

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

IEEE Power & Energy Society

Sponsored by the
Transmission and Distribution Committee

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

Sponsor

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of the
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Abstract: Factors that contribute to lightning-caused faults on the line insulation of overhead distribution lines and suggested improvements to existing and new constructions are identified in this guide.

Keywords: direct-stroke protection, distribution, flashover, ground conductivity, IEEE 1410, induced over-voltage, insulation, lightning, overhead line, surge impedance

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Introduction

This introduction is not part of IEEE Std 1410-2010, 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. Five to ten percent of lightning-caused faults are thought to cause permanent damage to equipment. 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 strokes 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 estimates of lightning-caused faults that are linked to physical variables such as the line height, the presence of parallel neutral or overhead groundwires (OHGW), the intervals between ground electrodes and/or surge protective devices, the proximity of the line to nearby objects and the characteristics of the soil.

Another goal of this guide is to provide revised estimates of lightning-caused faults showing 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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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™-2009.¹

¹ Information on references can be found in Clause 2.

1.2 Purpose

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

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IEEE Std C62.22™-2009, IEEE Guide for the Application of Metal-Oxide Surge Arresters for Alternating-Current Systems (ANSI).

IEEE Std 1243™-1997, IEEE Guide for Improving the Lightning Performance of Transmission Lines.

3. Definitions

For the purposes of this document, the following terms and definitions apply. *The IEEE Standards Dictionary: Glossary of Terms & Definitions* should be consulted for terms not defined in this clause.²

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): The crest value of a standard lightning impulse for which the insulation exhibits a 90% probability of withstand (or a 10% probability of failure) under specified conditions.

3.3 cloud-to-ground lightning flash: A lightning discharge to ground consisting of a first return stroke that may be followed by subsequent strokes and other impulsive or continuing currents.

3.4 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.

3.5 direct flash: A lightning flash with one or more return strokes terminating directly to any part of a network or electric installation.

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

3.7 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, but possibly at a phase-to-phase voltage of up to 69 kV.

3.8 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.

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

² The *IEEE Standards Dictionary: Glossary of Terms & Definitions* is available at <http://shop.ieee.org/>.

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

3.11 guy insulator: An insulating element, possibly with elongated form and 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.

3.12 guy wire: A stranded cable used for a semi-flexible tension support between a pole or structure and the anchor rod, or between structures.

3.13 induced voltage (lightning strokes): The voltage induced on a network or electric installation by a nearby stroke.

3.14 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.

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

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

3.17 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.

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

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

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

3.21 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. An OHGW also functions as a shield wire.

3.22 shielding angle: The angle between the vertical line through the overheadground wire and a line connecting the overhead ground wire with the shielded conductor.

3.23 shield wire: Grounded wire(s) placed near the phase conductors for the purposes of: a) Reducing the incidence of direct lightning strokes to phase conductors, b) Reducing induced voltages from external electromagnetic fields, c) Lowering the self-surge impedance of an overhead groundwire (OHGW) system, or d) Raising the mutual surge impedance of an OHGW system to the protected phase conductors. A grounded neutral beneath a phase conductor functions as a shield wire (functions b,c,d) but not as an OHGW (function a).

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

3.25 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.

The reliability of a distribution line is dependent on its exposure to lightning. To determine exposure, the distribution-line designer needs to know the ground flash density (GFD), defined as the number of flashes per unit area per unit time. The preferred measure of GFD is N_g , the number of cloud-to-ground flashes per square km per year. This GFD may be estimated in several ways, as follows.

4.1.1 Statistical considerations

Lightning and lightning-caused interruption rates have considerable year-to-year variation, see Darveniza [B37], MacGorman et al. [B69]. 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 km × 10 km have a larger standard deviation of about 30% to 50% from the mean. Larger regions such as 500 km × 500 km have a smaller standard deviation of 20% to 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 estimate a mean value accurately. 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.

Estimates of average GFD may also be obtained directly from lightning-detection network data or from lightning flash counters. If enough years of data are present, this has the advantage of identifying regional variations. A minimum grid size that provides at least 400 registrations in each cell over the selected observation period shall be used to allow meaningful comparison of adjacent areas.

4.1.2 Ground flash density from thunder data

The ground flash density N_g for temperate areas may be estimated from T_d , the keraunic level, using Equation (1) from Anderson et al. [B6]:

$$N_g = 0.04T_d^{1.25} \quad (1)$$

where

N_g is the ground flash density in flashes per km² per year
 T_d is the number of days with thunder per year

Torres et al. [B29] noted that this expression has unacceptably large errors in tropical areas, recommending the alternative expressions for Equation (1):

Country	Alternative Expression for Equation (1)
Mexico	$N_g = 0.024 T_d^{1.12}$
Brazil	$N_g = 0.030 T_d^{1.12}$
Columbia	$N_g = 0.0017 T_d^{1.56}$

Another estimate of GFD may be obtained from thunderstorm hour records (MacGorman et al [B69]), as shown by Equation (2):

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

where

N_g is the ground flash density in flashes per km² per year
 T_h is the number of thunderstorm hours per year

With the uncertainty in the choice of appropriate expression, the poor statistical quality of observations in regions with limited lightning (a region with $T_d=5$ will require 80 years of observations to meet the criterion of 400 observations) and the ready availability of better alternatives, the use of thunder data to predict distribution line lightning performance should be discontinued.

4.1.3 Ground flash density from lightning optical transient density

In most areas of the world, an indication of lightning activity may be obtained from observations of lightning optical transients, see Christian et al. [B24]. Satellite-based sensors respond to all types of lightning with relatively uniform coverage in all areas. With sufficient averaging, optical transient density data in Figure 1 provide better estimates of ground flash density than thunder observations, which have a wide range of relations between ground flash density and thunderstorm-hours or days. There are also regional variations in the ratio of ground flashes to total flashes, see Boccippio et al. [B14], but a median value of 0.33 ground flashes to total flashes is recommended for both tropical and temperate regions.

For areas without ground-based lightning location systems or lightning flash counters, the recommended estimate of ground flash density is:

$$N_g = N_t / 3 \quad (3)$$

where

N_g is the ground flash density in flashes per km² per year
 N_t is the total (cloud + ground) density of optical flashes per km² per year obtained from Figure 1a through Figure 1c.

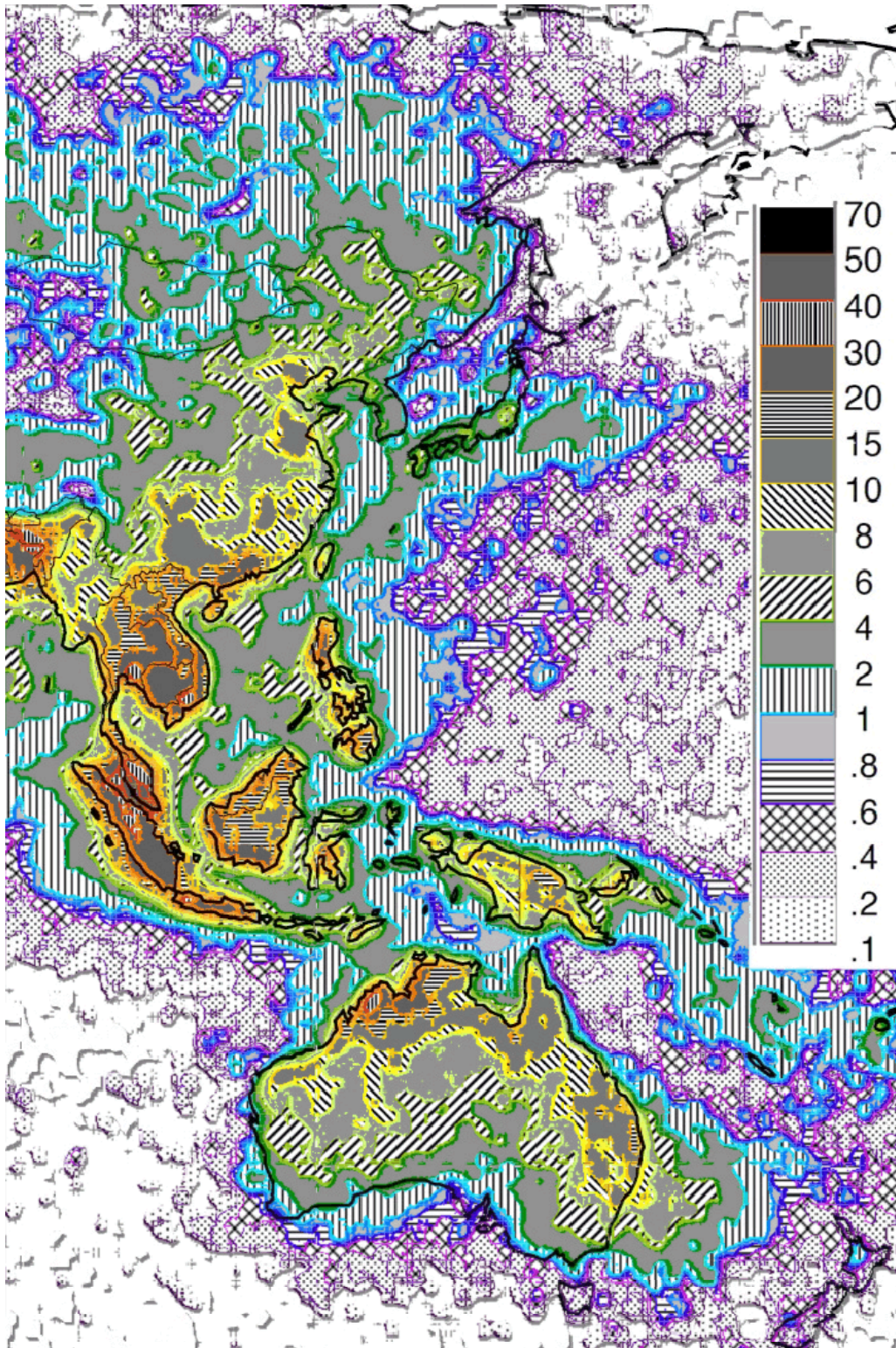


Figure 1 a— Total (cloud + ground) lightning activity (N_b , optical flashes per km² year⁻¹) for Asia and Australia, adapted from Christian et al. [B24]

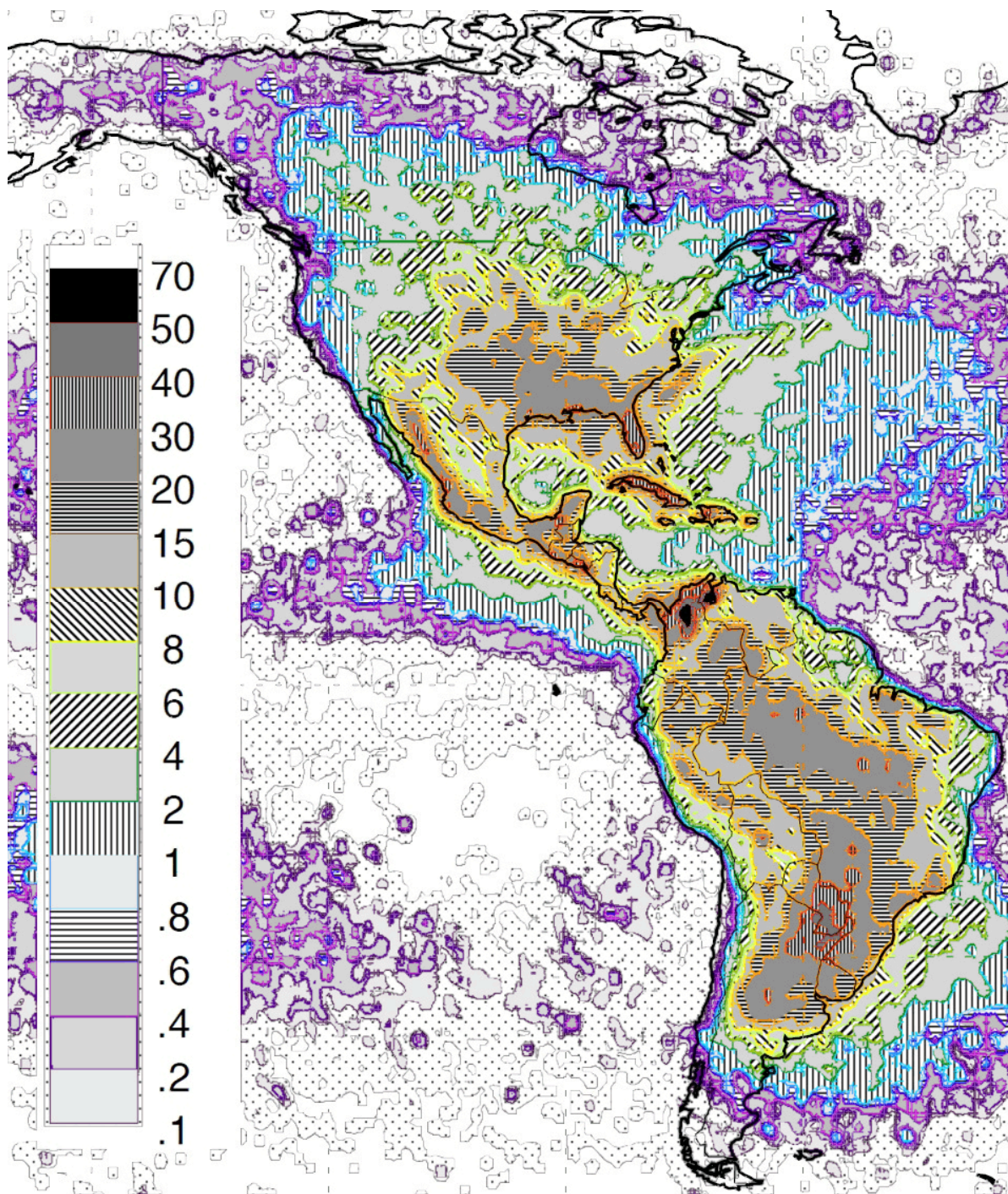


Figure 1b—Total (cloud + ground) lightning activity (N_b , optical flashes per km² year⁻¹) for North and South America, adapted from Christian et al. [B24]

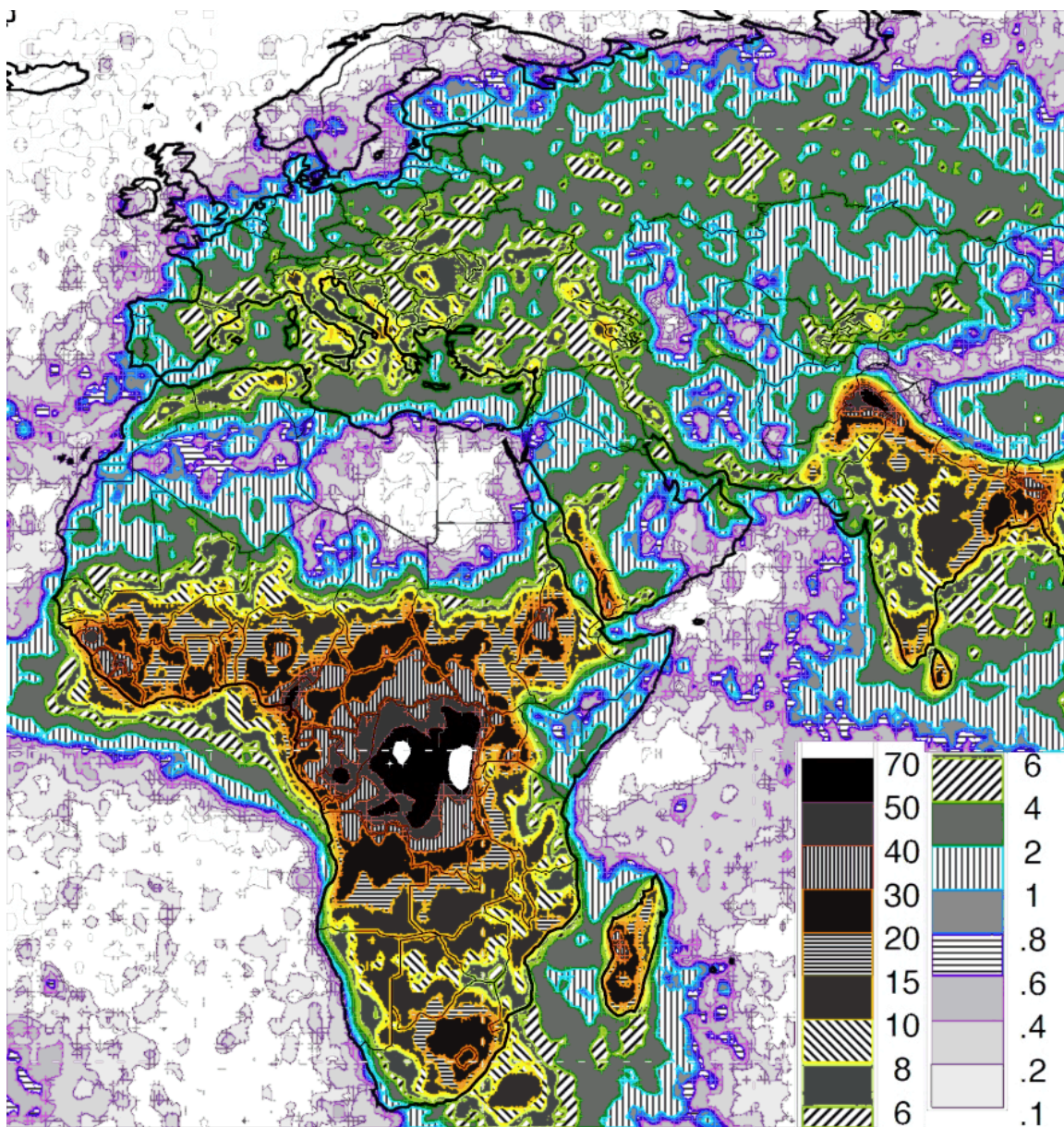


Figure 1c—Total (cloud + ground) lightning activity (N_t , optical flashes per $\text{km}^2 \text{ year}^{-1}$) for Africa and Eurasia, adapted from Christian et al. [B24]

4.1.4 Ground flash density from lightning location networks

A more detailed depiction of lightning activity may be obtained from lightning ground flash density (GFD) maps, which are created from information obtained via present-day lightning-detection networks or lightning flash counter networks that have been operated in the past. A sample GFD map of the United States from a lightning location network is shown in Figure 2.

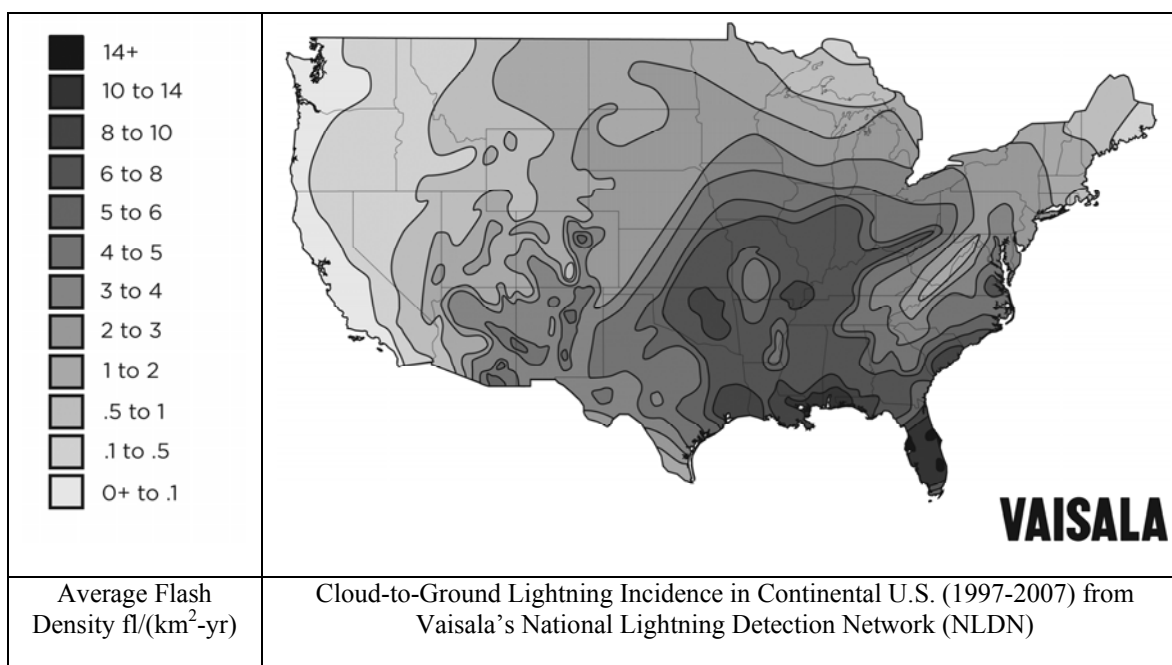


Figure 2— GFD map of contiguous USA (reprinted with permission of Vaisala) [B78]

Lightning location networks and lightning flash counter arrays have been deployed in North America and other parts of the world. With enough experience, these networks provide detailed GFD maps with much greater detail and accuracy than has been available with thunder or optical transient data. Location systems also provide measured quantities that are more useful and detailed than keraunic data. In addition to providing the GFD, lightning location networks may also provide the date, time, location, number of strokes, polarity, peak radiated electromagnetic field and the related estimate of stroke peak current.

In many areas of the world, these systems have accumulated sufficient data to satisfy design purposes in grid areas as fine as 20 km ×20 km. GFD maps are currently being used for distribution-line design, estimating lightning-caused flashovers, and for many other types of lightning analysis.

4.2 Electrical characteristics of lightning

4.2.1 Waveshape parameters

The impressed surge current is considered to be a current source. Direct flashes to unprotected conductors cause overvoltages that have the same waveshape as the stroke current. Figure 3 describes the typical concave lightning current waveshape with the use of the listed parameters.

Parameter in Figure 3	Description
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
$I_{100} = I_I$	Initial peak of current
I_F	Final peak of current
$T_{10/90}$	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_{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)
S_m	Maximum rate-of-rise of current along wavefront, typically at I_{90}
$t_{d\ 10/90}$	Equivalent linear wavefront duration derived from $I_F / S_{10/90}$
$t_{d\ 30/90}$	Equivalent linear wavefront duration derived from $I_F / S_{30/90}$
t_m	Equivalent linear waveform duration derived from I_F / S_m
Q_I	impulse charge (time integral of current) in stroke current waveshape

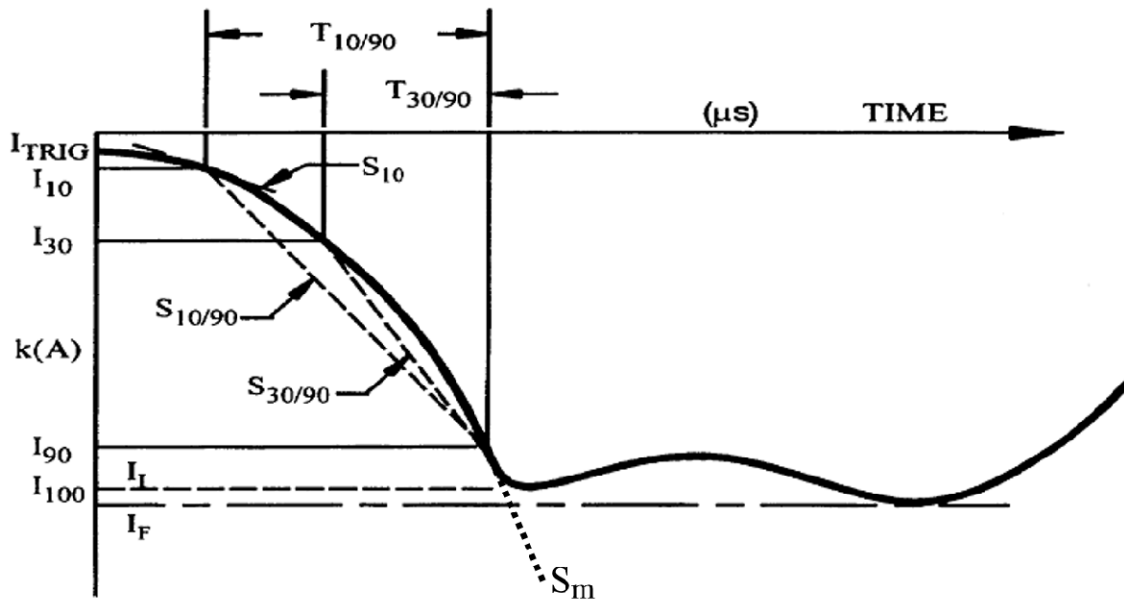


Figure 3— Description of lightning current waveform parameters [B27]

From a simplified circuit viewpoint, overvoltages from nearby lightning are inductively coupled to the current waveform. This means that the peak overvoltage magnitude is related to the maximum steepness S_m and the duration of the overvoltage is related to T_{10-90} .

4.2.2 Log-normal statistical distribution

From the comprehensive summary presented by CIGRE Working Group 33.01 [B27] and supplemented by transmission line observations in Japan by Takami and Okabe [B110], log-normal distributions of lightning parameters are assumed. The general equation for the log-normal probability density function for any particular parameter x is given by Equation (4):

$$f(x) = \frac{1}{\beta \cdot x \cdot \sqrt{2 \cdot \pi}} \cdot \exp\left(-\frac{z^2}{2}\right) \quad (4)$$

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

where

$f(x)$ is the probability density

M is the median value of x

β is the logarithmic standard deviation (to base e)

4.2.3 Parameters of negative downward strokes

Lightning flashes consist of a first stroke and may have one or more subsequent strokes, following the same path and terminating at the same location on the line. First strokes have higher peak currents and subsequent strokes have faster rate of current rise as shown in Table 1.

The values of M and β in Equation (4) for the most relevant lightning parameters used in calculation of distribution line outage rates are reported in Table 1, based on CIGRÉ Working Group 33.01 [B27].

Table 1— Recommended lightning current parameters (CIGRÉ Working Group 33.01 [B27])

Parameters of log-normal distribution for negative downward flashes				
Parameter	First stroke		Subsequent stroke	
	M , Median	β , logarithmic standard deviation	M , Median	β , logarithmic standard deviation
FRONT TIME (μ s)				
$t_{d10/90} = T_{10/90}/0.8$	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/ μ 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
Ratio, I_i/I_F	0.9	0.230	0.9	0.207
OTHER RELEVANT PARAMETERS				
Tail Time to Half Value t_n (μ s)	77.5	0.577	30.2	0.933
Number of strokes per flash	1	0	2.4	0.96 based on median $N_{total}=3.4$
Stroke Charge, Q_I (Coulomb)	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

For the sake of handling the probabilistic distribution in a simple way, the following expression is adopted (Anderson [B4]) for the probability of a first-stroke current peak value I_o that exceeds a value i_o :

$$P(I_o \geq i_o) = \frac{1}{1 + \left(\frac{i_o}{31}\right)^{2.6}} \quad (5)$$

where

$P(I_o \geq i_o)$ is the probability that the first return stroke has a peak current I_o that exceeds i_o
 i_o is the prospective first return stroke peak current (kA)

When the median first return stroke peak current of 31.1 kA from Table 1 is used for i_o in Equation (5), the probability that the lightning-peak current I_o that exceeds the median is about 0.5. Equation (5) applies to values of I_o lower than 200 kA. This is currently under review by Borghetti et al. [B17] and [B20]. Recent lightning detection network measurements in North America indicate the possibility of lower median current values, see Cummins et al. [B35], which may be the result of misclassification of subsequent strokes as first strokes in remote measurement systems. The distribution of subsequent-stroke peak current values is approximated by (IEEE Std 1243-1997):

$$P(I_o \geq i_o) = \frac{1}{1 + \left(\frac{i_o}{12}\right)^{2.7}} \quad (6)$$

where

$P(I_o \geq i_o)$ is the probability that a subsequent return stroke has a peak current I_o that exceeds i_o
 i_o is the prospective subsequent return stroke peak current (kA)

When the median subsequent return stroke peak current of 12.3 kA from Table 1 is used for i_o in Equation (6), the probability that the subsequent-stroke peak current I_o that exceeds the median is about 0.5.

Generally, shielding failures are caused by flashes with low first return-stroke currents with corresponding small striking distance [IEEE Std 1243-1997]. The probability of first-stroke peak current that is less i_o is $(1 - P(I_o \geq i_o))$, using Equation (5). These weak first-stroke currents are likely to be followed by one or more subsequent strokes with higher peak current, based on Equation (6). This means that almost all shielding failures result in insulation flashovers, no matter how low the peak current of the first stroke or how small the striking distance.

4.2.4 Amplitude and frequency dependence

There is a high correlation between the maximum steepness S_m and the peak current I_F in Table 1, meaning that the same waveshape in Figure 3 may be used even though the peak amplitude of current may vary over a factor of 100:1 from 2 kA to 200 kA. This correlation may be exploited by using the equivalent linear front time of 1.28 μ s for first strokes and 0.31 μ s for subsequent strokes in evaluation of distribution line lightning performance. An equivalent linear front time of 2.0 μ s, used in IEEE Std 1243-1997 is appropriate for the large-amplitude first stroke events that tend to cause backflashovers on transmission lines with higher levels of insulation strength and overhead groundwires.