

IEEE Guide for Direct Lightning Stroke Shielding of Substations

IEEE Power and Energy Society

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Substations Committee



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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 reduce 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, which involves the use of non-conventional lightning terminals and related design methods, is also reviewed.

Keywords: collection volume method (CVM), direct stroke shielding, electro-geometric model (EGM), field intensification factor method (FIFM), fixed angle, IEEE 998™, leader inception theory (LIT), leader progression model (LPM), lightning stroke protection, self-consistent leader inception and propagation model (SLIM), substations empirical curves

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Introduction

This introduction is not part of IEEE Std 998™-2012, IEEE Guide for Direct Lightning Stroke Shielding of Substations.

Work on the original guide began in 1973 and many former members made contributions toward its completion.

Working Group D5 of the IEEE PES Substations Committee began updating the guide in 2008. This guide provides information about various shielding methodologies to estimate and design direct lightning stroke shielding for outdoor substations. Calculation details, design estimates, and generally accepted practices for substation shielding designs are provided. This guide can be beneficial for engineers in evaluating direct lightning stroke shielding design for outdoor substations.

Dedication

This revision of IEEE Std 998 is dedicated to the memory of Gary R. Engmann. Gary through his membership in this working group and many others was always in the forefront with his statement “that the purpose of a guide is to disseminate information to practicing engineers.” Gary had a long association and leadership with the IEEE Substations Committee, NESC, IEEE-SA, and many other Technical Committees and Working Groups. He did not back away from tasks whether controversial or not. His leadership of the IEEE 998 “Bucket Brigade” was an insightful contribution to the development of this revision. His knowledge, humor, and keen insight into the day-to-day needs of all of us will be sorely missed.

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1. Overview

1.1 Scope

This ~~The scope of this~~ guide identifies and discusses design procedures to provide direct stroke shielding of outdoor distribution, transmission, and generating plant substations. ~~At~~ 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 [non-conventional active](#) lightning terminals [and related design methods](#), is [also](#) ~~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

[Direct strokes from lightning can damage substation equipment and bus work. To protect equipment, substation engineers can install direct stroke lightning shielding. This guide is intended to provide engineers with information pertaining to the interception of damaging direct lightning strokes to outdoor substations.](#)

[This guide includes methods that have been utilized for decades as well as some that have been developed more recently.](#) ~~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 [shielding](#) ~~protection~~ from direct [strokes](#) ~~strikes~~ are described ~~in clause 3~~. [Tables, formulas, and examples are provided to calculate whether substation equipment is effectively shielded from direct lightning strokes](#) ~~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.~~

Because of the unpredictability of lightning and the costs associated with damage from direct lightning strokes, research into lightning phenomenon is ongoing. This guide includes descriptions of four nonconventional modeling methods for lightning interception, as well as a review of active lightning terminals. The four non-conventional methods are in various stages of development and are presented as a sample of the continuing research in direct lightning stroke shielding. These methods have potential to be used as design models for substation direct lightning stroke shielding in the future.

A bibliography for further study is included to provide the substation shielding engineer with additional lightning research.

2. Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.¹

~~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.~~

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. The critical stroke amplitude can flow from the first stroke or any of the subsequent strokes in a lightning flash.

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

¹IEEE Standards Dictionary Online subscription is available at: http://www.ieee.org/portal/innovate/products/standard/standards/standards_dictionary.html.

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

effective shielding: That which permits lightning strokes no greater than those of critical amplitude (less design margin) to reach phase conductors. Effective (100% reliable) shielding cannot be achieved in substations because subsequent strokes can flow in the same channel established by the first stroke in a flash, and the models of first-stroke termination of flashes rely on statistical relationships among lightning parameters.

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 the first return stroke of a lightning flash ~~stroke~~ will terminate on the shielding system, the earth, or the element of the facility being protected.

electrogeometric model theory: The theory describing the electrogeometric model together with the related quantitative analyses including the correlation between the striking distance and the electrical parameters, such as charge and peak current, of the prospective ~~to the different elements of the model and the amplitude of the~~ first return stroke.

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

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

keraunic level: 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 in which thunder is heard during a 24-hour period. 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-minute period.

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

NOTE— For the purpose of this guide, the terms *lightning flash* and *lightning stroke* are used interchangeably because stroke multiplicity does not alter the design for direct stroke shielding of substations.²

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.

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.**

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.**

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.

² Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

shielding angle: (A) (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. (B) (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 [of the mast](#) to earth at some selected angle with the vertical. Rotation of this angle around the 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 [shielding angle](#); and negative shielding angle.**

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). *Syn:* **overhead ground wire (OHGW); static wire; sky wire.**

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.

striking distance: The length of the final jump [between](#) ~~of~~ the [downward](#) stepped leader [and the grounded structure](#), as [the electric field in this gap](#) ~~its potential~~ exceeds the [electrical breakdown strength](#). [The length of the final jump is a function of the leader potential, the associated charge, the rate of change of electric field, and the geometry of the gap. The first peak return stroke currents of negative downward lightning flashes are reasonably correlated with the respective impulse charge values](#) ~~resistance of this last gap; found to be related to the amplitude of the first return stroke.~~

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

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.

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

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

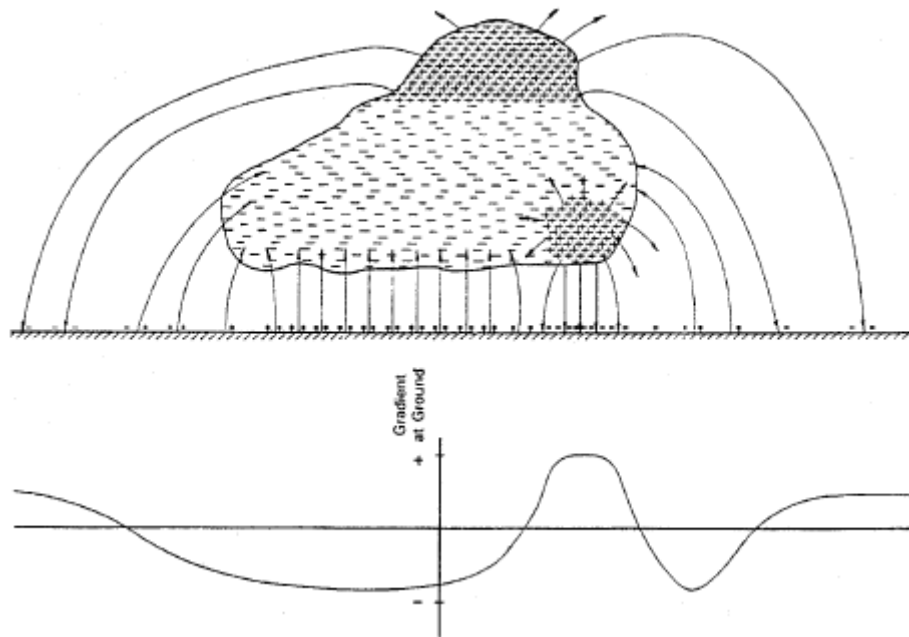
3. Lightning ~~stroke~~ phenomena

3.1 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 [by Wagner \[B142\]³](#) ~~in [B95]~~.)

³ [The numbers in brackets correspond to those of the bibliography in Annex I.](#)

It has even been suggested that perhaps all of the physical phenomena postulated in the various theories [can](#) ~~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 [by Wagner, McCann, and Beck](#), 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 [[B143](#) [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 1 (Note that the plot in Figure 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 1 have been verified by data obtained [by Fink and Beaty](#) from ground gradient measuring equipment during the passage of storm clouds [[B51](#) [B30](#)].



(From Orrell, J. T., "Direct Stroke Lightning Protection," paper presented at EEI Electrical System and Equipment Committee Meeting, Washington, D.C., 25 Oct. 1988 [reproduced in Annex G].)

~~Permission to use granted by Black & Veatch.~~

~~Originally presented at EEI Electrical System and
Equipment Committee Meeting, October 25, 1988.~~

~~Source: [874].~~

Figure 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.

3.2 Stroke formation

3.2.1 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.

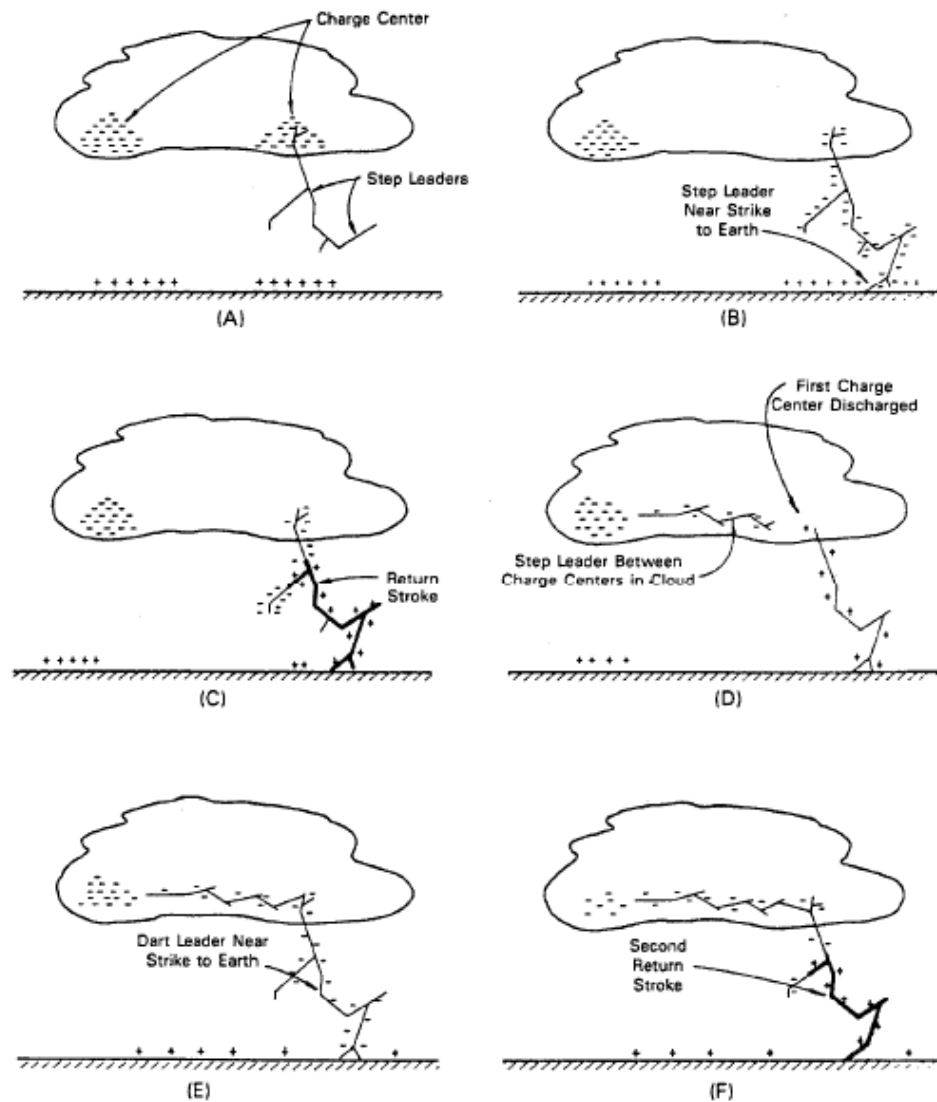
3.2.2 Stepped leaders

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 ([Wagner \[B142\]](#)) ~~[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 [150 000 m/s](#) ([Anderson \[B7\]](#)). [This produces electric fields near ground with rise times on the order of 100 to 500 microseconds. Electric fields of 250 microseconds from switching surge overvoltages tend to produce the minimum electrical strength of large air gaps compared to 1.2/50 microsecond lightning overvoltages](#) ~~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.

3.2.3 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 ([flat ground](#)) to cloud to neutralize the charge center ([Mousa and Srivastava \[B109\]](#)) ~~[B70]~~. The velocity of the return stroke propagation is [lower than](#) ~~about 10%~~ the speed of light [and varies with atmospheric conditions; an approximate value can be 10% of the speed of light \(Rakov and Uman \[B126\]\)](#) ~~, or approximately $100 \bullet 10^6$ ft/s ($30 \bullet 10^6$ 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. 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 are referenced as ~~a~~ *dart leaders* ([Wagner \[B142\]](#)) ~~[B95]~~.



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— Charge distribution at various stages of lightning discharge

3.3 Striking distance

The lightning attachment process is a complex process, and one of the least understood parts of lightning discharges. There are many models of the lightning attachment process and they can produce different, often conflicting, values for the protective radius of lightning air terminals.

Return stroke current magnitude and striking 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:

$$S = 2I + 30(1 - e^{-I/6.8}) \quad \text{Darveniza [B44]} \quad (1)$$

$$S = 10I^{0.65} \quad \text{Love [B7] [B77]} \quad (2)$$

$$S = 9.4I^{2/3} \quad \text{Whitehead [B146]} \quad (3)$$

$$S = 8I^{0.65} \quad \text{IEEE [B77]} \quad (4)$$

$$S = 3.3I^{0.78} \quad \text{Suzuki [B136]} \quad (5)$$

where

S is striking distance in meters

I is the return stroke current in kiloamperes

It ~~can may~~ be disconcerting to note that Equation (1), Equation (2), and Equation (3), vary by as much as a factor of 2:1. The Working Group makes use of the ~~However, lightning investigators now tend to favor the~~ shorter striking distances given by Equation (4) throughout this guide. J. G. Anderson, ~~for example, who~~ adopted Equation (2) in the 1975 edition of the *Transmission Line Reference Book* [B7], and then Equation (4) [B4], now feels that Eq 2-1D is more accurate. Mousa [B112 B67] also supports this form of the equation. Scientific research is ongoing and lightning experts can revise their position. Equation (4) has been adopted for this guide and restated ~~.The equation may also be stated~~ as follows:

$$I = 0.041S^{1.54} \quad (6)$$

This relationship is shown graphically in Figure 3. ~~From this point on, the return stroke current will be referenced in this guide as the stroke current.~~

Eriksson was the first of several researchers in the late 1980s to refine the calculation of striking distance by introducing height dependence. Height dependence, as well as geometry-specific gap factors, is an important part of switching surge overvoltage coordination, and this has guided development of leader progression models for the final jump. CIGRE Technical Brochure 118 [B34] provides a balanced review of the proposed models using these theories.

The refined Eriksson equations for striking distance including structure height are shown in Equation (7) for shield masts and Equation (8) for shield wires [B46].

$$S = 0.84I^{0.74}H^{0.6} \quad (7)$$

$$S = 0.67I^{0.74}H^{0.6} \quad (8)$$

where

S is striking distance in meters

I is the return stroke current in kiloamperes

H is the structure height in meters

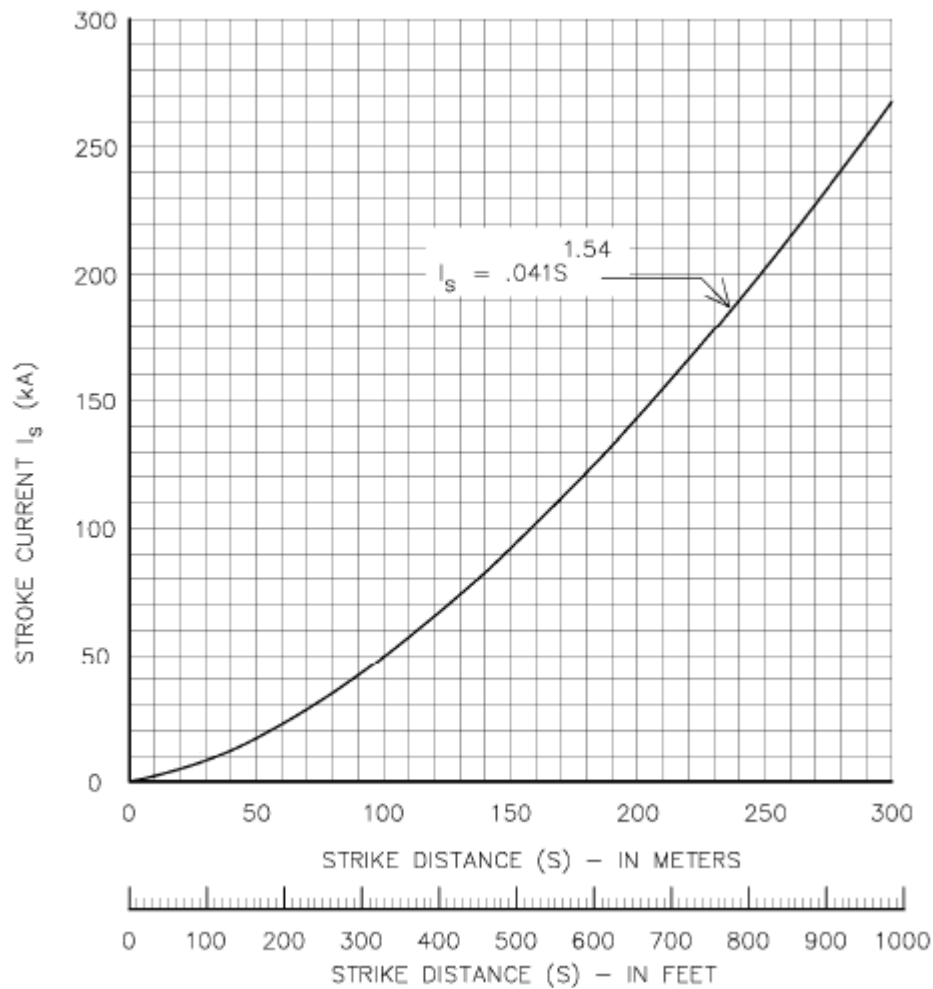


Figure 3—Stroke current versus striking distance

3.4 First negative return stroke current magnitude

The striking distance is correlated to the impulse charge, which in turn has a good correlation coefficient of 0.77 with peak negative first stroke current (Mousa and Srivastava [B19]). 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 overhead ground wire (OHGW), conductors, structures, and masts is often ~~usually~~ taken to be 31 kA [B4] (Anderson [B7 B4]). Anderson [B7] gave the probability that a certain peak current will be exceeded in any stroke as follows:

$$P(I) = \frac{1}{1 + \left(\frac{I}{31}\right)^{2.6}} \quad (9)$$

where

$P(I)$ is the probability that the peak current in any stroke will exceed I_s

I is the specified crest current of the stroke in kiloamperes

Mousa [B109 B70] has proposed the use of ~~shown that~~ a median stroke current of 24 kA as shown in Equation (10) for strokes to flat ground as these coorelated ~~produces the best correlation~~ with available field observations at the time. This gives a superior fit to the recommended CIGRE log-normal curve [B35] than Equation (9) in the shielding failure regime below 12 kA ~~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:~~

$$P(I) = \frac{1}{1 + \left(\frac{I}{24}\right)^{2.6}} \quad (10)$$

where the symbols have the same meaning as above.

Figure 4 is a plot of Equation (10), and Figure 5 is a plot of the probability that a stroke will be within the ranges shown on the abscissa.

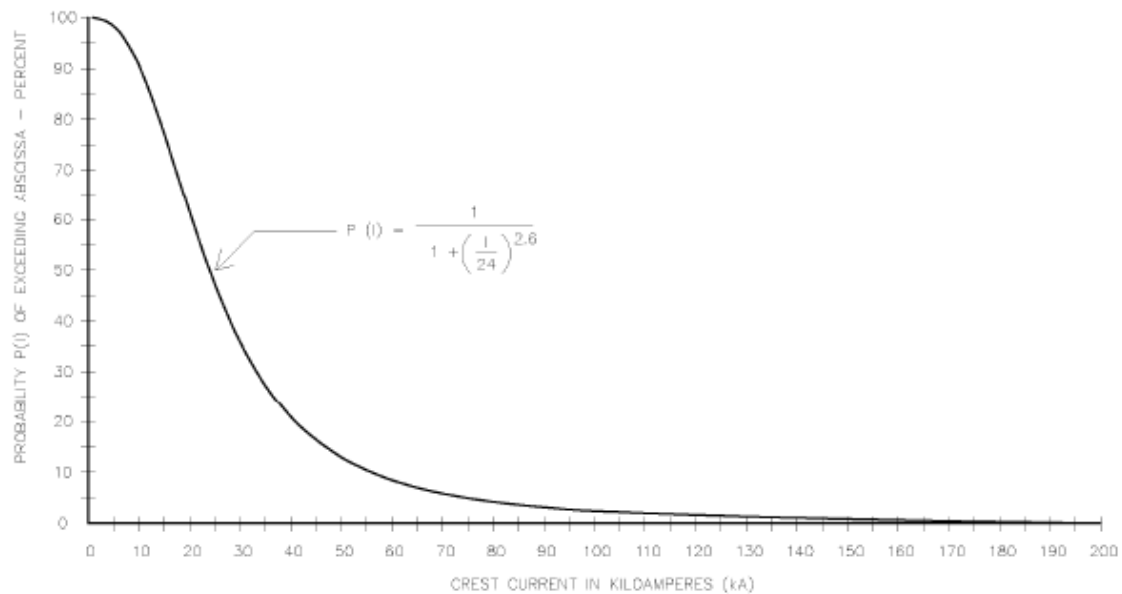
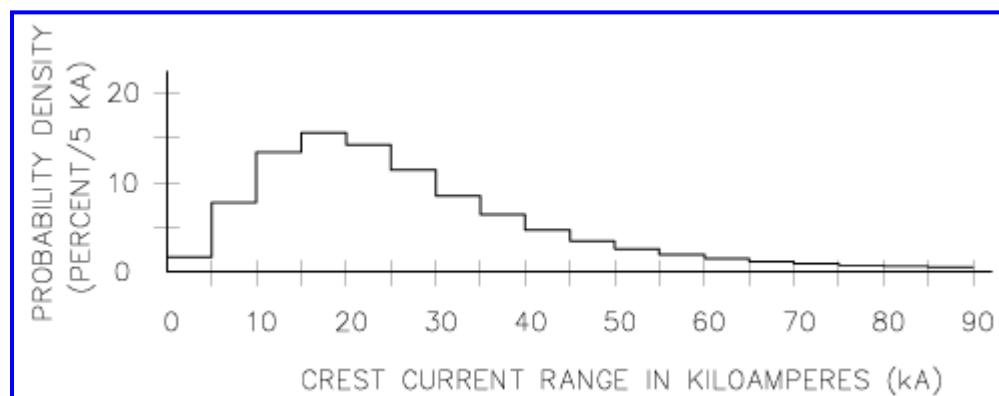
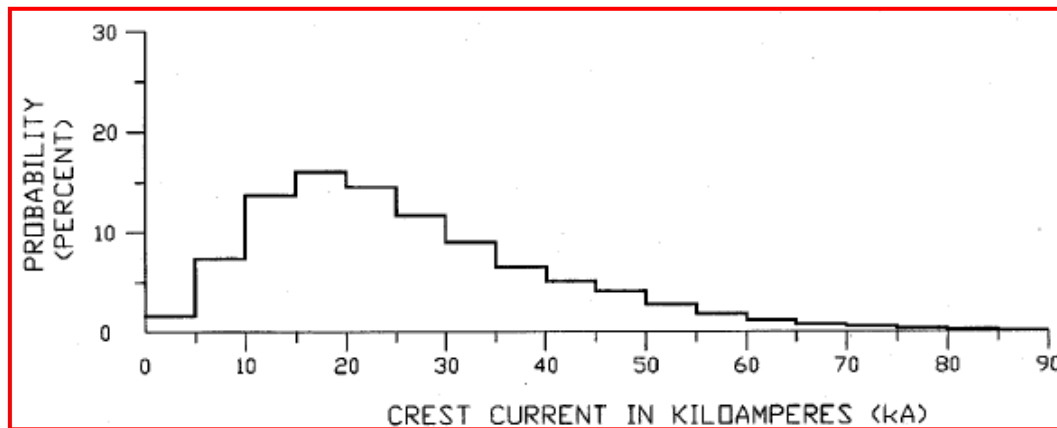


Figure 4—Probability of first negative return stroke peak current exceeding abscissa for strokes to flat ground



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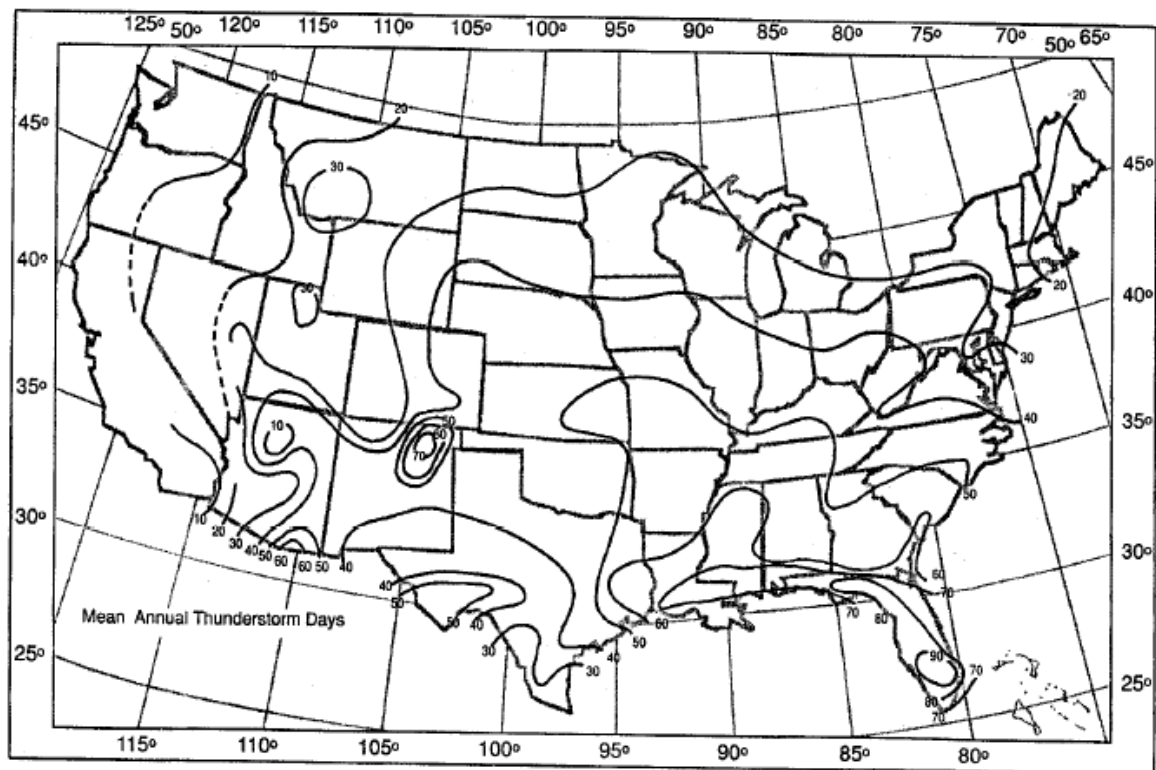
Figure 5—First negative return stroke peak current range probability for strokes to flat ground

3.5 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 is a day (24 hours) during ~~and is the average number of days per year on~~ which thunder has been ~~will be~~ heard at least once ~~during a 24 h period~~. By this definition, it makes no difference how many times thunder is heard during a 24-hour 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). Isokeraunic level is the average number of thunderstorm days in a year.

The National Oceanic and Atmospheric Administration (NOAA) now maintains ~~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 1-hour rain 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.

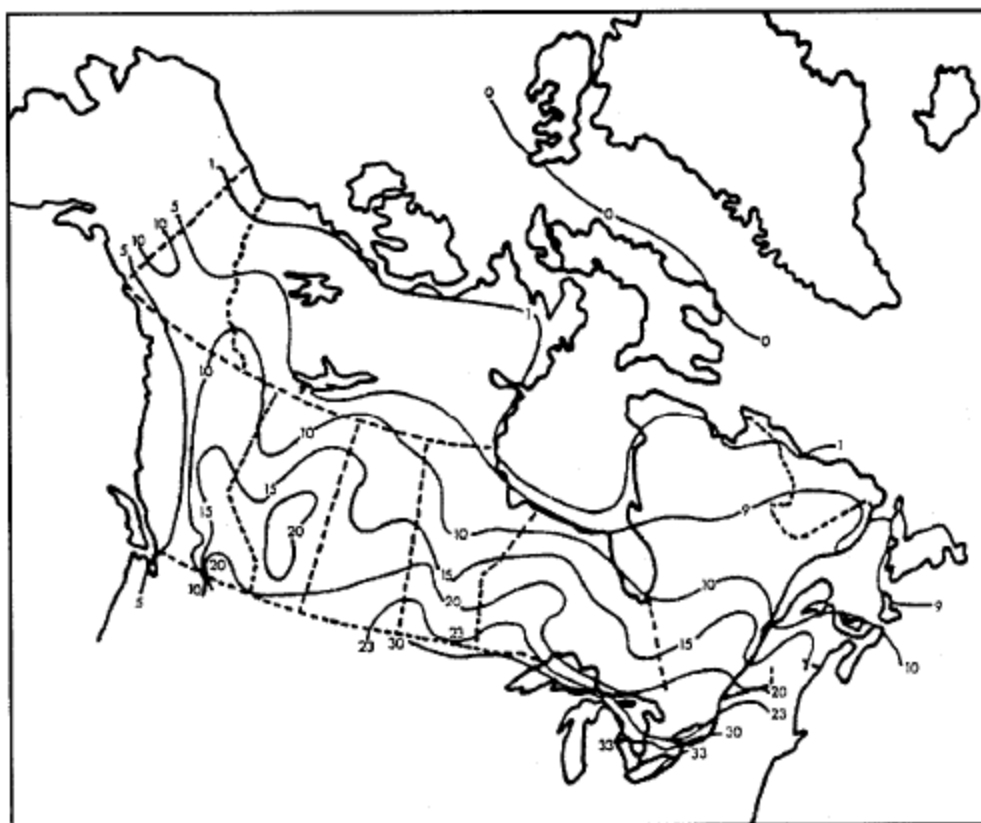
The average annual keraunic level for locations in the United States can be determined by referring to isokeraunic maps on which lines of equal keraunic level are plotted on a map of the country. Figure 6, Figure 7 and Figure 8 give the mean annual thunderstorm days for the United States, Canada, and the world ~~based on thunderstorm days~~. Figure 9 ~~shows gives~~ the keraunic level for the United States 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 [B90 B54]. ~~Combined thunderstorm hour data for the U.S. and Canada can also be found in Figure II of [B46a].~~



(Source: The National Oceanic and Atmospheric Administration [B90].)

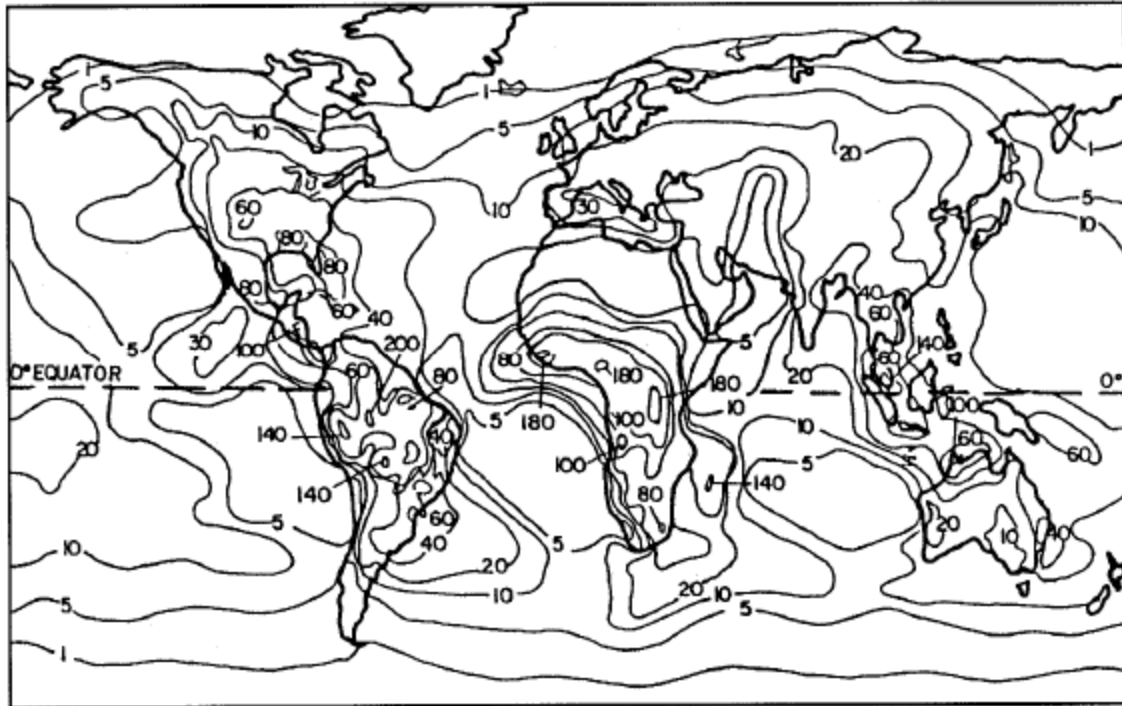
Source: NOAA

Figure 6—Mean annual thunderstorm days, United States



Source: (Data from Meteorological Division, Department of Transportation, Canada. [Copyright © Environment Canada, used with permission.](#))

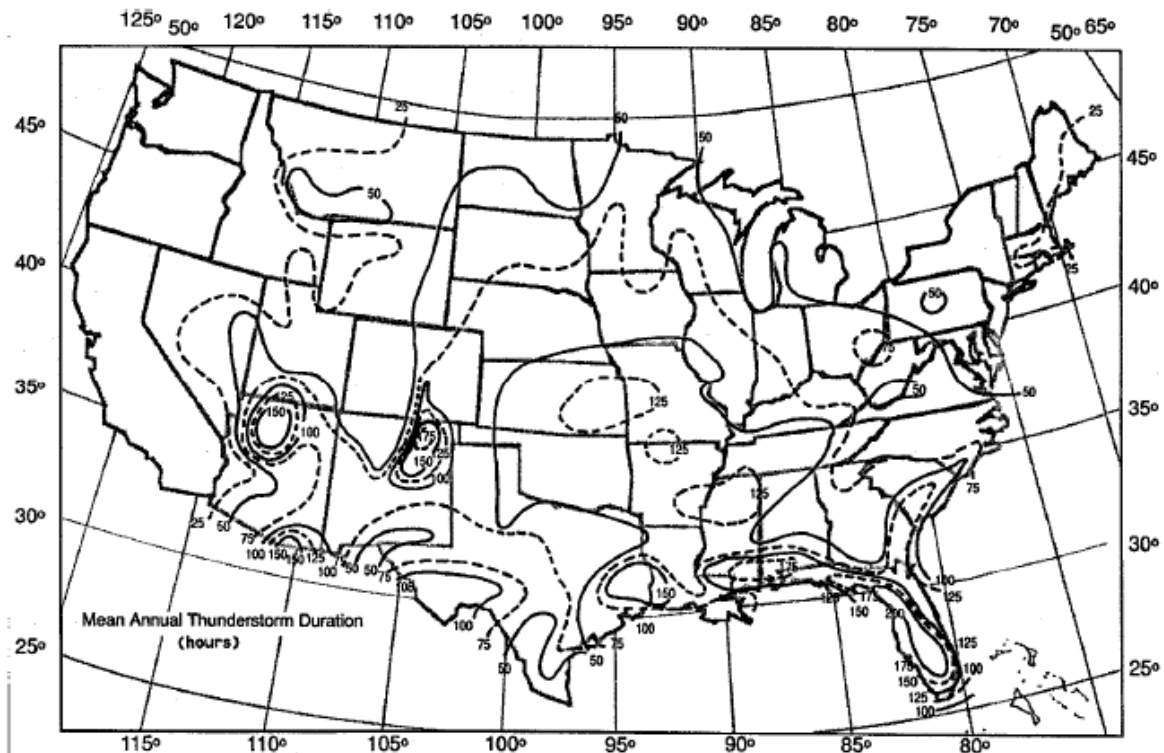
Figure 7—Mean annual thunderstorm days, Canada



(Source: The National Oceanic and Atmospheric Administration [B90].)

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

Figure 8— Mean annual thunderstorm days, the world



(Source: The National Oceanic and Atmospheric Administration [B90].)

Source: NOAA

Figure 9—Mean annual thunderstorm duration (hours), United States

3.6 Ground flash density

Ground flash density (GFD) is defined as the average number of [lightning](#) 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 1 ~~taken from [B4]~~ gives various equations for GFD [that have been](#) ~~as~~ developed by various researchers around the world. These researchers arrived at a proportional relationship ranging from $0.1 T$ to $0.19 T$ 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 either Equation (11) or Equation (12) [\(Anderson \[B7\]\)](#) ~~[B4]~~ be used:

$$N_k = 0.12T_d \quad (11)$$

$$N_m = 0.31T_d \quad (12)$$

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 [are](#) ~~is~~ to be used as a basis, Equation (13) or Equation (14) by MacGorman, [Maier, and Rust \[B90\]](#) ~~et al. [B54]~~ is [suggested](#) ~~recommended~~.

$$N_k = 0.054T_h^{1.1} \quad (13)$$

or

$$N_m = 0.14T_h^{1.1} \quad (14)$$

where

T_h is the average annual keraunic level, thunderstorm hours

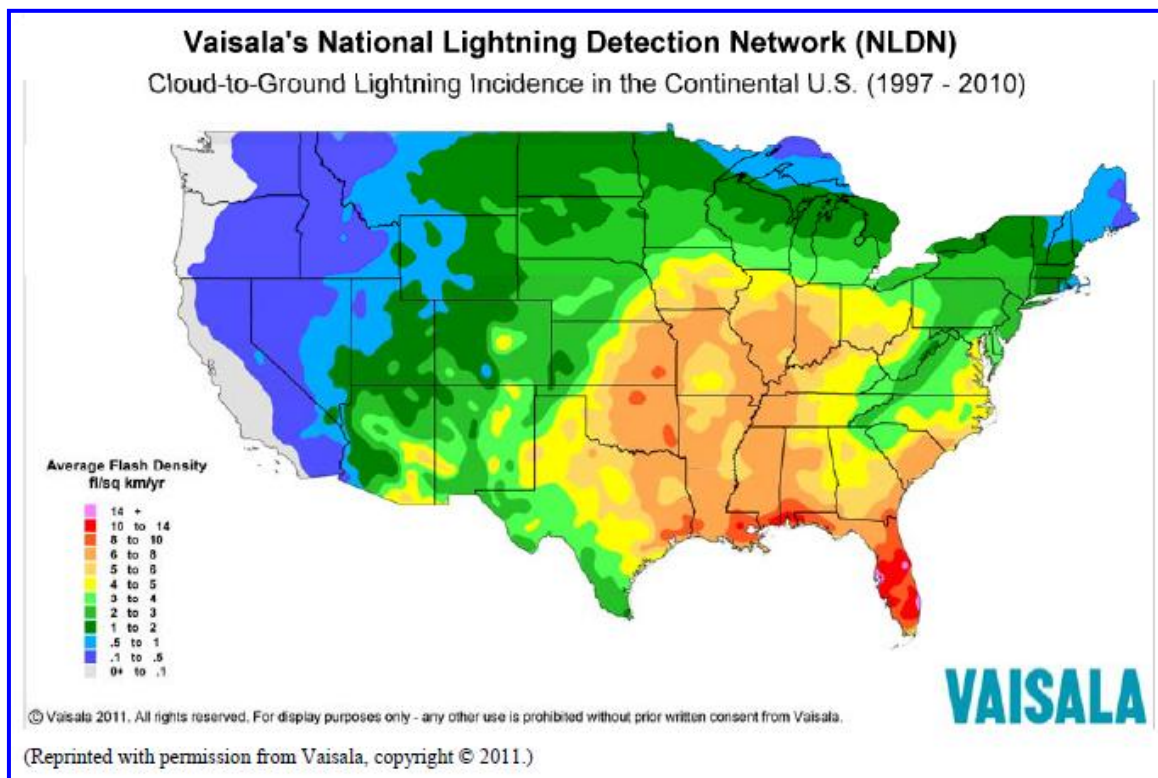
The resulting ground flash density using Eq 2-4A is shown in figure 2-10.

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

Location	Ground Flash Density <u>Ground Flashes</u> /km2/year	Reference
<u>World (Temperate Areas)</u>	<u>$0.040T^{1.25}$</u>	<u>Anderson [B7], [B8], [B9]</u>
<u>Mexico</u>	<u>$0.024T^{1.12}$</u>	<u>IEEE Std 1410™ -2010 [B74]</u>
<u>Brazil</u>	<u>$0.030T^{1.12}$</u>	<u>IEEE Std 1410-2010</u>
<u>Columbia</u>	<u>$0.0017T^{1.56}$</u>	<u>IEEE Std 1410-2010</u>
India	$0.1T$	Aiya (1968)
Rhodesia	$0.14T$	Anderson and Jenner (1954)
South Africa	$0.04T^{1.25}$	Eriksson [B50] (1987)
Sweden	$0.004T^2$ (approx.)	Muller-Hillebrand [B114] (1964)
United Kingdom	<u>$0.0026T^{1.9}$</u> aT^b	Stringfellow [B136] (1974) $\{a=2.6\pm0.2\times10^{-3}; b=1.9\pm0.1\}$
United States (North)	$0.11T$	Horn and Ramsey [B64] (1951)

Location	Ground Flash Density Ground Flashes /km2/year	Reference
United States (South)	0.17T	Horn and Ramsey [B64] ~~(1951)~~
United States	0.10T	Anderson et al. [B10] ~~and others (1968)~~
United States	0.15T	Brown and Whitehead [B25] ~~(1969)~~
Russia	0.036T ^{1.30}	Kolokolov and Pavlova [B80] ~~(1972)~~
~~World (temperate climate)~~	~~0.19T~~	~~Brooks (1950)~~
World (Temperate Climate)	0.15T	Golde [B57] ~~(1966)~~
~~World (tropical climate)~~	~~0.13T~~	~~Brooks (1950)~~

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



[\(New\)](#)

Figure 10— Ground flash density map of contiguous United States

3.7 Lightning detection networks

Lightning detection networks have been installed in North America and other parts of the world. These lightning detection networks have improved the accuracy of ground flash density maps as shown in Figure 10.

Vaisala's National Lightning Detection Network contains over 100 ground-based lightning detection systems in the United States. Whenever lightning strikes the earth, the electromagnetic signal is detected and information is relayed to a satellite-based network. Users of the system can receive information such as time, location, amplitude, and polarity of each strike within seconds.

Studies from lightning data captured from this network have provided a wealth of new information about lightning activity. There can be up to 20 return strokes in a flash and these flashes can terminate in multiple locations. Separation of these return flashes can vary up to 7 km.

~~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.~~

4. 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:

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

There is no 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 versus cost benefit. There is now cost effective, commercially available software to help in the analysis of lightning shielding.

Because of the above factors, it is suggested that an ~~a four-step~~ approach including at least the following four steps 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.
- 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 [can](#) ~~listed in clause 7 will~~ assist the engineer in performing these steps.

CAUTION

This guide makes no claim as to the accuracy, applicability, or preference of any of the following design methods in Clause 5, Clause 6, and Clause 7.

5. Empirical design methods

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

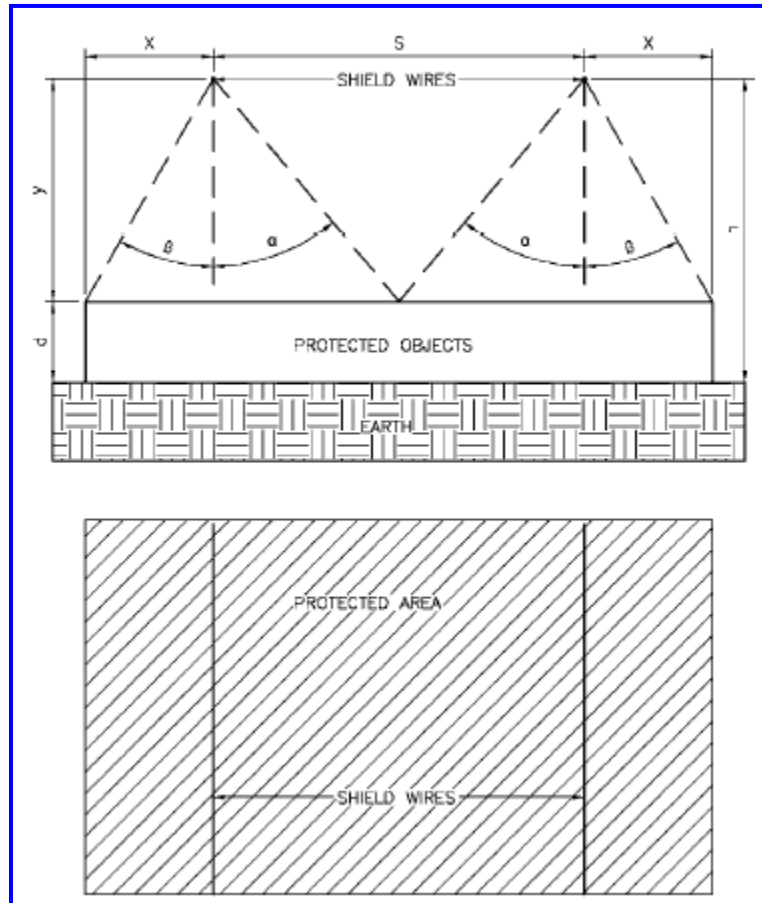
- a) Fixed angles
- b) Empirical curves

These two methods have generally provided acceptable protection.

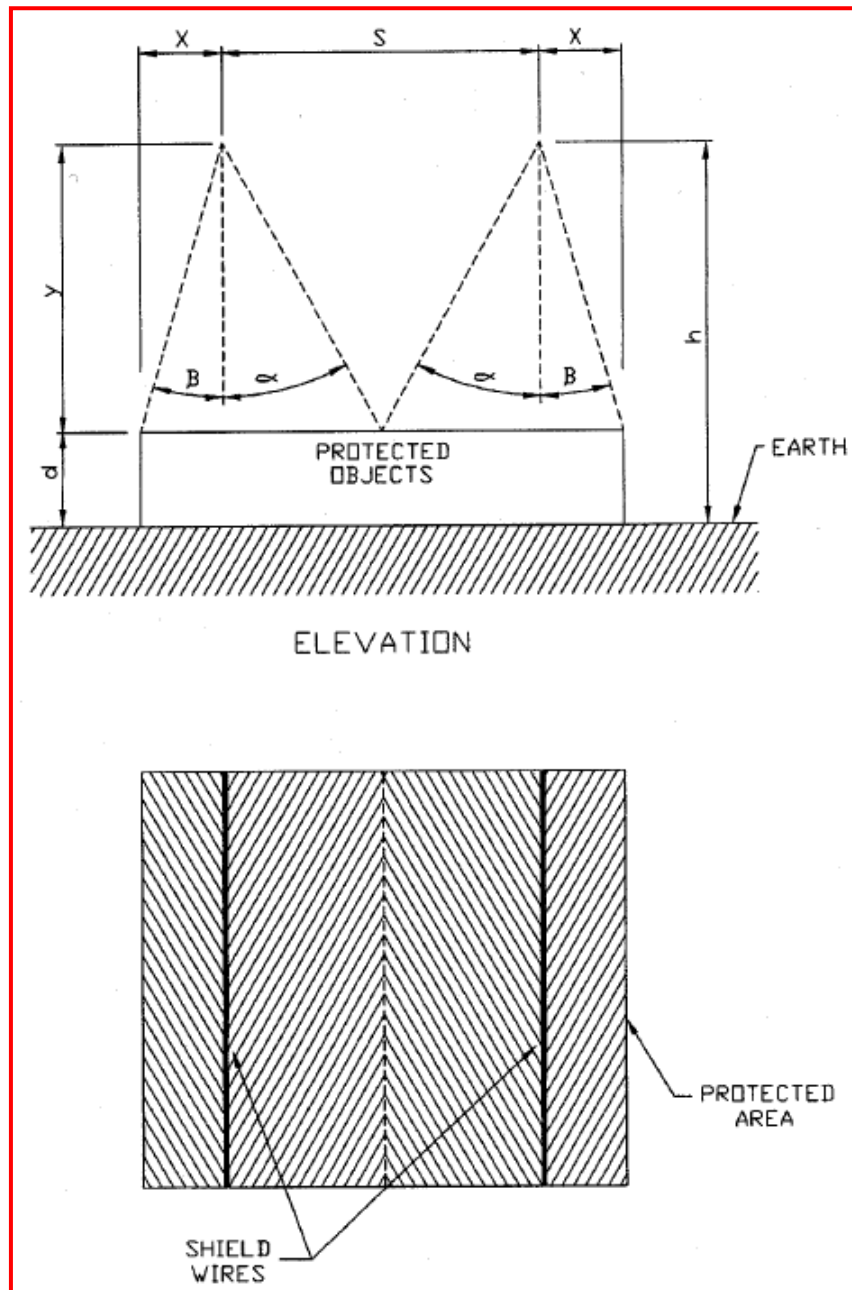
5.1 Fixed angles

It is not known when the use of fixed angles first began. F. W. Peek, Jr., and other investigators recognized as early as 1924 [[B119](#) ~~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 [[B145](#) ~~B93~~]. The fixed angle continues in use today as a design [method](#) ~~tool~~.

The fixed-angle design method uses vertical angles to determine the number, position, and height of shielding wires or masts. Figure 11 illustrates the method for shielding wires, and Figure 12 illustrates the method for shielding masts.



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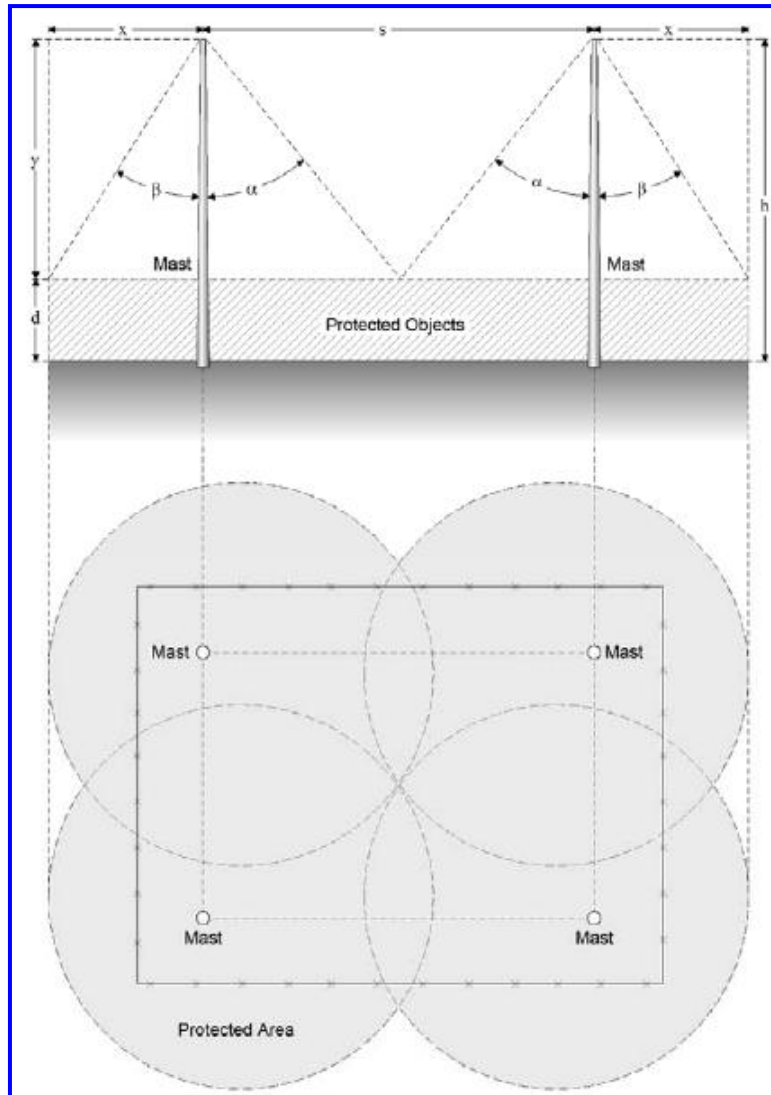


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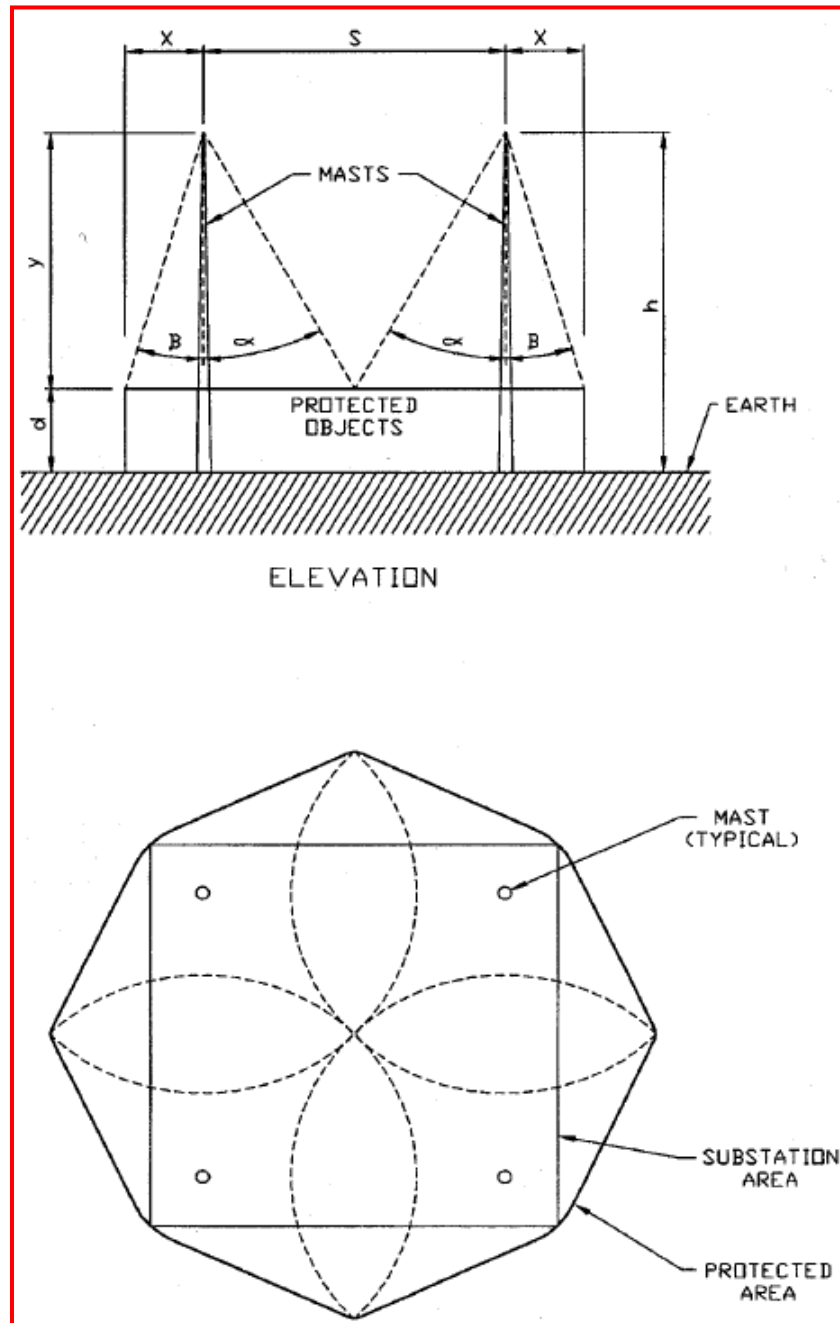
Figure 11 — Fixed angles for shielding wires

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. [Referring to Figure 11 and Figure 12](#), the value of the angle alpha that is commonly used is 45 degrees. Both 30 degrees and 45 degrees are widely used for angle beta. ~~(See annex E.)~~

Designers using the fixed-angle method [can](#) ~~may want to~~ reduce the shielding angles as the height of the structures increases in order to maintain a low failure rate. Horvath [[B65](#) ~~B42~~], using the [electrogeometric model](#) (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 [is](#) ~~must be~~ decreased as the [protective wire height is increased](#) ~~conductor is raised in order to maintain a uniform failure rate.~~

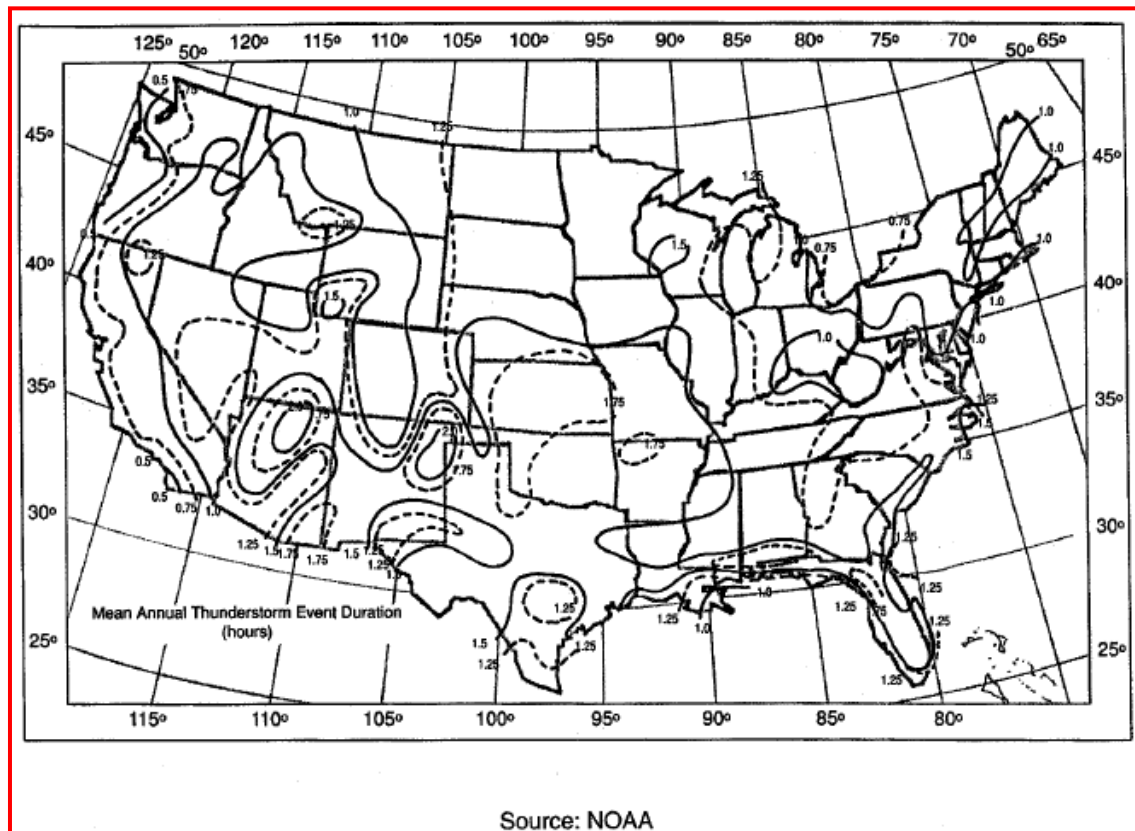


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Figure 12—Fixed angles for masts



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

Horvath suggests a protective angle of 40 degrees to 45 degrees for heights up to 15 m (49 ft), 30 degrees for heights between 15 and 25 m (49 to 82 ft), and less than 20 degrees for heights to 50 m (164 ft). A failure rate of 0.1 to 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 shield ~~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 versus conductor heights.

5.2 Origin of empirical curves

The use of empirical curves finds its origin in a paper published in 1941 by Wagner, McCann, and MacLane [B145 B93]. Scale model tests were conducted employing a $1.5 \times 40 \mu\text{s}$ 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 database for analysis. Plots were then made from this database 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 over 60 ~~fifty~~ years and continue to be used.

~~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.							

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The following year, 1942, Wagner, McCann, and Lear published a paper on shielding of substations [B144 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.

5.3 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 (Wagner [B142]), (Wagner, McCann, and Beck [B143]), (Wagner, McCann, and Lear [B144]) [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 Figure A.1, Figure A.2, Figure A.3, Figure A.4, Figure A.5, and Figure 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.

Figure A.1, Figure A.2, Figure A.3, Figure A.4, Figure A.5, and Figure A.6 use ratios of d/h , x/h , and s/h , which were used in the original study (Wagner, McCann, and Lear [B144]) [B94]. Figure 13, Figure 14, Figure 15, Figure 16, Figure 17, and Figure 18 have been developed using Figure A.1, Figure A.2, Figure A.3, Figure A.4, Figure A.5, and Figure 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 Figure A.1, Figure A.2, Figure A.3, Figure A.4, Figure A.5, and Figure 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 $x = x/h \times h$ ($s = s/h \times h$). 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 Figure 13, Figure 14, Figure 15, Figure 16, Figure 17, and Figure 18. 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.