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IEEE Guide for Improving the Lightning Performance of Transmission Lines

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Abstract: The effects of routing, structure type, insulation, shielding, and grounding on transmission lines are discussed. The way these transmission-line choices will improve or degrade lightning performance is also provided. An additional section discusses several special methods that may be used to improve lightning performance. Finally, a listing and description of the FLASH program is presented.
Keywords: grounding, lightning protection, overhead electric power transmission, shielding

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Introduction

(This introduction is not part of IEEE Std 1243-1997, IEEE Guide for Improving the Lightning Performance of Transmission Lines.)

For most overhead power transmission lines, lightning is the primary cause of unscheduled interruptions. Several methods for estimating lightning-outage rates have been developed in the past, and many publications have been written on how to design transmission lines that experience minimum interruptions.

The methods for estimating the lightning performance of transmission lines show several approaches to a real-life engineering problem that is ill-defined. Precise constants are rarely known and are often not really constant, input data is difficult to describe mathematically except in idealized ways, and outputs may be depictable only by probabilities or average values. By its nature, lightning is difficult to study and model. Lightning transients are so fast that air ionization time constants lead to a time- and waveshape-dependent insulation strength. Lightning peak currents may be ten times higher or lower than the median 31 kA value. Typical ground-flash densities are between 1 and 10 flashes/km^2, so a typical 100 km long strip of width 20 m should receive 2–20 flashes per year. A transmission line of normal height will receive ten times more flashes because it is tall. Structure footing impedances vary with soil characteristics, flash current, and time. Nonlinear corona and surge response effects change the waveshape and magnitude of stresses. As a further complication, lightning flash density varies widely from year to year and changes with location and season.

Any method of judging the lightning performance of transmission lines must cope with these uncertainties. It is pointless, and indeed misleading, to promote a method that is more precise than the accuracy of the input data. The uncertainties of the problem do permit some simplification of the method; rough estimates are likely to be as correct as a much more detailed solution. It is in this spirit that this guide and the FLASH program have been prepared. If the transmission-line designer keeps these limitations in mind, the factors that most influence the lightning performance of a given transmission line may be evaluated.

Knowledge has improved in recent years in such areas as shielding design, stroke characteristics, impulse current behavior of grounds, and lightning ground-flash density. Work is continuing in these areas, as well as others. However, a simple design guide is needed now. It is the purpose of this publication to provide a simplified guide that includes new advances in this field, for use by transmission-line designers.

The IEEE Working Group on Estimating the Lightning Performance of Overhead Transmission Lines had the following membership during the preparation of this guide:

James T. Whitehead, *Chair,* 1985-1989
William A. Chisholm, *Chair,* 1989-1997

John G. Anderson
John W. Anderson
Philip Barker
Ralph Bernstein
James E. Chapman
Pritindra Chowdhuri
Ernico Cinieri
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Luigi Dellera
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Abdul M. Mousa
Richard E. Orville
Dee E. Parrish
Charles Pencinger
John B. Posey
Joseph D. Renowden
Farouk A. M. Rizk
Thomas Short
Mohamed H. Shwehdi
Martin A. Uman
Edward R. Whitehead

The Working Group would like to thank the many individuals who reviewed the text and provided comments in the review and balloting process.

This document is dedicated to the work and memory of Ed Whitehead:

“Lightning is the enemy,
Trees are your friends,
They’ll shield your lines
Howe’er the leader bends.”

The following persons were on the balloting committee:

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Glenn Andersen
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James E. Applequist
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James T. Whitehead
Jeffrey S. Williams
Frank S. Young
Luciano E. Zaffanella
Peter Zhao
Rich Zinser
William B. Zollars

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*Member Emeritus

Also included are the following nonvoting IEEE Standards Board liaisons:

Satish K. Aggarwal
Alan H. Cookson

Erika H. Murphy
IEEE Standards Project Editor

Contents

IEEE Guide for Improving the Lightning Performance of Transmission Lines

1. Overview

1.1 Scope

For this guide, a transmission line is any overhead line with a phase-to-phase voltage exceeding 69 kV and an average conductor height of more than 10 m. The transmission line is usually shielded by one or more overhead ground wires (OHGWs), at least for a short distance from a substation. While reference is primarily made to ac transmission characteristics, the guide is also relevant for high-voltage direct-current (HVDC) overhead lines.

The guide is written for the transmission-line designer. When given the problem of designing or redesigning a transmission line, the designer should consider certain limiting factors such as the voltage level, the beginning and ending points for the transmission line, and the desired ampacity of the line. Sometimes the exact route, and the type of conductor and structure have already been determined. Usually the designer may choose structural details, the geometry of the structure, the structure height, the exact placement of the OHGWs, the amount and type of insulation, the type of grounding, and other design features of a line. This guide is written to show the designer which choices will improve or degrade lightning performance. Sections of the guide discuss the effect of routing, structure type, insulation, shielding, and grounding. An additional section discusses several special methods, which may be used to improve lightning performance. Finally, in Annex B, a listing and description of the FLASH program is presented.

The line designer should be aware that lightning performance is not of primary importance in the economics of line designing. Other factors, such as line length, right-of-way costs, construction costs, material costs, and losses affect the economics of a line design much more than lightning performance. The designer should always balance the costs of higher insulation levels, improved grounding, better shielding, or line relocation against the benefits of improved reliability.

1.2 Purpose

This guide contains simple mathematical equations, tables, and graphs that provide the information needed to design an overhead power transmission line with minimum lightning interruptions. Versions 1.6 and 1.7 of the FLASH program are provided on the diskette included with this guide. Annex B includes a description of the program. The FLASH program uses the models in the design guide along with a description of transmission-line features to estimate the lightning outage rate that may be expected. These simplified models may also be adapted to assess the benefits of novel methods for improving lightning performance.

1.3 Disclaimer

The FLASH program is included in this guide as a convenience to the user. Other numerical methods may be more appropriate in certain situations. The IEEE Working Group on Estimating the Lightning Performance of Overhead Transmission Lines of the Lightning and Insulator Subcommittee has made every effort to ensure that the program yields representative calculations under anticipated conditions. However, there may well be certain calculations for which the method is not appropriate. It is the responsibility of the user to check calculations against field experience or other existing calculation methods.

2. References

This guide shall be used in conjunction with the following standards. When the following standards are superseded by an approved revision, the revision shall apply.

ANSI C2-1997, National Electrical Safety Code® (NESC®).[1]

ANSI C29.1-1988 (Reaff 1996), American National Standard for Electric Power Insulators—Test Methods.[2]

ANSI C29.2-1992, American National Standard for Insulators—Wet Process Porcelain and Toughened Glass—Suspension Type.

ANSI C29.8-1985 (Reaff 1995), American National Standard for Wet-Process Porcelain Insulators (Apparatus, Cap, and Pin Type).

3. Definitions and Acronyms

3.1 Definitions

3.1.1 active air terminal: An air terminal which has been modified to lower its corona inception gradient.

3.1.2 air terminal (lightning protection): The combination of an elevation rod and brace, or footing placed on upper portions of structures, together with tip or point, if used.

3.1.3 back flashover (lightning): A flashover of insulation resulting from a lightning stroke to part of a network or electric installation which is normally at ground potential. *See also:* **direct-stroke protection.**

3.1.4 back-flashover rate: The annual outage rate on a circuit or tower-line length basis caused by back flashover on a transmission line.

3.1.5 counterpoise: A conductor or system of conductors arranged beneath the line; located on, above, or most frequently below the surface of the earth; and connected to the grounding systems of the towers or poles supporting the transmission lines.

3.1.6 critical current: The first-stroke lightning current to a phase conductor which produces a critical impulse flashover voltage wave.

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[1] The NESC is available from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA. It is also available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

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

3.1.7 critical impulse flashover voltage (insulators) (CFO): The crest value of the impulse wave which, under specified conditions, causes flashover through the surrounding medium on 50% of the applications.

3.1.8 direct stroke protection (lightning): Lightning protection designed to protect a network or electric installation against direct strokes.

3.1.9 flashover: A disruptive discharge through air around or over the surface of solid or liquid insulation, between parts of different potential or polarity, produced by the application of voltage wherein the breakdown path becomes sufficiently ionized to maintain an electric arc.

3.1.10 ground electrode: A conductor or group of conductors in intimate contact with the ground for the purpose of providing a connection with the ground.

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

3.1.12 lightning first stroke: A lightning discharge to ground initiated when the tip of a downward stepped leader meets an upward leader from the earth.

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

3.1.14 lightning subsequent stroke: A lightning discharge that may follow a path already established by a first stroke.

3.1.15 lightning outage: A power outage following a lightning flashover that results in system fault current, thereby necessitating the operation of a switching device to clear the fault.

3.1.16 line lightning performance: The performance of a line expressed as the annual number of lightning flashovers on a circuit mile or tower-line mile basis. *See also:* **direct-stroke protection.**

3.1.17 line surge arrester: A protective device for limiting surge voltages on transmission-line insulation by discharging or bypassing surge current; it prevents continued flow of follow-current to ground and is capable of repeating these functions.

3.1.18 overhead ground wire (OHGW): Grounded wire or wires placed above the phase conductors for the purpose of intercepting direct strokes in order to prevent the phase conductors from the direct strokes. They may be grounded directly or indirectly through short gaps. *See also:* **direct-stroke protection.**

3.1.19 shielding failure flash-over rate (SFFOR): The annual number of flashovers on a circuit or tower-line length basis caused by shielding failures.

3.1.20 shielding failure rate (SFR): The annual number of lightning events on a circuit or tower-line length basis, which bypass the overhead ground/shield wire and terminate directly on the phase conductor. This event may or may not cause flashover.

3.2 shield wire: Grounded wire(s) placed near the phase conductors for the purposes of

a) Protecting phase conductors from direct lightning strokes,
b) Reducing induced voltages from external electromagnetic fields,
c) Lowering the self-surge impedance of an OHGW system, or
d) Raising the mutual surge impedance of an OHGW system to the protected phase conductors.

3.2.1 standard lightning impulse: A unidirectional surge having a 30–90% equivalent rise time of 1.2 μs and a time to half value of 50 μs.

3.2.2 transmission line: Any overhead line used for electric power transmission with a phase-to-phase voltage exceeding 69 kV and an average conductor height of more than 10 m.

3.2.3 underbuilt shield wires: Shield wires arranged among or below the average height of the protected phase conductors for the purposes of lowering the OHGW system impedance and improving coupling. Underbuilt shield wires may be bonded to the structure directly or indirectly through short gaps. Insulated earth return conductors on HVDC transmission lines, and/or faulted phases, both function as underbuilt shield wires.

3.2 Acronyms

ACSR	aluminum conductor, steel reinforced
AWG	American Wire Gage
CFO	critical flashover
EGM	electro-geometric
EHV	extra-high voltage
GFD	ground flash density
HV	high voltage
HVDC	high-voltage direct current
OHGW	overhead ground wire
RTS	rated tensile strength
SFR	shielding failure rate
SFFOR	shielding failure flashover rate

4. Route selection

Many factors play an important role in route selection. Power system considerations dictate where the transmission line should begin and end. Economic considerations require the line to be as short as possible, because construction costs and electrical losses are high. Certain environmental constraints dictate where and how a transmission line may be built. Even with these restrictions, there are still ways for the transmission-line designer to make decisions that will affect the lightning performance of the line. It is the purpose of this clause to illustrate the ways that a designer may improve the lightning performance of a transmission line by selecting the proper route.

4.1 Lightning frequency of incidence

Lightning location systems and flash-counter networks have been deployed in North America [B11], [B34][3] and elsewhere. With enough experience, these networks may provide detailed ground flash-density (GDF) maps. Orographic and geographic features, such as proximity to large bodies of water or elevation changes, will affect the flash density. Flash-density maps will provide much greater detail and accuracy than what was previously available with thunder data. A typical GDF map is shown in [B35]. Lightning severity maps may also be available to show where more damaging lightning strokes occur. When two routes with similar soil characteristics are being compared, the route through a region with lower density of severe flashes will have fewer outages.

With more detailed maps averaged over enough time, the designer may select a route with a minimum exposure to lightning. By way of guidance about the averaging time required, MacGorman et al. [B29] found that

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[3] The numbers in brackets correspond to those of the bibliography in Annex C.

one-year average thunder data had roughly 35–40% standard deviations, five-year averages had 30% standard deviations, and ten-year averages had 25% standard deviations. A similar variation would be expected for GFD. Thus, a minimum of 5–10 years of GFD observations are desirable. The natural scatter of lightning activity may make it impossible to estimate a mean value with more precision than the ten-year standard deviation.

4.2 Route effects

The transmission-line designer is often faced with the choice of routing a line through a valley, along the side of a mountain, or on the top of a mountain. This decision may affect the lightning performance of the line in two ways. First, the route may affect the exposure of the line to lightning. Second, soil resistivity may be different for alternate routes. The effects of soil resistivity are discussed in 4.4.

Transmission line exposure is affected by both GFD and by the line's physical relation to its environment. A structure that protrudes above the surrounding terrain is more likely to be struck by lightning than a structure shielded by natural features. Structures located along the top of mountains, ridges, or hills will be likely targets for lightning strikes. These locations should be avoided as much as possible. It is preferable to locate structures along mountain sides where the top of the structure does not appear higher than the top of the mountain or ridge. Locating lines in the floor of a narrow valley may provide the line with useful lightning protection. Detailed design of lines should consider the effects of different routes on structure height, soil, or overburden depth and the adjacent environment.

4.3 Structure height

The first factor of a line route that affects lightning performance is structure height, especially if its towers are higher than the surrounding terrain. Increasing the tower height has two important effects: more flashes are collected by the taller structure, and the shielding characteristics of overhead conductors change as height is increased, as explained in Clause 5.

The flash collection rate, N_s, is given by the following equation [B18]:

$$N_S = N_g\left(\frac{28h^{0.6}+b}{10}\right) \tag{1}$$

where

h is the tower height (m);
b is the OHGW separation distance (m);
N_g is the GFD (flashes/km^2/yr);
N_s is the flashes/100 km/yr.

From Equation (l), if the tower height is increased by 20%, the flash rate to the line would increase by 12%. If a measured value of N_g is not available, it may be estimated [B18], [B29] using

$$N_g = 0.04T_d^{\ 1.25} \tag{2}$$

$$N_g = 0.04T_h^{\ 1.1} \tag{3}$$

where

T_d is the number of thunderstorm days/yr (Keraunic Level);

T_h is the number of thunderstorm hours/yr.

Data for T_d and T_h may be obtained from several meteorological sources, (e.g., [B11], [B29]).

4.4 Soil resistivity

The second factor of a line route that affects lightning performance is soil resistivity. Resistivity has a linear relationship to footing impedance, which is explained in Clause 7. Substantial voltages are generated on grounded members of the structure when either the OHGW or the structure are struck by lightning. High structure footing impedances cause increased voltages and more lightning outages for a given lightning exposure.

A complete line design will specify the types and sizes of ground electrodes needed to achieve the required footing impedance. The electrode sizes and shapes will depend on the range of soil conductivities found on installation. In some geographic areas, surveys of apparent ground resistivity have been carried out for radio-frequency broadcast [B25] or geological purposes. In particular, airborne electromagnetic surveys [B36] at 10–50 kHz return a suitable conductivity-depth product which may be analyzed further or used directly for tower spotting.

High footing impedances occur in rocky terrain, which should be avoided as much as possible. When rocky terrain may not be avoided, improved grounding methods should be used to lower footing impedances to acceptable values. These improved methods usually require large-ring or radial-crowfoot installation at considerable cost. Rocky terrain usually occurs on mountain tops and mountain sides, while river lowlands tend to have low soil resistivity. This is a second reason why transmission-line routes away from hill crests will tend to have better lightning performance.

4.5 Adjacent environment

One way to prevent structures from being a target for lightning is to take advantage of surrounding forestation. Tall trees located near the transmission line may intercept a lightning stroke which may have caused an outage if the tree had not been there. Most transmission lines have sufficient impulse strength to be immune to the resulting induced voltages. Reference [B31] provides additional information about the effects of forestation. When possible, lines may be routed through forestation and tall trees may be left in place near the line. Trees that may fall on the line or reduce operating clearances will require more frequent trimming, and forest fires may degrade the line protection locally. However, the reduction in apparent line height and corresponding reduction in lightning outages may still be worthwhile.

Tall structures located in flat, open fields make excellent targets for lightning. In these conditions, the structure height should be minimized, and the structure footing impedance should be reduced much as possible.

Another way to use the surrounding environment to shield a transmission line from lightning is to route the line next to existing transmission line structures. Experience has shown that a line sharing right-of-way with another line having taller structures will have fewer lightning outages than if it were on a separate right-of-way. Two lines of identical design and on adjacent rights-of-way share lightning strikes resulting in lower than normal outage rates for both lines. This improvement should be balanced with the greater risk of multiple line outages.

5. Shielding

When lightning strikes a phase conductor, no other object shares in carrying the lightning current. Most flashes to an unprotected phase conductor are therefore capable of producing flashovers. OHGWs may intercept the stroke and shunt the current to the ground through the tower impedance and footing resistance if they are properly located. The resultant voltages across the transmission-line insulation, and the likelihood of flashover are substantially reduced. Outside phases are discussed in 5.1–5.4, while 5.5 focuses on the shielding of inner phases.

5.1 Shielding angle

One important task of transmission-line designers is to locate the OHGWs. Well-planned geometry will reduce the probability of lightning striking the phase conductors to an acceptable level. The proper placement of the OHGW around the phase conductors is usually defined by the shielding angle, as shown in Figure 1. The shielding angle is negative if the OHGWs are horizontally disposed outside the phase conductors.

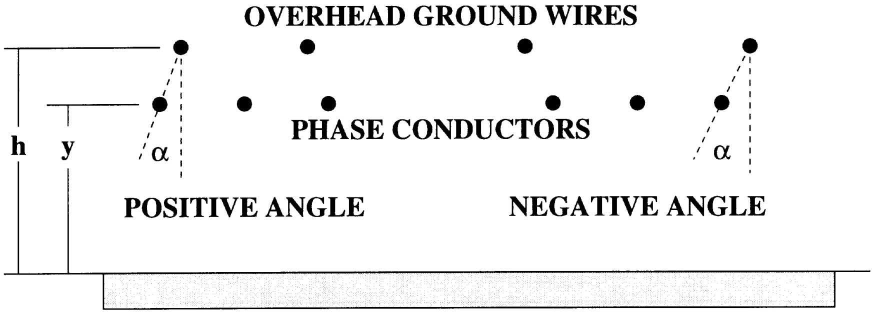


Figure 1—Definition of shielding angles

Before about 1951 [B41], [B42], a shielding angle of 30° was usually employed for transmission lines. This produced acceptable lightning performance on existing lines of voltages up to 230 kV. In the mid 1950s, 345 kV lines were introduced and tall double-circuit lines were constructed [B38]. The lightning performances of these lines were considerably worse than expected. After extensive theoretical, field, and laboratory investigations, a general agreement was reached that the usual 30° shielding angle should be decreased as the height of the transmission-line structures increased.

5.2 The final leader step

Several researchers, notably Wagner et al., [B43], [B44], [B45], Young et al., [B48], Armstrong and Whitehead [B5], Brown and Whitehead [B9], Love [B28], and Mousa [B31], [B32], [B33], have contributed to the electro-geometric model (EGM) of the last step or striking distance of the lightning flash. As the downward leader approaches the earth, a point of discrimination is reached for a final leader step. The EGM portrays this concept with the use of striking distances. Other models, such as those of Eriksson [B19], Dellera-Garbagnati [B17], and Rizk [B39], model the upward-directed leaders from objects. The striking distance is of the form

$$r_{c,g} = AI^b \tag{4}$$

where

A and b	are constants that depend on the object;
I	is the stroke current.

The model for the final jump appears in Figure 2, for a specific value of stroke current. The striking distance to a conductor, r_c, is computed from Equation (4). Local electric field gradients around conductors are somewhat higher than at ground level, so r_c is usually considered to be greater than r_g (the striking distance to ground), resulting in $r_c \geq r_g$. Arcs of circles with the radii r_c are drawn centered at the phase conductor and OHGW. A horizontal line is then drawn at a distance r_g from earth.

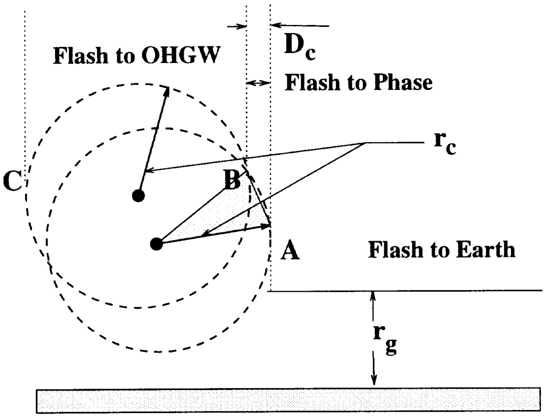


Figure 2—Exposed distance for final jump in electro-geometric model

If a downward leader, having a prospective current *I* for which the arcs were drawn, touches the arcs between A and B, the leader will strike the phase conductor. If the leader touches between B and C, it will strike the shield wire. If all leaders are considered vertical, the exposure distance for a shielding failure is D_c. In the two-conductor case shown, there would only be a shielding-failure rate (SFR) on one side of $N_g \times D_c \times L$, given one specific value of current for a line of length *L*.

Since the final jump length in the EGM depends on current, the statistics of the stroke-current distribution will be needed to compute the SFR. The probability density, $f_1(I)$, of the first stroke current, I_f, is given by a pair of log-normal distributions as follows [B13]:

$$f_1(I) = \left(\frac{1}{\sqrt{2\pi}\sigma_{ln} I}\right) e^{\frac{-(\ln I/\bar{I})^2}{2\sigma^2_{\ln}}} \tag{5}$$

$$I < 20\text{kA} \quad \bar{I} = 61.1 \text{ kA} \quad \sigma_{ln} = 1.33 \tag{6}$$

$$I > 20\text{kA} \quad \bar{I} = 33.3 \text{ kA} \quad \sigma_{ln} = 0.605 \tag{7}$$

The cumulative probability of I_f exceeding *I* is given by integrating Equation (5), or approximated by Equation (8) [B3]:

$$P(I_f > I) = \frac{1}{1 + \left(\frac{I}{\bar{I}_{first}}\right)^{2.6}} \tag{8}$$

where

$2 \text{ kA} < I < 200 \text{ kA}$;
$\bar{I}_{first}$ is 31 kA;
I is in kA.

Outside of these limits, Equation (5) should be integrated.

As the current increases, the striking distances r_c and r_g also increase; the exposed distance, D_c , decreases for normal shielding angles. Finally, a point is reached at a current I_{max} where D_c is zero. The SFR is the number of flashes per unit time to the conductor. It is obtained by integrating the exposure width D_c for each current times the probability of that current on each side for all possible currents up to I_{max}.

$$SFR = 2N_g L\int_{I=0}^{I=I_{max}} D_c(I)f_1(I)dI \tag{9}$$

As noted in Figure 2, the striking distances to the shield wire and to the phase conductor are assumed equal, while the striking distance to earth is smaller. At present, the following striking distance equations are recommended:

$$r_c = 10I^{0.65} \tag{10}$$

$$r_g = \begin{cases} [3.6 + 1.7\,ln\,(43 - y_c)]\,I^{0.65} & y_c < 40\text{ m} \\ 5.5I^{0.65} & y_c \geq 40\text{ m} \end{cases} \tag{11}$$

where

y_c is the average conductor height in meters, given by the height at the tower minus two-thirds of the midspan sag.

Some researchers of EGM assume all striking distances are equal, while others have different striking distances to phase conductors, shield wires, and earth. In addition, some researchers do not use a striking distance to earth. Estimates of striking distance sometimes differ by a factor of two. However, this uncertainty has not prevented the design and operation of lines with low lightning outage rates. In particular, when an engineering judgment is made to accept a low but non-zero shielding failure flashover rate (SFFOR), most models suggest similar shielding angles.

5.3 Flashover from shielding failure

At higher transmission voltages, a shielding failure with a low current may not necessarily cause a flashover. The minimum or critical current I_c required for flashover would be

$$I_c = \frac{2CFO}{Z_{surge}} \tag{12}$$

$$Z_{surge} = 60\sqrt{\ln\frac{2h}{r}\,\ln\frac{2h}{R_C}} \tag{13}$$

where

Z_{surge} is the conductor surge impedance under corona;
h is the average conductor height (m);
r is the conductor radius (m);
R_C is the corona radius of the conductor at a gradient of 1500 kV/m (m);
CFO is the critical flashover voltage, as defined in 6.1.

Thus, the number of shielding failures per unit time that result in flashovers, or the *SFFOR* is

$$SFFOR = 2N_g L\int_{I=I_c}^{I=I_{max}} D_c(I)f_1(I)dI \tag{14}$$

This leads to the apparent possibility of perfect shielding, where the shielding angle is increased until $I_{max} = I_c$ in Equation (14). However, this perfection has a limitation. Even if the first stroke-current magnitude is less than the critical current I_c, subsequent strokes that follow the same leader may possess current magnitudes that exceed I_c and result in flashover. Anderson and Eriksson [B4] found that the median subsequent-stroke current was 12 kA, there was a median of two subsequent strokes per flash, and each subsequent-stroke current was uncorrelated with the first-stroke magnitude. There is only an 8% chance that the first-stroke amplitude is less than 12 kA. However, for most overhead conductor geometries, shielding failure will only occur when the first-stroke amplitude is low, giving a small striking distance. The probability that an individual subsequent stroke current I_s will exceed I_c is given approximately by

$$P(I_s > I_c) = \frac{1}{1 + \left(\frac{I_c}{\bar{I}_{subs}}\right)^{2.7}} \tag{15}$$

where

$\bar{I}_{subs}$ is 12 kA;
I_c is also in kA.

Equation (16) gives P_S, the probability of flashover on any subsequent stroke, given that no flashover occurs on the previous strokes.

$$P_S = \sum_{n=2}^{n=\infty} P_n(1 - [1 - P(I_s > I_c)]^{n-1}) \tag{16}$$

where

P_n is the probability that there are *n* strokes/flash, from data in [B40].

The total SFR will be the sum of the first-stroke failure rate *SFFOR* and the added rate $SFFOR_S$ obtained from:

$$SFFOR_S = 2N_gLP_S\int_{I=0}^{I=I_c} D_c(I)f_1(I)dI \tag{17}$$

If the critical current I_c is low, most shielding failures will lead to flashover, either from the small first stroke or from the 60–70% chance that there will be a subsequent stroke that exceeds I_c. If the critical current is higher, P_S from Equation (16) is lower (e.g., $P_S = 0.4$ for I_c of 16 kA). The extra contribution of subsequent-stroke effects to total SFFOR ensures that perfect shielding (*SFFOR* = 0) will rarely be achieved. This philosophy leads us to accept a low but non-zero total SFFOR, as discussed in 5.4.

5.4 Shielding and engineering

The primary aim in the selection of the OHGW location(s) is to provide a means of intercepting the lightning flash and to reduce the SFR to an acceptable level, fully realizing that an SFFOR of zero is virtually impossible. The design value of the SFFOR is frequently selected independently of the backflash rate. However, both SFFOR and backflash contribute to the line lightning performance.

In the past, design of shielding angle was frequently selected to obtain perfect shielding. This may be proper for areas of high GFD, $N_g > 10$. In other areas with low flash density, $N_g < 2$, the attempt to achieve to a perfect shielding angle, may severely handicap an economical design. Thus, one OHGW may be adequate for areas of low-flash density, whereas two OHGWs are required in areas of higher lightning frequency.

The SFFOR is a function of the line geometry and the local GFD. For this reason, a design based on the required SFFOR is suggested, so that the designer may evaluate the most economical configurations. For lines serving a critical load, a design SFFOR value of 0.05 outages/100 km/yr may be suitable, while values of 0.1–0.2 outages/100 km/yr are recommended for general practice.

To assist in the selection of shielding angle, the curves of Figure 3 have been prepared based on the equations for striking distance in 5.2 . The curves are based on vertical strokes to flat terrain and a design SFFOR value of 0.05 outages/100 km/yr. The shielding angle required to maintain this SFFOR is a strong function of OHGW height, and is less dependent on the critical current I_c or the flash density N_g.

To illustrate the use of Figure 3, assume an SFFOR design value of 0.05/100 km/yr in an area having a GFD of N_g = 10 flashes/km^2/yr. For an average OHGW height of 30 m and a critical current I_c of 10 kA, a shielding angle of 15° is obtained from Figure 3. For these same conditions, but with a GFD N_g = 1 flash/km^2/yr, the required SFFOR may be obtained with a shielding angle of 23°. In an area with the low-flash density of N_g = 0.1 flash/km^2/yr, a shielding angle of 34° gives the design SFFOR.

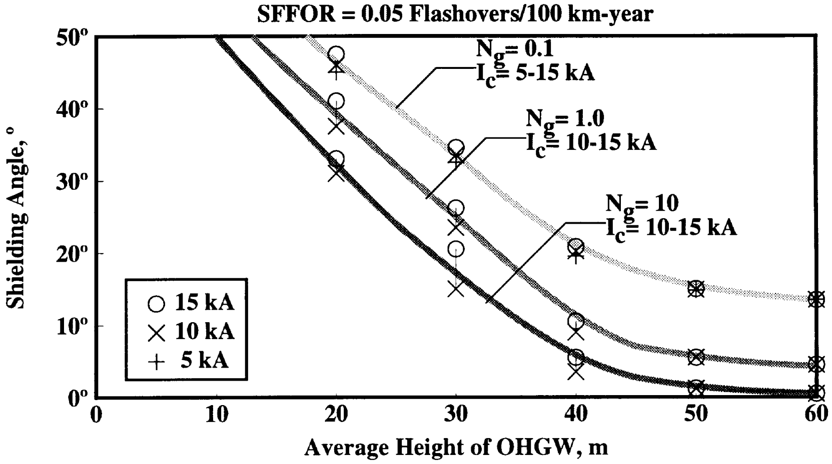


Figure 3—Shielding angles for constant SFFOR using striking distance equations from 5.2 and assuming vertical strokes

The shielding angles obtained from Figure 3 are average angles within the span; the shielding angle at the tower will be larger. The angles also assume flat or rolling terrain. For towers located on hillsides, as in Figure 4, the average shielding angle is obtained by subtracting the hill angle relative to horizontal from the angle given in Figure 3. Trees and structures beside the line right-of-way are also beneficial, because they increase the height of the effective earth plane, and may sometimes reduce the exposure distance of the phase conductor. In contrast, lines located along hilltops are especially vulnerable since the effective height above ground is increased.

The industry has noted that the performance of a few towers or line sections frequently dominates the general line performance; thus the name *rogue towers* has come into colloquial language. A typical rogue tower is located at the crest of a hill or ridge. Both lightning exposure and footing impedance are higher than average, and shielding angles are adversely affected by the slope of the hill. With all these factors, the final selection of shielding angle at the tower should be based on the judgment of the designer, tempered with the experience of similar shielding angles within the utility system.

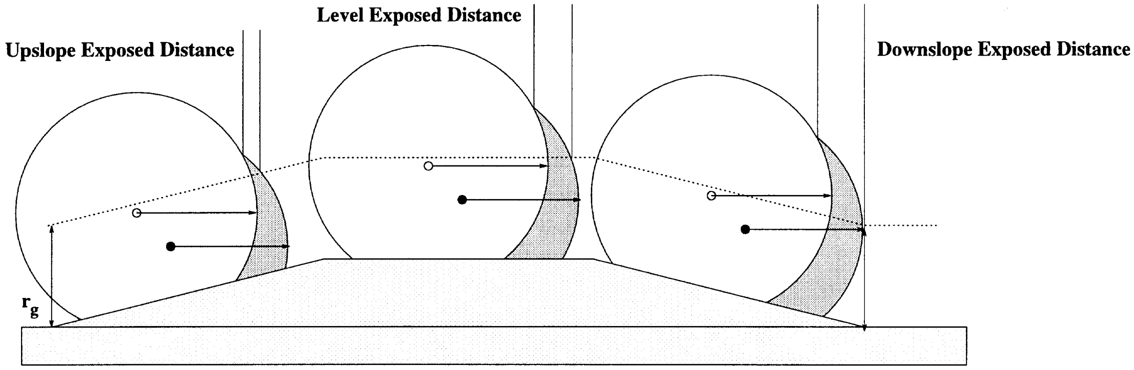


Figure 4—Exposed distances on hillsides

5.5 Shielding of the center phase

So far, the discussion on shielding has focused on the outside phases of a line. While shielding failures to the center phase have been observed on transmission lines, the low lightning-current magnitude needed for this to occur did not lead to flashover. Shielding failures to the center phase should be ignored except in cases where the OHGW separation exceeds twice the striking distance associated with I_c. Using the equations in 5.2 with $I_c = 5$ kA, the OHGW separation would have to exceed 57 m before center-phase shielding would be a concern. This factor of greatly improved shielding to objects between shield wires or masts is employed, for example, in the design of station shielding, a subject beyond the scope of this guide.

5.6 Overhead ground wire size and operating losses

Preliminary designs for OHGW locations should be checked for their contribution to the resistive loss and the reactance of the line. The OHGW needs to be capable of withstanding the levels of current that are placed on them by a lightning stroke. Usually, OHGWs that are mechanically suitable are also suitable to withstand lightning stroke currents without failures. Other factors that influence the size of the wire are system fault currents and the possible use to support a fiber optic cable.

Phase currents in the conductors will induce currents in the OHGWs. These induced currents are small, but the resistances of typical OHGWs from [B2], given in Table 1, are high.

With an OHGW resistance of 2.5 Ω /km and an average induced current of 30 A, the I^2R power losses for a pair of OHGWs would be 450 kW for a 100 km line. The energy of the continuous loss would be 4 GWh/yr, and additional generating capacity to supply the 450 kW at peak times would be needed. In general, moving OHGWs out from the tower for better shielding will reduce I^2R power losses while increasing tower cost. By trading off the significant cost of losses against the small incremental cost of horizontal OHGW displacement, a superior shielding angle may sometimes be justified. In some designs, OHGWs have been electrically isolated to eliminate induced-current losses or to reduce AM broadcast reradiation. Insulating the OHGWs from the towers, either with tangent insulators or with suspension insulators, will not degrade (or improve) lightning performance, because the OHGW insulation flashes over easily, which ground the conductor. However, the insulation should be coordinated with safety concerns when the OHGWs carry significant fault currents.

Table 1—DC resistances of typical OHGW at 20 °C

Diameter	Description	Resistance (Ω/km)
7.9 mm (0.31 in)	Galvanized steel	4.7
9.5 mm (0.37 in)	Galvanized steel	4.0
12.7 mm (0.50 in)	Galvanized steel	2.5
7.8 mm (0.31 in)	7 #10 aluminum-clad steel	2.3
9.8 mm (0.39 in)	7 #10 aluminum-clad steel	1.5
11.0 mm (0.43 in)	7 #10 aluminum-clad steel	1.2
14.0 mm (0.55 in)	4/0 American Wire Gage (AWG) (6/1) Aluminum conductor, steel reinforced (ACSR)	0.26
18.3 mm (0.72 in)	336 kcmil (26/7) ACSR	0.17

6. Insulation

Lightning may cause the insulators of a transmission line to flashover in the following two ways:

- A lightning flash being intercepted by the tower or the OHGWs (backflash)
- A direct lightning flash to a phase conductor (shielding failure)

In either event, the following three main factors govern whether insulation will flashover:

- The waveshape and polarity of the lightning surge voltage stressing the insulator
- The withstand characteristics of the insulators, specified for example by the number of standard disks in an insulator string or by the arcing distance from conductor to tower (see ANSI C29.2-2983)
- The power frequency component of the voltage across the insulator

Clause 6 explores the relationships between the above factors and lightning performance of transmission lines.

6.1 Effect of voltage waveshapes

The dielectric performance of line insulation when exposed to lightning surges is often evaluated analytically or determined experimentally by subjecting the insulation to standard double-exponential impulses. Figure 5 shows the standard impulse-voltage waveshape. The front time is effectively 1.2 μs, and the time to half-value is 50 μs. If the magnitude of the voltage is sufficiently low, the insulator does not flash over and a full impulse-voltage waveform is developed. As the magnitude of the impulse is gradually increased, there exists a voltage level where the insulation breaks down on 50% of the tests. The breakdown occurs late on the impulse wave. This voltage is termed the critical flashover (CFO) voltage. When breakdown occurs, the resulting waveshapes shown in Figure 5 are called *chopped waves*. When the voltage magnitude is increased above the CFO, breakdown occurs on most applications and at shorter times. As the voltage magnitude is increased even further, the breakdowns occur before the lightning impulse has reached its prospective peak voltage. The resulting impulses are referred to as *steep front impulses*.

Dielectric strength of line insulators under lightning conditions depends on the impulse waveshape, magnitude, and polarity. A lightning-impulse voltage, with a magnitude that exceeds the CFO, may still not last long enough to carry the streamers all the way to complete insulation breakdown. A plot of the magnitude of the breakdown voltage versus the time to breakdown is called a *volt-time curve*, as shown in Figure 6. The amount by which the voltage exceeds the CFO voltage is referred to as the *volt-time turn-up*.

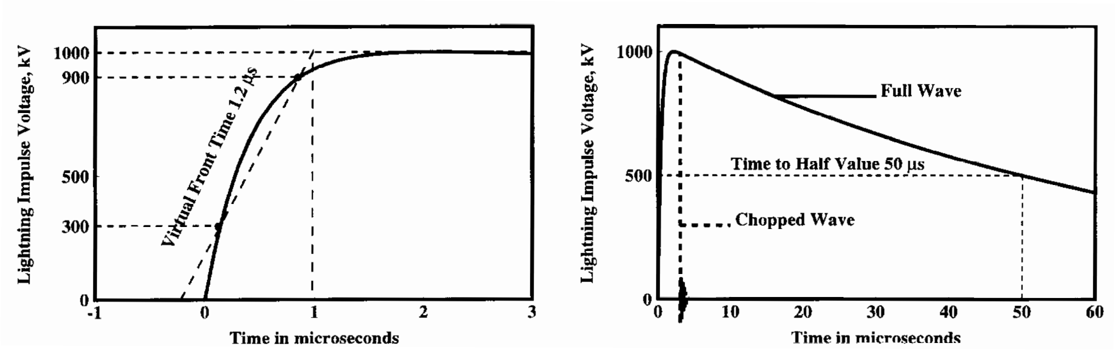


Figure 5—Standard lightning impulse

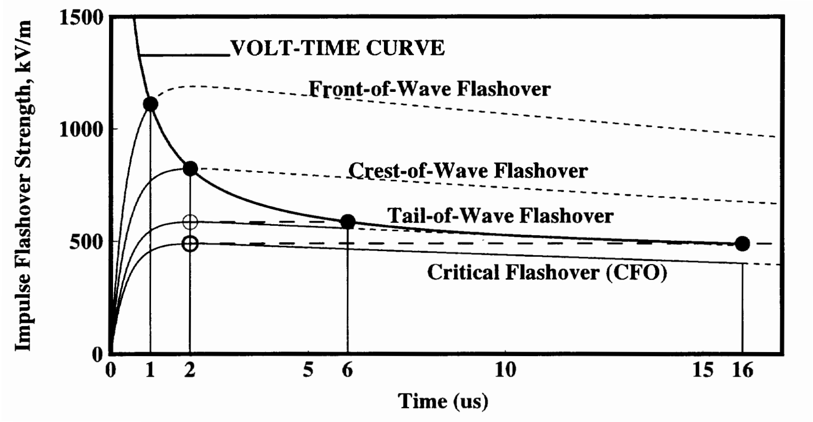


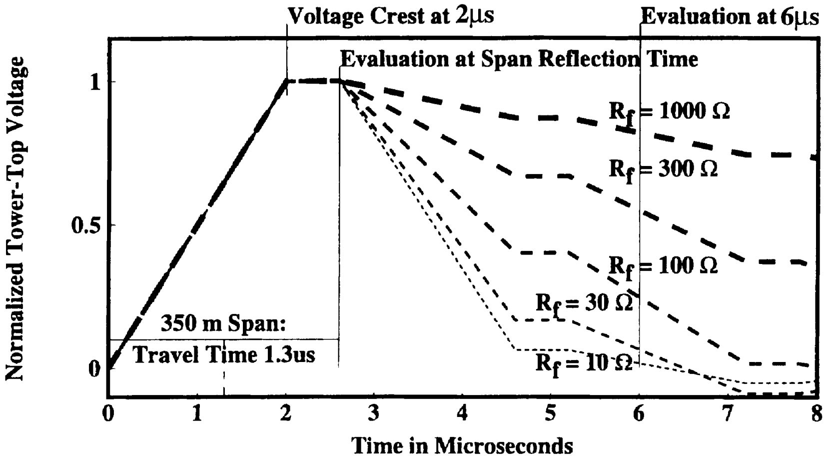
Figure 6—Volt-time curve for cap-and-pin insulators

Nonlinear effects such as corona, soil ionization, tower surge response, and reflections from adjacent towers tend to distort the surge voltages from the standard impulse waveshape. The partial chopping that occurs when reflections return from adjacent towers is particularly important. At present, the only satisfactory way to evaluate the electrical strength of line insulation under these conditions is by testing the desired tower/insulator window with the desired voltage waveshape. Pigini et al. [B37] have summarized physical-model formulas that may be used for various nonstandard impulses to produce volt-time curves similar to those in Figure 6. These models fall into the following three general categories:

a) Methods that model the breakdown phenomena directly, such as the leader progression model
b) Methods derived from the leader progression model, such as the disruptive index model
c) Methods that use the standard volt-time or time-lag curve directly during the period before the waveshape becomes nonstandard

All three methods are in current use, but none is universally accepted. A simple leader progression method was selected by CIGRE Working Group 33.01 [B13]. The disruptive index approach was shown in [B24] to be unsatisfactory for describing a volt-time curve for a standard impulse wave, with typical errors in excess of 5%.

The third method is used in the FLASH program [B22], [B23]. In all versions of FLASH, the voltage across the line insulation is evaluated at two times. The most recent FLASH 1.7 version uses the time of maximum stress, just before the return of reflections from the two adjacent towers, as shown in Figure 7. The full impulse-voltage waveshape, peaking as shown at 2 μs, is preserved up to this point. Previous versions of FLASH evaluated the stress at the 2 μs voltage peak and thus ignored an important reflection effect for longer spans. All versions of FLASH still evaluate stress at 6 μs. The magnitude at 6 μs will be affected by reflections from four or more adjacent towers, depending on span length.



NOTE—Combined OHGW impedance is 300 Ω.

Figure 7—Tower-top voltage for 350 m span with various footing resistance (R_f) values

A transfer impedance of the insulator voltage per ampere of stroke current is computed at the wave peak, 2 μs. This transfer impedance is a result of both the tower and footing impedance components. This impedance value is used along with Equation (18), the volt-time curve of the insulation. One important time of maximum stress is just before the cancelling reflections from adjacent towers arrive, as shown in Figure 7. For a 350 m span with a propagation speed of 90% of the speed of light c, a two-way return time $t = 2.6$ μs is used to estimate the volt-time curve strength in Equation (18). The waveshape, cresting at 2 μs and followed by a drop to lower voltage only at the return time t, is reasonably close to the standard lightning impulse waveshape used to determine Equation (18).

$$V_{ImpulseFlashover}(t) = \left(400 + \frac{710}{t^{0.75}}\right) W \tag{18}$$

where

V is the flashover strength (kV);
t is the time to flashover, (μ*s*) (for 0.5 μ*s*–16 μ*s*);
W is the gap or insulator length (m).

Equation (18) is only valid for standard lightning-impulse waveshapes. For instances when the time to flashover is greater than 16 μ*s*, the CFO strength of 490 V/m is achieved. Strengths of 822 kV/m (1.68 CFO) at 2 μ*s* and 585 kV/m (1.20 CFO) at 6 μ*s* are given by Equation (18). Reference [B12] shows that the volt-time model gives reasonable physical values of leader propagation velocities in comparison with Pigini et al [B37].

Following the peak at 2 μ*s*, Figure 7 shows that the voltage decays at rates determined by the span length L_s, the combined impedance of OHGW Z_s, and the adjacent tower footing impedances R_f. An approximate estimate of the wave-tail time constant τ_{tail} is given by

$$\tau_{\text{tail}} = \frac{L_s(R_f + Z_s)}{0.9cR_f} \tag{19}$$

where

L_s is the span length in (m);
R_f is the tower footing impedance (Ω);
Z_s is the combined parallel impedance of OHGW (Ω);
c is the speed of light, 300 m/μs.

When R_f is high relative to Z_s, Figure 7 shows significant voltage on the tail of the wave. Under these conditions, a second evaluation is needed. The FLASH program evaluates using Equation (18) and the tower system at $t = 6$ μs. Usually, between one and five adjacent spans are involved in this calculation, depending on the span length.

6.2 Effect of insulation levels and insulation type

External insulation design of high-voltage transmission lines is determined by requirements set forth by power frequency voltages, contamination, switching overvoltages, and lightning overvoltages. The number of standard disks (254 mm × 146 mm) used in typical insulator strings for various system voltages is shown in Table 2. For all voltages, lightning and contamination levels may be controlling parameters. For line voltages greater than 345 kV, switching surge performance may also be a controlling parameter in insulator selection.

Table 2—Typical line insulation

Line-to-line voltage (kV)	Standard 146 mm disks, line-to-ground
115	7–9
138	7–10
161	10–12
230	11–14
345	15–18
500	22–28
765	30–37

Currently, most insulators are made of glazed porcelain and have been used at transmission line voltages up to 765 kV. Glass insulators have also been used on a significant portion of transmission lines. More recently, nonceramic insulators have become increasingly attractive, since their strength-to-weight ratio is significantly higher than that of porcelain, sometimes leading to reduced tower costs [B6]. Reference [B30] contains extensive laboratory test results on impulse-flashover characteristics of various porcelain-insulator types and lengths.

Regardless of the insulator type or length, withstand characteristics of insulators and air gaps are influenced by meteorological conditions such as relative air density and absolute humidity. At higher elevations, as relative air density decreases, the breakdown strength of air also decreases. Air-gap strength tends to increase with humidity unless condensation forms on nearby insulator surfaces. Washoff effects of rain seem to have little influence on lightning performance of insulators.

The minimum strike distance between the conductor and the grounded tower members should usually equal or exceed the insulator string length. For insulator strings unrestrained from movement, wind may decrease or increase this strike distance, possibly degrading the CFO and increasing the backflash rate. However, considering the wind speeds and their probability distribution, the increase in backflash rate is minor and, for most cases, may be neglected [B21]. Strike distances for vertical insulator strings are often limited by the National Electrical Safety Code® (NESC®)[4].

In general, if the lightning performance of the line is unsatisfactory, it is often more efficient to improve OHGW placement, reduce tower footing impedance, or add line-surge arresters than to add insulation. Finally, when specifying or purchasing line insulators, designers should consult ANSI C29 standards.

6.3 Wood or fiberglass in series with insulators

The use of wood or fiberglass in series with insulators (porcelain or nonceramic) has two beneficial aspects. The total CFO voltage of the combined insulation may be increased above that for the insulators only. For example, the combined CFO voltage of crossarm-insulator combinations is greater than the CFO voltage of the crossarm alone or the insulator alone. Also, wood is somewhat more effective than air in quenching a power-frequency arc to prevent an outage. AC flashover voltage of composite insulation is not increased by wood or fiberglass components because both conduct under wet conditions.

In general, to gain a significant increase in the total CFO voltage of the combined insulation, the CFO voltage of wood or fiberglass should exceed that of the porcelain or nonceramic insulator. Darveniza [B16] suggests a minimum impulse flashover voltage strength of about 200 kV/m for full-length poles of up to 8 m. Thus, the wood should be about three times longer than the insulator.

The average added-CFO voltage was defined and evaluated by Grzybowski and Jenkins [B20] for 1–2 m fiberglass crossarms for 115 kV lines. The added-CFO value of 450 kV/m under dry conditions fell to 420 kV/m under wet conditions. The wet/dry electric strength ratio of 0.94 for fiberglass fell to 0.82 for wood, since the wood absorbs water and its surface is not hydrophobic.

The ability of wood to successfully interrupt a power arc is a function of the power-frequency voltage gradient along the flashover path, and the magnitude of the fault current. Lightning-outage rates for distribution lines with wood-porcelain insulation are one-half to one-third the rates for lines with equivalent porcelain alone. Darveniza [B16] suggests that ac gradients of less than 10 kV/m are needed to provide a low probability that lightning flashovers develop into power arcs and faults. Based on this observation, at least 4 m of wood would be required for arc quenching on a 69 kV transmission line. Arc quenching would be more difficult to obtain at higher transmission voltage levels.

The use of wood for additional insulation may increase the risk of pole fires or crossarm fires. In wood-pole applications at 345 kV, a 300 mm distance between staples is recommended to alleviate damage caused by the high electric fields and the resulting capacitive currents. On all lines with wooden insulation, pole fires may be caused by leakage currents across contaminated insulators. The benefit of the impulse insulation value of wood may be gained, while the chance of crossarm and pole fires is reduced with special isolated bonding. These have been applied with success on both distribution and transmission systems. The isolated bonding schemes are described in Annex A.

6.4 Effect of power-line voltage

The rapid voltage stress created by the lightning stroke on the tower and grounded components either adds to or subtracts from the normal power-frequency ac or dc voltage on the conductor. This affects the total voltage

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[4] Information on references can be found in Clause 2.

across the insulation. For example, in the dc case, the positive pole should experience more backflashovers than the negative pole because the usual lightning polarity is negative. The power-frequency voltage is often high enough to influence the critical current needed for backflashover.

For any given phase angle, the instantaneous power-frequency voltage on each phase may be computed and the lightning voltages may then be superimposed. Considering all values of power-frequency voltage, the average voltage added during the highest third of the ac wave is 83% of the crest line-to-ground system voltage for three-phase systems, and 100% of the line-to-ground voltage for dc systems. Multicircuit calculations are more complicated. The FLASH program [B22], [B23] considers instantaneous power-frequency voltages of each phase in 15° increments through a full 360° to establish the backflashover rate to each phase.

Theoretical models for the inception of upward-connecting leaders predict that the incidence of shielding failures should also be affected slightly by the instantaneous power-frequency voltage on the conductor. This effect is considered to be masked by larger uncertainties in the shielding models.

7. Tower footing impedance

When a stroke contacts a tower, a portion of the stroke current travels down the tower. The remainder passes out along the OHGWs. The initial fractions along these two paths are determined by their relative surge impedances. The tower current flows to earth at the base of the tower through the tower footing impedance. The resultant voltage drop, and the magnitude of the voltage wave reflected back up the tower, depend directly on the value of the footing impedance encountered by the current. The voltage stress across the insulator strings is the difference between the tower voltage and the instantaneous value of the voltage of the phase conductors. A sufficiently high voltage stress may result in backflashover. Since the tower voltage is highly dependent on the footing impedance, it follows that footing impedance is an extremely important factor in determining lightning performance.

The tower footing impedance depends on the area of the tower steel (or grounding conductor) in contact with the earth, and on the resistivity of the earth. The latter is not constant—it fluctuates over time and is a function of soil type, moisture content, temperature, current magnitude, and waveshape. Customarily, the low-frequency, low-current value of footing resistance is used as an input in performance calculations (e.g., the FLASH program) because this value may be measured or computed easily. Surge reduction models of varying complexity for footing ionization are then applied to the basic data to estimate the insulator voltage magnitude under the lightning surge conditions.

7.1 Composite line performance

The lightning performance of an entire transmission line [B46], [B47] is influenced by the individual performance of each tower, rather than by the performance of a tower with the average tower-footing impedance. In areas of nonhomogeneous earth resistivity, even a few towers located in high-resistivity soil may degrade line performance. When spotting towers, every attempt should be made to locate each one where the local resistivity is low. When this may not be done, line performance computations should be made separately for each significant class of tower footing impedance encountered. The results may then be combined to determine the composite performance by the equation:

$$T = \frac{\Sigma T_n L_n}{\Sigma L_n} \tag{20}$$

where

T is the total outage rate;
L_n is the length of line section n with homogeneous resistance;

T_n is the outage rate computed for line section n.

If computed or observed lightning performance is unsatisfactory due to high-footing impedance at one or more towers, additional measures may be considered to lower the resistance.

7.2 Supplemental grounding

The inherent construction of the tower may result in a substantial surface area of tower steel, grillage, and foundation reinforcing cages in contact with the earth. Foundation reinforcing cages should be electrically continuous and bonded to the structure to achieve this desirable effect. If this is not done, structural damage may result when lightning does strike. In cases when the basic design does not give satisfactory resistance on its own, supplementary tower grounding may be required.

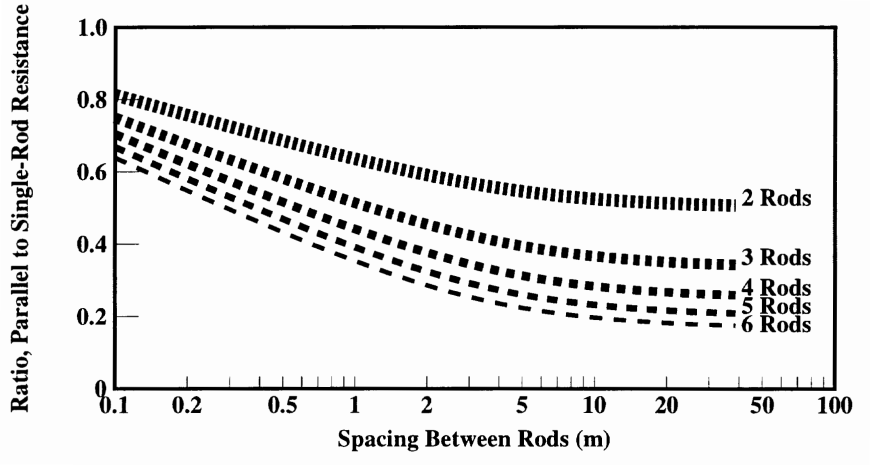
The most common grounding electrode is a driven rod. Its resistance may be computed from [B3]

$$R = \frac{\rho}{2\pi s}\ln\left(\frac{2s}{r}\right) \tag{21}$$

where

R is the resistance (Ω);
ρ is the earth resistivity (Ω·m);
s is the length of the rod in contact with the earth (m);
r is the rod radius in (m).

While increasing the rod radius reduces the resistance, increasing the length makes better use of a given volume of metal. Increasing the number of rods in parallel is also more effective, as shown in Figure 8. If the rods are closely spaced compared with their length, the electrode behaves as one rod with a larger apparent diameter, and there is a small reduction in resistance. As the rod spacing increases, the combined resistance decreases. For spacings that are large compared with rod length, the resistance will be reduced in inverse proportion to the number of rods. Figure 8 illustrates the effect of increasing the separation for small numbers of rods in parallel.



NOTE—Rods are 20 mm diameter, 3 m deep.

Figure 8—Ratio of resistance of ground rods in parallel to that of isolated rods

If the interconnection between rods has good electrical contact with the soil, it will act as a counterpoise wire with the benefits outlined in 7.3. However, in rocky areas, good contact with most of the wire surface is difficult to obtain. Here, the inductance of the interconnection (typically 1 μH/m) will start to dominate the impedance for lightning surges, leading to diminishing returns. The total voltage from the ground electrode will be the sum of rod resistance RI and interconnection inductance $L\, dI/dt$. For a fixed rise time of 2 μs, the additional inductive voltage, per meter of interconnection, would be equivalent to an impedance of 0.5 Ω. Thus, there would be little point to providing a low-resistance ground rod at the end of a 200 m wire, since the inductance of the connection would have 100 Ω impedance in series with the rod resistance for a typical lightning stroke. In some cases, improved soil contact may be obtained by backfilling the counterpoise trench with concrete or other stabilized low-resistivity material.

7.3 Counterpoise

Another method for increasing the contact area of a grounding system with the earth is the installation of a counterpoise. The counterpoise is a conductor buried in the ground parallel to or at an angle to the line conductors. It may be considered a horizontal electrode as compared with the vertical electrode created by a driven ground rod. Common arrangements include one or more radial wires extending out from each tower base; single, or multiple continuous wires from tower to tower; or combinations of radial and continuous wires. The counterpoise may sometimes be augmented with periodic driven rods.

A surge current, when applied to a single counterpoise, initially encounters the surge impedance of the conductor, which is about 150 Ω [B7]. The surge travels along the conductor at 1/3 the speed of light or 100 m/μs. As the current reaches more of the conductor, it effectively uses more of the contact area with the earth. The impedance thus decreases with time and reaches a steady-state value when the current is distributed through the entire length. The steady-state contact resistance may be calculated as [B3]

$$R = \frac{\rho}{\pi s}\left(\ln\left(\frac{2s}{\sqrt{4rd}}\right) - 1\right) \tag{22}$$

where

r is the wire radius in (m);
d is the depth of burial in (m);
s is the counterpoise length (m), and s » d .

The steady-state contact resistance is not greatly influenced either by r or d. Customary burial depth for a counterpoise is from about 0.5 m to 1 m. For a 20 mm diameter, 100 m long counterpoise, increasing the burial depth from 0.5 m to 1.5 m would decrease resistance by less than 9%. The choice of a thin, wide strap cross-section, rather than a large circular wire, may reduce inductive effects by as much as 15% and may increase exposed surface area at the same time.

Several short wires, arranged radially, may be more effective than a single long wire even if the total length and contact resistance of both are the same. The initial surge impedance of several wires is lower and the steady-state contact resistance is reached sooner. For grounding the lightning surge, the first 80 –100 m of counterpoise length is the most effective.

Since counterpoise is usually either not buried or buried at shallow depths, it may be subject to theft and vandalism, especially if the counterpoise is made of copper. Consideration should be given to the selection of a counterpoise with less commercial value, such as copper-clad steel, which is also considerably more difficult to vandalize. Concerns with cathodic protection of the counterpoise and its connections should be satisfied. These concerns are particularly difficult for HVDC lines, where copper components may accelerate foundation corrosion. Also, a similar investment in additional shield wires may be more effective.

7.4 Resistance of complex footings

The low-frequency, low-current electrode resistance R_f depends mainly on the electrode dimensions and soil resistivity. Equation (21) gives the resistance of a single vertical rod. The resistance of a hemisphere to remote earth is given by

$$R_{hemisphere} = \frac{\rho}{2\pi s} \tag{23}$$

where

s is the radius of the hemisphere.

Equations (21) and (23) may be used to give a general expression for electrode resistance as a function of the maximum three-dimensional radius s and the surface area A . In this model, s and A values of wire-frame and solid electrodes are identical for both the hemisphere, $A = 2\pi s^2$, and for the rod, $A = 2\pi sr$. A surface array of radial or crowfoot wires of length s (or a circular disk of radius s) would have a surface area of roughly $A = \pi s^2$. A two-vertical-rod electrode with separation D and lengths l, or a vertical plate of length D and depth l, would have $s = \sqrt{D^2/4 + l^2}$ and $A = 2Dl$. A four-vertical-rod electrode with separation D and length l, or equivalently a block with sides D and depth l, would have $s = \sqrt{D^2/2 + l^2}$ and $A = D^2 + 4Dl$, assuming the top surface does not contact the soil.

The three-dimensional area A and extent s may be used to compute resistance in an expression of the form

$R_f = \rho/(2\pi s) \ln(Cs^2/A)$.

For a driven rod, Equation (21) results in $C = 4\pi$. For a hemisphere, Equation (23) results in $C' = 2\pi e$, as shown in Equation (24).

$$R_f = \frac{\rho}{2\pi s} \ln\left(\frac{2\pi e s^2}{A}\right) \tag{24}$$

where

e is the exponential constant 2.718.

Rods tend to have large ratios of s^2/A, so the error in using the hemisphere constant C', not the rod constant C, is usually less than 10%. Electrodes varying in shape from long and thin, through flat-surface, to three-dimensional, are all described reasonably well when C' is used. Reference [B12] notes that this approach gives a reasonably accurate approximation to the low-frequency, low-current footing resistance of most complex electrode shapes. This model is recommended because grounding electrodes at the bases of typical transmission towers may consist of complex networks of driven rods, radial wires and supports, and be surrounded by semiconducting materials such as concrete, clay, or chemically treated soil.

7.5 Special grounding effects

Three special grounding effects have been found to affect lightning performance. There is a residual inductance in any grounding arrangement which contributes some stress to line insulation. Balancing this, soil ionization, and capacitive displacement currents tend to reduce the apparent resistivity. Electrode inductance adds between 2 Ω and 14 Ω [B12] to footing impedance, which would only be important for lines with low footing impedance. The ionization effects are important for many soil types, and decrease resistance by effectively increasing the radius of the conductor. The capacitive displacement current is only important for grounding in areas with soil resistivities greater than 10^4 Ω·m.

The FLASH program incorporates an indirect surge reduction mechanism. Transmission lines with high footing impedance are more sensitive to midspan stroke effects than lines with low footing impedance. However, the FLASH program uses a factor of 0.6, which describes the low-impedance case (effective number of tower flashes, step 2.35). This provides a reasonable match to observed lightning performance of many high-voltage (HV) and extra-high voltage (EHV) lines. The agreement degrades, however, for lines that have low (< 10 Ω) or high (> 50 Ω) footing impedance. FLASH provides a platform for the study of new surge reduction models, but no model has been found to describe all cases. In soils with two or more soil layers, ionization will only reduce the resistance between the metal electrode and the upper soil layer. In most of these cases, the effective resistivity and the total resistance are dominated by the lower-layer characteristics, making ionization effects unimportant.

8. Special methods of improving lightning performance

In addition to the standard methods of improving lightning performance of transmission lines (e.g., adding OHGWs, reducing ground resistance, adding counterpoise, increasing insulation), there are several special methods that have been used with some success. This clause provides a brief review of the best known of these special methods. Designers should recognize, however, that industry experience has usually been limited to a few applications, and more experience is being accumulated.

8.1 Additional shield wires

Since the mid 1910s, it has been recognized that OHGWs on a transmission line reduce the lightning voltage created across the insulators. This reduction comes about in the three following ways:

a) By intercepting strokes that would otherwise hit the phase conductors
b) By draining off part of the stroke current that would otherwise flow through the footing impedance
c) By increasing the common-mode coupling of voltage surges on the shield wires to the phase conductors, causing the insulator voltage at the tower to be reduced

Only the first of these effects requires the grounded wire to be above the phase conductors. One or more shield wires under the phase conductors will not intercept lightning strokes, but they may improve coupling and reduce insulator lightning voltages almost as effectively as if they were above the phase conductors. Figure 9 shows estimates of tripout rates for a typical 345 kV double-circuit line [B22] when either a third shield wire or a new pair of wires separated by 4 m is added.

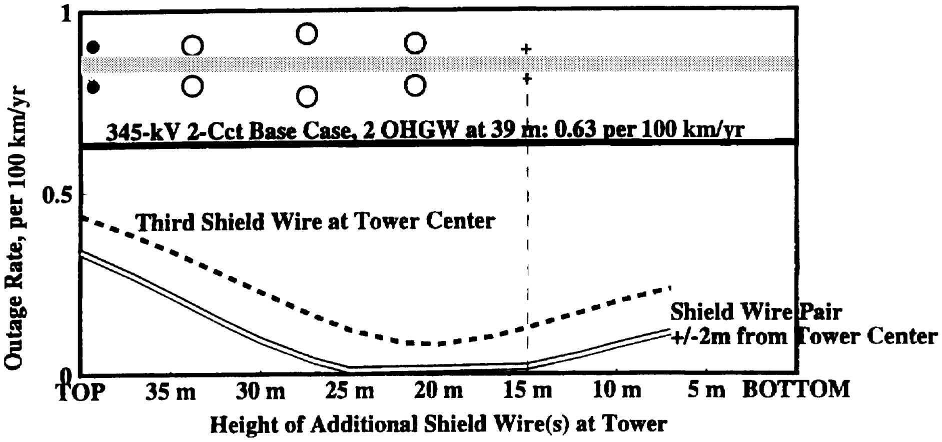


Figure 9—Improvement in lightning performance with three or four shield wires

The large improvement is caused mainly by the increase in coupling coefficient from shield wires to phases rather than in the small reduction in total shield-wire surge impedance. Table 3 lists some of the advantages and disadvantages to the use of underbuilt shield wires.

While underbuilt shield wires increase tower loadings during ice or high wind conditions, their location makes a much smaller contribution to overturning moment than a similar wire at the top of the tower. This provides an attractive option when improved performance is required from an older line having only a single existing OHGW. Underbuilt ground wires seem to have their best application in regions of high ground resistance or where unusually frequent flashovers have been experienced. When ground resistances are high, the additional cost of losses is lower because circulating currents are smaller. Since underbuilt shield wires tend to have less sag than phase conductors, care should be taken to allow for adequate electrical clearances under emergency loading conditions.

8.2 Guy wires on transmission towers

In some cases, towers are uprated by fitting new or additional guy wires from the tower to rock or soil anchors. This treatment should also improve lightning performance in two ways. First, each new guy anchor will behave as an additional ground electrode, as described in Figure 8. The anchors may be grouted with low-resistivity material such as concrete, and bonded to any existing counterpoise or structure, to maximize the benefit. Second, the guy wires will mitigate the tower surge response. Four widely separated guy wires may reduce the impedance of a tower from 100 Ω to 50 Ω [B13]. This factor alone may reduce the outage rate of a tall line by 30%.

8.3 Ground wire on separate structures

OHGWs may be supported by separate outboard towers or poles instead of being mounted on the same structure that supports the phase conductors. This arrangement may give extreme negative shielding angles, which minimize induction losses and provide excellent security from shielding failures. Tower height and wind loading may also be reduced. While an expensive option, OHGWs on separate structures may result in excellent lightning performance. Connections from the OHGWs to towers, if required for ac fault-current management, should be designed to have a high impedance to lightning through long interconnection length to minimize risk of backflashover.

8.4 Line surge arresters

OHGWs add to the line height, increase the flash collection rate, escalate the line losses, augment the mechanical moment loads, and affect the line cost. Nonlinear devices to limit surge voltages, such as protector tubes, arcing horns, rod or pipe gaps, and gapped or gapless surge arresters have been applied with some success to distribution lines and transmission lines. Surge arresters at every insulator location (line arresters) present an alternative to the OHGWs both for new construction and for improvements to older unshielded lines when improved lightning performance is required. For special applications such as river crossings and on one circuit of double-circuit lines, properly applied line arresters may also provide specific benefits such as reduced double-circuit outage rate.

Line arresters have been successfully used on many transmission lines. Excellent results were reported [B27] on a line that crossed mountain ridges of high ground resistivity (usually rock) and high lightning exposure, leading to frequent lightning flashovers and insulator damage. These localities are difficult to reach by the line crews, making maintenance expensive. Also, the high ground resistivity and thin soil layer make installation of counterpoise or deep-driven ground rods costly and of little benefit. The improved single- and double-circuit reliability and decreased maintenance and operating costs may sometimes balance the cost of the arresters.

Table 3—Advantages and disadvantages of underbuilt shield wires

Advantages	Disadvantages
Lower overturning moment	Cost of extra conductor
Easier access to optical fibers	Cost of extra losses
Harder to steal than counterpoise	Reduced ground clearance
Better magnetic field mitigation	Lower zero-sequence impedance
Cheaper inter-conductor spacers	Different sag from phases

Line arresters would be exposed to higher wind and vibration loads than ground-based station arresters. Mechanically strong and nonfragmenting construction would be required. For installation in remote locations, light weight and resistance to gunfire would also be needed. These requirements may be addressed by nonceramic housing technology.

Applying arresters to transmission towers to limit lightning flashovers is entirely different from, and also more complex than, station applications. This type of arrester application should be handled with care if a major performance improvement is to be realized. For example, if arresters are applied only on one tower, the result may well be that the flashovers are transferred to adjacent towers. A careful analytical evaluation of arrester locations, footing impedance, series gap characteristics, OHGW benefits, and arrester energy sharing is recommended before any installation is made [B8]. Also, the probability of arrester failures from all causes should be added into estimates of line reliability.

8.5 Unbalanced insulation on double-circuit lines

Unbalanced insulation on double-circuit lines, first applied by Kawai et al. [B26], is a deliberate effort to force most of the flashovers onto one circuit so that the other circuit will experience few flashovers, if any. When the weaker circuit flashes over, its phase conductors are suddenly connected to the tower by the flashover path, thereby making them momentarily underbuilt shield wires until the breaker opens. Insulator voltages on the unfaulted circuits are reduced by draining away some stroke current into the phase-surge impedance. Common-mode voltage coupling is also enhanced, decreasing the normal-mode voltage appearing across the insulation. The lowest circuits have the lowest surge impedances to ground. They will also offer the greatest improvement in coupling, and would logically be selected as the weaker circuits.

Line designs with more than one circuit voltage on a single tower provide extreme examples of unbalanced insulation. The lightning performance of the higher-voltage circuits in these cases is better than would be expected if the lower-voltage circuits were not present.

These advantages reduce the likelihood of flashover of the stronger circuit. On existing lines, it is not always possible to over-insulate one circuit enough to provide an adequate insulation differential. In such cases, the insulation strength on the other circuit may be reduced. While this provides an adequate differential, it will increase flashover rate on the weaker circuit, which may not be acceptable. If tower height permits, the use of underbuilt shield wires may be considered in order to return the total flashover rate to acceptable levels.

8.6 Active air terminals

In some cases, older lines were constructed with shielding angles that are now considered to be poor. Line shielding may be somewhat improved by increasing the proportion of strikes that hit the tower. This has traditionally been done through the addition of lightning masts at existing towers, although other products are now offered commercially. At this time, there is little full-scale evidence that either supports or contradicts [B10], [B49] the additional effectiveness of these devices.

Any projection will increase the effective tower height and the resulting lightning incidence, which leads to more backflashovers. However, an advantageous trade-off may sometimes be made. Rizk [B39] describes the two important physical conditions for positive leader inception from a structure or conductor. These conditions are basically determined by structure or by wire height above ground. Under negative leader space charge, small details of the structure surface would appear to have only minor effects on the lightning incidence.

Annex A

(informative)

Isolated bonding of wooden structures

When the impulse strength of wooden insulation is used in a transmission line, there is often an increased risk of pole fires under operating voltage. The pole fires usually result from the heating effect of leakage currents that pass through the high resistance of the wood path. Conventional mitigation of this effect is discussed in [B16] and elsewhere. The following method has been found to further mitigate the incidence of pole fires by reducing the ac currents injected into the pole. The scheme is shown in Figure A.1.

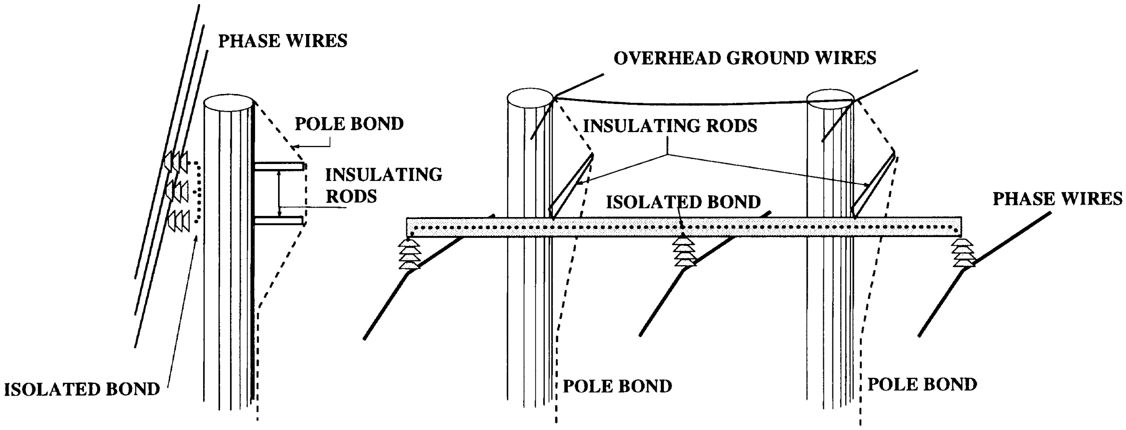


Figure A.1—Isolated bonding scheme for lines with wooden pole or crossarm

The three insulators in Figure A.1 are all on one face of the wooden pole. The bases of the insulators are connected with a bond wire. However, the pole bond is on the side of the pole opposite from the insulators, and is not connected to the isolated bond. In addition, the pole bond is insulated from the pole behind the phase insulators. Since the only electrical stress on the pole-bond insulation will be under lightning impulse conditions, inexpensive fiberglass rods have been used successfully for the stand-offs. Only the length of wood (and air) between the isolated bond and the pole bond will give an increase in the total CFO voltage. The leakage currents from the three phase insulators will tend to cancel as they will be out of phase and similar in amplitude. The only leakage-current flowing in the wood is the resultant, which will be small compared to any one phase. With lower leakage current levels, the risk of crossarm or pole fires is reduced. The isolated bonding scheme may be implemented on single-pole wooden structures or on H-Frame type structures. When line maintenance personnel climb the pole, the isolated bond should be connected to the pole bond to eliminate any voltage difference and provide a grounding path for personnel safety.

This method has been applied with success at both distribution and transmission voltage levels.

Annex B

(normative)

The FLASH program

The FLASH program was written to implement and test the IEEE methods [B22], [B23] for estimating lightning tripout rates of overhead lines. The IEEE methods are based on the approach of J. G. Anderson [B3], where 27 simple steps are needed to compute a shielding-failure rate and 39 additional tasks complete the calculation of the backflashover rate. The FLASH program was originally developed for use within the working group to replace Anderson's hand-calculator approach. The FLASH program was then used to test sensitivities of various models and to evaluate important simplifications. The ability of FLASH versions to predict the outage rates of lines has been improved through repeated comparisons with observations from a series of calibration lines [B23]. FLASH also has turned out to be a useful teaching tool in academic courses on lightning because its linear structure lets students focus on quality of the data and approximations, rather than focusing only on the calculation process.

B.1 FLASH 1.6

At present, two versions of FLASH are supported, 1.6 and 1.7. Version 1.6 has been in use since 1990. FLASH is written in BASICA for an IBM-PC DOS compatible computer. The FLASH program does not use either Windows™ or a mouse, and it requires that the print-screen key be used to print pages. The diskette distributed with this guide contains executable files of FLASH 1.6 and FLASH 1.7 (FLSH16.EXE and FLSH17.EXE, respectively), along with files containing the source code for each (flsh16.bas and flsh17.bas). Sample line data files are provided in this annex as follows:

```
FLSH16.BAS.....Executable program to compute line outage rates
FLSH16.ASC.....ASCII Source Code for FLSH16.BAS
******.DTA.....Calibration Line Data Files
```

To run FLASH with recent versions of Windows™ that do not support BASICA, open the disk from within Windows™ and double-click on the executable file (either FLSH16.EXE or FLSH17.EXE). To run FLASH with BASICA, the BASICA.EXE file provided with DOS must be on the same directory as the executable FLASH file. This may be accomplished by copying the BASICA.EXE file from the C drive onto the included diskette, or by copying the executable diskette files onto a C drive that contains the BASICA.EXE file. At the DOS prompt (either A:\ or C:\), type the command BASICA. After BASICA is loaded, the command LOAD"FLSH16.BAS"↙ is typed (the symbol ↙ is used denote the RETURN key) and the FLASH program begins with the prompt:

```
***************************************************
*                F L A S H 1.6                    *
*   PRODUCED BY IEEE WORKING GROUP ON ESTIMATING  *
* THE LIGHTNING PERFORMANCE OF TRANSMISSION LINES *
*                JANUARY, 1990                    *
***************************************************

On Which Drive Will Your Data Be On? A
```

After indicating which disk drive (A, B, C, or D ↙) contains the data files, the program moves on to a main menu as follows:

```
Do You Wish To:
1. Enter NEW DATA from KEYBOARD.
2. Read OLD DATA from DISK DRIVE.
3. Print SUMMARY of DATA.
4. Modify EXISTING DATA.
5. RUN PROGRAM with Current Data.
6. QUIT.
```

The menu selection determines the action to be taken, and all actions return to the main menu. Choices (1) and (4) bring up five DATA ENTRY/EDIT screens in sequence. When the first time item (1) is selected, data for a typical 500 kV single circuit line appears in the input areas. These values are to be changed by overtyping and pressing ↙ to move to the next field. Data editing is done in the same way as data entry. The cursor only moves in the forward direction.

The first screen requests the following data:

```
 D A T A   E N T R Y / E D I T # 1
Do You Wish To Use (1) English or (2) Metric Units? 2
What is the Line Name? FLASH 1.5 Base Case
How Many Phases? 3
How Many Overhead Ground Wires (0,1 or 2)? 2
Thunder DAY Level (Enter 0 to use Thunder HOUR Level)? 40
For Each SHIELDWIRE, ENTER: (All Distances in Meters)
 Distance From Centerline       Height Above Ground at Tower
          -3                             40
           3                             40
```

The dimensions given in the pre-programmed base case are in meters. Care should be taken to check the values twice after changing from metric to English units. Up to 12 phases may be analyzed on the same tower, but FLASH version 1.6 does not evaluate shielding effects of multiple transmission lines on the same right-of-way. If a GFD value N_g is known from long-term lightning location system data, it may be input as an equivalent thunder-day level, inverting Equation (2) to give $T_d = (25\ N_g)^{0.8}$. The data entry is simplified if the distances of phases are taken from the center-line of the tower.

The second screen requests more detailed data about the phase conductors, as follows:

```
D A T A   E N T R Y / E D I T # 2
For each PHASE, ENTER: (All Distances in Meters)
 Distance    Conductor    Insulation    Phase    Phase AC
   From        Height      Striking    Voltage   Angle or
Centerline                 Distance      (kV)    (deg) DC
    -5          35            3          500        0   AC
     0          35            3          500      120 AC
     5          35            3          500      240 AC
```

If an HVDC line is being modeled, the positive pole is indicated by a phase angle of 0° and the negative pole has a phase angle of 180°. A plot of the conductor locations is then produced, with the scale of 1 m per character horizontal and 3 m per line vertical. Since the conductors are entered in various orders, the indices given to the outermost conductors on each side should be noted along with the corresponding OHGW.

```
C O N D U C T O R   L O C A T I O N S
Note the OUTER-MOST INDEX Values Near OHGW locations S1 and S2.
Hit Any Key to Continue.
```

```
                         S1    S2
                        1    2    3
...
-30      -20      -10        0       10       20       30
 |        |        |        |        |        |        |
```

In some cases, the outermost conductor may not have the largest (positive) shielding angle, as defined in Figure 1. In these cases, shielding of the conductors with the largest positive shielding angles should also be evaluated. The shielding design should be based on the larger of the two SFR estimates. The next data entry screen accepts the index data.

```
D A T A   E N T R Y / E D I T # 3
Shielding Evaluation: Select the highest, outer-most conductors.
At least one conductor should be checked on each side.
How many conductors should be checked? 2
INDEX of Exposed Conductor     INDEX of Closest Shield Wire
            1                                1
            3                                2
```

The selection of shielding evaluations could be made automatic, but no algorithm will cover all possible cases such as river crossings, nearby lines, or extreme OHGW separation. Manual selection also forces the user to understand the nature and terminology of the shielding process.

```
D A T A   E N T R Y / E D I T # 4

ENTER: Number of SUBCONDUCTORS in each Bundled Conductor (1-4)? 4

Use MILLIMETRES for the following three dimensions:
Subconductor SPACING? 457
Conductor DIAMETER? 30
OHGW DIAMETER? 14

Use METRES for the following three dimensions:
Average SPAN Length? 300
Conductor Midspan SAG (Enter 0 for our guess)? 6.3
Overhead Groundwire Midspan SAG (Enter 0 for our guess)? 4.05
```

The estimates of sags are based on typical aluminum conductor, steel reinforced (ACSR) phase-conductor and steel OHGW weights, strung at 20% rated tensile strength (RTS). Sags for different stringing tensions may be obtained using sag-tension programs or estimated from the following equations, for spans in meters:

$$Sag_{ACSR} \sim \frac{0.0014 Span^2}{\% RTS} \tag{B.1}$$

$$Sag_{Steel} \sim \frac{0.009 Span^2}{\% RTS} \tag{B.2}$$

The final data-entry screen accepts data about the tower shape and the distribution of footing impedance. Four different types of towers are modeled, as shown in Figure B.1.

The shape that most closely approximates the line tower should be used. Note that small tower-width or downlead diameters are adjusted to a minimum of 0.2 m to model the corona radius of these downleads under lightning surge conditions.

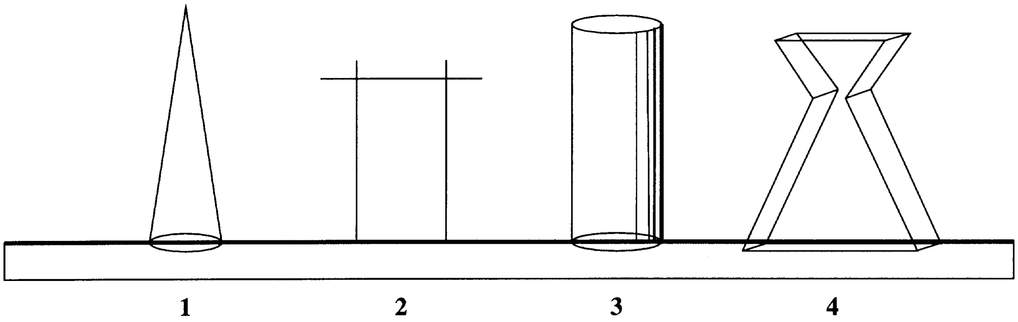


Figure B.1—Tower shapes supported by FLASH version 1.6

```
 D A T A   E N T R Y / E D I T # 5
Tower Type (1=Conical,2=H-Frame,3=Cylindrical,4=Waist): 4
ENTER: Tower Dimensions?
(All Distances in Meters)
Tower HEIGHT? 40
Tower BASE DIAMETER? 8
Tower Midsection WIDTH? 4
Tower-Top DIAMETER 2
DISTANCE from Middle to Top 70

ENTER: Tower Footing Resistance DISTRIBUTION:
% of Values GREATER THAN Footing Resistance (ohms)
100% >? 10
90 % >? 20
80 % >? 30
70 % >? 40
60 % >? 50
50 % >? 60
40 % >? 70
30 % >? 80
20 % >? 90
10 % >? 100
```

The footing impedance values can be estimated from soil resistivity measurements using Equation (24), from measured construction values, or from in-service measurements with high-frequency instrumentation.

Once the input data has been entered, checked, and reedited, the program returns to the main menu. Option (2) allows data from a previous run, or from one of the calibration lines to be read in from the current disk drive.

```
I N P U T   F R O M   D I S K   F I L E
Insert Line Parameter Disk Into DRIVE A
Press any key to continue.
Type the FILE NAME as <filenm.ext> and press RETURN.(! for dir)!
Current Drive:
A:
```

Option (3) prints a brief summary of the data, and option (5) runs the FLASH 1.6 algorithm on the current data. The first set of screens allows the user to save either the raw data or the output results on a disk file.

```
 D A T A   S T O R A G E
```

```
BASE      .TST   BASICA   .EXE     FLSH16   .BAS     FLSH15   .ASC

FLSH15    .BAS   TUPOX    .DTA     18A      .DTA     22A      .DTA

BEAULEA   .DTA   BFDAV    .DTA     BFWP     .DTA     CEAEP    DTA

CEDMAR    .DTA   CIGRE30  .DTA     CIGRE31  .DTA     CIGRE32  .DTA

DIXGR138  .DTA   JVILCOR  .DTA     NEPC115  .DTA     NEPC230  .DTA

NEPCPOL   .DTA   NEPCSC   .DTA     PLANO    .DTA     SEQCHAR  .DTA

REDBOOK   .DTA   STAND110 .DTA     TIDDWAG  .DTA     TULWEL   .DTA

FLSH16    .ASC
```

```
Do you want to SAVE this data to a DISK FILE? (Y/N)? Y
Enter the DISK FILE NAME <filenm.ext>? BASE.TST
Do you want to SAVE output to a DISK FILE? (Y/N)? Y
Enter the DISK FILE NAME <filenm.ext>? OUTPUT.RES
```

The next screen describes the shielding calculations.

```
 S H I E L D I N G   C A L C U L A T I O N
Value of BETA (Enter 0 for our guess)? 0
Our guess of BETA = 0.7142858
Accept (Y/N)? Y

THE SHIELD ANGLE REQUIRED FOR CONDUCTOR 1 IS -10.52 DEGREES
THE ACTUAL SHIELD ANGLE FOR CONDUCTOR   1 IS 17.1 DEGREES
THE SHIELD ANGLE REQUIRED FOR CONDUCTOR 3 IS -10.52 DEGREES
THE ACTUAL SHIELD ANGLE FOR CONDUCTOR   3 IS 17.1 DEGREES
Press Any Key to Continue.
```

The calculation of backflashover is carried out ten times, once for each of the footing-resistance values provided in DATA ENTRY/EDIT screen 5.

```
B A C K F L A S H   C A L C U L A T I O N
 Footing RESISTANCE = 100.0 Ohms
 Tower WAVE IMPEDANCE = 10.38132 Ohms.
Cond.   Coupling   Flashover Insulator   Flashover Insulator   Critical
No.     Factor     Voltage   Voltage     Voltage   Voltage     Current
                    at 2 us    at 2 us     at 6 us    at 6 us
                      (kV)     (kV/kA)       (kV)      (kV/kA)    (kA)
1       0.5041     2460       29.55       1755       16.99        83.23
2       0.5466     2460       27.00       1755       15.53        91.09
3       0.5041     2460       29.55       1755       16.99        83.23
The PROBABILITY of BACKFLASHOVER by each PHASE is:
 Cond. No.      Probability (%)
    1               38.9
    2               22.2
    3               38.9
....
Press Any Key to Continue.
```

The backflashover rate and SFR are summed in the last step to give the total estimate of lightning outage rate.

```
F I N A L   R E S U L T S
*****************************************************************
 THE BACKFLASHOVER RATE = 2.326 FLASHOVERS/100 KM-YEARS
                        = 3.74 FLASHOVERS/100 MI-YEARS
THE SHIELDING FAILURE
          FLASHOVER RATE =.59 FLASHOVERS/100 KM-YEARS
                         =.94 FLASHOVERS/100 MI-YEARS
 TOTAL FLASHOVER RATE    = 2.916 FLASHOVERS/100 KM-YEARS
                         = 4.68 FLASHOVERS/100 MI-YEARS
*****************************************************************
HIT ANY KEY FOR MAIN MENU
```

The source code for the program is found in the file named FLSH16.ASC. Versions of FLASH 1.6 have been translated into FORTRAN, and a professional version of FLASH for Windows™ has also been developed. The (identical) performance of FLASH 1.5/1.6 in predicting outage rates on calibration transmission lines was evaluated in [B23].

B.2 FLASH 1.7

Several changes and corrections are recommended to bring FLASH Version 1.6 into agreement with this guide. Some of these changes are simple to incorporate into existing copies of FLASH 1.6, which has had a wide distribution. These changes are described here, and the source code with these modifications is renamed FLASH 1.7 with the revision date of 01/96.

```
*** Striking Distance Model --- Change
44 DEF FNS(IN)=8*IN^.65: REM     STRIKING DISTANCE (m) FROM CURRENT (kA)
 --- to ---
44 DEF FNS(IN)=10*IN^.65: REM       STRIKING DISTANCE (m) FROM CURRENT
(kA)
```

The equation now provides the average, rather than the minimum, striking distance. This will provide better estimates of SFRs, but will give less conservative “perfect” designs as discussed in 5.3.

```
*** Lightning Incidence Model --- Change
45 DEF FNW(H)=4*H^1.09: REM            ATTRACTIVE WIDTH OF CONDUCTOR (m)
 --- to ---
45 DEF FNW(H)=28*H^0.6: REM            ATTRACTIVE WIDTH OF CONDUCTOR (m)
and
1555 RN=GF/10*(ABS(GX(1)-GX(2))+FNW(EM))
 --- to ---
1555 RN=GF/10*(ABS(GX(1)-GX(2))+FNW(GY))
and
2030 HAVG=.5*(HRIGHT+HLEFT)-2/3*CS
 --- to ---
2030 HAVG=.5*(HRIGHT+HLEFT)
```

The new attractive-width equation is based on conductor height at the tower. The recommended expression for r_g in Equation (11) is not presently used in FLASH 1.7.

```
*** Evaluate Insulation Strength at Span Reflection Time --- Change
2880 REM STEP---2.10---SPAN TRAVEL TIME
```

```
2885 TS=SP/(VL*.9)
 --- to ---
2331 REM STEP---2.10---SPAN TRAVEL TIME
2332 TS=SP/(VL*.9)
and
2545 F2(I)=FNC(SI(I))
 --- to ---
2545 IF (TS>=1) THEN F2(I)=SI(I)*(400 + 710*((2*TS)^(-0.75)))
2546 IF (TS<1) THEN F2(I)=FNC(SI(I))
```

These changes evaluate the volt-time curve strength just at the point when the insulator voltage-waveshape becomes non-standard, which is at the return of reflections from adjacent towers.

```
*** Correction to HVDC Calculation
3515   IF(ACDC$(I)="AC") THEN IA(J)=IS(I)*(1+(PV*LV(I)/VR(I))*(COS(T2)-
COS(T1))/ TH(J))
3516    IF(ACDC$(I)="DC") THEN IA(J)=IS(I)*(1-COS(PI*PA(I)/180)*LV(I)/
VR(I))
```

Figure B.2 shows the calculated results for the 500 kV single-circuit base case provided as a default for data entry. The base case should give a SFR of 0.65 outages per 100 km/year and a backflash rate of 3.22 outages per 100 km/year. The evaluation of insulation strength at the span return time, rather than at 2 μs, gives an increasing backflashover rate with increasing span length.

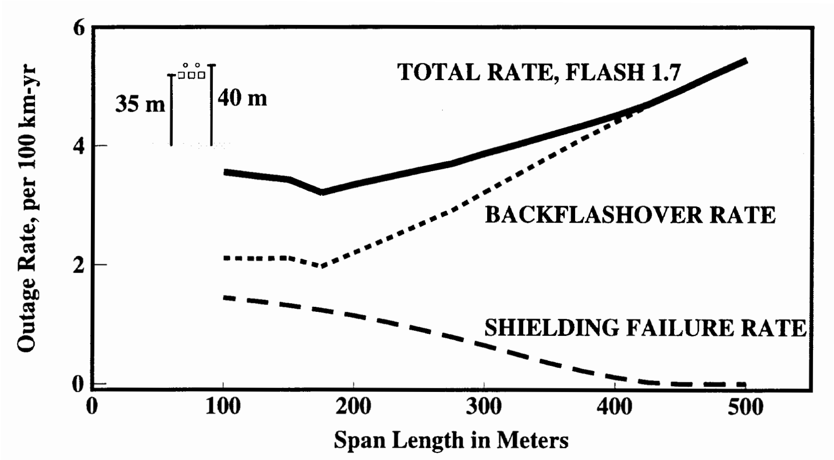


Figure B.2—Predicted outage rate from FLASH version 1.7 versus span length

Several researchers have tested the inclusion of models of the reduced surge impedance of footings under high-current conditions, alone, and in conjunction with advanced models for transient ground plane surge impedance. No model improves the predictive accuracy of the FLASH program beyond version 1.7.

B.3 FLASH 2.0

Based on the need to update several analytical models [B23], version 2.0 of FLASH is being constructed by the IEEE Working Group on Estimating Lightning Performance of Overhead Transmission Lines. The current version is not a working model of the other programs, is not user friendly, is written mainly in FORTRAN, and requires the preparation of input data files rather than item-by-item menu-driven input. FLASH V2.0 may be obtained by joining the IEEE Working Group on Estimating the Lightning Performance of Overhead Transmission Lines, and contributing either to testing or further model development.

Annex C

(informative)

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