEE Standard for Surge Arresters for AC Power Circuits.

[D2] ANSI/IEEE Std 100-1988, IEEE Standard Dictionary of Electrical and Electronic Terms.

[D3] ANSI C92.1-1982, American National Standard Voltage Values for Preferred Transient Insulation Levels.

D2. Overvoltages

D2.1 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).

D2.2 Surge. A transient wave of current, potential, or power in an electric circuit; see ANSI/IEEE Std C62.1-1984 [D1].

D2.2.1 Lightning Surge. A transient electrical disturbance in an electric circuit caused by lightning; see ANSI/IEEE Std C62.1-1984 [D1].

D2.2.2 Lightning Overvoltage. The crest voltage appearing across an arrester or insulation caused by a lightning surge.

D2.3 Switching Overvoltage. Any combination of switching surge(s) and temporary overvoltage(s) associated with a single switching episode.

D2.3.1 Switching Surge. A heavily damped transient electrical disturbance associated with switching. System insulation flashover (see D5.7) may precede or follow the switching in some cases but not all.

D2.3.2 Temporary Overvoltage. An oscillatory overvoltage associated with switching of relatively long duration, which is undamped or slightly damped.

D2.3.3 Coefficient of Grounding. The ratio, E_{LG}/E_{LL} (expressed as a percentage), of the highest root-mean-square 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.

D2.4 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 ANSI/IEEE Std 100-1988 [D2].

D3. Impulses

D3.1 Impulse. A surge of unidirectional polarity.

D3.2 Crest (Peak) Value of an Impulse. The maximum value that an impulse attains.

D3.3 Wave Front of an Impulse. That part of an impulse that occurs prior to the crest value.

D3.4 Wave Tail of an Impulse. That part between crest value and the end of the impulse; see ANSI/IEEE Std C62.1-1984 [D1].

D3.5 Wave Shape of an Impulse Test Wave. The graph of the wave as a function of time; see ANSI/IEEE Std C62.1-1984 [D1].

D3.6 Wave Shape Designation of an Impulse

D3.6.1 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 wave front, is the virtual duration of the wave front in microseconds as defined in D3.8. The second, an index of the wave tail, is the time in microseconds from virtual zero to the instant at which one-half of the crest value is reached on the wave tail.

Examples are 1.2/50 μs and 8/20 μs waves; see ANSI/IEEE Std C62.1-1984 [D1].

D3.6.2 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 x 1000 μs wave; see ANSI/IEEE Std C62.1-1984 [D1].

D3.7 Virtual Zero Point of an Impulse. The intersection with the zero 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 ANSI/IEEE C62.1-1984 [D1].

D3.8 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.

D3.9 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.

D4. Standard Impulses

D4.1 Standard Lightning Impulse. The wave shape of standard impulse used (when it is not in conflict with product standards) is 1.2/50 μs.

D4.2 Standard Switching Impulses. The wave shapes of standard impulse tests depend on equipment being tested.

D4.2.1 Air Insulation and Switchgear. For air insulation and switchgear: 250 x 2500 μs; see ANSI C92.1-1982 [D1].

D4.2.2. Transformer Products. For transformer products: 100 x 1000 μs.

D4.2.3. Arrester Sparkover Tests. For arrester sparkover tests:[7]

(1) 30–60 x 90–180 μs

(2) 150–300 x 450–900 μs

(3) 1000–2000 x 3000–6000 μs

D5. Insulation Coordination

D5.1 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 [D1].

D5.2 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 [D1].

D5.3 Basic Lightning Impulse Insulation Level. The electrical strength of insulation expressed in terms of the crest value of a standard lightning impulse. The basic lightning impulse insulation level (BIL) may be either a statistical BIL or a conventional BIL, defined as follows (see ANSI C92.1-1982 [D1]).

D5.3.1 Statistical BIL. Applicable specifically to self-restoring insulations. The crest value of a standard lightning impulse for which the insulation exhibits a 90% probability of withstand (or a 10% probability of failure) under specified conditions.

D5.3.2 Conventional BIL. Applicable specifically to nonself-restoring insulations. 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.

D5.4 Basic Switching Impulse Insulation Level. The electrical strength of insulation expressed in terms of the crest value of a standard switching impulse. The basic switching impulse insulation level (BSL) may be either a statistical BSL or a conventional BSL, defined as follows (see ANSI C92.1-1982 [D1]).

[7]The tail duration is not critical; see ANSI/IEEE C62.1-1984 [1].

D5.4.1 Statistical BSL. Applicable specifically to self-restoring insulations. 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.

D5.4.2 Conventional BSL. Applicable specifically to nonself-restoring insulations. The crest value of a standard switching impulse for which the insulation does not exhibit disruptive discharge when subjected to a specific number of applications of this impulse under specific conditions.

D5.5 Disruptive Discharge. The sudden and large increase in current through an insulating medium due to the complete failure of the medium under the electrostatic stress; see ANSI/IEEE C62.1-1984 [D1].

D5.6 Flashover. A disruptive discharge around or over the surface of a solid or liquid insulator; see ANSI/IEEE C62.1-1984 [D1].

D6. Arresters

D6.1 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 ANSI/IEEE C62.1-1984 [D1].

D6.2 Valve Arrester. An arrester that includes a valve element; see ANSI/IEEE C62.1-1984.

D6.2.1 Arrester Rating. The designated maximum permissible operating voltage between an arrester's terminals at which it is designed to perform its duty cycle. It is the voltage rating specified on the nameplate; see ANSI/IEEE C62.1-1984 [D1].

D6.3 Series Gap. An intentional gap(s) between spaced electrodes. It is in series with the valve element of the arrester, substantially isolating the element from line or ground or both under normal line-voltage conditions; see ANSI/IEEE C62.1-1984 [D1].

D6.4 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 ANSI/IEEE C62.1-1984 [D1].

D6.5 Unit Operation. Discharging a surge through an arrester while the arrester is energized; see ANSI/IEEE C62.1-1984 [D1].

D6.6 Arrester Discharge Current. The surge current that passes through an arrester when sparkover occurs.

D6.6.1 Arrester Discharge Voltage. The voltage that appears across the terminals of an arrester during passage of discharge current. Published discharge voltages are determined by tests using 8/20-μs impulses.

D6.7 Arrester Sparkover. A disruptive discharge between electrodes of an arrester.

D6.7.1 Let-Through Sparkover. A measure of the highest lightning surge an arrester is likely to withstand without sparkover in 3 μs or less. The value determined by a 1.2/50 μs impulse sparkover test; see ANSI/IEEE C62.1-1984.

D6.8 Follow (Power) Current. The current from the connected power source that flows through an arrester during and following the passage of discharge current; see ANSI/IEEE C62.1-1984.

D6.9 Arrester Recovery Voltage. The crest voltage that occurs across the terminals of an arrester following a unit operation.

D6.10 Reseal Voltage Rating of an Arrester. The maximum arrester recovery voltage permitted for a specified time following one or more unit operation(s) with discharge currents of specified magnitude and duration.

D7. System Voltages

D7.1 System Voltage. The root mean square (rms) phase-to-phase power frequency voltage on a three-phase alternating-current electric system.

D7.2 Maximum System Voltage. The highest rms phase-to-phase voltage that occurs on the system under normal operating conditions, and the highest rms phase-to-phase voltage for which equipment and other system components are designed for satisfactory continuous operation without derating of any kind. (This voltage excludes voltage transients and temporary overvoltages caused by abnormal system conditions such as faults, load rejection, and so forth.)

D7.3 Nominal System Voltage. The system voltage by which the system may be designated, and to which certain operating characteristics of the system are related. (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 the system components are designed.)

Appendix E

Coefficient-of-Grounding (COG) Calculations

As an aid to users of Fig 2, the following equations can be used to calculate the coefficients of grounding (COG). The equations are applicable for $Z_1 = Z_2$, as are the curves in Fig 2.

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 $k = Z_0/Z_1 = (R_0 + jX_0) / (R_1 + jX_1)$

The curves in Fig 2 include the effects of fault resistance. For each point, a fault resistance was chosen that produced the maximum COG. In general, however, fault resistance tends to reduce the COG, except in low-resistance systems. To include fault resistance R_f, the definition of k above would have to be modified as follows:

For SLG fault:

$$k = (R_0 + R_f + jX_0) / (R_1 + R_f + jX_1)$$

ForDLG fault:

$$k = (R_0 + 2R_f + jX_0)/(R_1 + 2R_f + jX_1)$$

where R_f = fault resistance.

Appendix F

Arrester Stroke Currents-Arresters Connected to Distribution Lines

The magnitude of lightning stroke currents, discharged through distribution surge arresters, was investigated in an Electric Power Research Institute (EPRI) study, EPRI EL-1140, Study of Lightning Current Magnitude through Distribution Arresters. Sept, 1979. Values obtained are tabulated:

.08%	will exceed	100	kA
.41%	will exceed	61	kA
1.8%	will exceed	40	kA
3.4%	will exceed	30	kA
9.3%	will exceed	20	kA
23.3%	will exceed	10	kA
45.4%	will exceed	5	kA