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IEEE Guide for Direct Lightning Stroke Shielding of Substations

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Abstract: Design information for the methods historically and typically applied by substation designers to minimize direct lightning strokes to equipment and buswork within substations is provided. Two approaches, the classical empirical method and the electrogeometric model, are presented in detail. A third approach involving the use of active lightning terminals is also briefly reviewed.

Keywords: direct stroke shielding, lightning stroke protection, substations

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Introduction

[This introduction is not part of IEEE Std 998-1996, IEEE Guide for Direct Lightning Stroke Shielding of Substations (ANSI).]

This guide was prepared by the Direct Stroke Shielding of Substations Working Group of the Substations Committee, Transmission Substations Subcommittee. Work on this guide began in 1973 and many former members made contributions towards its completion. The membership of the working group during the preparation of this draft was as follows:

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IEEE Guide for Direct Lightning Stroke Shielding of Substations

1. Overview

1.1 Scope

The scope of this guide is the identification and discussion of design procedures to provide direct stroke shielding of outdoor distribution, transmission, and generating plant substations. All known methods of shielding from direct strokes were investigated during the preparation of this guide, and information is provided on two methods found to be widely used:

- a) The classical empirical method
- b) The electrogeometric model

A third approach, which involves the use of active lightning terminals, is briefly reviewed in clause 6.

This guide does not purport to include all shielding methods that may have been developed. The guide also does not address protection from surges entering a substation over power or communication lines or the personnel safety issues.

Users of this guide should thoroughly acquaint themselves with all factors that relate to the design of a particular installation and use good engineering judgment in the application of the methods given here, particularly with respect to the importance and value of the equipment being protected.

1.2 Purpose

The intent of this guide is to provide design information for the methods historically and typically applied by substation designers to minimize direct lightning strokes to equipment and buswork within substations. The general nature of lightning is discussed in clause 2 and the problems associated with providing protection from direct strikes are described in clause 3. The methods reviewed in this guide for designing a system of protection are explained in clauses 4 and 5, and sample calculations are given in annex B to illustrate use of the methods. Clause 7 contains an extensive bibliography for further study of the subject.

1.3 Definitions

The definitions of terms contained in this document are not intended to embrace all legitimate meanings of the terms. They may only be applicable to the subject treated in this document. For additional definitions refer to IEEE Std 100-1992 [B44]¹.

1.3.1 critical stroke amplitude: The amplitude of the current of the lightning stroke that, upon terminating on the phase conductor, would raise the voltage of the conductor to a level at which flashover is likely.

1.3.2 dart leader: The downward leader of a subsequent stroke of a multiple-stroke lightning flash.

1.3.3 effective shielding: That which permits lightning strokes no greater than those of critical amplitude (less design margin) to reach phase conductors.

1.3.4 electrogeometric model (EGM): A geometrical representation of a facility, that, together with suitable analytical expressions correlating its dimensions to the current of the lightning stroke, is capable of predicting if a lightning stroke will terminate on the shielding system, the earth, or the element of the facility being protected.

1.3.5 electrogeometric model theory: The theory describing the electrogeometric model together with the related quantitative analyses including the correlation between the striking distances to the different elements of the model and the amplitude of the first return stroke.

1.3.6 ground flash density (GFD): The average number of lightning strokes per unit area per unit time at a particular location.

1.3.7 isokeraunic lines: Lines on a map connecting points having the same keraunic level.

1.3.8 keraunic level: The average annual number of thunderstorm days or hours for a given locality. (1) A daily keraunic level is called a thunderstorm-day and is the average number of days per year in which thunder is heard during a 24 h period. (2) An hourly keraunic level is called a thunderstorm-hour and is the average number of hours per year that thunder is heard during a 60 min period.

1.3.9 lightning flash: The complete lightning discharge, most often composed of leaders from a cloud followed by one or more return strokes.

1.3.10 lightning mast: A column or narrow-base structure containing a vertical conductor from its tip to earth, or that is itself a suitable conductor to earth. Its purpose is to intercept lightning strokes so that they do not terminate on objects located within its zone of protection.

1.3.11 negative shielding angle: The shielding angle formed when the shield wire is located beyond the area occupied by the outermost conductors. *See also: shielding angle, positive shielding angle.*

1.3.12 positive shielding angle: The shielding angle formed when the shield wire is located above and inside of the area occupied by the outermost conductors. *See also: shielding angle, negative shielding angle.*

1.3.13 rolling sphere method: A simplified technique for applying the electrogeometric theory to the shielding of substations. The technique involves rolling an imaginary sphere of prescribed radius over the surface of a substation. The sphere rolls up and over (and is supported by) lightning masts, shield wires, fences, and other grounded metal objects intended for lightning shielding. A piece of equipment is protected from a direct stroke if it remains below the curved surface of the sphere by virtue of the sphere being elevated by shield wires or other devices. Equipment that touches the sphere or penetrates its surface is not protected.

1.3.14 shielding angle (1) (of shield wires with respect to conductors): The angle formed by the intersection of a vertical line drawn through a shield wire and a line drawn from the shield wire to a protected conductor. The angle is chosen to provide a zone of protection for the conductor so that most lightning strokes will terminate on the shield wire rather than on the conductor.

(2) (of a lightning mast): The angle formed by the intersection of a vertical line drawn through the tip of the mast and another line drawn through the tip to earth at some selected angle with the vertical. Rotation of this angle around the

¹The numbers in brackets correspond to those of the bibliography in clause 7.

structure forms a cone-shaped zone of protection for objects located within the cone. The angle is chosen so that lightning strokes will terminate on the mast rather than on an object contained within the protective zone so formed. *See also:* **positive and negative shielding angle**.

1.3.15 shield wire (overhead power line or substation): A wire suspended above the phase conductors positioned with the intention of having lightning strike it instead of the phase conductor(s). *Synonyms:* **overhead ground wire (OHGW), static wire, and sky wire.**

1.3.16 stepped leader: Static discharge that propagates from a cloud into the air. Current magnitudes that are associated with stepped leaders are small (on the order of 100 A) in comparison with the final stroke current. The stepped leaders progress in a random direction in discrete steps from 10 to 80 m in length. Their most frequent velocity of propagation is about 0.05% of the speed of light, or approximately 500 000 ft/s (150 000 m/s). It is not until the stepped leader is within striking distance of the point to be struck that the stepped leader is positively directed toward this point.

1.3.17 striking distance: The length of the final jump of the stepped leader as its potential exceeds the breakdown resistance of this last gap; found to be related to the amplitude of the first return stroke.

1.3.18 surge impedance: The ratio between voltage and current of a wave that travels on a conductor.

1.3.19 thunder: The sound that follows a flash of lightning and is caused by the sudden expansion of the air in the path of electrical discharge.

1.3.20 thunderstorm day: A day on which thunder can be heard, and hence when lightning occurs.

1.3.21 thunderstorm hour: An hour during which thunder can be heard, and hence when lightning occurs.

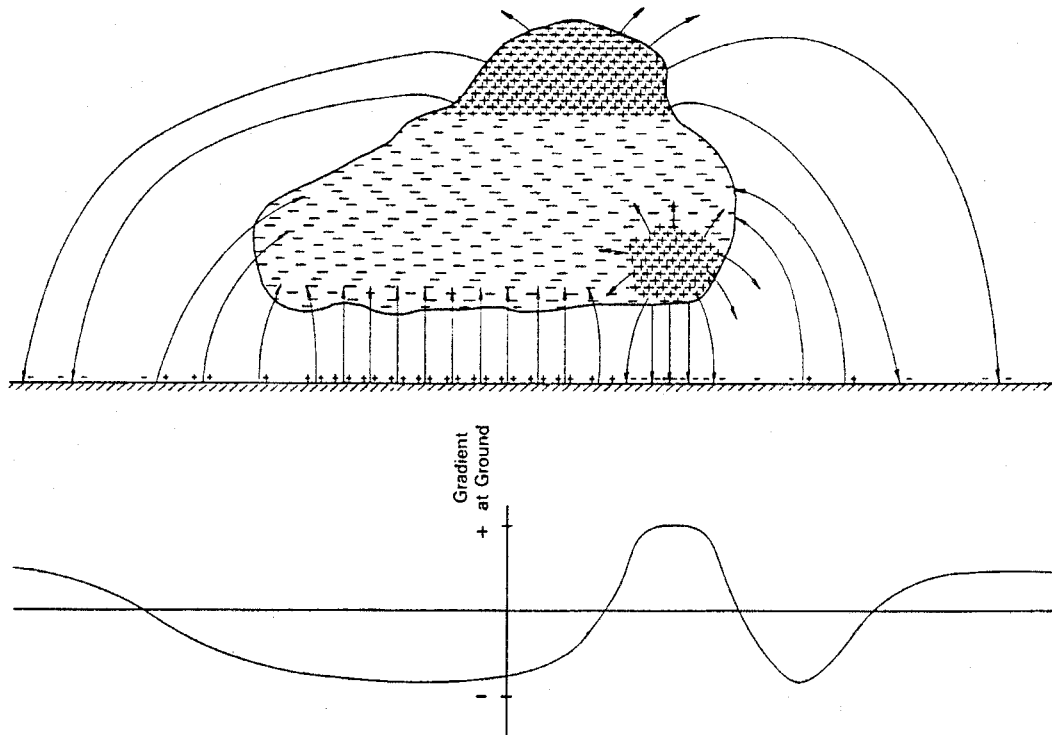
2. Lightning stroke phenomena

2.1 Charge formation in clouds

Numerous theories have been advanced regarding the formation of charge centers, charge separation within a cloud, and the ultimate development of lightning strokes. One theory attributes charge separation to the existence of both positive and negative ions in the air and the existence of a normal electric field directed toward the earth. Large drops of water in the electric field are polarized, the upper sides acquiring a negative charge and the lower sides a positive charge. As the polarized drops of water fall due to gravity, the undersides (positive sides) attract negative ions, while no such action occurs at the upper surfaces. As a result of this action, the drops accumulate negative charge. Thus, the original charges, which were distributed at random and produced an essentially neutral space charge, become separated. The large drops of water carry the negative charges to the lower portion of the cloud, causing the lower portion to be negatively charged and the upper portion to be positively charged. Another theory is that the interaction of ascending wind currents in the leading head of a cloud breaks up the water droplets causing the resulting droplets to be positively charged and the air to be negatively charged. The positively charged water droplets are unable to fall through the ascending wind currents at the head of the cloud, which causes this portion of the cloud to be positively charged while the remaining larger portion becomes negatively charged. Yet another theory suggests that there are regions of subzero temperature within a cloud and the subsequent formation of ice crystals is an essential factor in the explanation of the charge centers within clouds. (These three theories are presented in [B95].)

It has even been suggested that perhaps all of the physical phenomena postulated in the various theories may occur. At best, the processes occurring within a cloud formation that cause charge separation are complicated. The important fact to the designing engineer is that a charge separation does occur in thunderstorm clouds. Experiments using balloons equipped with electric gradient measuring equipment have been performed to investigate typical charge distribution in thunderclouds, and these experiments have shown that, in general, the main body of a thundercloud is negatively charged and the upper part positively charged [B95]. A concentration of positive charge also frequently exists in the base of the cloud. Such charge distribution in a cloud causes an accumulation of charge of the opposite polarity on the earth's surface and on objects (e.g., trees, buildings, electric power lines, structures, etc.) beneath the

cloud. A typical charged cloud and the resulting electric fields are shown in figure 2-1. (Note that the plot in figure 2-1 is of the electric gradient as the cloud moves over the ground, not the amount of charge below the cloud.) The electric fields shown in figure 2-1 have been verified by data obtained from ground gradient measuring equipment during the passage of storm clouds [B30].



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Source: [B74].

Figure 2-1—Charged cloud and resulting electric fields

The electrical charge concentrations within a cloud are constrained to the size of the cloud. The cloud size, in relation to the earth, is small. Therefore, the electrical gradient that exists in the cloud is much greater than at the earth. Because of this, an electrical discharge tends to be initiated at the cloud rather than at the ground.

2.2 Stroke formation

2.2.1 Types of strokes

There are a number of different types of lightning strokes. These include strokes within clouds, strokes between separate clouds, strokes to tall structures, and strokes that terminate on the ground. The positive and negative strokes terminating on the ground are the types of most interest in designing shielding systems and the following discussion will be confined to those types.

2.2.2 Stepped leaders

The actual stroke development occurs in a two-step process. The first step is ionization of the air surrounding the charge center and the development of *stepped leaders*, which propagate charge from the cloud into the air. Current magnitudes associated with stepped leaders are small (in the order of 100 A) in comparison with the final stroke current [B95]. The stepped leaders progress in a random direction in discrete steps from 10 to 80 m in length. Their most frequent velocity of propagation is about 0.05% the speed of light, or approximately 500 000 ft/s (150 000 m/s) [B4]. It is not until the stepped leader is within striking distance of the point to be struck that the leader is positively diverted toward this point. *Striking distance* is the length of the last step of leader under the influence of attraction toward the point of opposite polarity to be struck.

2.2.3 Return stroke

The second step in the development of a lightning stroke is the *return stroke*. The return stroke is the extremely bright streamer that propagates upward from the earth to the cloud following the same path as the main channel of the downward stepped leader. This return stroke is the actual flow of stroke current that has a median value of about 24 000 A and is actually the flow of charge from earth to cloud to neutralize the charge center [B70]. The velocity of the return stroke propagation is about 10% the speed of light, or approximately $100 \cdot 10^6$ ft/s ($30 \cdot 10^6$ m/s) [B95].

The amount of charge (usually negative) descending to the earth from the cloud is equal to the charge (usually positive) that flows upward from the earth. Since the propagation velocity of the return stroke is so much greater than the propagation velocity of the stepped leader, the return stroke exhibits a much larger current flow (rate of charge movement). The various stages of a stroke development are shown in figure 2-2. Approximately 55% of all lightning flashes consist of multiple strokes that traverse the same path formed by the initial stroke. The leaders of subsequent strokes have a propagation velocity much greater than that of the initial stroke (approximately 3% the speed of light) and is referenced as a *dart leader* [B95].

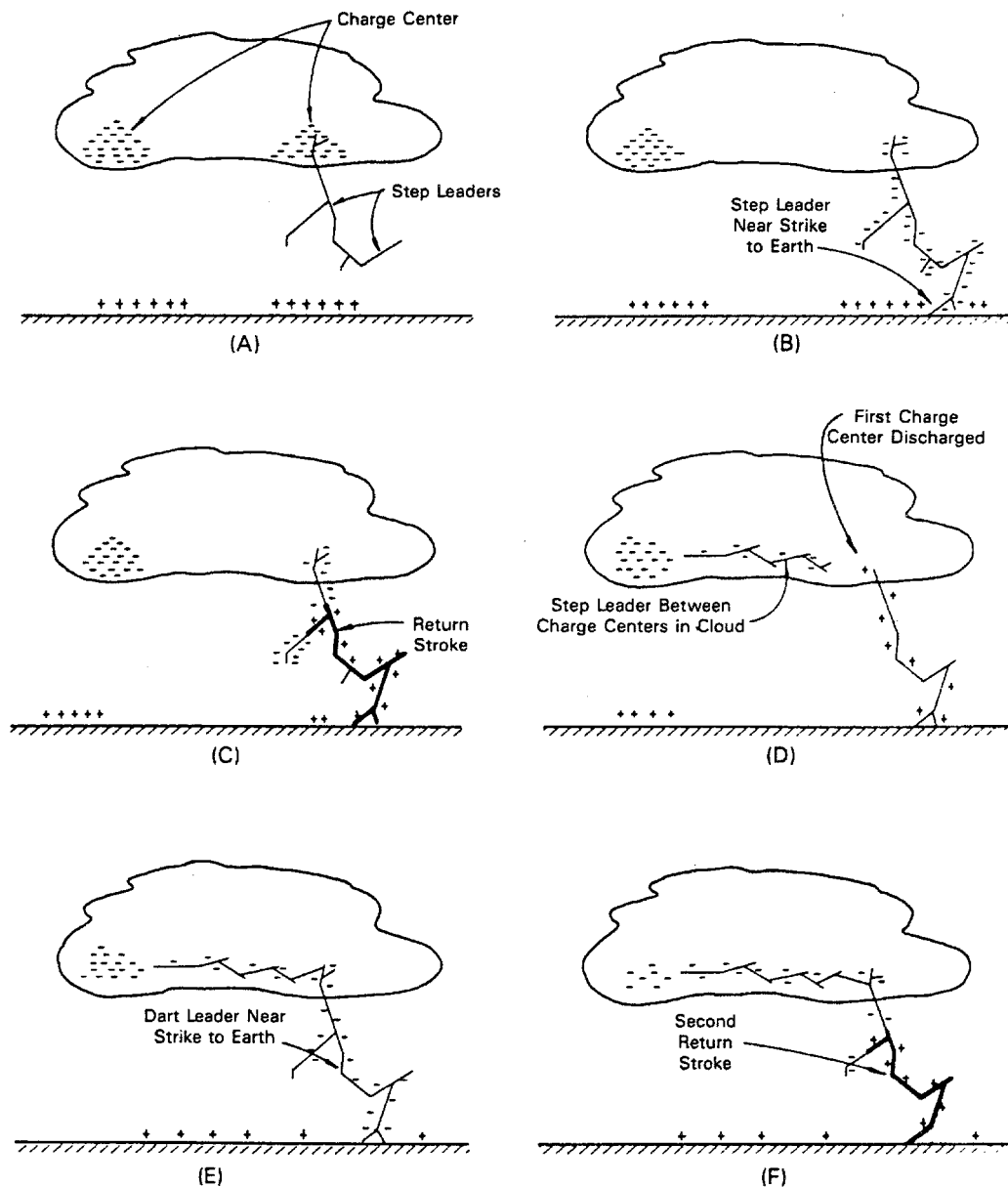
2.3 Strike distance

Return stroke current magnitude and strike distance (length of the last stepped leader) are interrelated. A number of equations have been proposed for determining the striking distance. The principal ones are as follows:

$$S = 2 I + 30 (1 - e^{-I/6.8}) \quad \text{Darveniza [B26]} \quad (2-1A)$$

$$S = 10 I^{0.65} \quad \text{Love [B4, 46a]} \quad (2-1B)$$

$$S = 9.4 I^{2/3} \quad \text{Whitehead [B98]} \quad (2-1C)$$



Adapted from: *Electrical Transmission and Distribution Reference Book*, by Central Station Engineers of the Westinghouse Electric Corporation, East Pittsburgh, Pennsylvania, Fourth Edition, 1964.

Figure 2-2 — Charge distribution at various stages of lightning discharge

$$S = 8 I^{0.65} \quad \text{IEEE [B46]} \quad (2-1D)$$

$$S = 3.3 I^{0.78} \quad \text{Suzuki [B89]} \quad (2-1E)$$

where

S is the strike distance in meters
 I is the return stroke current in kiloamperes

It may be disconcerting to note that the above equations vary by as much as a factor of 2:1. However, lightning investigators now tend to favor the shorter strike distances given by Eq 2-1D. J. G. Anderson, for example, who adopted Eq 2-1B in the 1975 edition of the *Transmission Line Reference Book* [B4], now feels that Eq 2-1D is more accurate. Mousa [B67] also supports this form of the equation.

Equation 2-1D has been adopted for this guide. The equation may also be stated as follows:

$$I = 0.041 S^{1.54} \quad (2-1F)$$

This relationship is shown graphically in figure 2-3. From this point on, the return stroke current will be referenced in this guide as the *stroke current*.

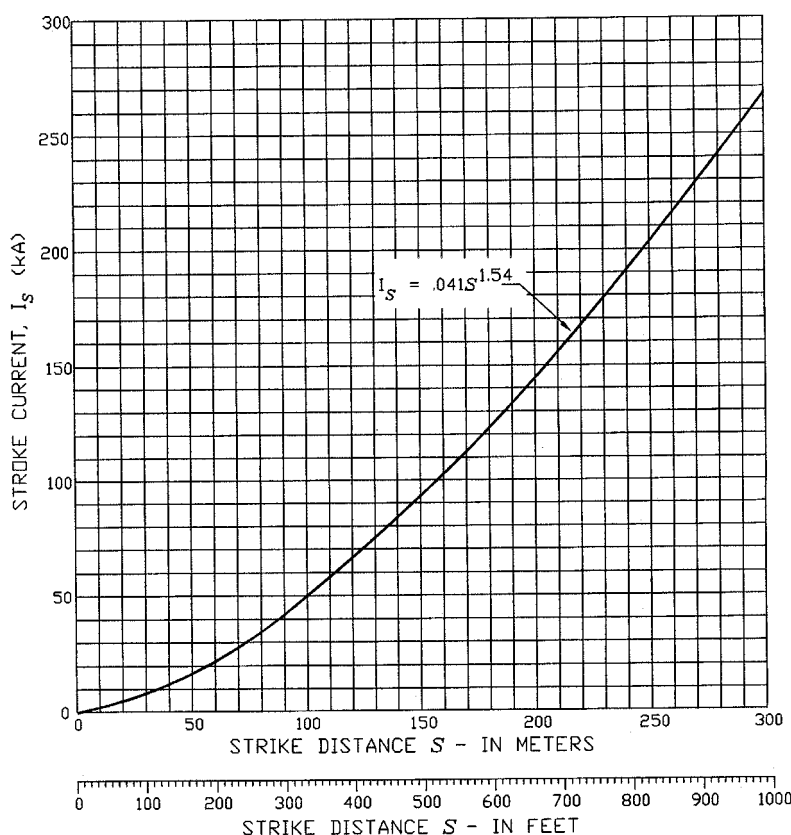


Figure 2-3 — Strike distance vs. stroke current

2.4 Stroke current magnitude

Since the stroke current and striking distance are related, it is of interest to know the distribution of stroke current magnitudes. The median value of strokes to OHGW, conductors, structures, and masts is usually taken to be 31 kA [B4]. Anderson [B4] gave the probability that a certain peak current will be exceeded in any stroke as follows:

$$P(I) = \frac{1}{1 + \left(\frac{I}{31}\right)^{2.6}} \quad (2-2A)$$

where

$P(I)$ is the probability that the peak current in any stroke will exceed I
 I is the specified crest current of the stroke in kiloamperes

Mousa [B70] has shown that a median stroke current of 24 kA for strokes to flat ground produces the best correlation with available field observations to date. Using this median value of stroke current, the probability that a certain peak current will be exceeded in any stroke is given by the following equation:

$$P(I) = \frac{1}{1 + \left(\frac{I}{24}\right)^{2.6}} \quad (2-2B)$$

where the symbols have the same meaning as above.

Figure 2-4 is a plot of Eq 2-2B, and figure 2-5 is a plot of the probability that a stroke will be within the ranges shown on the abscissa.

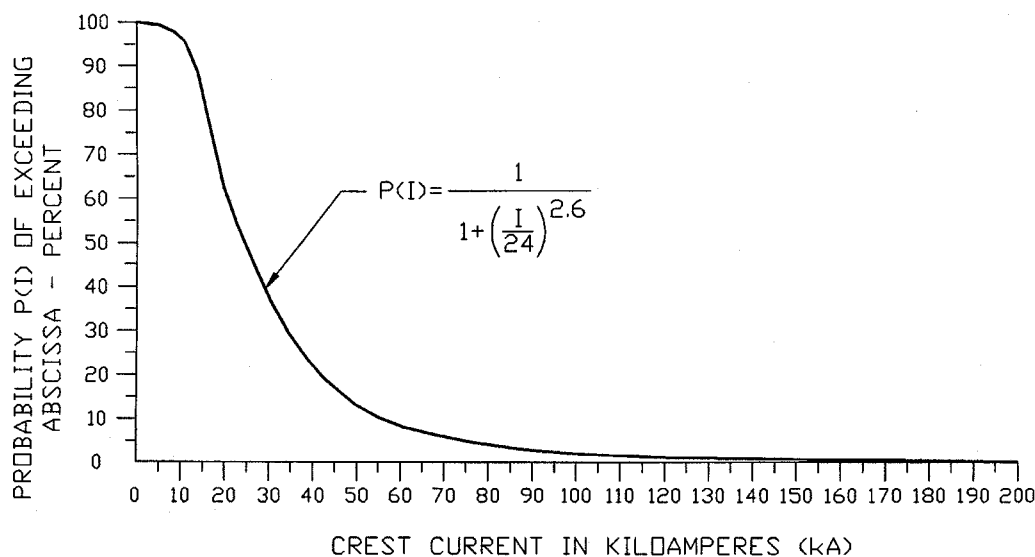


Figure 2-4 — Probability of stroke current exceeding abscissa for strokes to flat ground

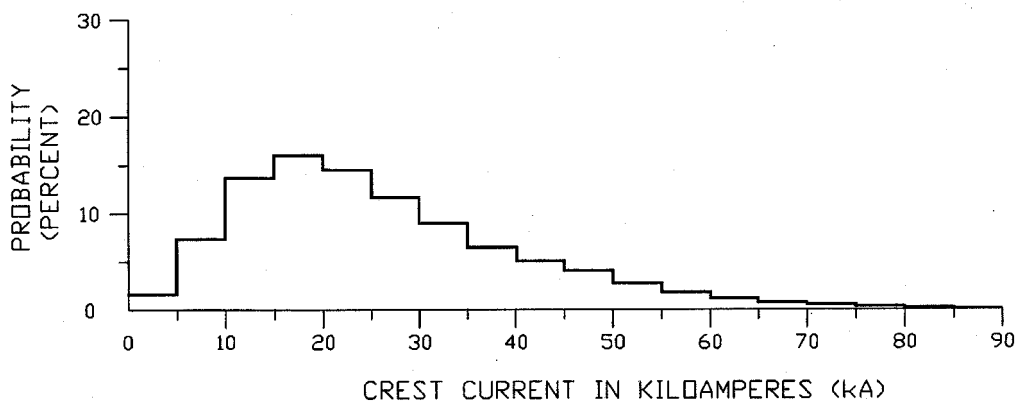


Figure 2-5 —Stroke current range probability for strokes to flat ground

2.5 Keraunic level

Keraunic level is defined as the average annual number of thunderstorm days or hours for a given locality. A daily keraunic level is called a thunderstorm-day and is the average number of days per year on which thunder will be heard during a 24 h period. By this definition, it makes no difference how many times thunder is heard during a 24 h period. In other words, if thunder is heard on any one day more than one time, the day is still classified as one thunder-day (or thunderstorm day).

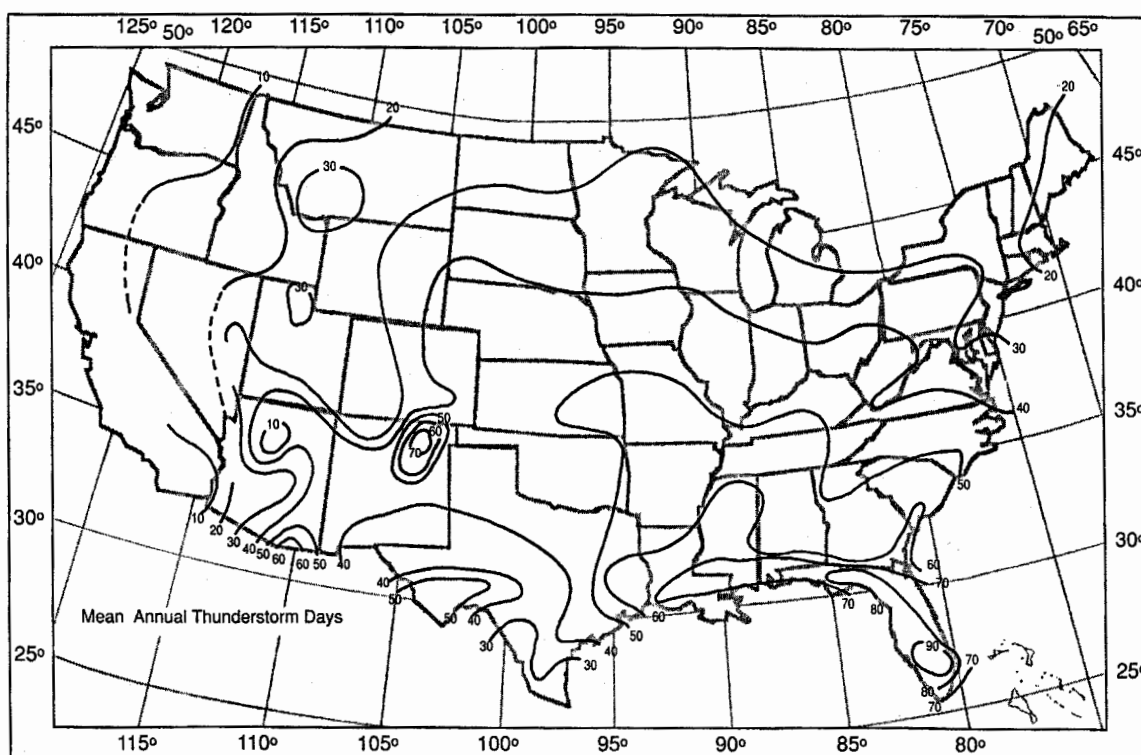
The National Oceanic and Atmospheric Administration (NOAA) now keeps hourly thunderstorm records. An hourly keraunic level is called a thunderstorm-hour and is the average number of hours per year on which thunder will be heard during a 60 min period. In other words, if thunder is heard on any one hour more than one time, the hour is still classified as one thunder-hour (or thunderstorm hour). This provides a more accurate picture of the lightning density in a given area.

The average annual keraunic level for locations in the United States can be determined by referring to isokeraunic maps on which lines of equal keraunic level are plotted on a map of the country. Figures 2-6, 2-7, and 2-8 give the mean annual thunderstorm days for the U.S., Canada, and the world based on thunderstorm days. Figure 2-9 gives the keraunic level for the U.S. based on thunderstorm-hours. This latter data was prepared by MacGorman, Maier, and Rust for the Nuclear Regulatory Commission (NRC) under the auspices of NOAA [B54]. Combined thunderstorm-hour data for the U.S. and Canada can also be found in Figure II of [B46a].

2.6 Ground flash density

Ground flash density (GFD) is defined as the average number of strokes per unit area per unit time at a particular location. It is usually assumed that the GFD to earth, a substation, or a transmission or distribution line is roughly proportional to the keraunic level at the locality. Table 2-1, taken from [B4], gives various equations for GFD as developed by various researchers around the world. These researchers arrived at a proportional relationship ranging from $0.1T$ to $0.19T$ ground flashes per square kilometer per year, where T is the average annual keraunic level. If thunderstorm days are to be used as a basis, it is suggested that the following equation be used [B4]:

$$N_k = 0.12 T_d \quad (2-3A)$$



Source: NOAA

Figure 2-6 — Mean annual thunderstorm days—U.S.

or

$$N_m = 0.31 T_d \quad (2-3B)$$

where

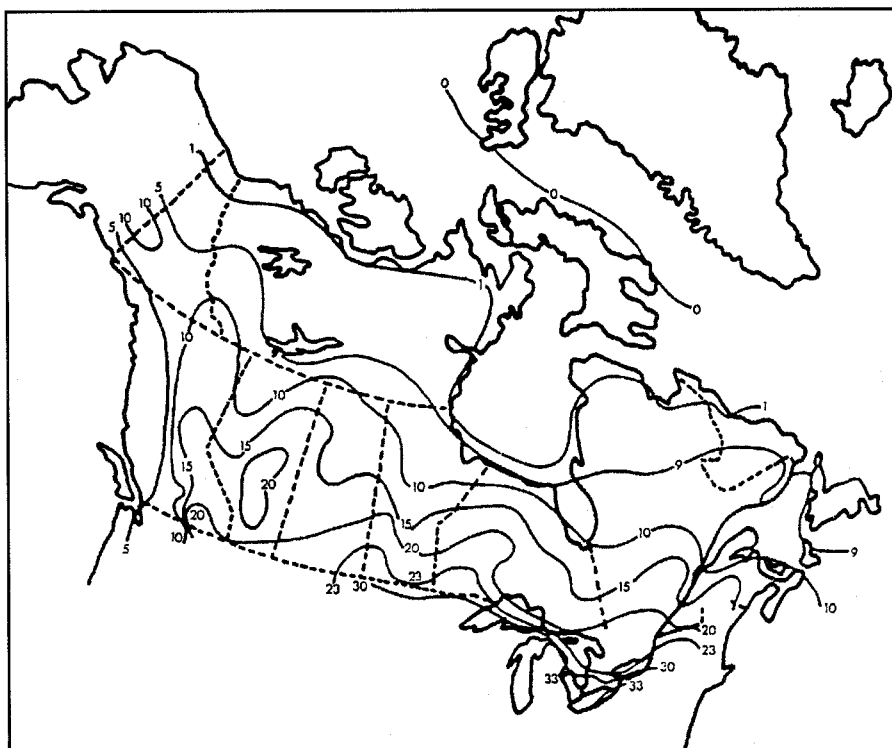
N_k is the number of flashes to earth per square kilometer per year
 N_m is the number of flashes to earth per square mile per year
 T_d is the average annual keraunic level, thunderstorm days

If thunderstorm hours is to be used as a basis, the following formula by MacGorman, et al. [B54] is recommended.

$$N_k = 0.054 T_h^{1.1} \quad (2-4A)$$

or

$$N_m = 0.14 T_h^{1.1} \quad (2-4B)$$



Source: Data from Meterological Division, Department of Transportation, Canada

Figure 2-7 — Mean annual thunderstorm days—Canada

where

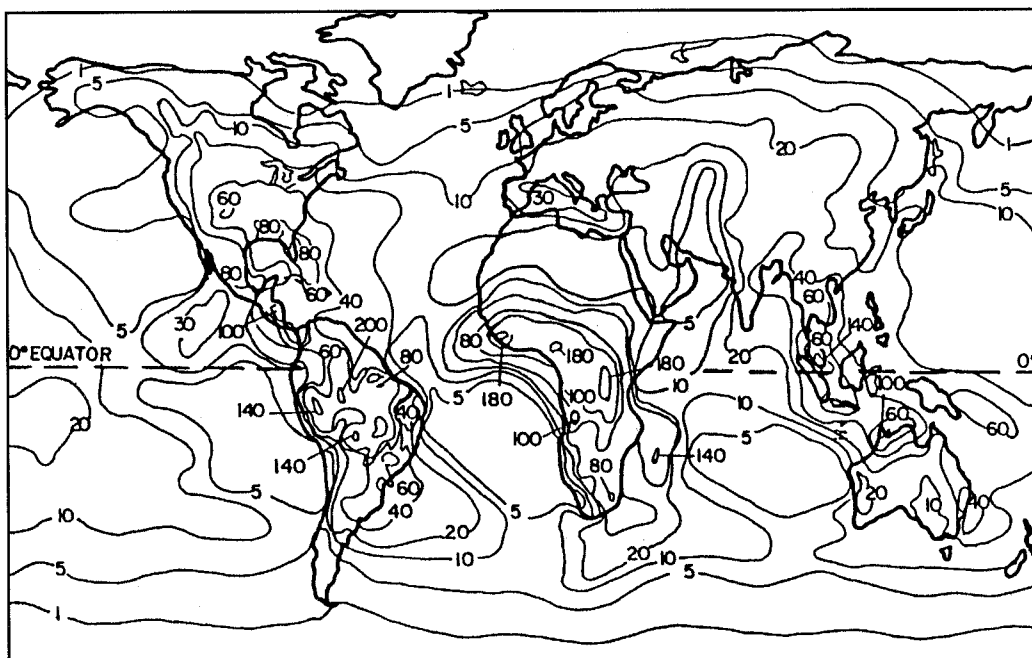
T_h is the average annual keraunic level, thunderstorm hours

The resulting ground flash density using Eq 2-4A is shown in figure 2-10.

2.7 Lightning detection networks

A new technology is now being deployed in Canada and the U.S. that promises to provide more accurate information about ground flash density and lightning stroke characteristics. Mapping of lightning flashes to the earth has been in progress for over a decade in Europe, Africa, Australia, and Asia. Now a network of direction finding receiving stations has been installed across Canada and the U.S. By means of triangulation among the stations, and with computer processing of signals, it is possible to pinpoint the location of each lightning discharge. Hundreds of millions of strokes have been detected and plotted to date.

Ground flash density maps have already been prepared from this data, but with the variability in frequency and paths taken by thunderstorms from year to year, it will take a number of years to develop data that is statistically significant. Some electric utilities are, however, taking advantage of this technology to detect the approach of thunderstorms and to plot the location of strikes on their system. This information is very useful for dispatching crews to trouble spots and can result in shorter outages that result from lightning strikes.



Source: World distribution of thunderstorm days, Part II,
published by World Meteorological Organization (1956)

Figure 2-8 — Mean annual thunderstorm days—the world

3. The design problem

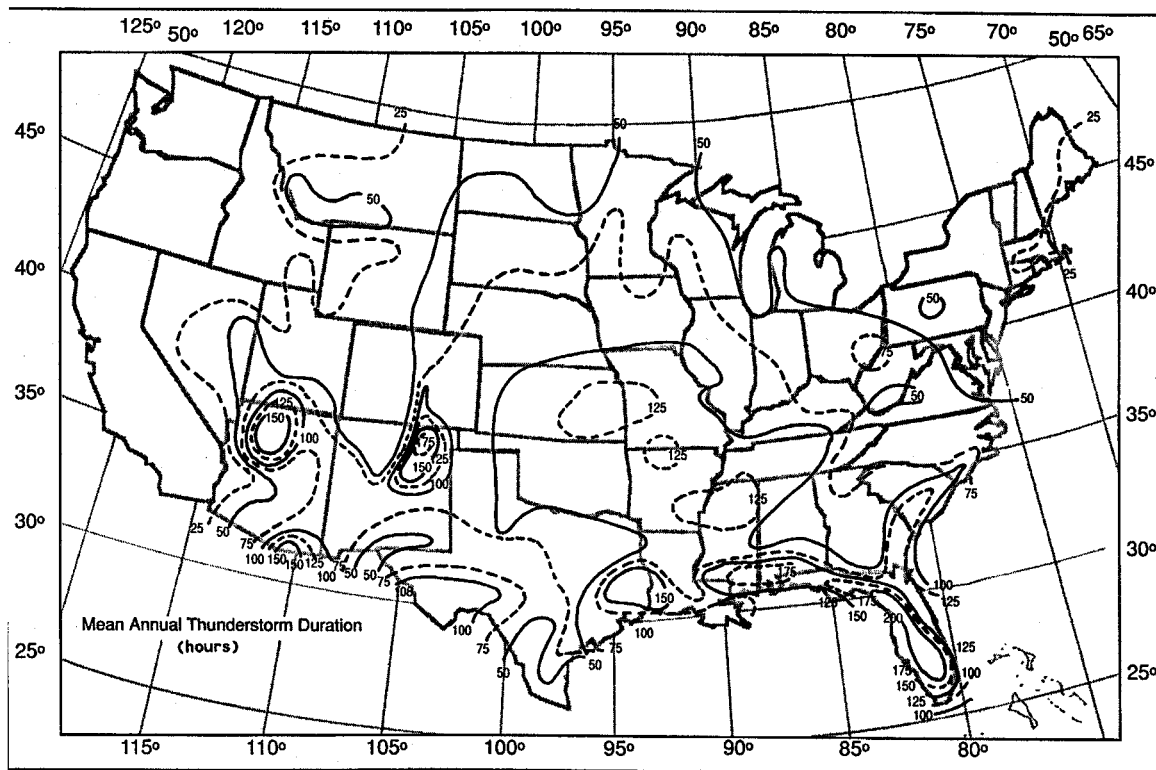
The engineer who seeks to design a direct stroke shielding system for a substation or facility must contend with several elusive factors inherent with lightning phenomena, namely:

- The unpredictable, probabilistic nature of lightning
- The lack of data due to the infrequency of lightning strokes in substations
- The complexity and economics involved in analyzing a system in detail

There is known method of providing 100% shielding short of enclosing the equipment in a solid metallic enclosure. The uncertainty, complexity, and cost of performing a detailed analysis of a shielding system has historically resulted in simple rules of thumb being utilized in the design of lower voltage facilities. Extra high voltage (EHV) facilities, with their critical and more costly equipment components, usually justify a more sophisticated study to establish the risk vs. cost benefit.

Because of the above factors, it is suggested that a four-step approach be utilized in the design of a protection system:

- a) Evaluate the importance and value of the facility being protected.
- b) Investigate the severity and frequency of thunderstorms in the area of the substation facility and the exposure of the substation.



Source: NOAA

Figure 2-9 —Mean annual thunderstorm duration (hours), U.S.

- c) Select an appropriate design method consistent with the above evaluation and then lay out an appropriate system of protection.
- d) Evaluate the effectiveness and cost of the resulting design.

The following clauses and the bibliography listed in clause 7 will assist the engineer in performing these steps.

4. Empirical design methods

Two classical design methods have historically been employed to protect substations from direct lightning strokes:

- a) Fixed angles
- b) Empirical curves

The two methods have generally provided acceptable protection.

Table 2-1—Empirical relationships between lightning ground flash density and annual thunder-days (7)

Location	Ground flash density $\text{km}^{-2} \text{ yr}^{-1}$	Reference
India	$0.1T$	Aiya (1968)
Rhodesia	$0.14T$	Anderson and Jenner (1954)
South Africa	$0.04T^{1.25}$	Eriksson (1987)
Sweden	$0.004T^2$ (approx.)	Muller-Hillebrand (1964)
U.K.	aT^b	Stringfellow (1974) [$a = 2.6 \pm 0.2 \times 10^{-3}$; $b = 1.9 \pm 0.1$]
U.S.A. (North)	$0.11T$	Horn and Ramsey (1951)
U.S.A. (South)	$0.17T$	Horn and Ramsey (1951)
U.S.A.	$0.1T$	Anderson and others (1968)
U.S.A.	$0.15T$	Brown and Whitehead (1969)
U.S.S.R.	$0.036T^{1.3}$	Kolokolov and Pavlova (1972)
World (temperate climate)	$0.19T$	Brooks (1950)
World (temperate climate)	$0.15T$	Golde (1966)
World (tropical climate)	$0.13T$	Brooks (1950)

Reprinted from [B82] with permission of Academic Press Ltd.

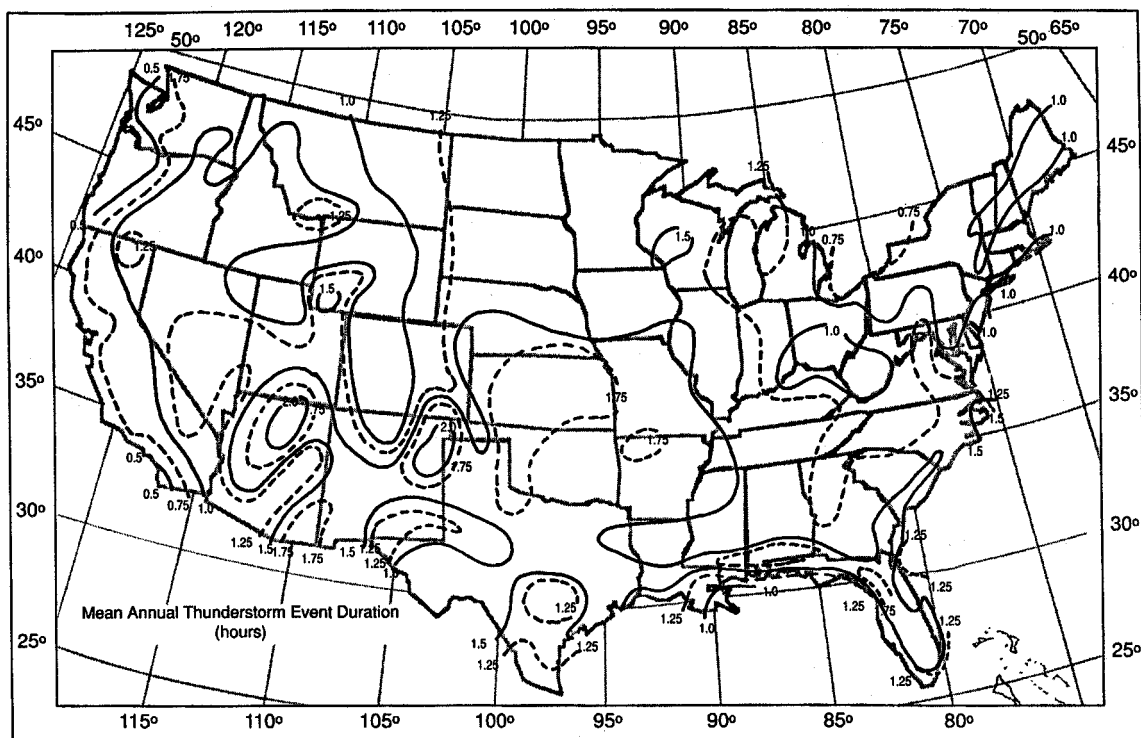
4.1 Fixed angles

It is not known when the use of fixed angles first began. F. W. Peek, Jr., and other investigators recognized as early as 1924 [B78] that the area protected by a rod was bounded by a curved surface rather than a plane surface. It is likely, therefore, that fixed angles were originally used by designers as a convenient approximation of the boundary of protection against lightning strokes. Wagner, McCann, and MacLane, Jr., formalized the use of fixed angles in 1941 [B93]. Fixed angles continue in use today as a design tool.

The fixed-angle design method uses vertical angles to determine the number, position, and height of shielding wires or masts. Figure 4-1 illustrates the method for shielding wires, and figure 4-2 illustrates the method for shielding masts.

The angles used are determined by the degree of lightning exposure, the importance of the substation being protected, and the physical area occupied by the substation. The value of the angle alpha that is commonly used is 45° . Both 30° and 45° are widely used for angle beta. (See annex E.)

Designers using the fixed angle method may want to reduce the shielding angles as the height of the structures increases in order to maintain a low failure rate. Horvath [B42], using the EGM, calculated shielding failures as a function of the height of the conductor above ground and the protective angle for transmission lines. As can be seen from table 4-1, the protective angle must be decreased as the conductor is raised in order to maintain a uniform failure rate.



Source: NOAA

Figure 2-10 — Mean annual ground flash density—U.S.

Horvath suggests a protective angle of 40° – 45° for heights up to 15 m (49 ft), 30° for heights between 15–25 m (49–82 ft) and less than 20° for heights on up to 50 m (164 ft). A failure rate of 0.1–0.2 shielding failures/100 km/year was assumed in these recommendations. (Horvath did not state the ground flash density used in his example.) This approach could also be used for selecting shielding angles for ground wires in substations.

A similar approach could be used for applying lightning masts in substations. Horvath suggested using the rolling sphere method (see clause 5.) to compile a table of shielding angles vs. conductor heights.

4.2 Origin of empirical curves

The use of empirical curves finds its origin in a paper published in 1941 by Wagner, McCann, and MacLane [B93]. Scale model tests were conducted employing a $1\text{-}1/2 \times 40 \mu\text{s}$ positive impulse to initiate a discharge from a rod (representing the charged cloud) to a ground plane or a horizontal shield wire and conductor located near the electrode. The relative spacing of the electrode, shield wire, and conductor was varied with each discharge so as to produce an adequate data base for analysis. Plots were then made from this data base showing the percent of discharges striking the shield wire, conductor, or ground plane. The authors also studied the lightning performance of many existing lines and the shielding system used and correlated the findings with their scale model work. The resulting recommendations have been used for fifty years and continue to be used.

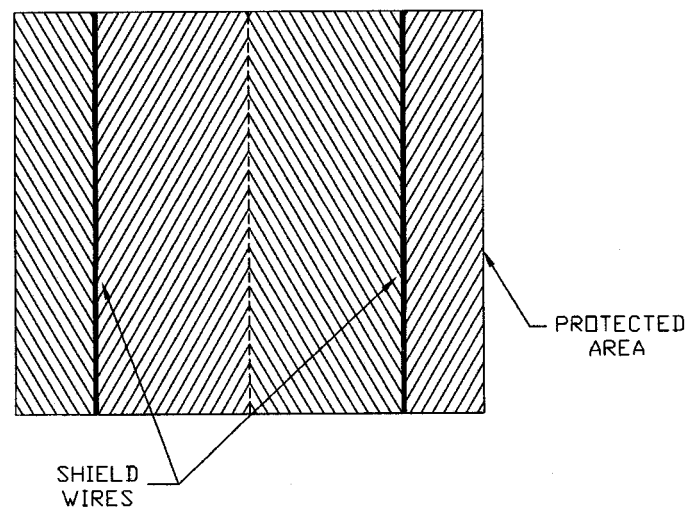
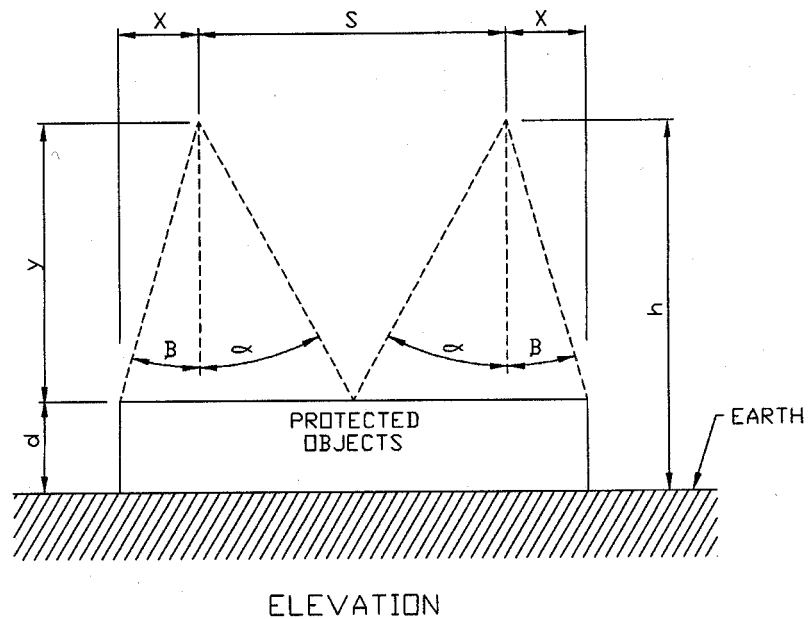


Figure 4-1 — Fixed angles for shielding wires

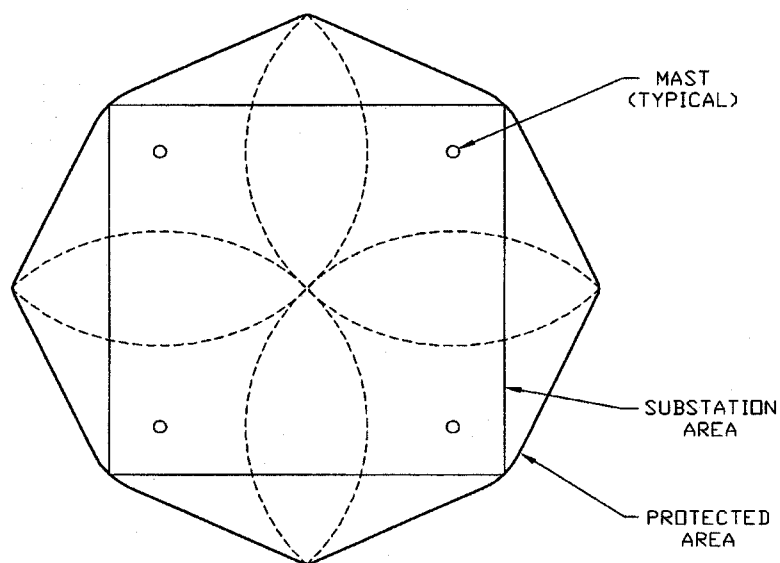
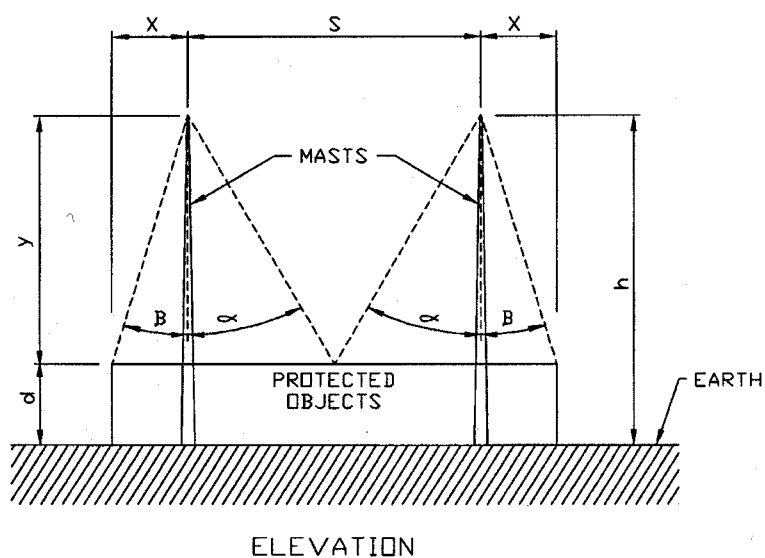


Figure 4-2 — Fixed angles for masts

Table 4-1 — Calculated frequency of shielding failures as a function of the height and the protective angle

Height of earth wire in m	Shielding failure/100 km per year with protective angle:						
	15°	20°	25°	30°	35°	40°	45°
10	0	0	1.1E-4	0.0087	0.0383	0.1032	0.2286
15	0	6.4E-5	0.0068	0.0351	0.0982	0.2182	0.4483
20	8.3E-6	0.0026	0.0214	0.0711	0.1695	0.3466	0.6903
25	0.0011	0.0087	0.0404	0.1123	0.2468	0.4819	0.9429
30	0.0035	0.0170	0.0620	0.1565	0.3275	0.6208	1.2008
35	0.0069	0.0269	0.0853	0.2024	0.4100	0.7616	1.4608
40	0.0109	0.0378	0.1096	0.2494	0.4936	0.9035	1.7214
45	0.0155	0.0493	0.1345	0.2969	0.5776	1.0462	1.9820
50	0.0204	0.0612	0.1598	0.3447	0.6619	1.1892	2.2423
Source: [B42]. Reprinted with permission of Research Studies Press Ltd.							

The following year, 1942, Wagner, McCann, and Lear published a paper on shielding of substations [B94]. These investigations were based on additional scale model tests, and a series of curves were developed relating height and spacing of shield wires and masts to various failure rates. These curves produce a more accurate design than straight line approximations. This design method also continues to find wide use today.

4.3 Application of empirical curves

From field studies of lightning and laboratory model tests, empirical curves have been developed to determine the number, position, and height of shielding wires and masts [B93], [B94], [B96].

The curves were developed for shielding failure rates of 0.1, 1.0, 5.0, 10, and 15%. Curves for different configurations of shielding wires and masts are shown in figures A.1 through A.6 of annex A for failure rates of 0.1 and 1.0%. A failure rate of 0.1% is commonly used in design.

Figures A.1 through A.6 use ratios of d/h , x/h , and s/h , which were used in the original study [B94]. Figures 4-3 through 4-14 have been developed using figures A.1 through A.6 for a variety of protected object heights, d , to eliminate the necessity of using ratios. For a given x/h (s/h) ratio along the abscissa in figures A.1 through A.6, the ordinate value yields a d/h ratio for a desired failure rate. For each selected value of d , a value of h for each discrete value of x/h can be calculated as $h = d/(d/h)$. Now, for these discrete values of h for a selected d , values of the horizontal separation, x (s), can be calculated from $x = x/h \cdot h$ ($s = s/h \cdot h$). The difference between the protected object height, d , and the shielding mast, or wire, height, h , can be calculated as $y = h - d$. These values of y can be plotted as a continuous curve $f(x, y)$ for a constant value d as shown in figures 4-3 through 4-14. For example, in figure A.2, data points from the original study appear to be plotted at x/h values of 0.25, 0.6, and 1.0. At the value of x/h equal to 0.6, d/h is estimated to be 0.46 for a 0.1% failure rate.

For $d = 20$ ft:

$$h = 20/0.46 = 43.48 \text{ ft}$$

$$x = 0.6 \times 43.48 = 26.09 \text{ ft}$$

$$y = 43.48 - 20 = 23.48 \text{ ft}$$

Similarly, values of d/h can be estimated for other values of x/h and the resulting x and y values plotted for each selected value of d for each failure rate. These particular values are illustrated in figure 4-5.

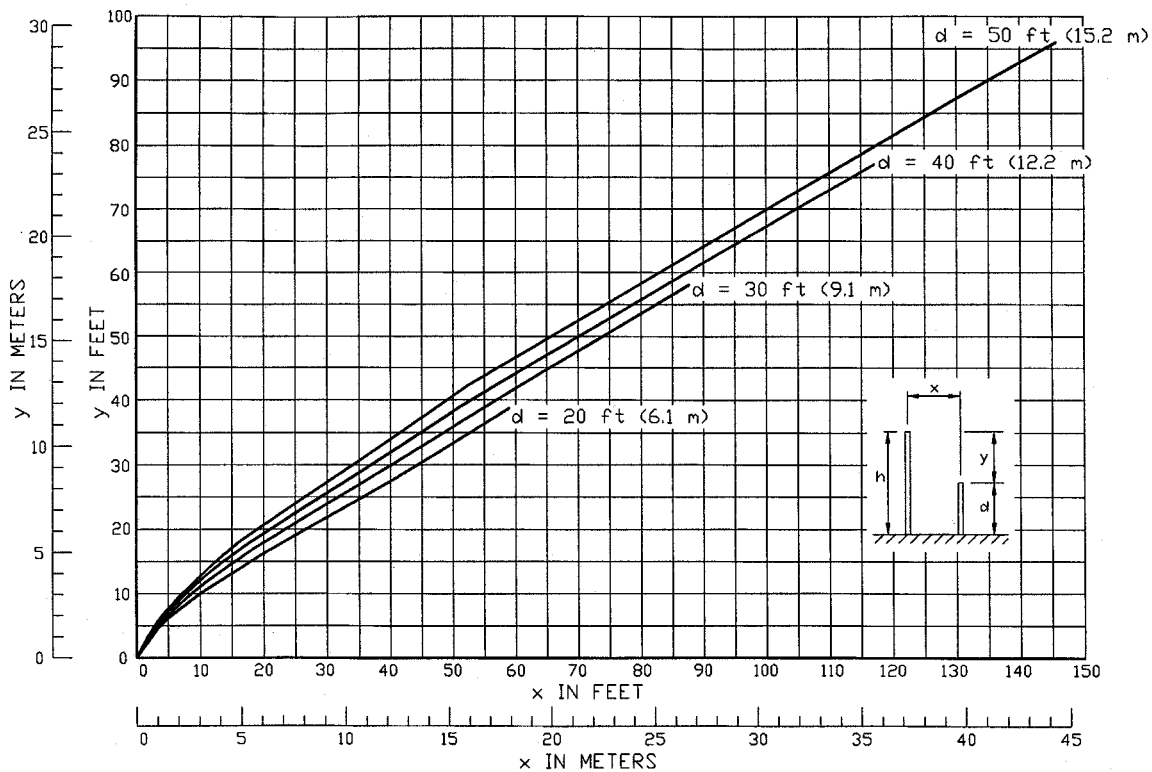


Figure 4-3 —Single lightning mast protecting single object—0.1% exposure.
Height of lightning mast above protected object, y , as a function of horizontal separation, x , and height of protected object, d

To evaluate the expected shielding performance of a substation site, proceed as follows:

- Determine the ground flash density using Eq 2-3 or Eq 2-4.
- Calculate the number of flashes to the substation area, N_s .

$$N_s = GFD \times A / (1000)^2$$

where

GFD is the ground flash density in strokes per square kilometer per year
 A is the substation area in square meters

- Calculate number of strokes per year penetrating the shield, SP .

$$SP = N_s \times \text{exposure rate} \quad (1)$$

Choose acceptable exposure rate (Example 0.1% or 0.001)

WARNING

The user is warned not to extrapolate the curves of figure 4-3 through figure 4-14 beyond their limits as plotted. Such extrapolations can result in exposures beyond the listed values.

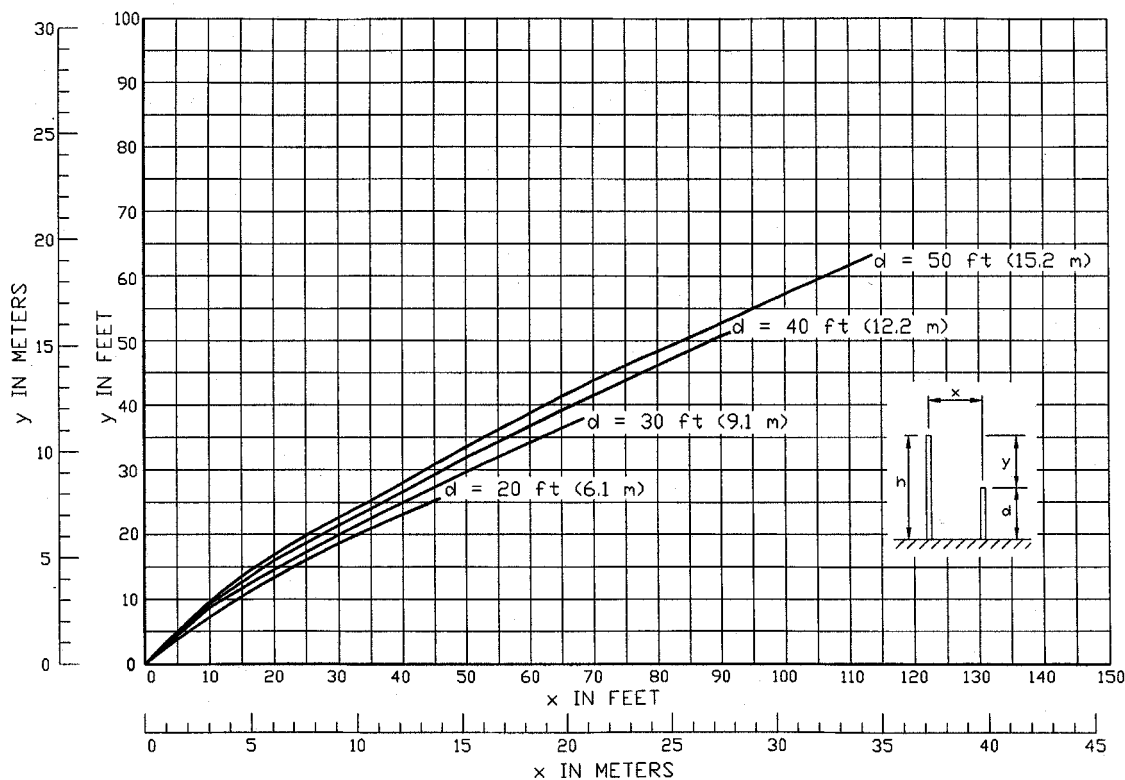


Figure 4-4 — Single lightning mast protecting single object—1% exposure.
Height of lightning mast above protected object, y , as a function of horizontal separation, x , and height of protected object, d

4.3.1 Areas protected by lightning masts

Figures 4-15 and 4-16 illustrate the areas that can be protected by two or more shielding masts [B94]. If two masts are used to protect an area, the data derived from the empirical curves give shielding information only for the point B , midway between the two masts, and for points on the semicircles drawn about the masts, with radius x , as shown in figure 4-15(a). The locus shown in figure 4-15(a), drawn by the semicircles around the masts, with radius x , and connecting the point B , represents an approximate limit for a selected exposure rate. For given values of d and y , a value of s from figure 4-7 and x from figure 4-5 can be determined for an exposure rate of 0.1%. Any single point falling within the cross-hatched area should have $< 0.1\%$ exposure. Points outside the cross-hatched area will have $> 0.1\%$ exposure. Figure 4-15(b) illustrates this phenomenon for four masts spaced at the distance s as in figure 4-15(a).

The protected area can be improved by moving the masts closer together, as illustrated in figure 4-16. In figure 4-16(a), the protected areas are, at least, as good as the combined areas obtained by superimposing those of figure 4-15(a). In figure 4-16(a), the distance s' is one-half the distance s in figure 4-15(a). To estimate the width of the overlap, x' , first obtain a value of y from figure 4-7 corresponding to twice the distance, s' , between the masts. (Figure 4-9 has been prepared to facilitate this estimate directly.) Then use figure 4-5 to determine x' for this value of y . This value of x is used as an estimate of the width of overlap x' in figure 4-16. As illustrated in figure 4-16(b), the size of the areas with an exposure greater than 0.1% has been significantly reduced.

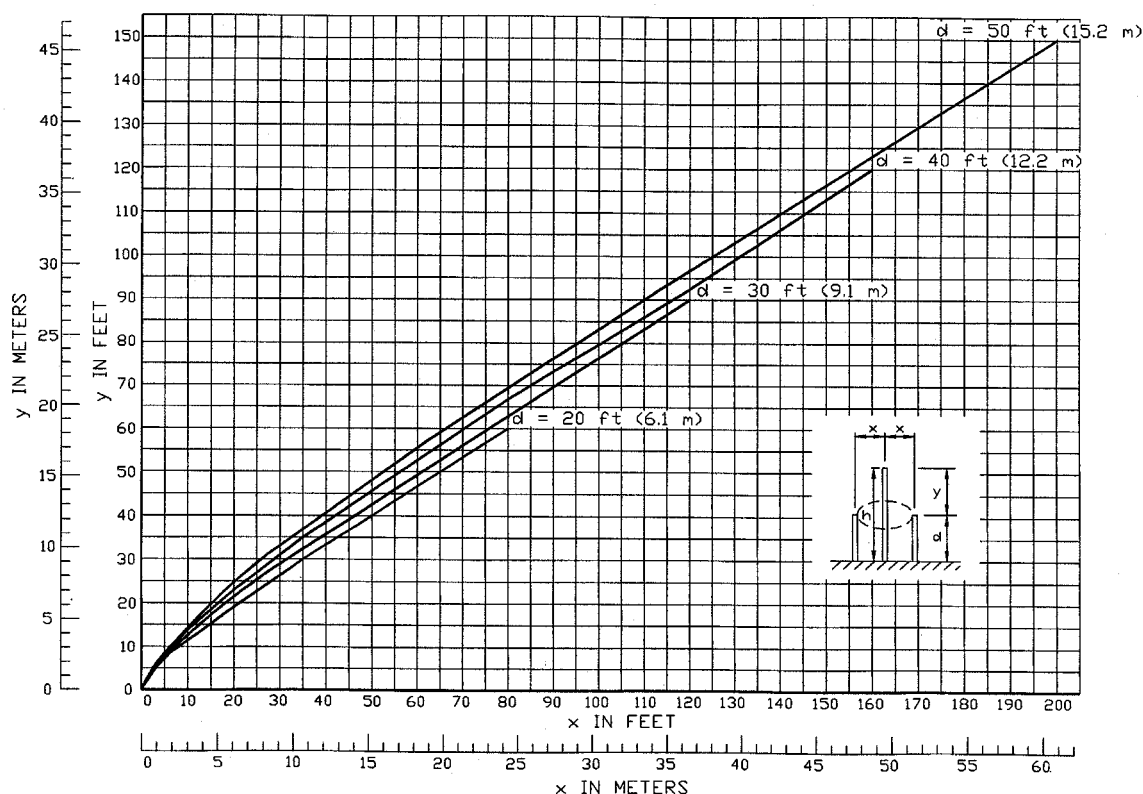


Figure 4-5 — Single lightning mast protecting single ring of objects—0.1% exposure.
 Height of lightning mast above protected object, y , as a function of horizontal separation, x , and height of protected object, d

4.3.2 Effect of hillsides

For the application of the data presented here to stations located on hillsides, the dimensions h (the shielding conductor height) and d (the height of the protected object) should be measured perpendicular to the earth's surface as illustrated in figure 4-17 [B94].

5. The electrogeometric model (EGM)

5.1 History

A rudimentary version of the electrogeometric model was developed by Golde in 1945 [B35], but the method was never adapted to shielding systems. In the mid-1950s, the first North American 345 kV transmission lines were placed in service. The shielding design of the lines was based primarily on the methods found in [B1]. The outage rate from lightning strokes subsequently proved to be much higher than expected, and this set in motion a thorough investigation of the problem. The modern EGM emerged as a result of this research.

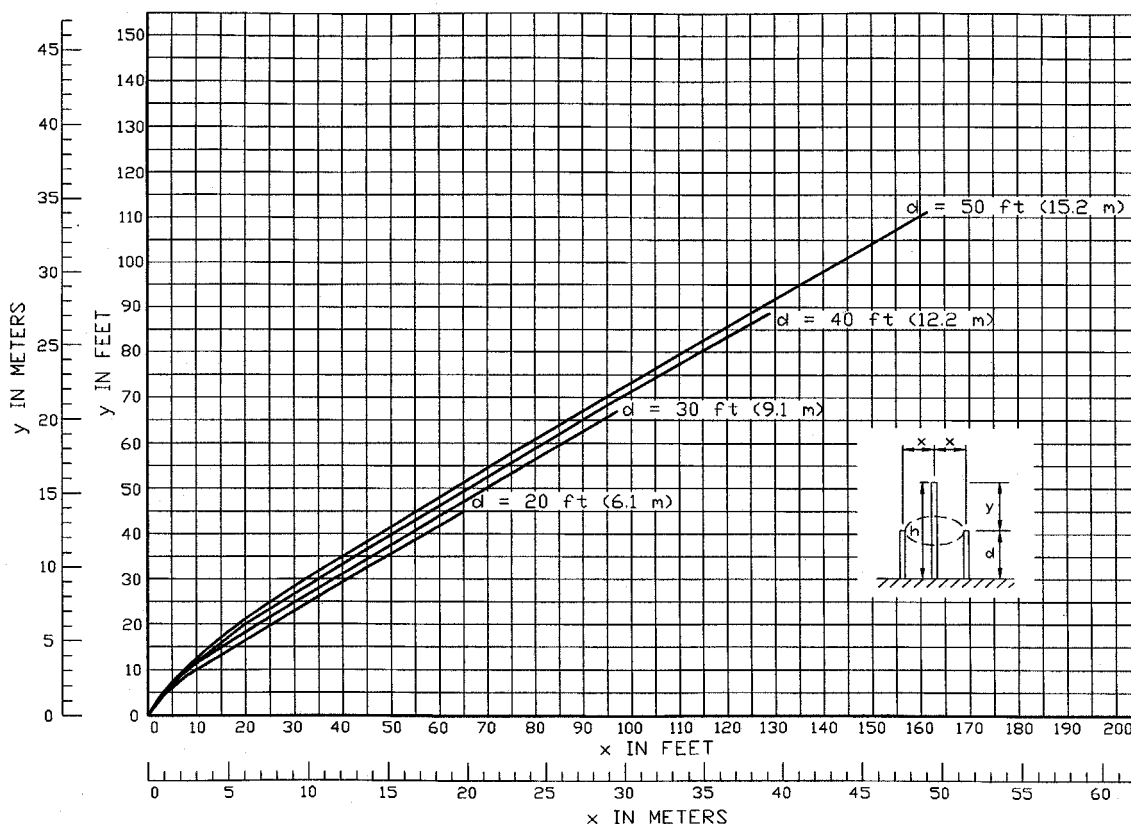


Figure 4-6 — Single lightning mast protecting single ring of objects—1% exposure.
Height of lightning mast above protected object, y , as a function of horizontal separation, x , and height of protected object, d

5.1.1 Whitehead's EGM

In 1960, J. G. Anderson developed a computer program for calculation of transmission line lightning performance that uses the *Monte Carlo Method* [B3]. This method showed good correlation with actual line performance. An early version of the EGM was developed in 1963 by Young et al. [B101], but continuing research soon led to new models.

One extremely significant research project was performed by E. R. Whitehead [B97]. Whitehead's work included a theoretical model of a transmission system subject to direct strokes, development of analytical expressions pertaining to performance of the line, and supporting field data which verified the theoretical model and analyses. The final version of this model was published by Gilman and Whitehead in 1973 [B33].

5.1.2 Recent improvements in the EGM

Sargent made an important contribution with the *Monte Carlo Simulation* of lightning performance [B85] and his work on lightning strokes to tall structures [B84]. Sargent showed that the frequency distribution of the amplitudes of strokes collected by a structure depends on the structure height as well as on its type (mast vs. wire). Figure 5-1 shows the effect of the height of the structure, according to Sargent. In 1976 Mousa [B60] extended the application of the EGM (which was developed for transmission lines) to substation facilities.

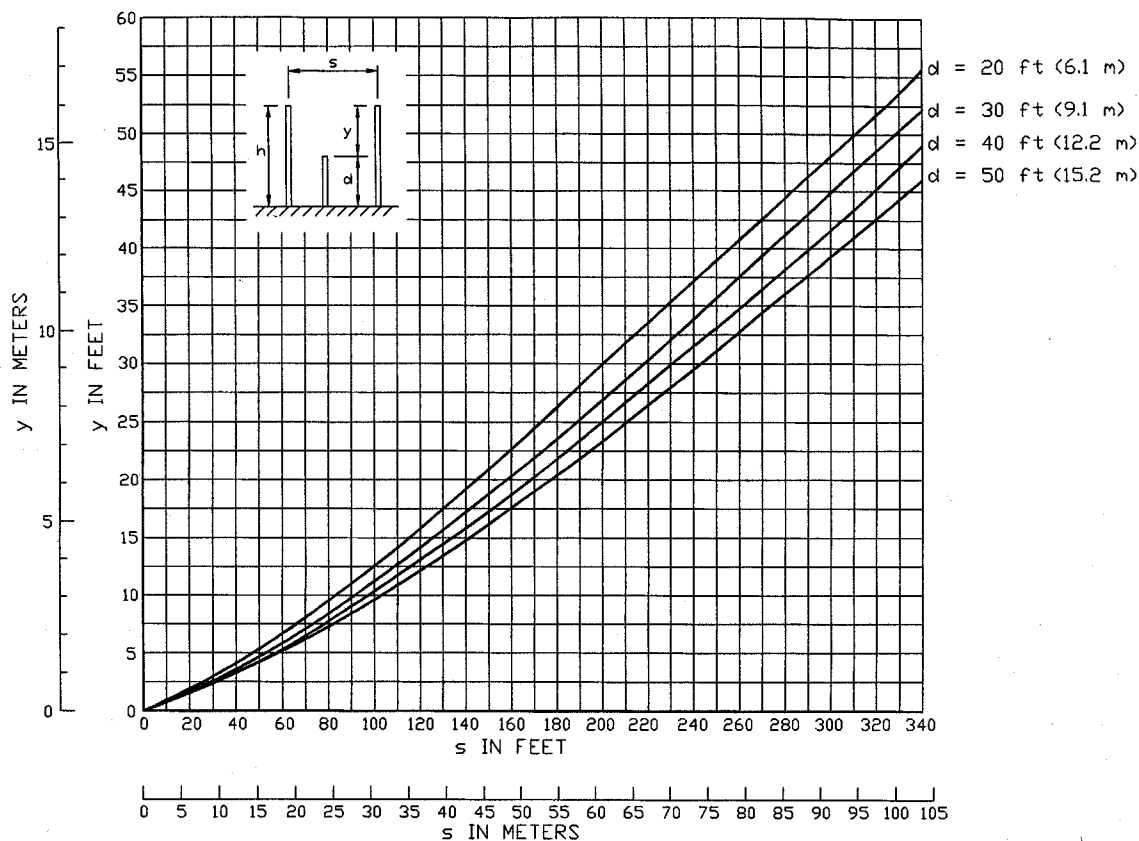


**Figure 4-7 — Two lightning masts protecting single object, no overlap—0.1% exposure.
Height of mast above protected object, y , as a function of
horizontal separation, s , and height of protected object, d**

5.1.3 Criticism of the EGM

Work by Eriksson reported in 1978 [B27] and later work by Anderson and Eriksson reported in 1980 [B5] revealed apparent discrepancies in the EGM that tended to discredit it. Mousa [B67] has shown, however, that explanations do exist for the apparent discrepancies, and that many of them can be eliminated by adopting a revised electrogeometric model. Most investigators now accept the EGM as a valid approach for designing lightning shielding systems.

5.2 A revised EGM

This guide uses the revised EGM as developed by Mousa and Srivastava [B63], [B67]. Two methods of applying the EGM are the modified version of the rolling sphere method [B49], [B50], [B74] described in 5.3, and the method given by Mousa and Srivastava [B67], [B71] described in 5.4.

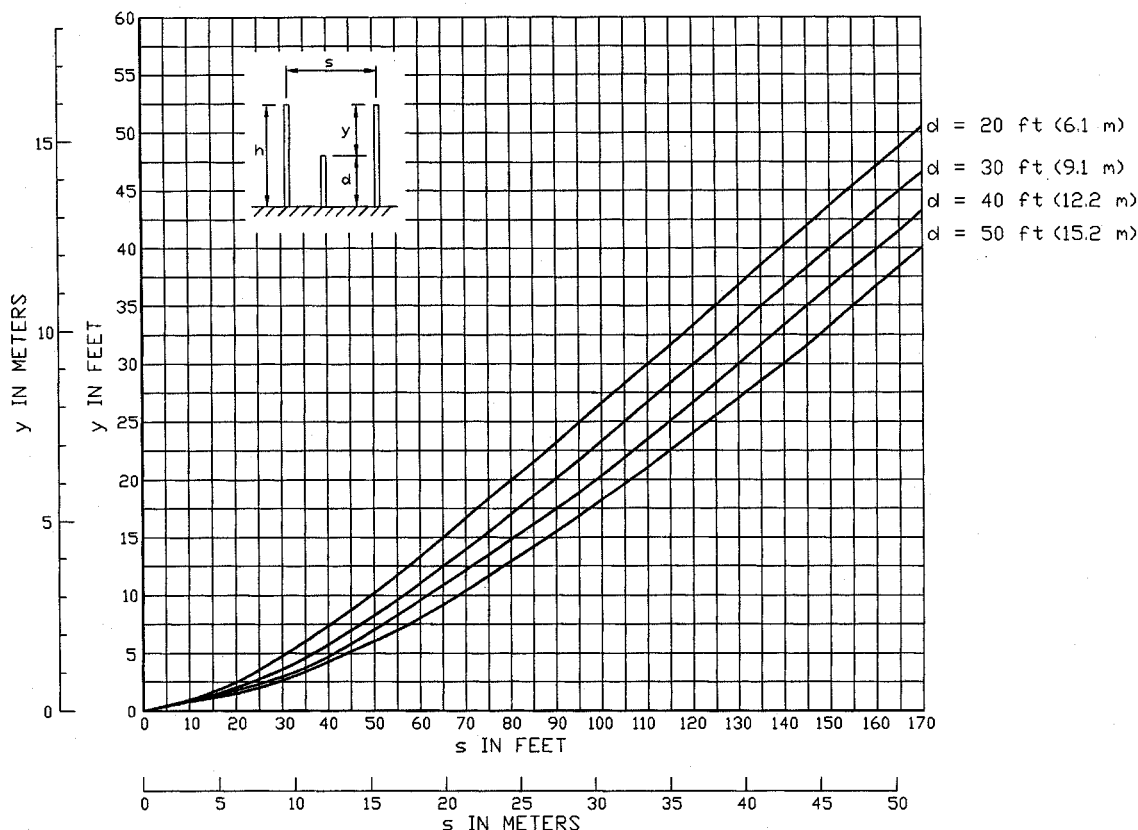


**Figure 4-8 —Two lightning masts protecting single object, no overlap—1% exposure.
Height of mast above protected object, y as a function of
horizontal separation, s , and height of protected object, d**

The revised EGM model differs from Whitehead's model in the following respects:

- The stroke is assumed to arrive in a vertical direction. (It has been found that Whitehead's assumption of the stroke arriving at random angles is an unnecessary complication.) [B67]
- The differing striking distances to masts, wires, and the ground plane are taken into consideration.
- A value of 24 kA is used as the median stroke current [B70]. This selection is based on the frequency distribution of the first negative stroke to flat ground. This value best reconciles the EGM with field observations.
- The model is not tied to a specific form of the striking distance equations Eq 2-1. Continued research is likely to result in further modification of this equation as it has in the past. The best available estimate of this parameter may be used.

5.2.1 Description of the revised EGM

In clause 2. of this guide the process of stroke formation was discussed. The concept that the final striking distance is related to the magnitude of the stroke current was introduced and Eq 2-1D was selected as the best approximation of this relationship. A coefficient k accounts for the different striking distances to a mast, a shield wire, and to the ground. Eq 2-1D is repeated here with this modification:

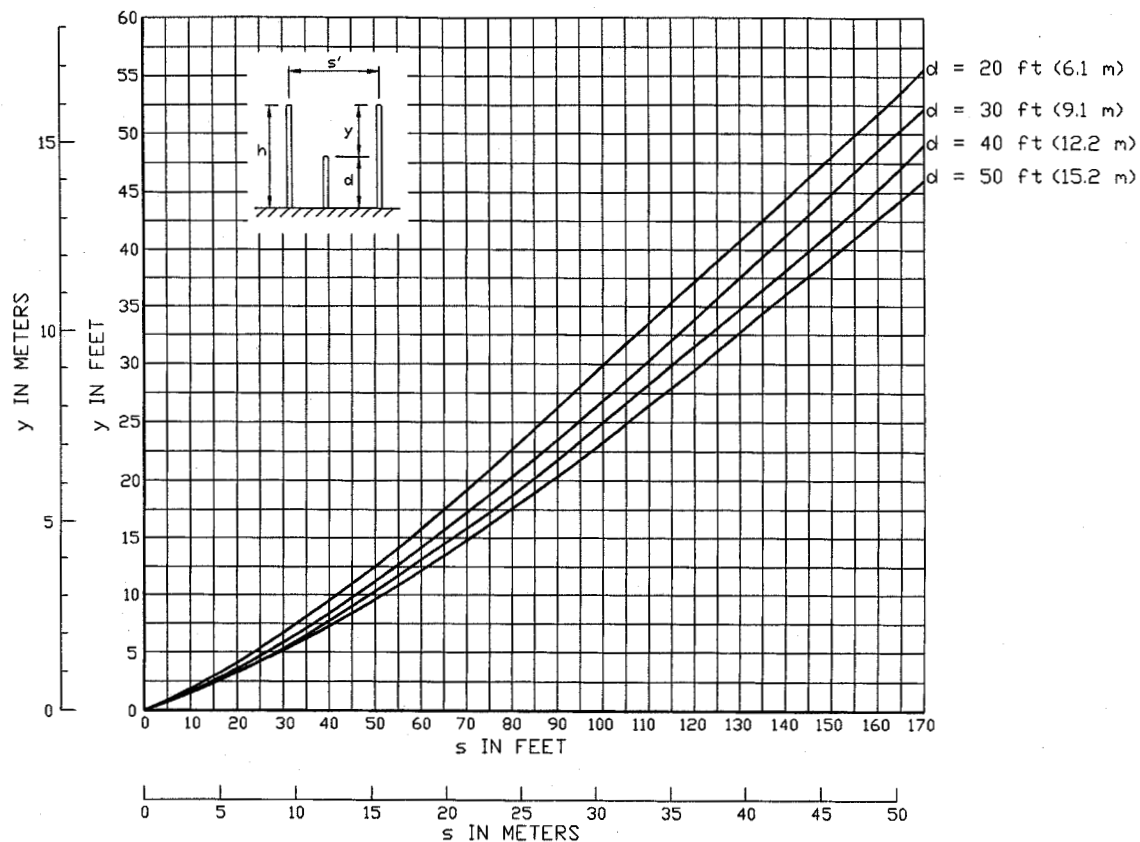


**Figure 4-9—Two lightning masts protecting single object, with overlap—0.1% exposure.
Height of mast above protected object, y , as a function of
horizontal separation, s , and height of protected object, d**

$$S_m = 8 k I^{0.65} \quad (5-1A)$$

or

$$S_f = 26.25 k I^{0.65} \quad (5-1B)$$

where

- S_m is the strike distance in meters
- S_f is the strike distance in feet
- I is the return stroke current in kiloamperes
- k is a coefficient to account for different striking distances to a mast, a shield wire, or the ground plane.

Mousa [B67] gives a value of $k = 1$ for strokes to wires or the ground plane and a value of $k = 1.2$ for strokes to a lightning mast.

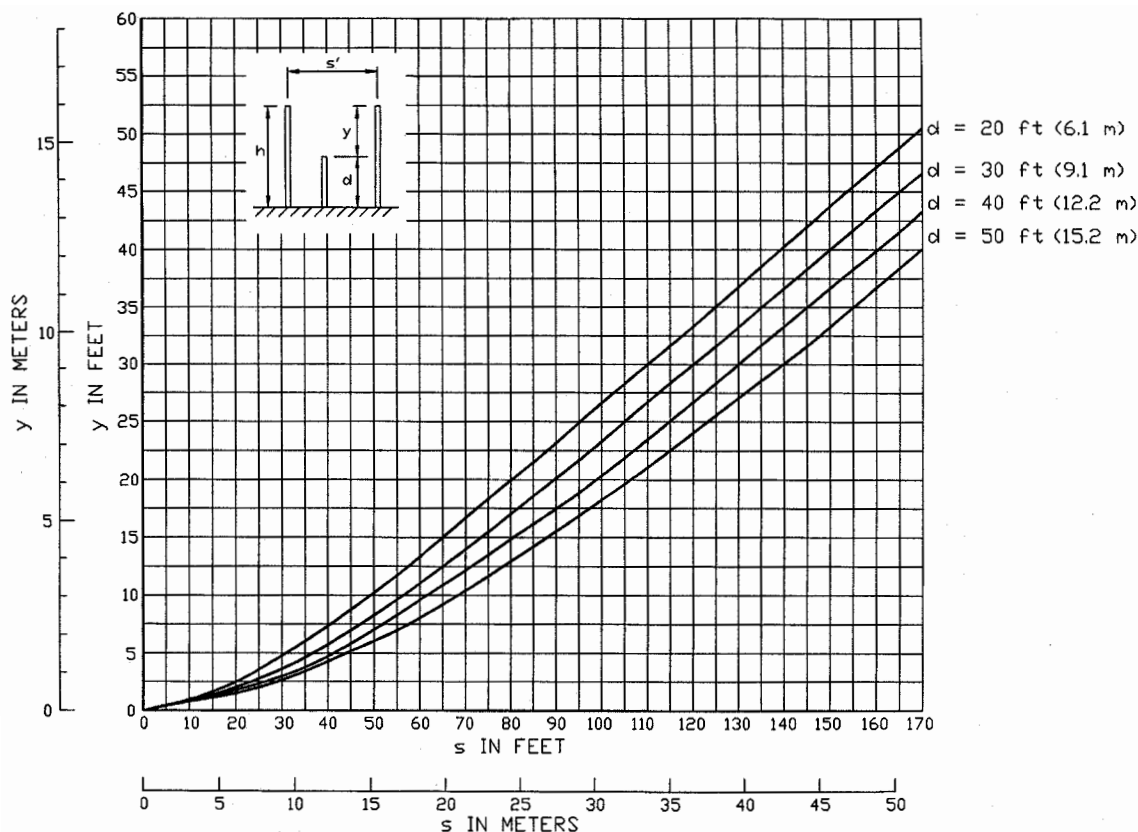


Figure 4-10 — Two lightning masts protecting single object, with overlap—1% exposure.
Height of mast above protected object, y , as a function of horizontal separation, s , and height of protected object, d

Lightning strokes have a wide distribution of current magnitudes, as shown in figure 2-4. The EGM theory shows that the protective area of a shield wire or mast depends on the amplitude of the stroke current. If a shield wire protects a conductor for a stroke current I_s , it may not shield the conductor for a stroke current less than I_s that has a shorter striking distance. Conversely, the same shielding arrangement will provide greater protection against stroke currents greater than I_s that have greater striking distances. This principle is discussed in more detail in 5.3.

Since strokes less than some critical value I_s can penetrate the shield system and terminate on the protected conductor, the insulation system must be able to withstand the resulting voltages without flashover. Stated another way, the shield system should intercept all strokes of magnitude I_s and greater so that flashover of the insulation will not occur.

5.2.2 Allowable stroke current

Some additional relationships need to be introduced before showing how the EGM is used to design a zone of protection for substation equipment. Bus insulators are usually selected to withstand a *basic lightning impulse level* (BIL). Insulators may also be chosen according to other electrical characteristics including negative polarity *impulse critical flashover* (C.F.O.) voltage. Flashover occurs if the voltage produced by the lightning stroke current flowing through the surge impedance of the station bus exceeds the withstand value. This may be expressed by the Gilman & Whitehead equation [B33]:

$$I_s = \frac{\text{BIL} \times 1.1}{(Z_s/2)} = \frac{2.2 (\text{BIL})}{Z_s} \quad (5-2A)$$

or

$$I_S = \frac{0.94 \times \text{C.F.O.} \times 1.1}{(Z_S/2)} = \frac{2.068 (\text{C.F.O.})}{Z_S} \quad (5-2B)$$

where

- I_S is the allowable stroke current in kiloamperes
- BIL is the basic lightning impulse level in kilovolts
- C.F.O. is the negative polarity critical flashover voltage of the insulation being considered in kilovolts
- Z_S is the surge impedance of the conductor through which the surge is passing in ohms
- 1.1 is the factor to account for the reduction of stroke current terminating on a conductor as compared to zero impedance earth [B33]

A method of computing the surge impedance under corona is given in annex C.

In Equation 5-2B, the C.F.O. has been reduced by 6% to produce a withstand level roughly equivalent to the BIL rating for post insulators.

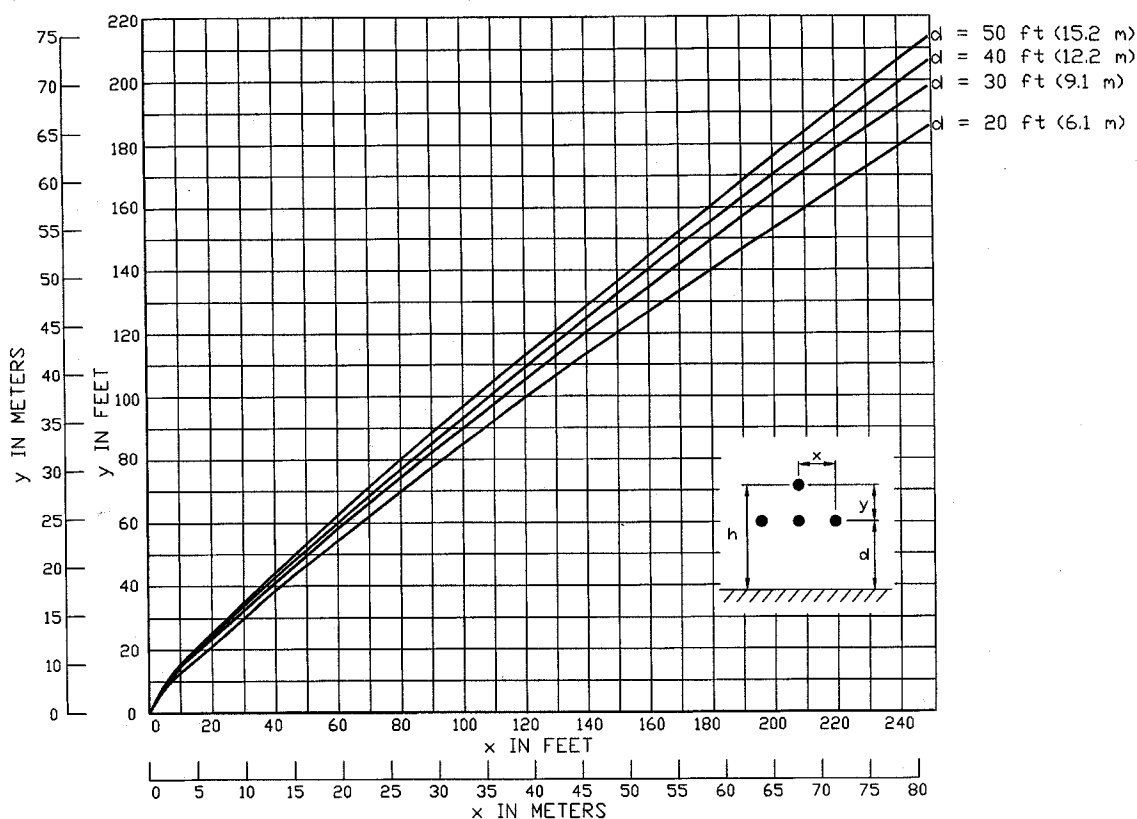


Figure 4-11 — Single shield wire protecting horizontal conductors—0.1% exposure.
Height of shield wires above conductors, y, as a function of
horizontal separation, x, and height of protected conductors, d

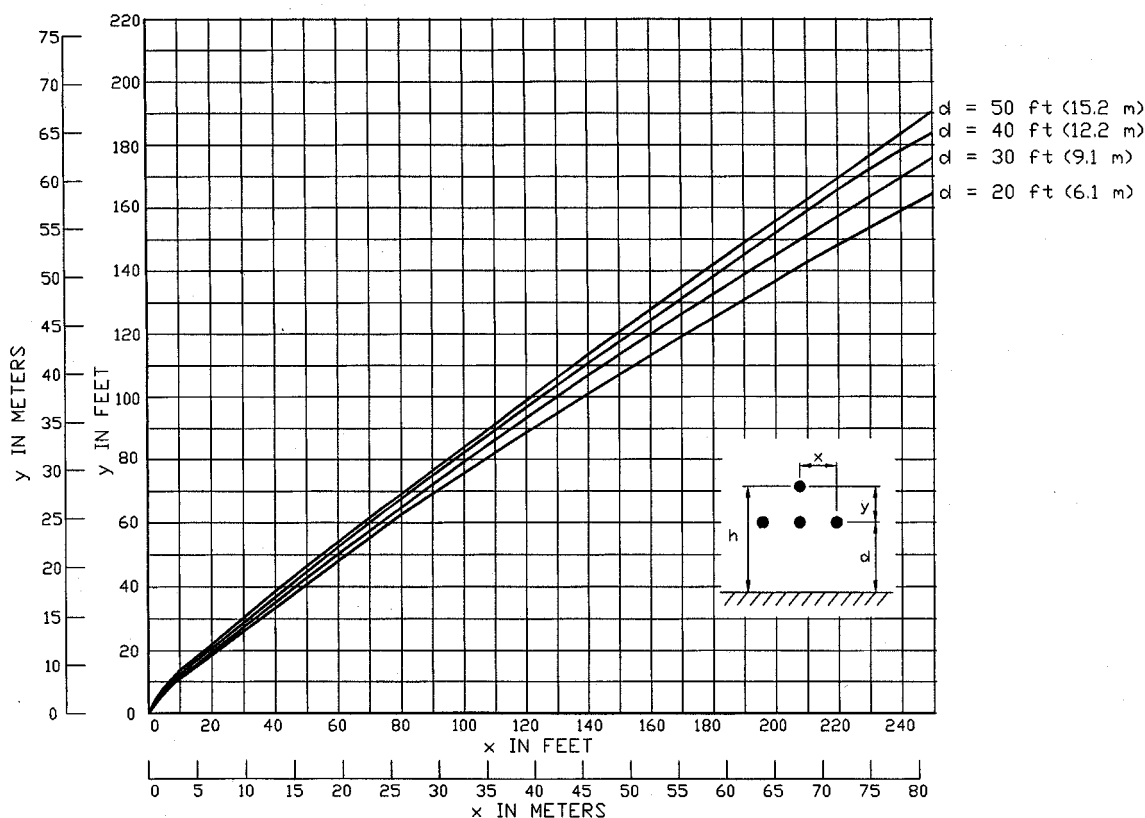


Figure 4-12 —Single shield wire protecting horizontal conductors—1% exposure.
Height of shield wires above conductors, y , as a function of horizontal separation, x , and height of protected conductors, d

5.2.2.1 Adjustment for end of bus situation

Equations 5-2A and 5-2B address the typical situation in which a direct lightning stroke to a conductor would have at least two directions to flow. The equations assume the surge impedances are the same in both directions, and therefore the total surge impedance is the parallel combination of the two, or $1/2 Z_S$. Occasionally a designer may be concerned with a situation in which the entire direct stroke current produces a surge voltage across the equipment. An example would be a direct stroke to the end of a radial bus. The surge can only flow in one direction, and the surge voltage impressed across the insulators of the bus would be the product of the total direct stroke current multiplied by the bus surge impedance. For such situations, the allowable stroke current I_S can be determined by dividing the results of calculations using equations 5-2A and 5-2B by 2.

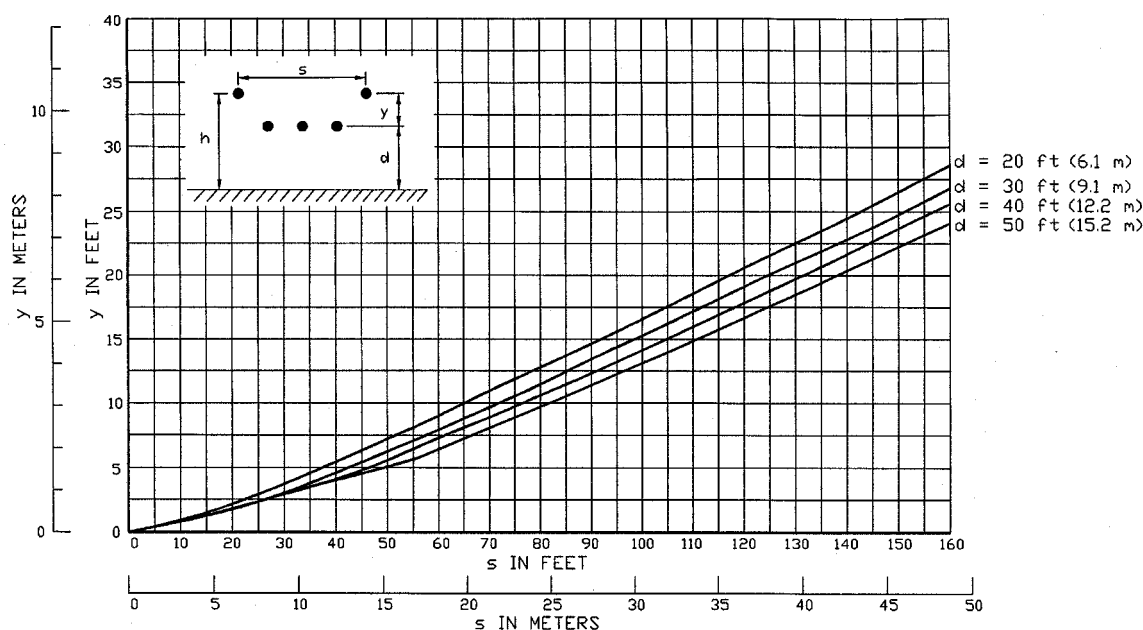


Figure 4-13 — Two shield wires protecting horizontal conductors—0.1% exposure.
Height of shield wires above conductors, y , as a function of
horizontal separation, s , and height of protected conductors, d

5.2.2.2 Adjustment for transformer, open switch or open breaker

Another situation where a designer may have concern is at open points in the conductor (such as open switches and open breakers), or points along the conductor where the surge impedance changes to a large value such as at transformer windings. At such locations, the voltage wave will reverse its direction of flow and return along the conductor. The voltage stress at these points will be up to two times the incoming value. This is referred to as the voltage doubling effect. If the design has incorporated surge arresters at the point of high surge impedance change, such as at the bushings of transformers, the concern for voltage doubling is minimized. The arresters should operate and maintain the voltage at the discharge voltage level of the arresters. However, if arresters have not been applied at such points, the designer may wish to determine the allowable stroke currents for these locations considering voltage doubling. The allowable stroke current I_S can again be determined by dividing the results of calculations using Equations 5-2A and 5-2B by 2.

The designer should keep in mind that reduced BIL equipment is not protected by a design based on stroke current I_S . Such equipment should be protected by surge arresters in accordance with IEEE Std C62.22-1991 [B45].

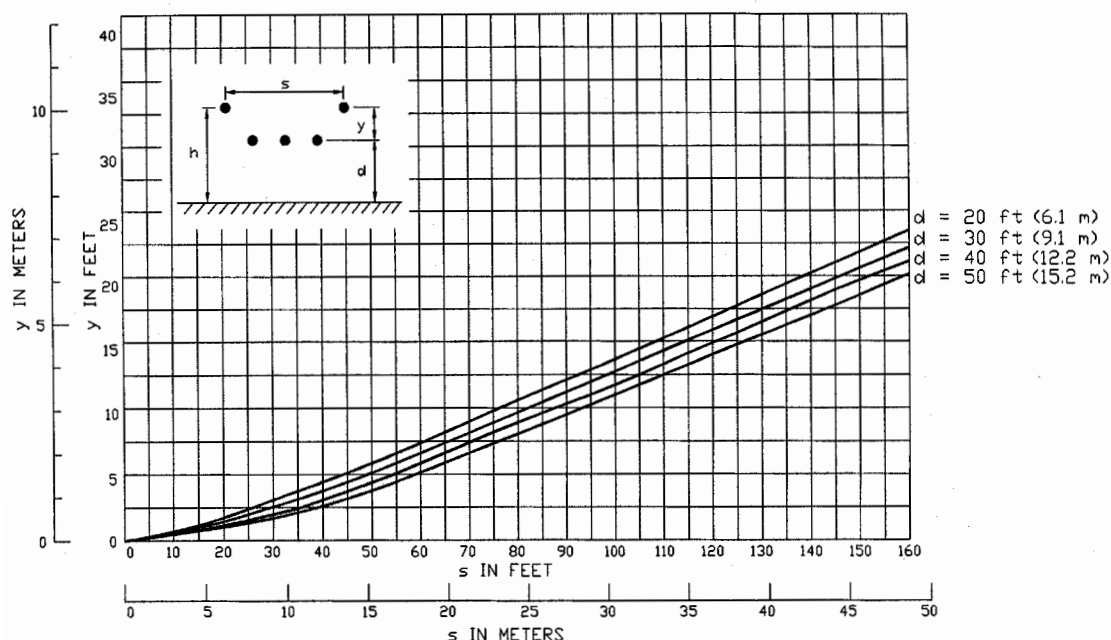


**Figure 4-14 —Two shield wires protecting horizontal conductors—1% exposure.
Height of shield wires above conductors, y , as a function of
horizontal separation, s , and height of protected conductors, d**

5.2.3 Withstand voltage of insulator strings

BIL values of station post insulators can be found in vendor catalogs. A method is given below for calculating the withstand voltage of insulator strings. Figure 5-2 gives the critical flashover voltage of insulator strings. These were compiled by Darveniza, et al. [B26] based on the experimental work of Paris, et al. [B76] and Fujitaka, et al. [B31], and were adopted by Anderson [B4]. The withstand voltage in kV at 2 μ s and 6 μ s can be obtained from figure 5-2 or calculated as follows:

$$V_{I2} = 0.94 \times 820 w \quad (5-3)$$

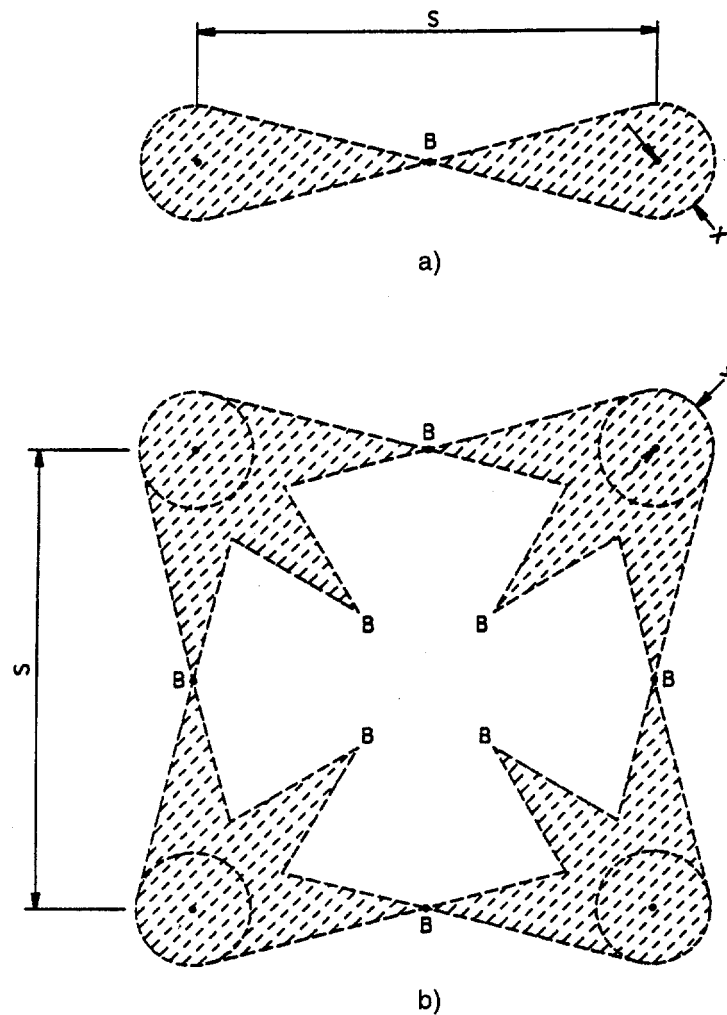
$$V_{I6} = 0.94 \times 585 w \quad (5-4)$$

where

- w is the length of insulator string (or air gap) in meters
- 0.94 is the ratio of withstand voltage to C.F.O. voltage
- V_{I2} is the withstand voltage in kilovolts at 2 μ s
- V_{I6} is the withstand voltage in kilovolts at 6 μ s

Equation 5-4 is recommended for use with the EGM.

Note that figure 5-2 is based on the application of pure lightning impulses. However, it can also be applied to the case where the stress on the insulators includes a power frequency component (ac or dc) as follows: A combined voltage surge stress consisting of an ac component equal to a (kV) and a lightning surge component equal to b (kV) can be considered equivalent to a pure lightning surge having an amplitude equal to $(a + b)$. This is the approach used by Anderson [B4] and by Clayton and Young [B23]. The paper by



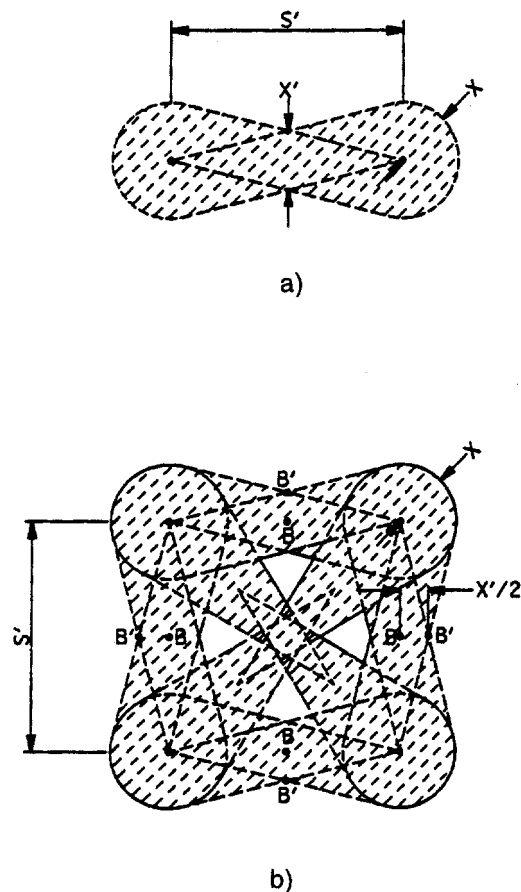
Source: Adapted from [B94]

Figure 4-15 —Areas protected by multiple masts for point exposures shown in figures 4-5 and 4-7 or 4-6 and 4-8
(a) With two lightning masts
(b) With four lightning masts

Hepworth, et al. [B41] and its discussion by K. Feser support the above approach, while an IEEE Working Group [B43] suggests that a dc bias may have a conditioning effect that would increase the *switching surge* strength of the gap under the combined stress beyond the value for a pure switching surge.

5.3 Application of the EGM by the rolling sphere method

The previous clauses introduced the concept of the electrogeometric model and gave the tools necessary to calculate the unknown parameters. The concept will now be further developed and applied to substation situations.



Source: Adapted from [B94]

Figure 4-16 —Areas protected by multiple masts for point exposures shown in figures 4-5 and 4-9 or 4-6 and 4-10 ($S'=0.5S$ in figure 4-15)
(a) With two lightning masts
(b) With four lightning masts

It was previously stated that it is only necessary to provide shielding for the equipment from all lightning strokes greater than I_s that would result in a flashover of the buswork. Strokes less than I_s are permitted to enter the protected zone since the equipment can withstand voltages below its BIL design level.

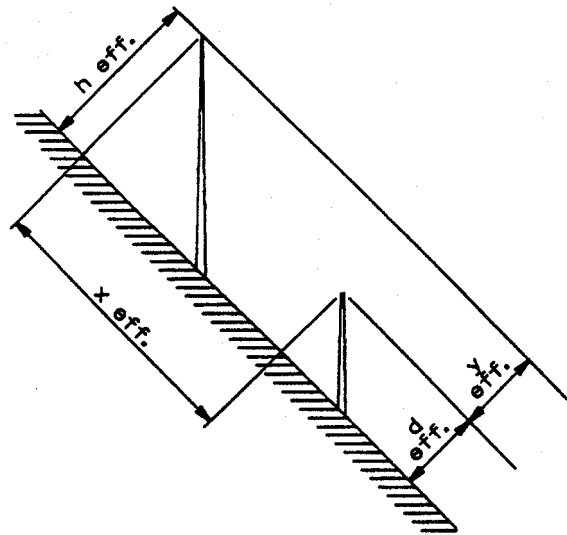
This will be illustrated by considering three levels of stroke current; I_s , stroke currents greater than I_s , and stroke current less than I_s . First, let us consider the stroke current I_s .

5.3.1 Protection against stroke current I_s

I_s is calculated from Eq 5-2 as the current producing a voltage the insulation will just withstand. Substituting this result in Eq 5-1 gives the striking distance S for this stroke current.

In 1977, Ralph H. Lee developed a simplified technique for applying the electromagnetic theory to the shielding of buildings and industrial plants [B48], [B49], [B50]. J.T. Orrell extended the technique to specifically cover the protection of electric substations [B74]. The technique developed by Lee has come to be known as the *rolling sphere* method. For the following illustration, the *rolling sphere* method will be used. This method employs the simplifying

assumption that the striking distances to the ground, a mast, or a wire are the same. With this exception, the rolling sphere method has been updated in accordance with the revised EGM described in 5.2.



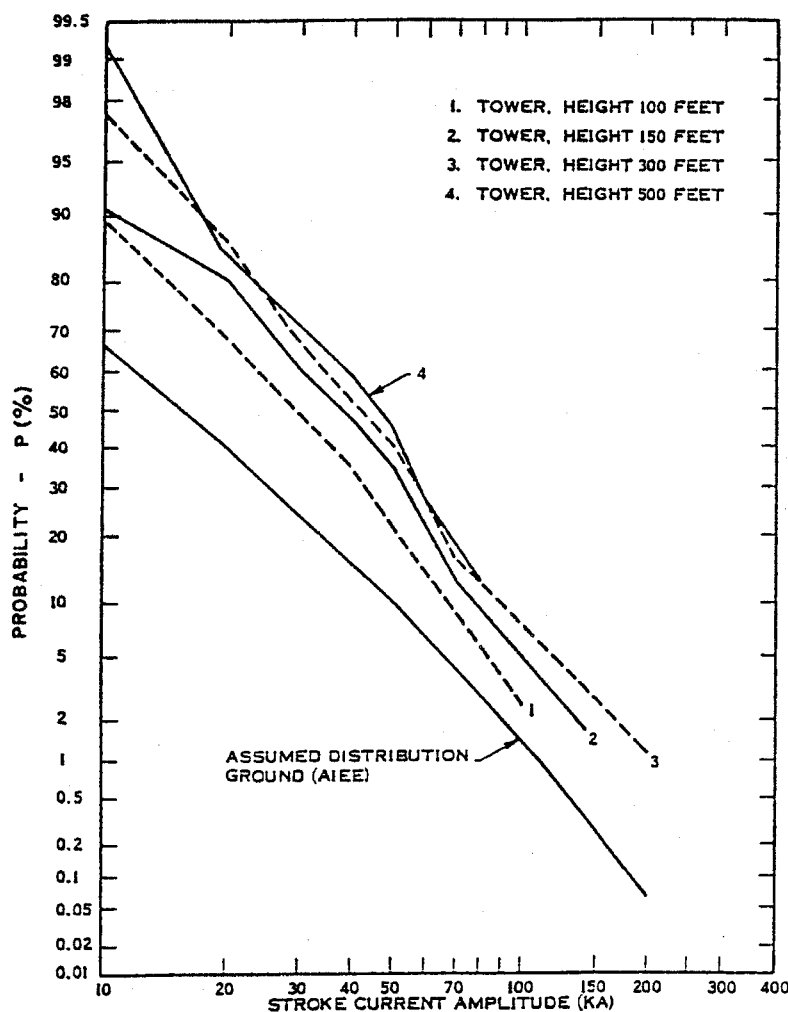
Source: Adapted from [B94]

Figure 4-17 —Effect of hillsides

Use of the *rolling sphere* method involves rolling an imaginary sphere of radius S over the surface of a substation. The sphere rolls up and over (and is supported by) lightning masts, shield wires, substation fences, and other grounded metallic objects that can provide lightning shielding. A piece of equipment is said to be protected from a direct stroke if it remains below the curved surface of the sphere by virtue of the sphere being elevated by shield wires or other devices. Equipment that touches the sphere or penetrates its surface is not protected. The basic concept is illustrated in figure 5-3.

Continuing the discussion of protection against stroke current I_s , consider first a single mast. The geometrical model of a single substation shield mast, the ground plane, the striking distance, and the zone of protection are shown in figure 5-4. An arc of radius S that touches the shield mast and the ground plane is shown in figure 5-4. All points below this arc are protected against the stroke current I_s . This is the protected zone.

The arc is constructed as follows (see figure 5-4). A dashed line is drawn parallel to the ground at a distance S (the striking distance as obtained from Eq 5-1) above the ground plane. An arc of radius S , with its center located on the dashed line, is drawn so the radius of the arc just touches the mast. Stepped leaders that result in stroke current I_s and that descend outside of the point where the arc is tangent to the ground will strike the ground. Stepped leaders that result in stroke current I_s and that descend inside the point where the arc is tangent to the ground will strike the shield mast, provided all other objects are within the protected zone. The height of the shield mast that will provide the maximum zone of protection for stroke currents equal to I_s is S . If the mast height is less than S , the zone of protection will be reduced. *Increasing the shield mast height greater than S will provide additional protection in the case of a single mast. This is not necessarily true in the case of multiple masts and shield wires.*



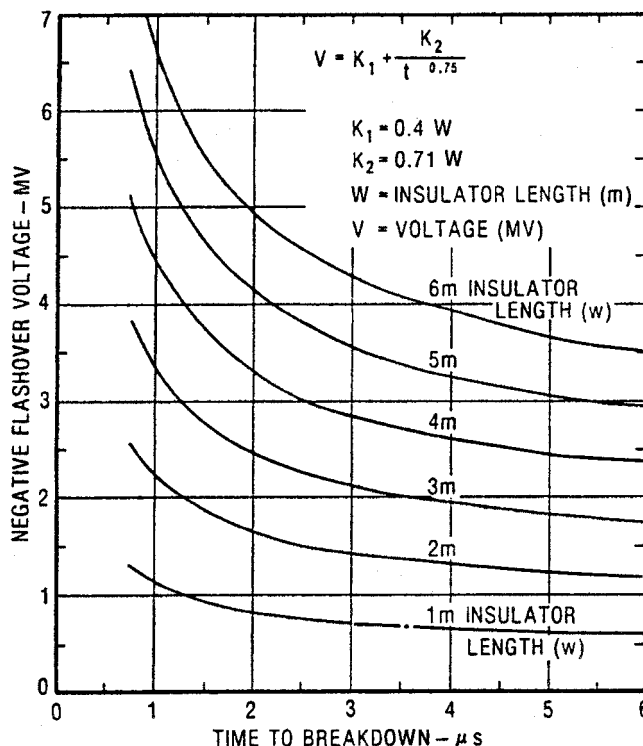
Source: [B84]

Figure 5-1 —Effect of height of structure on frequency distribution of lightning current amplitudes according to Sargent

The protection zone can be visualized as the surface of a sphere with radius S that is rolled toward the mast until touching the mast. As the sphere is rolled around the mast, a three-dimensional surface of protection is defined. It is this concept that has led to the name *rolling sphere* for simplified applications of the electrogeometric model.

5.3.2 Protection against stroke currents greater than I_s

Subclause 5.3.1 demonstrated the protection provided for a stroke current I_s . A lightning stroke current has an infinite number of possible magnitudes, however, and the substation designer will want to know if the system provides protection at other levels of stroke current magnitude.



Source: [B26]

Figure 5-2 — Volt-time curves for insulator strings

Consider a stroke current I_{s1} with magnitude greater than I_s . Strike distance, determined from Eq 5-1, is S_1 . The geometrical model for this condition is shown in figure 5-5. Arcs of protection for stroke current I_{s1} and for the previously discussed I_s are both shown. The figure shows that the zone of protection provided by the mast for stroke current I_{s1} is greater than the zone of protection provided by the mast for stroke current I_s .

Stepped leaders that result in stroke current I_{s1} and that descend outside of the point where the arc is tangent to the ground will strike the ground. Stepped leaders that result in stroke current I_{s1} and that descend inside the point where the arc is tangent to the ground will strike the shield mast, provided all other objects are within the S_1 protected zone. Again, the protective zone can be visualized as the surface of a sphere touching the mast. In this case, the sphere has a radius S_1 .

5.3.3 Protection against stroke currents less than I_s

It has been shown that a shielding system that provides protection at the stroke current level I_s provides even better protection for larger stroke currents. The remaining scenario to examine is the protection afforded when stroke currents are less than I_s .

Consider a stroke current I_{so} with magnitude less than I_s . The striking distance, determined from Eq 5-1, is S_o . The geometrical model for this condition is shown in figure 5-6. Arcs of protection for stroke current I_{so} and I_s are both shown. The figure shows that the zone of protection provided by the mast for stroke current I_{so} is less than the zone of protection provided by the mast for stroke current I_s . It is noted that a portion of the equipment protrudes above the dashed arc or zone of protection for stroke current I_{so} . Stepped leaders that result in stroke current I_{so} and that descend outside of the point where the arc is tangent to the ground will strike the ground. However, some stepped leaders that

result in stroke current I_{so} and that descend inside the point where the arc is tangent to the ground could strike the equipment. This is best shown by observing the plan view of protective zones shown in figure 5-6. Stepped leaders for stroke current I_{so} that descend inside the inner protective zone will strike the mast and protect equipment that is h in height. Stepped leaders for stroke current I_{so} that descend in the shaded unprotected zone will strike equipment of height h in the area. If, however, the value of I_s was selected based on the withstand insulation level of equipment used in the substation, stroke current I_{so} should cause no damage to equipment.

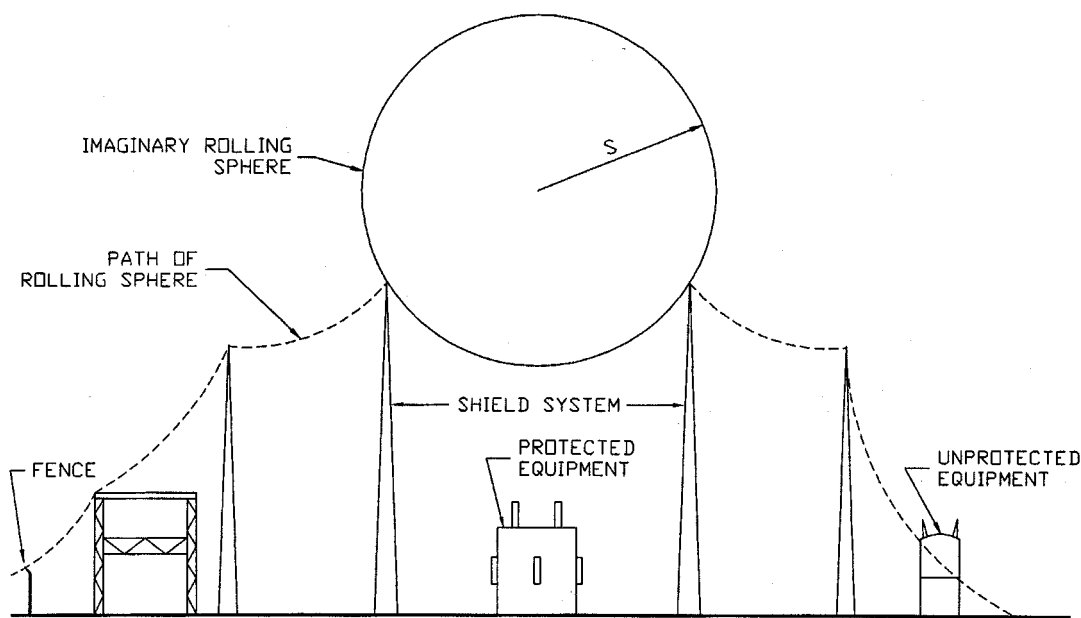


Figure 5-3 — Principle of rolling sphere

5.3.4 Multiple shielding electrodes

The electrogeometric modeling concept of direct stroke protection has been demonstrated for a single shield mast. A typical substation, however, is much more complex. It may contain several voltage levels and may utilize a combination of shield wires and lightning masts in a three-dimensional arrangement.

The above concept can be applied to multiple shielding masts, horizontal shield wires, or a combination of the two. Figure 5-7 shows this application considering four shield masts in a multiple shield mast arrangement. The arc of protection for stroke current I_s is shown for each set of masts. The dashed arcs represent those points at which a descending stepped leader for stroke current I_s will be attracted to one of the four masts. The protected zone between the masts is defined by an arc of radius S with the center at the intersection of the two dashed arcs. The protective zone can again be visualized as the surface of a sphere with radius S , which is rolled toward a mast until touching the mast, then rolled up and over the mast such that it would be supported by the masts. The dashed lines would be the locus of the center of the sphere as it is rolled across the substation surface. Using the concept of rolling sphere of the proper radius, the protected area of an entire substation can be determined. This can be applied to any group of different height shield masts, shield wires, or a combination of the two. Figure 5-8 shows an application to a combination of masts and shield wires.

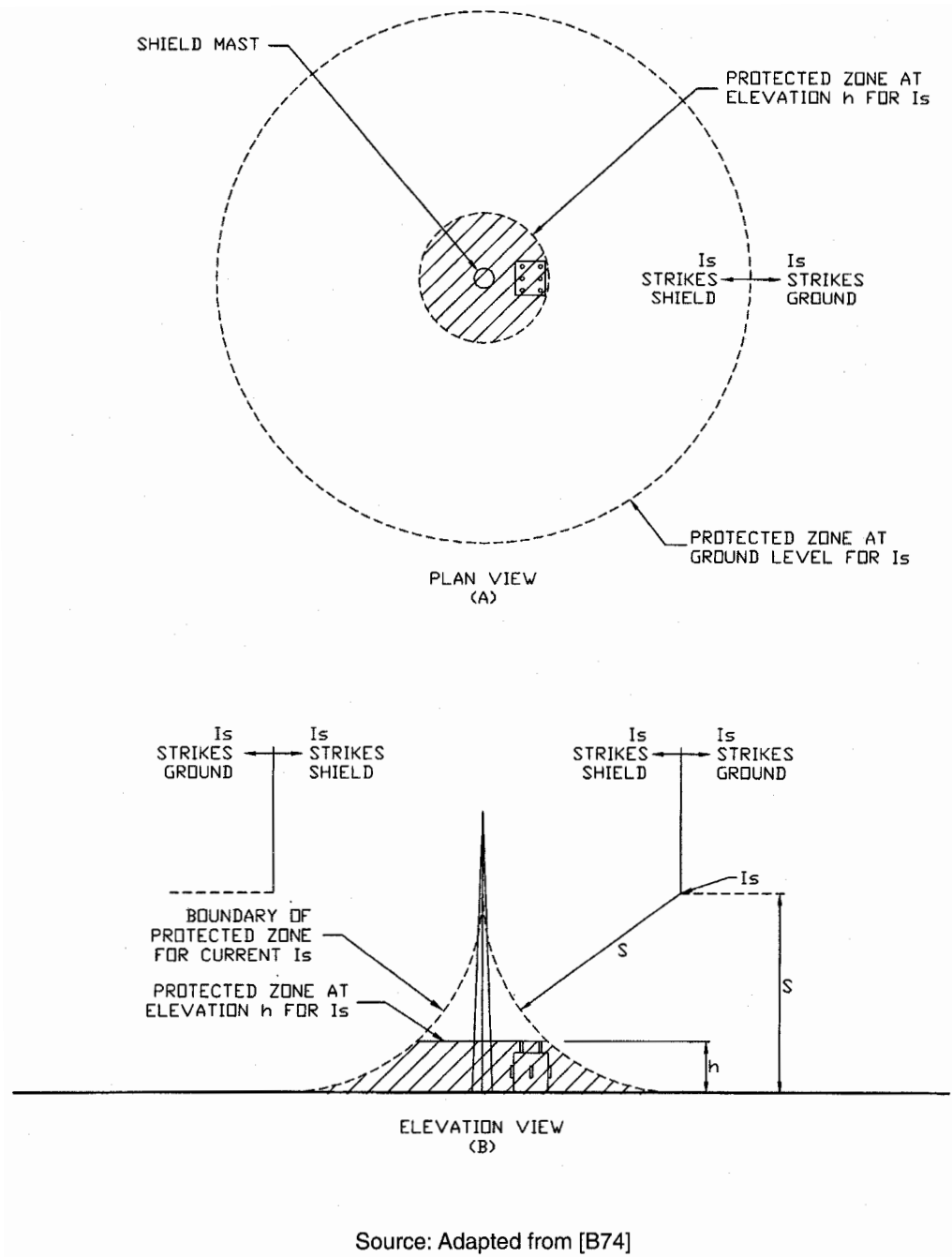
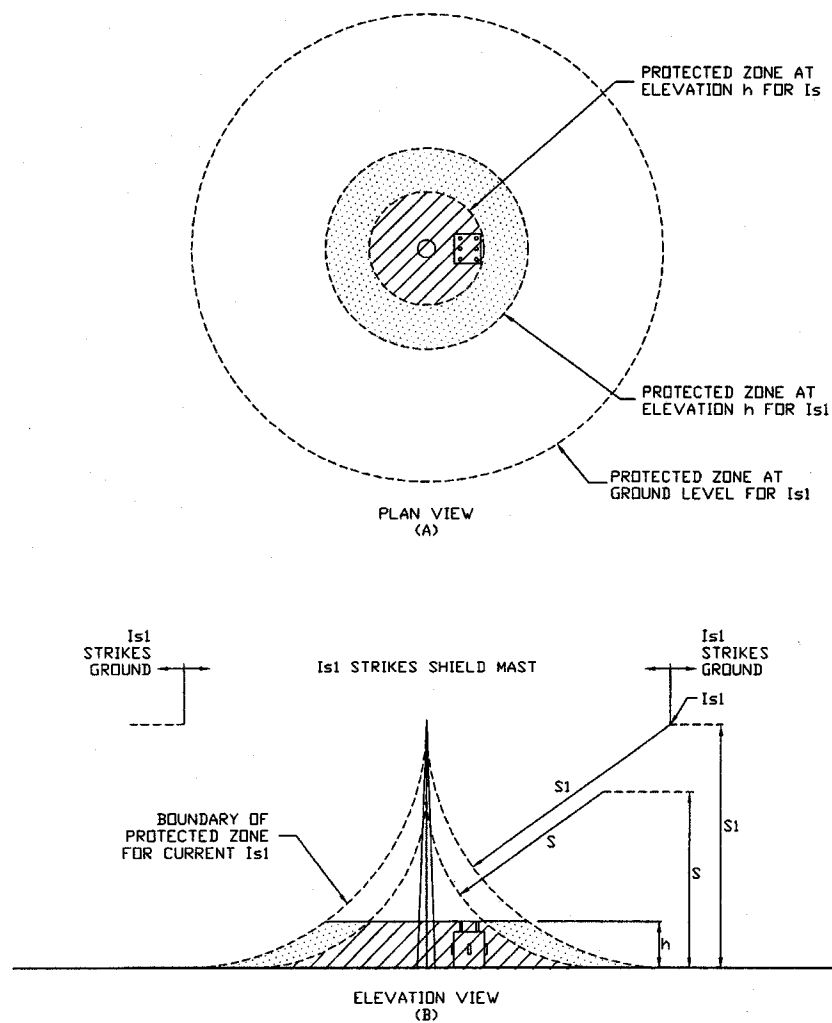
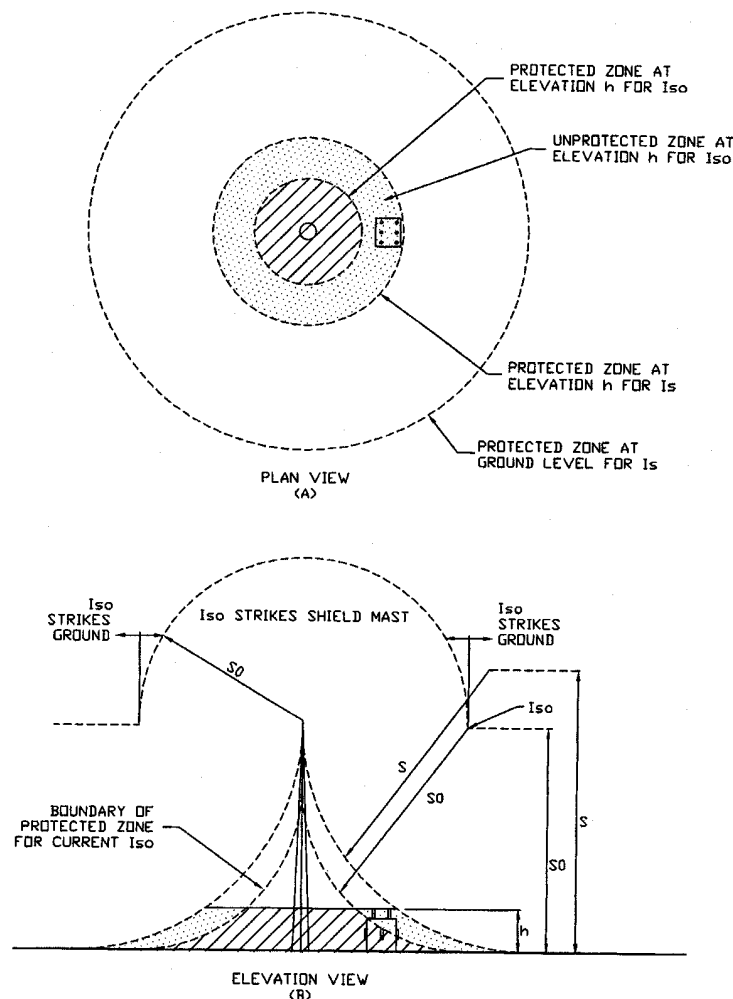


Figure 5-4 — Shield mast protection for stroke current I_s



Source: Adapted from [B74]

Figure 5-5 —Shield mast protection for stroke current I_{s1}



Source: Adapted from [B74]

Figure 5-6 — Shield mast protection for stroke current I_{so}

5.3.5 Changes in voltage level

Protection has been illustrated with the assumption of a single voltage level. Substations, however, have two or more voltage levels. The rolling sphere method is applied in the same manner in such cases, except that the sphere radius would increase or decrease appropriate to the change in voltage at a transformer. (Example calculations for a substation with two voltage levels are given in annex B.)

5.3.6 Minimum stroke current

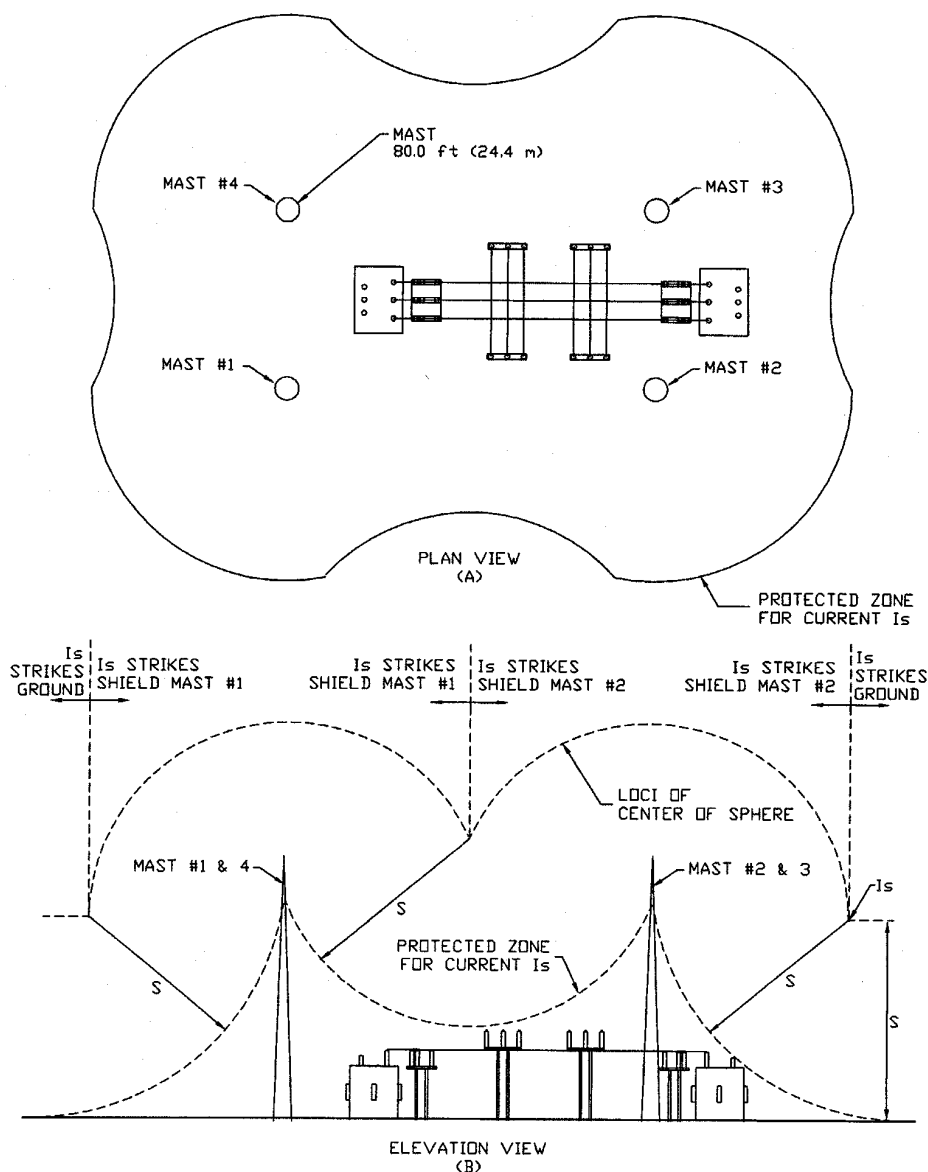
The designer will find that shield spacing becomes quite close at voltages of 69 kV and below. It may be appropriate to select some minimum stroke current, perhaps 2 kA for shielding stations below 115 kV. Such an approach is justified by an examination of figures 2-4 and 2-5. It will be found that 99.8% of all strokes will exceed 2 kA. Therefore, this limit will result in very little exposure, but will make the shielding system more economical.

5.4 Application of revised EGM by Mousa and Srivastava method

The rolling sphere method has been used in the preceding subclauses to illustrate application of the EGM. Mousa describes the application of the revised EGM [B60.] Figure 5-9 depicts two shield wires, G_1 and G_2 , providing shielding for three conductors, W_1 , W_2 , and W_3 . S_c is the critical striking distance as determined by Eq 5-1A, but

reduced by 10% to allow for the statistical distribution of strokes so as to preclude any failures. Arcs of radius S_c are drawn with centers at G_1 , G_2 , and W_2 to determine if the shield wires are positioned to properly shield the conductors. The factor ψ is the horizontal separation of the outer conductor and shield wire, and b is the distance of the shield wires above the conductors. Figure 5-10 illustrates the shielding provided by four masts. The height h_{mid} at the center of the area is the point of minimum shielding height for the arrangement. For further details in the application of the method, see [B60].

At least two computer programs have been developed that assist in the design of a shielding system. One of these programs [B71] uses the revised EGM to compute the surge impedance, stroke current, and striking distance for a given arrangement of conductors and shield systems, then advises the user whether or not effective shielding is provided. Sample calculations are provided in annex B to further illustrate the application.



Source: Adapted from [B74]

Figure 5-7 — Multiple shield mast protection for stroke current I_s

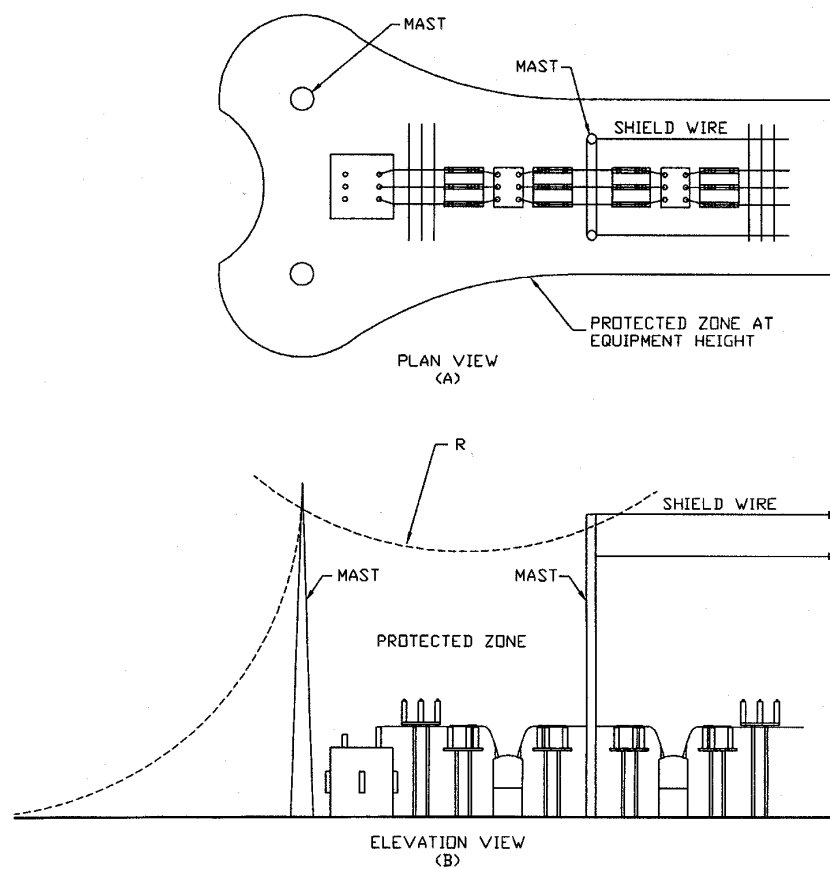
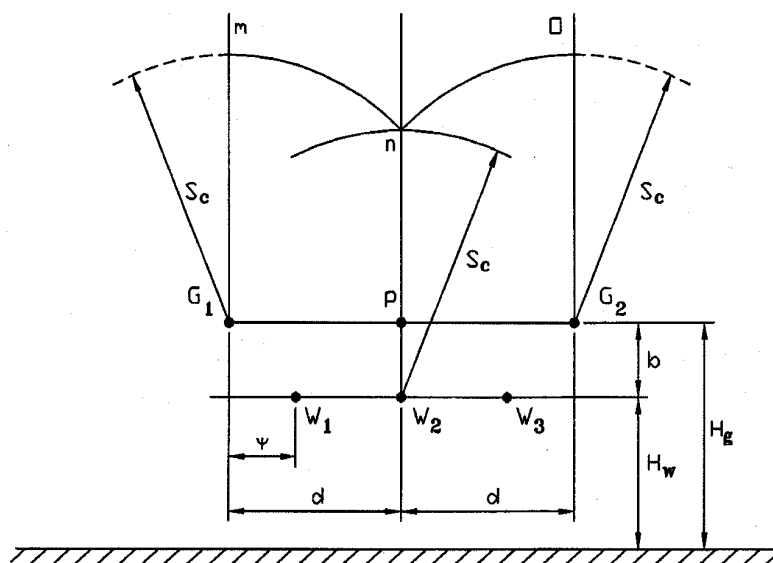
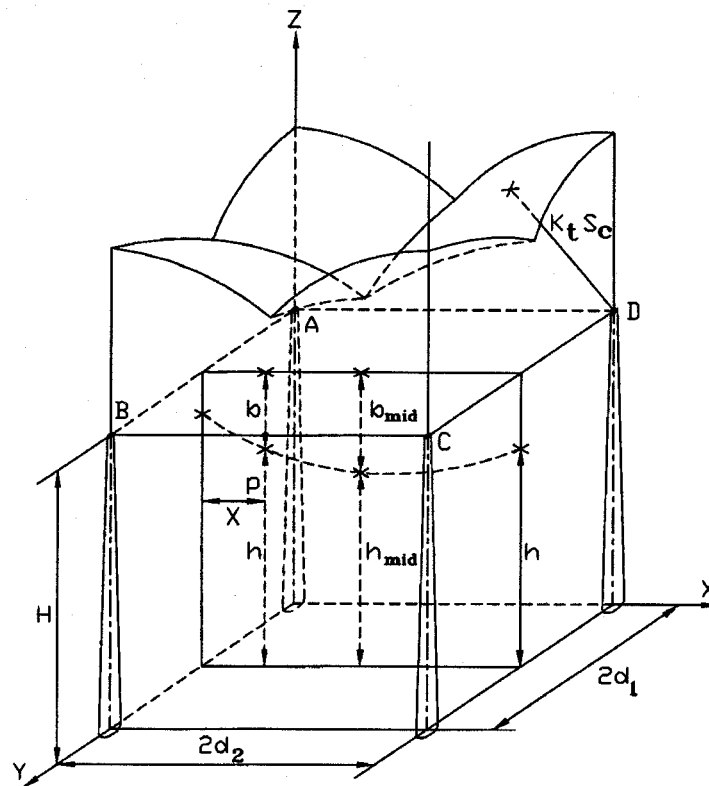


Figure 5-8 — Protection by shield wires and masts



Source: [B60]

Figure 5-9 — Shielding requirements regarding the strokes arriving between two shield wires



Source: [B60]

Figure 5-10 —Shielding of an area bounded by four masts

5.5 Calculation of failure probability

In the revised EGM just presented, striking distance is reduced by a factor of 10% so as to exclude all strokes from the protected area that could cause damage. In the Empirical design approach of clause 4, on the other hand, a small failure rate is permitted. Linck [B53] also developed a method to provide partial shielding using statistical methods.

It should be pointed out that for the statistical approach to be valid, the size of the sample needs to be large. For power lines that extend over large distances, the total exposure area is large and the above criterion is met. It is questionable, therefore, whether the statistical approach is as meaningful for substations that have very small exposure areas by comparison.

Engineers do, however, design substation shielding that permits a small statistical failure rate. Orrell [B74] has developed a method of calculating failure rates for the EGM rolling sphere method. This can be found in annexes D and G.

6. Active lightning terminals

In the preceding methods described in clauses 4 and 5, the lightning terminal is considered to be a *passive* element that intercepts the stroke merely by virtue of its position with respect to the live bus or equipment. Suggestions have been

made that lightning protection can be improved by using what may be called *active* lightning terminals. Three types of such devices have been proposed over the years:

- a) *Lightning rods with radioactive tips* [B36]. These devices are said to extend the attractive range of the tip through ionization of the air.
- b) *Early Streamer Emission (ESM) lightning rods* [B11]. These devices contain a triggering mechanism that sends high-voltage pulses to the tip of the rod whenever charged clouds appear over the site. This process is said to generate an upward streamer that extends the attractive range of the rod.
- c) *Lightning prevention devices*. These devices enhance the *point discharge* phenomenon by using an array of needles instead of the single tip of the standard lightning rod. It is said that the space charge generated by the many needles of the array neutralize part of the charge in an approaching cloud and prevent a return stroke to the device, effectively extending the protected area [B18].

Some of the latter devices have been installed on facilities (usually communications towers) that have experienced severe lightning problems. The owners of these facilities have reported no further lightning problems in many cases.

There has not been sufficient scientific investigation to demonstrate that the above devices are effective, and since these systems are proprietary, detailed design information is not available. It is left to the design engineer to determine the validity of the claimed performance for such systems. It should be noted that IEEE does not recommend or endorse commercial offerings.

7. Bibliography

- [B1] AIEE Committee, "A method of estimating lightning performance of transmission lines," *AIEE Transactions*, vol. 69, pt. 2, pp. 1187–1196, 1950.
- [B2] Alizade, A. A., Muslimov, M. M., and Khydyrov, E. L., "Study of Electric Field Strength Due to Lightning Stroke Currents," *Electric Technology USSR*, 1976, no. 4, pp. 51–56.
- [B3] Anderson, J. G., "Monte Carlo computer calculation of transmission-line lightning performance," *AIEE Transactions*, vol. 80, pp. 414–420, Aug. 1961.
- [B4] Anderson, J. G., Chapter 12 of *Transmission Line Reference Book 345 kV and Above*, 2nd Ed. Rev. Palo Alto, Calif.: Electric Power Research Institute, 1987.
- [B5] Anderson, R. B., and Eriksson, A. J., "Lightning Parameters for Engineering Application," *Electra*, no. 69, pp. 65–102, Mar. 1980.
- [B6] Berger, K., "Novel Observations on Lightning Discharges: Results of Research on Mount San Salvatore," *Journal of the Franklin Institute*, vol. 283, no. 6, pp. 478–525, June 1967.
- [B7] Berger, K., "Discussion of Group 33 on Lightning and Surges," *CIGRE Proceedings*, vol. 2, pp. 2, 10–11, 1968.
- [B8] Berger, K., "The Earth Flash," Chapter 5 in Golde, R. H. (Ed.), *Lightning*, vol. 1, London: Academic Press, 1977.
- [B9] Berger, K., and Vogelsanger, E., "New Results of Lightning Observations," CIGRE Paper no. 33–03, 11 pages (in vol. 2), 1968.
- [B10] Berger, K., Anderson, R. B., and Kroninger, H., "Parameters of Lightning Flashes," *ELECTRA*, no. 41, pp. 23–37, July 1975.

- [B11] Berger, G., and Floret, N., "Collaboration Produces a New Generation of Lightning Rods," *Power Technology International*, pp. 185–190, London: Sterling Publications, 1991.
- [B12] Bibliography of Publications Pertaining to Lightning Protection, IEEE Transmission Substation Subcommittee, *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-94, no. 4, pp. 1241–1247, July/Aug. 1975.
- [B13] Braunstein, A., "Lightning strokes to power transmission lines and the shielding effect of ground wires," *IEEE Transactions on Power Apparatus Systems*, vol. PAS-89, pp. 1900–1910, Nov./Dec. 1970.
- [B14] Brook, M., and Ogawa, T., "The Cloud Discharge," Chapter 6 in Golde, R. H. (Ed.), *Lightning*, vol. 1, London: Academic Press, 1977.
- [B15] Brown, G. W., "Lightning performance II—Updating backflash calculations," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-97, no. 1, pp. 39–52, 1978.
- [B16] Brown, G. W. and Whitehead, E. R., "Field and analytical studies of transmission line shielding: Part II," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-88, no. 5, pp. 617–626, 1969.
- [B17] Burgsdorf, V. V., "Lightning Protection of Overhead Transmission Lines and Operating Experience in the USSR," CIGRE Paper 326, 29 pages, 1958.
- [B18] Carpenter, R. B., Jr., "Lightning Elimination." Paper PCI-76-16 given at the 23rd Annual Petroleum and Chemical Industry Conference 76CH1109-8-IA.
- [B19] Changery, M. J., "National Thunderstorm Frequencies for the Contiguous United States," Report no. NUREG/CR-2252, *National Oceanic and Atmospheric Administration*, Ashville, NC, Nov. 1981.
- [B20] "Charge Dissipation Gives, For the First Time, Lightning Prevention." *Broadcast Management Engineering*, Sept. 1972.
- [B21] Cianos, N., Pierce, E. T., "A Ground-Lightning Environment for Engineering Usage." Stanford Research Institute, Technical Report 1, Aug. 1972.
- [B22] "CIGRE Sums up Lightning Research." *Electrical World*, vol. 194(2), pp. 72–75, July 15, 1980.
- [B23] Clayton, J. M. and Young, F. S., "Estimating lightning performance of transmission lines," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-83, pp. 1102–1110, 1964.
- [B24] Cobine, J. D., "Gaseous Conductors, Theory and Engineering Application." New York: Dove, 1952.
- [B25] Dainwood, W. H. and Kerckel, S. W., "An analytical approach to the design of a three-dimensional array of overhead shield wires," IEEE Conference Paper no. C75 044-3, 1975.
- [B26] Darveniza, M., Popolansky, F., and Whitehead, E. R., "Lightning Protection of UHV Transmission Lines," *Electra*, no. 41, pp. 39–69, July 1975.
- [B27] Eriksson, A. J., "Lightning and Tall Structures," *Trans. South African IEE*, vol. 69, no. 8, pp. 238–252, Aug. 1978. Discussion and Closure published May 1979, vol. 70, no. 5, 12 pages.
- [B28] Eriksson, A. J., "The incidence of lightning strikes to power lines," *IEEE Transactions on Power Delivery*, vol. PWRD-2, no. 3, pp. 859–870, 1987.
- [B29] Eriksson, A.J., "An improved electrogeometric model for transmission line shielding analysis," *IEEE Transactions on Power Delivery*, vol. PWRD-2, no.3, pp. 871–886.
- [B30] Fink, D. B., Beaty H.W., *Standard Handbook for Electrical Engineers*, 11th ed. New York: McGraw-Hill, 1978.