

An American National Standard

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**

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Foreword

(This Foreword is not a part of ANSI/IEEE Std C62.2-1987 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, “Coefficient 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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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 flash-overs 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.

1.2 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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¹The numbers in brackets correspond to those of the references listed in 1.2; numbers in brackets preceded by letters correspond to numbers in the reference sections of the Appendixes.

²ANSI publications are available from the Sales Department, American National Standards Institute, 1430 Broadway, New York, NY 10018; IEEE publications may be obtained from the IEEE Service Center, 445 Hoes Lane, PO Box 1331, Piscataway, NJ 08855-1331.

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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 $\mu\text{s}/\text{km}$ 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:

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

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 approximate 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.

Table 1—Lightning Stroke Current Data

	First Stroke					Subsequent Strokes				
	% Exceeding the Value					% 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/ μ s	9	24.3	65	0.60	0.38	10	39.9	162	0.85	0.56
Minimum Linear Front, μ s	0.5	1.28	3.5	0.61	—	0.1	0.31	1.0	0.71	—
Time-to-Half Value, μ s	30	77.5	200	0.58	—	7	30.2	140	0.93	—

The first stroke crest current data in Table 1 obtained by Berger et al [3] was combined with other data. The resultant distribution is piece-wise 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:

$$P(I) = [1 + (I/31)^{2.6}]^{-1}$$

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, N_g , in flashes per km². However, at present within the USA, data on the average N_g 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 N_g may be approximated from T_d by the equation:

$$N_g = 0.04 T_d^a$$

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

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

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 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 μ s 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 μ s 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 μ s 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 μ s (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 μ s wave shape approximates the standard 1.2/50 μ s 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 μ s. 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 μ s) (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 μ s for impulses having times to crest between 30 and 2000 μ s.

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- μ s 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).

- a) 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- μ s 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- μ s impulses as specified in the appropriate equipment standard.
- 3) Basic Switching Impulse Insulation Level (BSL). The test impulse depends on the type of equipment.

2.5 Separation Effects

The voltage at the protected insulation will 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:

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

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

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

The protective margin (PM) in percent is defined as: $PM = [PR-1] \cdot 100$. 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 A-4 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 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.

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- μ s 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 ≥ 1.2
- PR(2): BIL/LPL ≥ 1.2
- PR(3): BSL/SSP ≥ 1.15

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

(2) If separation effects cannot be disregarded:

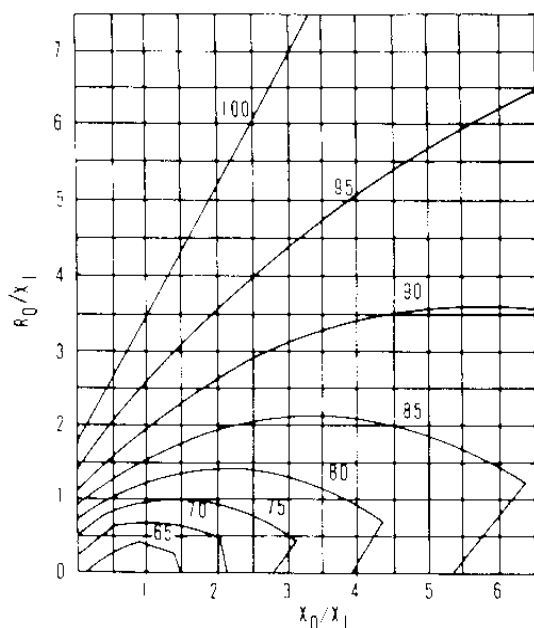
- (a) Find voltage at equipment, E_i , using methods of Appendix C. Where front is such that sparkover occurs in $\leq 2 \mu$ s, base E_i on FOW sparkover and use formula PR(1S) in (b) below. Otherwise, base E_i on LPL in accordance with II(2b) above, and use formula PR(2S) in (b) below.
- (b) All of 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 ≥ 1.15

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

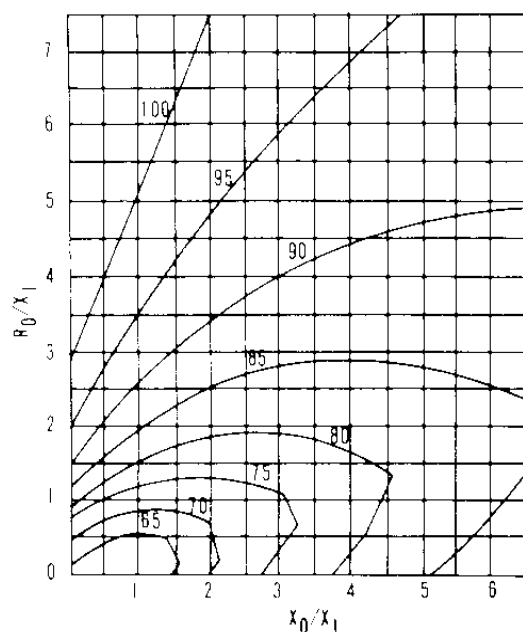
- (a) Use arrester with lower lightning or switching surge protective levels.
- (b) Change arrester location to reduce separation.
- (c) Use higher withstand voltage.
- (d) Improve shielding.
- (e) Add arresters.

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



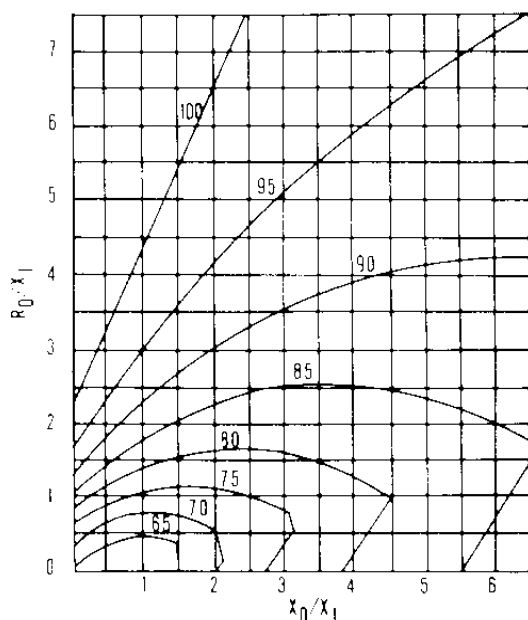
Voltage conditions neglecting positive- and negative-sequence resistance: $R_1 = R_2 = 0$

(a)



Voltage conditions for $R_1 = R_2 = 0.1X_2$

(b)



Voltage conditions for $R_1 = R_2 = 0.1X_1$

(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 impedance 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.

Figure 2—Coefficients of Grounding for Various System Conditions