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

IEEE Power Engineering Society

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

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Abstract: Measures for improving the lightning protection performance of schemes applied to overhead power distribution lines are discussed in this guide.

Keywords: distribution networks, IEEE guide, IEEE standards, lightning protection, overhead power distribution lines, power overhead lines, power system lightning protection, power system protection, protection performance improvement

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Introduction

(This introduction is not part of IEEE Std 1410-2004, 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 (EPRI Project 2542-1 [B31]^a 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.

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^aThe numbers in brackets correspond to those of the bibliography in Annex C.

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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 C62.22TM-1997.

1.2 Purpose

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

2. References

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 When the following standard is superseded by an approved revision, the revision shall apply.

IEEE Std C62.22-1997, IEEE Guide for the Application of Metal-Oxide Surge Arresters for Alternating-Current Systems.^{1,2}

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) (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 strike: A lightning stroke direct to any part of a network or electric installation.

3.5 distribution line: Electric power lines that distribute power from a main source substation to consumers, usually at a voltage of 34.5 kV or less.

NOTE—This guide applies only for voltages 69 kV and below.³

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) (N_g): The average number of lightning flashes 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 to provide insulation between structure and anchor, and also to provide protection in case of broken wires.

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 induced voltage (lightning strikes): The voltage induced on a network or electric installation by a nearby strike.

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

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

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³Notes in text, tables, and figures are given for information only and do not contain requirements needed to implement the standard.

3.14 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.

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

3.16 line lightning performance: The performance of a line expressed as the annual number of lightning flashovers on a circuit km or tower-line km basis.

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

3.18 nearby strike: A lightning stroke that does not directly strike any part of a network but induces a significant overvoltage in it.

3.19 overhead ground wire (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. *Syn:* **shield wire.**

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.

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.

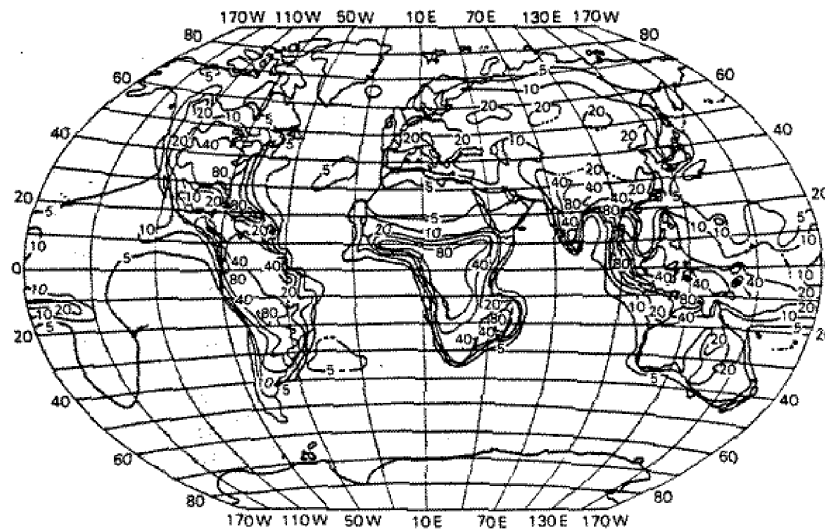


Figure 1—World isokeraunic map

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 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 stroke peak current, and polarity.

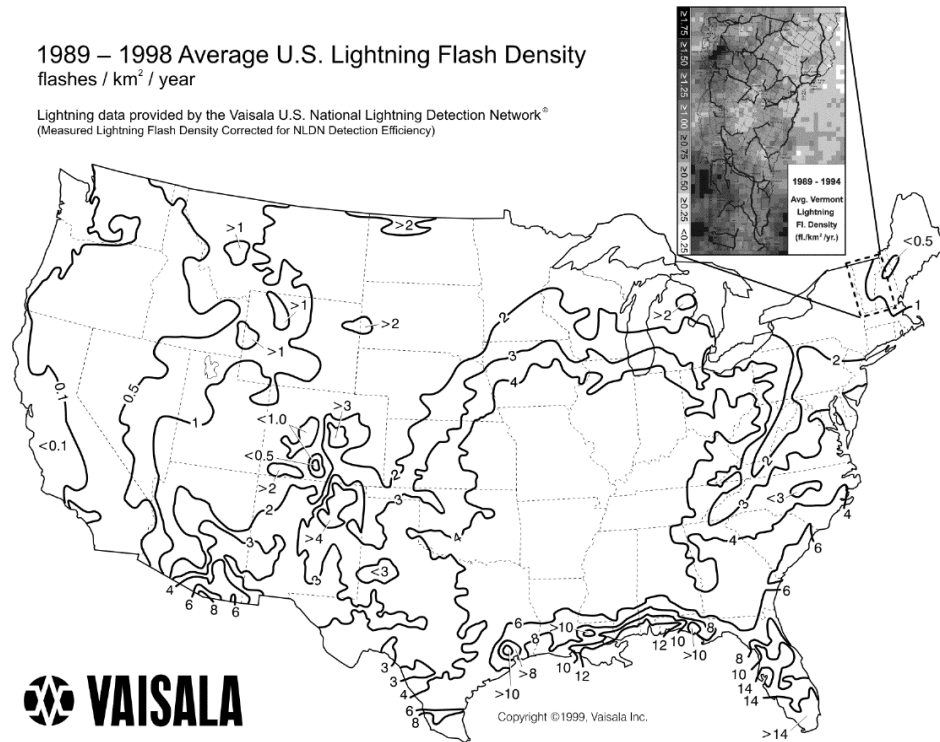
In some areas of the world, these systems have, or are close to having, enough data (seven years at a minimum) for design purposes. GFD maps are currently being used for distribution-line design, estimating lightning-caused flashovers, and for many other types of lightning analysis.

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 (Anderson et al. [B5])⁴ using Equation (1):

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

⁴The numbers in brackets correspond to those of the bibliography in Annex C.



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Figure 2—GFD Map

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 (MacGorman et al. [B48]), as shown by Equation (2):

$$N_g = 0.054T_h^{1.1} [\text{flashes}/\text{km}^2/\text{yr}] \quad (2)$$

where

T_h is the number of thunderstorm hours per year.

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 (Darveniza [B22], MacGorman et al. [B48]). The historical standard deviation for yearly measurements of lightning activity ranges from 20–50% 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 presented by CIGRE Working Group 33.01 [B17], a log-normal distribution of lightning parameters is assumed. The equation for the log-normal probability density function for any particular parameter x is given by Equation (3):

$$f(x) = \frac{1}{\sqrt{2 \cdot \pi \cdot \beta \cdot x}} \cdot \exp\left(-\frac{z}{2}\right) \quad (3)$$

where

$$z = \frac{\ln(x/M)}{\beta}$$

M is the median parameter value and β is the logarithmic standard deviation (base e). The values of M and β for every parameter are reported in Table 1 (CIGRE Working Group 33.01 [B17]).

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

$$P(I_o \geq i_o) = \frac{1}{1 + (i_o/31)^{2.6}} \quad (4)$$

Equation (4) shows the probability for lightning-peak current I_o to be equal or larger than a given value i_o (kA) and applies to values of I_o lower than 200 kA. This is currently under review (Borghetti et al. [B10]), and recent lightning-detection network measurements in North America indicate the possibility of lower median current values (Cummins et al. [B20]).

Table 1—CIGRE lightning current parameters (CIGRE Working Group 33.01 [B17])

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 kA/ μs	—	—	—	—
S_m , Maximum	24.3	0.599	39.9	0.852
S_{10} , at 10%	2.6	0.921	18.9	1.404

**Table 1—CIGRE lightning current parameters (CIGRE Working Group 33.01 [B17])
(continued)**

Parameters of log-normal distribution for negative downward flashes				
Parameter	First stroke		Subsequent stroke	
	Median	β , logarithmic standard deviation	Median	β , logarithmic standard deviation
$S_{10/90}$, 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_F , 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 , μ s	77.5	0.577	30.2	0.933
CHARGE, Q_F , C	4.65	0.882	0.938	0.882
$\int I^2 dt$, (kA) ² s	0.057	1.373	0.0055	1.366
Inter stroke interval, ms	—	—	35	1.066

The following is a 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
$t_{d10/90}$	=	Equivalent linear wavefront duration derived from $T_{10/90}$
$t_{d30/90}$	=	Equivalent linear wavefront duration derived from $T_{30/90}$
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

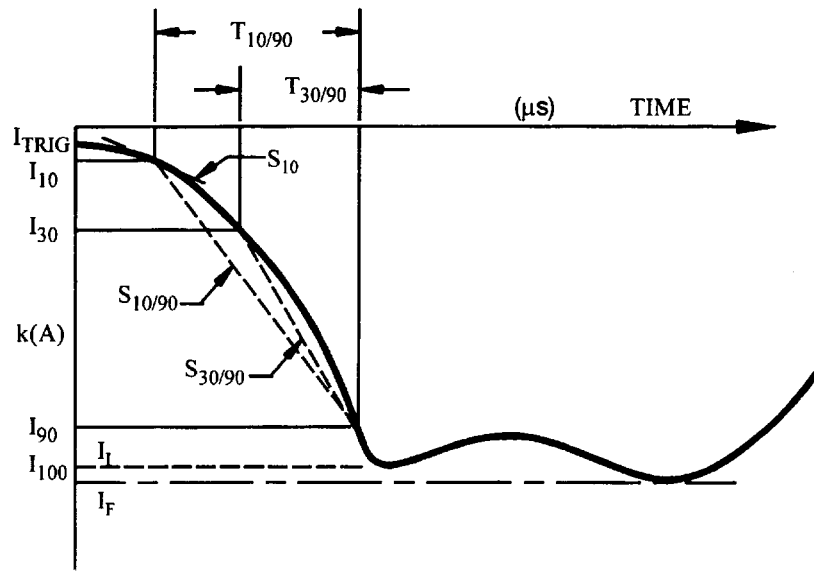


Figure 3—Description of lightning waveform parameters

5. Lightning performance of overhead distribution lines

This clause 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 the following:

- Direct strikes
- Induced voltages from nearby strikes

Direct lightning strikes 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 that 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.

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 the 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 [B33], as show in Equation (5):

$$N = N_g \left(\frac{28h^{0.6} + b}{10} \right) \quad (5)$$