

IEEE Guide for Improving the Lightning Performance of Electric Power Overhead Distribution Lines

Sponsor

**Transmission and Distribution Committee
of the
IEEE Power Engineering Society**

Approved 26 June 1997

IEEE Standards Board

The Institute of Electrical and Electronics Engineers, Inc.
345 East 47th Street, New York, NY 10017-2394, USA

Copyright © 1997 by the Institute of Electrical and Electronics Engineers, Inc.
All rights reserved. Published 1997. Printed in the United States of America.

ISBN 1-55937-940-5

No part of this publication may be reproduced in any form, in an electronic retrieval system or otherwise, without the prior written permission of the publisher.

IEEE Standards documents are developed within the IEEE Societies and the Standards Coordinating Committees of the IEEE Standards Board. Members of the committees serve voluntarily and without compensation. They are not necessarily members of the Institute. The standards developed within IEEE represent a consensus of the broad expertise on the subject within the Institute as well as those activities outside of IEEE that have expressed an interest in participating in the development of the standard.

Use of an IEEE Standard is wholly voluntary. The existence of an IEEE Standard does not imply that there are no other ways to produce, test, measure, purchase, market, or provide other goods and services related to the scope of the IEEE Standard. Furthermore, the viewpoint expressed at the time a standard is approved and issued is subject to change brought about through developments in the state of the art and comments received from users of the standard. Every IEEE Standard is subjected to review at least every five years for revision or reaffirmation. When a document is more than five years old and has not been reaffirmed, it is reasonable to conclude that its contents, although still of some value, do not wholly reflect the present state of the art. Users are cautioned to check to determine that they have the latest edition of any IEEE Standard.

Comments for revision of IEEE Standards are welcome from any interested party, regardless of membership affiliation with IEEE. Suggestions for changes in documents should be in the form of a proposed change of text, together with appropriate supporting comments.

Interpretations: Occasionally questions may arise regarding the meaning of portions of standards as they relate to specific applications. When the need for interpretations is brought to the attention of IEEE, the Institute will initiate action to prepare appropriate responses. Since IEEE Standards represent a consensus of all concerned interests, it is important to ensure that any interpretation has also received the concurrence of a balance of interests. For this reason, IEEE and the members of its societies and Standards Coordinating Committees are not able to provide an instant response to interpretation requests except in those cases where the matter has previously received formal consideration.

Comments on standards and requests for interpretations should be addressed to:

Secretary, IEEE Standards Board
445 Hoes Lane
P.O. Box 1331
Piscataway, NJ 08855-1331
USA

Note: Attention is called to the possibility that implementation of this standard may require use of subject matter covered by patent rights. By publication of this standard, no position is taken with respect to the existence or validity of any patent rights in connection therewith. The IEEE shall not be responsible for identifying patents for which a license may be required by an IEEE standard or for conducting inquiries into the legal validity or scope of those patents that are brought to its attention.

Authorization to photocopy portions of any individual standard for internal or personal use is granted by the Institute of Electrical and Electronics Engineers, Inc., provided that the appropriate fee is paid to Copyright Clearance Center. To arrange for payment of licensing fee, please contact Copyright Clearance Center, Customer Service, 222 Rosewood Drive, Danvers, MA 01923 USA; (508) 750-8400. Permission to photocopy portions of any individual standard for educational classroom use can also be obtained through the Copyright Clearance Center.

Introduction

(This introduction is not part of IEEE Std 1410-1997, IEEE Guide for Improving the Lightning Performance of Electric Power Overhead Distribution Lines).

Lightning is a major cause of faults on typical overhead distribution lines. These faults may cause momentary or permanent interruptions on distribution circuits. Power-quality concerns have created more interest in lightning, and improved lightning protection of overhead distribution lines against faults is being considered as a way of reducing the number of momentary interruptions and voltage sags.

Lightning usually causes temporary faults on overhead distribution lines. If the fault is cleared by a breaker or a recloser, the circuit may be successfully reclosed. In the past, this was acceptable—but now with the proliferation of sensitive loads, momentary interruptions are a major concern.

Lightning may also cause permanent faults. From 5–10% of lightning-caused faults are thought to cause permanent damage to equipment ([B22] recorded 9%). Temporary faults may also cause permanent interruptions if the fault is cleared by a one-shot protective device, such as a fuse.

Estimates of the lightning performance of distribution lines contain many uncertainties. Some of the basics such as lightning intensity measured by ground flash density (GFD), or estimating the number of direct strikes to a distribution line may have significant errors. Often, rough estimates or generally accepted practices are just as effective as detailed calculations. This guide is intended to provide straightforward estimates of lightning-caused faults.

The goal of this guide is to provide estimates of lightning-caused faults and the effectiveness of various improvement options. Estimates using this guide may be used to compare improved lightning protection with other methods of improving system reliability and power quality such as tree trimming programs or improved protection schemes such as the use of additional reclosers or sectionalizers. This guide should also be beneficial in evaluating design standards.

At the time this recommended practice was completed, the Working Group on the Lightning Performance of Electric Power Overhead Distribution Lines had the following membership:

Tom Short, Chair

Ronald H. Ammon	David L. Flaten	Francesco Muzi
John G. Anderson	Manuel M. Gonzalez	Randy Newman
Gene Baker	Stan Grzybowski	David Nichols
Philip P. Barker	Stan Harper	Carlo Nucci
E.M. Berckmiller	Richard W. Hensel	John Posey
Ralph Bernstein	Chris Hickman	Farhad Rachidi
Steve Brewer	W. Janischewskyj	E. Ray Ross, Jr.
Bill Chisholm	George G. Karady	Thomas J. Rozek
Pritindra Chowdhuri	Joe L. Koepfinger	Dr. Mohamed Shwehdi
Enrico Cinieri	William A. Maguire	Leroy S. Taylor
Maria Teresa Correia De Barros	Juan A. Martinez-Velasco	Jeff Tuel
Ken Cummins	Michael B. Marz	Michael G. Vermilye
Francisco de la Rosa Costilla	John McDaniel	R.A. Walling
R. Clay Doyle	Robert E. Moore	Arthur C. Westrom
Ed Dziedzic	Duilio Moreira Leite	Charlie Williams
		Richard L. Zinser

This document is dedicated to the memory of Dee Parrish, Chair of the Working Group on the Lightning Performance of Distribution Lines from 1978 to 1993.

The following persons were on the balloting committee:

Harold Adams	Jerome G. Hanson	Mark Ostendorp
Stuart Akers	Donald G. Heald	Carlos Peixoto
Ronald H. Ammon	W. S. C. Henry	Robert C. Peters
J.G. Anderson	Richard W. Hensel	Trevor Pfaff
Gene Baker	Christopher W. Hickman	Tim Rahill
Phil P. Barker	Andrew Robert Hileman	Parvez Rashid
Edmund M. Berckmiller	Magdi F. Ishac	Peter R. Reed
R.Allen. Bernstorf	Wasył Janischewskyj	Joseph Renowden
Nelson G. Bingel	John G. Kappenman	E. Ray Ross, Jr.
Steve Brewer	Richard Kennon	Thomas J. Rozek
Joseph F. Buch	Robert O. Kluge	John S. Rumble
Kris K. Buchholz	Joseph L. Koepfinger	Lawrence Salberg
James J. Burke	Nestor Kolcio	Hazairin Samaulah
Vernon L. Chartier	Samy G. Krishnasamy	Roger A. Schoneman
William A. Chisholm	Michael B. Marz	Minesh Shah
Prit Chowdhuri	Mike McCafferty	Mohamed H. Shwehdi
Sam Cluts	T.J. McCarthy	Stephen F. Smith
Mike G. Comber	John E. Merando Jr	Leroy S. Taylor
F. Leonard Consalvo	J. David Mitchell	Dan Thiemann
John B. Dagenhart	Robert Moore	J. G. Tzimirangas
M.T. Correia de Barros	J. H. Moran	S. S. Venkata
R. Decker	Abdul M. Mousa	Reigh Walling
Frank A. Denbrock	Franklin D. Myers	Daniel J. Ward
William E. Feero	Shantanu Nandi	Arthur C. Westrom
George Gela	Jay L. Nicholls	James T. Whitehead
Donald A. Gillies	D. L. Nickel	Charles W. Williams
Edwin J. Tip Goodwin	George B. Niles	Luciano E. Zaffanella
Stan Grzybowski	Stig L. Nilsson	Rich Zinser

When the IEEE Standards Board approved this standard on 26 June 1997, it had the following membership:

Donald C. Loughry, *Chair*

Richard J. Holleman, *Vice Chair*

Andrew G. Salem, *Secretary*

Clyde R. Camp	Lowell Johnson	Louis-François Pau
Stephen L. Diamond	Robert Kennelly	Gerald H. Peterson
Harold E. Epstein	E. G. "Al" Kiener	John W. Pope
Donald C. Fleckenstein	Joseph L. Koepfinger*	Jose R. Ramos
Jay Forster*	Stephen R. Lambert	Ronald H. Reimer
Thomas F. Garrity	Lawrence V. McCall	Ingo Rüschi
Donald N. Heirman	L. Bruce McClung	John S. Ryan
Jim Isaak	Marco W. Migliaro	Chee Kiow Tan
Ben C. Johnson		Howard L. Wolfman

*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

1. Overview.....	1
1.1 Scope.....	1
1.2 Purpose.....	1
2. References.....	1
3. Definitions.....	2
4. Lightning parameters	3
4.1 Lightning incidence	3
4.2 Electrical characteristics of lightning.....	5
5. Lightning performance of overhead distribution lines.....	7
5.1 Lightning strokes to overhead lines	7
5.2 Induced-voltage flashovers	9
6. Distribution-line insulation level	11
6.1 CFO voltage of combined insulation	11
6.2 Determining the CFO voltage of structures with series insulation.....	12
6.3 Practical considerations	14
6.4 Arc-quenching capability of wood.....	15
6.5 Wood damage caused by lightning	16
7. Shield-wire protection of distribution lines	17
7.1 Shielding angle.....	17
7.2 Insulation requirements.....	17
7.3 Effect of grounding and insulation level.....	18
7.4 Shield wires and arresters	18
8. Arrester protection of lines	19
8.1 Arrester lead length considerations.....	19
8.2 Flashovers from indirect strokes	20
8.3 Flashovers from direct strokes	20
Annex A (informative) Examples of guide usage.....	22
Annex B (informative) Technical modeling and assumptions	27
Annex C (informative) Bibliography.....	36

IEEE Guide for Improving the Lightning Performance of Electric Power Overhead Distribution Lines

1. Overview

This design guide contains information on methods to improve the lightning performance of overhead distribution lines, and is written for the distribution-line designer. This guide recognizes that a perfect line design does not exist, and that a series of compromises are made in any distribution-line design. While some parameters such as voltage, routing, and capacity may be predetermined, other decisions are made at the discretion of the designer. The designer may exercise control over structure material and geometry, shielding (if any), amount of insulation, grounding, and placement of arresters. This guide will help the distribution-line designer optimize the line design in light of cost-benefit considerations.

1.1 Scope

This guide will identify factors that contribute to lightning-caused faults on overhead distribution lines and suggest improvements to existing and new constructions.

This guide is limited to the protection of distribution-line insulation for system voltages 69 kV and below. Equipment protection considerations are covered in IEEE Std C62.22-1991.¹

1.2 Purpose

The purpose of this guide is to present alternatives for reducing lightning-caused flashovers on overhead distribution lines.

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. These references will automatically be updated during the editing process.

IEEE Std C62.22-1991, IEEE Guide for the Application of Metal-Oxide Surge Arresters for Alternating-Current Systems (ANSI).²

¹Information on references can be found in Clause 2.

²IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

3. Definitions

3.1 back flashover (lightning): A flashover of insulation resulting from a lightning stroke to part of a network or electric installation that is normally at ground potential.

3.2 basic impulse insulation level (BIL, bil) (rated impulse withstand voltage) (surge arresters): A reference impulse insulation strength expressed in terms of the crest value of withstand voltage of a standard full impulse voltage wave.

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

3.4 direct stroke: A lightning stroke direct to any part of a network or electric installation.

3.5 distribution line: Electric power lines which distribute power from a main source substation to consumers, usually at a voltage of 34.5 kV or less. Note that this guide applies only for voltages 69 kV and below.

3.6 flashover (general): 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 electrical arc.

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

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

3.9 guy insulator: An insulating element, generally of elongated form with transverse holes or slots for the purpose of insulating two sections of a guy or provide insulation between structure and anchor and also to provide protection in case of broken wires. Porcelain guy insulators are generally designed to stress the porcelain in compression, but wooden insulators equipped with suitable hardware are generally used in tension.

3.10 guy wire: A stranded cable used for a semiflexible tension support between a pole or structure and the anchor rod, or between structures.

3.11 indirect stroke: A lightning stroke that does not directly strike any part of a network but induces an overvoltage in it.

3.12 induced voltage (lightning strokes): The voltage induced on a network or electric installation by an indirect stroke.

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

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

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

3.16 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.

3.17 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.

3.18 metal-oxide surge arrester (MOSA): A surge arrester utilizing valve elements fabricated from non-linear resistance metal-oxide materials.

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

3.20 shielding angle: The angle between the vertical line through the overhead ground wire and a line connecting the overhead ground wire with the shielded conductor. *See also:* direct-stroke protection.

3.21 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.

They may be electrically bonded directly to the structure or indirectly through short gaps.

3.22 spark gap: Any short-air space between two conductors electrically insulated from or remotely electrically connected to each other.

3.23 surge arrester: A protective device for limiting surge voltages on equipment by diverting surge current and returning the device to its original status. It is capable of repeating these functions as specified.

NOTE—The term *arrester* as used in this guide is understood to mean *surge arrester*.

4. Lightning parameters

4.1 Lightning incidence

Lightning occurs during rainstorms, snowstorms, and other natural phenomena. However, in most areas, rainstorms are the primary source of lightning. Storms produce intracloud, cloud-to-cloud, and cloud-to-ground lightning. Intracloud lightning is the most frequent, but cloud-to-ground lightning affects overhead distribution lines. During a storm, power interruptions are caused by wind and lightning. Interruptions caused by wind, trees, and damaged equipment are sometimes assumed to be caused by lightning, which will make the number of lightning-caused interruptions appear artificially high.

In most areas of the world, an indication of lightning activity may be obtained from keraunic data (thunderstorm days per year). A world isokeraunic map is shown in Figure 1. The keraunic level is an indication of regional lightning activity based on average quantities derived from historically available ground-level observations. More detailed keraunic data or maps for specific areas of the world are available. A more detailed depiction of lightning activity may be obtained from lightning ground flash density (GFD) maps, which are created from information obtained via lightning-detection networks. A sample GFD map of the United States is shown in Figure 2.

Lightning-location systems and flash-counter networks have been deployed in North America and other parts of the world. With enough experience, these networks may provide detailed GFD maps. GFD maps will provide much greater detail and accuracy than has been available with thunder data. Location systems

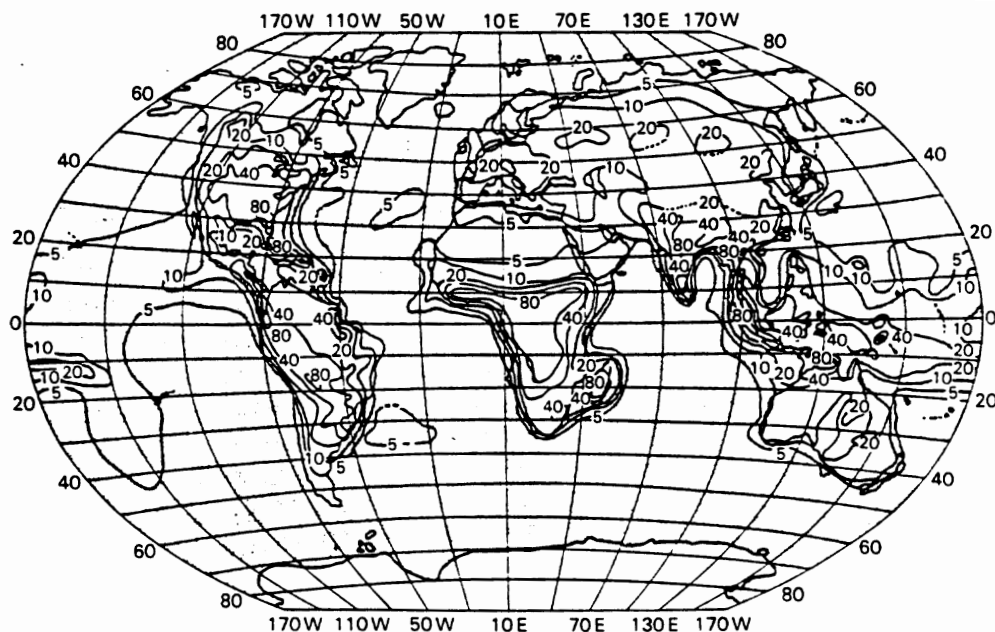
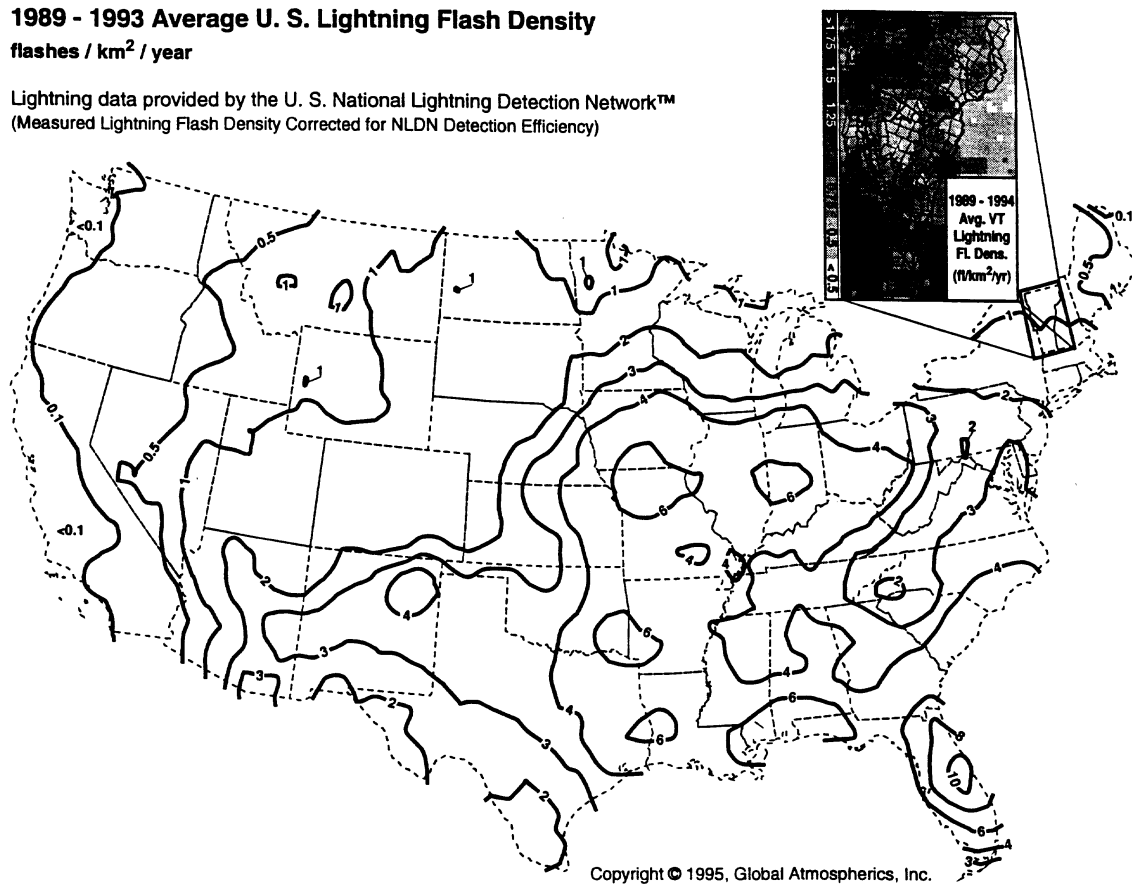


Figure 1—World isokeraunic map

1989 - 1993 Average U. S. Lightning Flash Density
flashes / km² / year

Lightning data provided by the U. S. National Lightning Detection Network™
(Measured Lightning Flash Density Corrected for NLDN Detection Efficiency)



Copyright © 1995, Global Atmospheric, Inc.

Figure 2—GFD map

also provide measured quantities that are more useful and detailed than keraunic data. In addition to providing the frequency of lightning, networks may also provide the date, time, location, number of strokes, estimate of peak stroke current, and polarity.

In some areas of the world, these systems have or are close to having enough data (seven years at a minimum) for design purposes. GFD maps are currently being used for distribution-line design, estimating lightning-caused flashovers, and for many other types of lightning analysis.

The reliability of a distribution line is dependent on its exposure to lightning. To determine exposure, the distribution-line designer needs to know the annual number of flashes per unit area per unit time. This GFD may be estimated in several ways.

The GFD may be estimated from the keraunic level [B5]³ using Equation (1).

$$N_g = 0.04T_d^{1.25} \text{ [flashes/ km}^2\text{/yr]} \quad (1)$$

where

T_d is the number of thunderstorm days per year (the keraunic level).

Another estimate of GFD may be obtained from thunderstorm hour records [B31], as shown by

$$N_g = 0.054T_h^{1.1} \quad (2)$$

Estimates of average GFD may also be obtained directly from lightning-detection network data or from flash counters. If enough years of data are present, this has the advantage of identifying regional variations.

Lightning and lightning-caused interruption rates have considerable year-to-year variation [B31, B15]. The historical standard deviation for yearly measurements of lightning activity ranges from 20% to 50% of the mean. Estimates of GFD for a small region such as 10 × 10 km have a larger standard deviation of about 30–50% from the mean. Larger regions such as 500 × 500 km have a smaller standard deviation of 20–25% from the mean. In areas with lower levels of lightning activity, the relative standard deviation is higher.

With such large standard deviations, it takes many years of data to accurately estimate a mean. This is especially true when using ground-flash data for a localized region or estimating lightning-caused interruption rates on a distribution line from outage data.

4.2 Electrical characteristics of lightning

4.2.1 Peak current distributions

From the very comprehensive summary of lightning parameters presented by CIGRE Working Group 33.01 (shown in Table 1) [B51], for first downward strokes, the variation of lightning-peak current I_0 may be approximated with a log-normal distribution.

For the sake of handling the probabilistic distribution of current peak values in a simple way, the following expression is adopted [B4]:

$$P(I_0 \geq i_0) = \frac{1}{1 + (i_0/31)^{2.6}} \quad (3)$$

Equation (3) shows the probability for lightning-peak current I_0 to be equal or larger than a given value i_0 [kA].

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

Table 1—CIGRE lightning current parameters [B51]

Parameters of log-normal distribution for negative downward flashes				
Parameter	First stroke		Subsequent stroke	
	Median	β , logarithmic standard deviation	Median	β , logarithmic standard deviation
FRONT, μs	—	—	—	—
$t_{d10/90} = T_{10/90}/0.8$	5.63	0.576	0.75	0.921
$t_{d30/90} = T_{30/90}/0.6$	3.83	0.553	0.67	1.013
$t_m = I_F/S_m$	1.28	0.611	0.308	0.708
STEEPNESS $\text{kA}/\mu\text{s}$	—	—	—	—
S_m , Maximum	24.3	0.599	39.9	0.852
S_{10} , at 10%	2.6	0.921	18.9	1.404
$S_{10/90}$, 10-90%	5.0	0.645	15.4	0.944
$S_{30/90}$, 30-90%	7.2	0.622	20.1	0.967
CREST CURRENT, kA	—	—	—	—
I_i , initial	27.7	0.461	11.8	0.530
I_f , final	31.1	0.484	12.3	0.530
Initial/final	0.9	0.230	0.9	0.207
TAIL, t_n , μs	77.5	0.577	30.2	0.933
CHARGE, Q_1 , C	4.65	0.882	0.938	0.882
$\int I^2 dt$, $(\text{kA})^2\text{s}$	0.057	1.373	0.0055	1.366
Inter stroke interval, ms	—	—	35	1.066

Description of waveshape parameters (see Figure 3)

I_{10}	=	10% intercept along the stroke current waveshape
I_{30}	=	30% intercept along the stroke current waveshape
I_{90}	=	90% intercept along the stroke current waveshape
$T_{10/90}$	=	time between I_{10} and I_{90} intercepts on the wavefront
$T_{30/90}$	=	time between I_{30} and I_{90} intercepts on the wavefront
S_m	=	$\tan G$, maximum rate-of-rise of current along wavefront
S_{10}	=	instantaneous rate-of-rise of current at I_{10}
$S_{10/90}$	=	average steepness (through I_{10} and I_{90} intercepts)
$S_{30/90}$	=	average steepness (through I_{30} and I_{90} intercepts)
Q_1	=	impulse charge in stroke current waveshape

5. Lightning performance of overhead distribution lines

This section describes how to estimate the number of direct and induced flashovers for distribution circuits. Lightning may account for many power interruptions in distribution lines. Lightning may cause flashovers from

- Direct strokes
- Induced voltages from nearby strokes

Direct lightning to power distribution lines causes insulation flashover in the great majority of the cases. For example, a stroke of as little as 10 kA would produce an overvoltage of around 2000 kV, far in excess of the insulation levels of overhead distribution lines operating up to 69 kV. However, experience and observations show that many of the lightning-related outages of low-insulation lines are due to lightning which hits the ground in proximity of the line. Most voltages induced on a distribution line by flashes that terminate near a line are less than 300 kV. Flashes may be collected by taller objects, so height and distance from the distribution line of shielding objects such as trees and buildings will influence the lightning performance of the line.

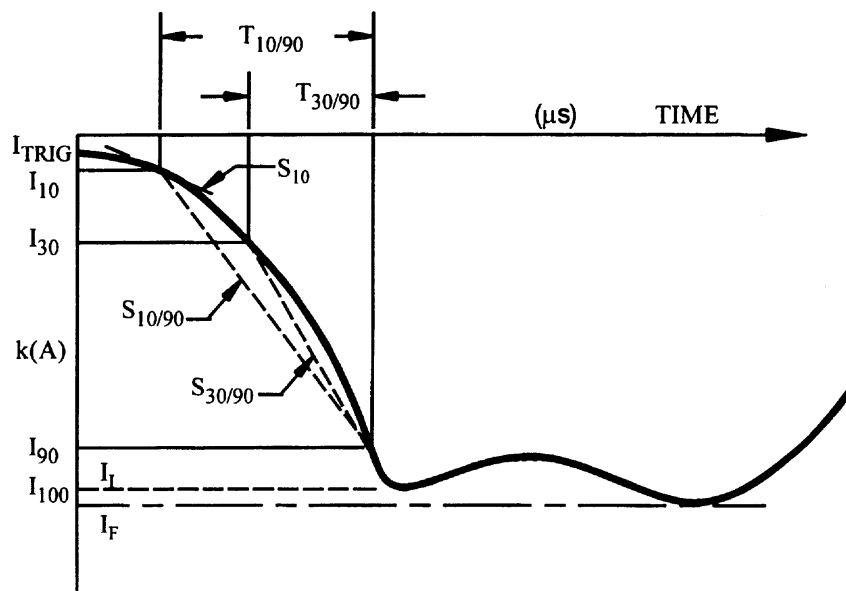


Figure 3—Description of lightning waveform parameters

5.1 Lightning strokes to overhead lines

5.1.1 Structure height

Lightning may have a significant effect on a line's reliability, especially if its poles are higher than the surrounding terrain. More flashes are collected by taller structures. The flash collection rate N , in open ground (no significant trees or building nearby), is estimated by Eriksson's equation [B23].

$$N = N_g \left(\frac{28h^{0.6} + b}{10} \right) \quad (4)$$

where

- h is the pole height (m);
 b is the structure width (m);

N_g is the ground density (flashes/km²/yr);
 N is flashes/100 km/yr.

For most distribution lines, the structure width factor b is negligible.

From Equation (4), if the pole height is increased by 20%, the flash rate to the overhead distribution line would increase by 12%. Note that a distribution line may collect many more flashes than would have been predicted by the $4 \times H$ model, which was used for several years. In the $4 \times H$ model, the number of flashes collected by the distribution line was estimated by a width of twice the line height on both sides of the line.

The exposure of the distribution line to lightning depends on how much the structures protrude above the surrounding terrain. Structures located along the top of mountains, ridges, or hills will be more likely targets for lightning strikes than those shielded by natural features.

5.1.2 Shielding from nearby structures and trees

Trees and buildings may play a major role in the lightning performance of distribution lines. Trees and buildings may intercept many lightning flashes which otherwise would have hit a line. The shielding factor, S_f , is defined as the per-unit portion of the distribution line shielded by nearby objects. The number of strikes to the line is then

$$N_s = N(1 - S_f) \quad (5)$$

A shielding factor of 0.0 means the distribution line is in the open ground with no shielding by nearby objects provided, and a factor of 1.0 means the distribution line is completely shielded from direct strikes.

Figure 4 gives a means for approximating the shielding factors for objects of various heights for a 10 m tall distribution line. The objects are assumed to be in a uniform row parallel to the distribution line. This could represent a row of trees or buildings paralleling the distribution line.

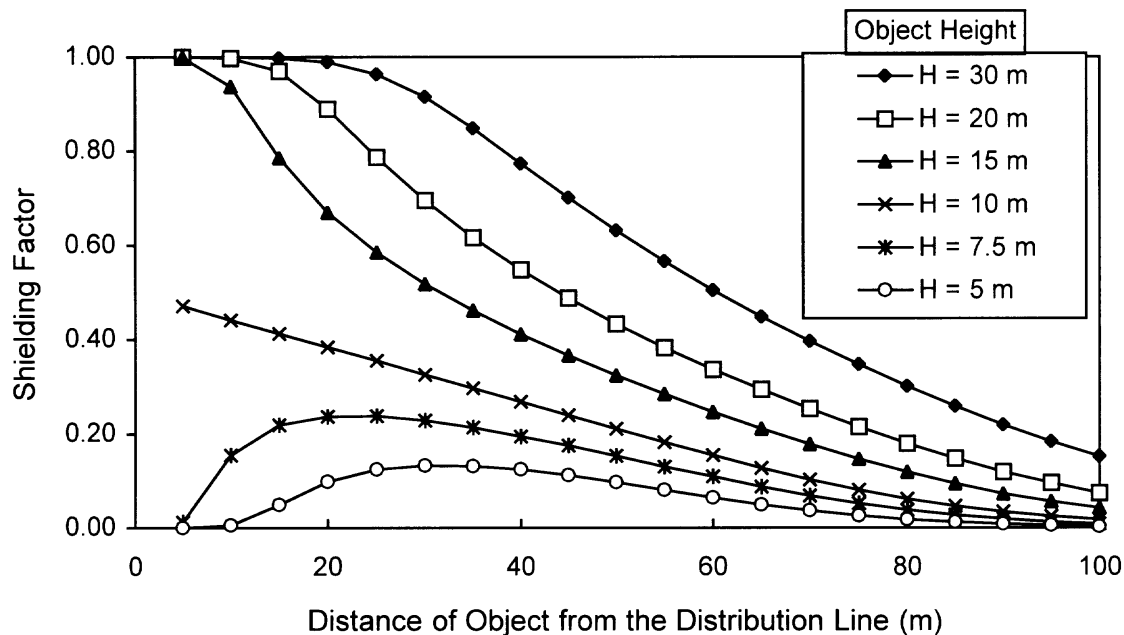


Figure 4—Shielding factors due to nearby objects of different heights for a 10 m tall distribution line