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

IEEE Power Engineering Society

Sponsored by the
Transmission and Distribution Committee

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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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[a]The 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 C62.22™-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.

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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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[2]IEEE publications are available from the Institute of Electrical and Electronics Engineers, Inc., 445 Hoes Lane, Piscataway, NJ 08854, USA (http://standards.ieee.org/).
[3]Notes in text, tables, and figures are given for information only and do not contain requirements needed to implement the standard.

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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 nonlinear 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.

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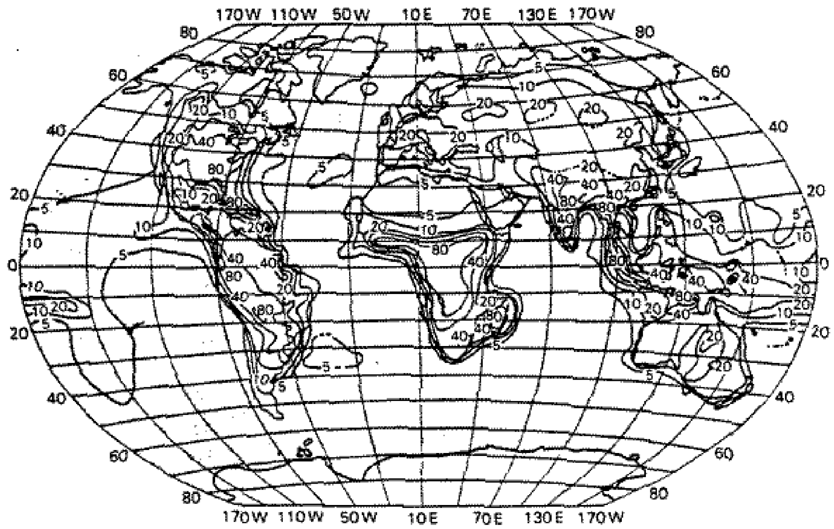

Figure 1—World isokeraunic map

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):

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

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

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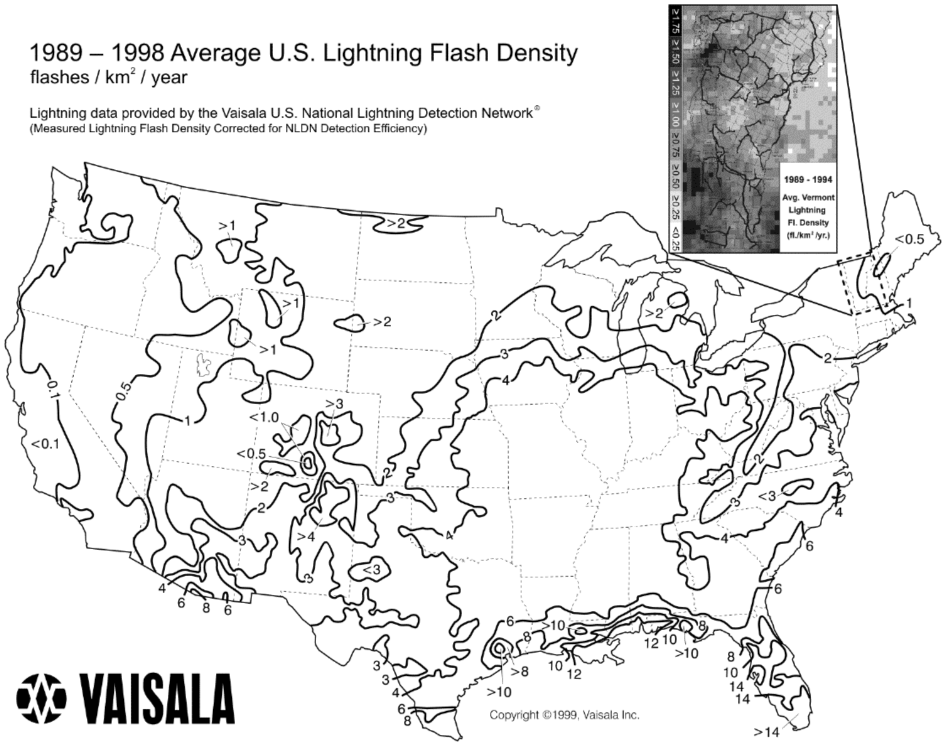

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Figure 2—GFD Map

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):

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

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.

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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):

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

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]):

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

Equation (4) shows the probability for lightning-peak current I_o to be equal or larger than a given value i_0 (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

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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_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_I, 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

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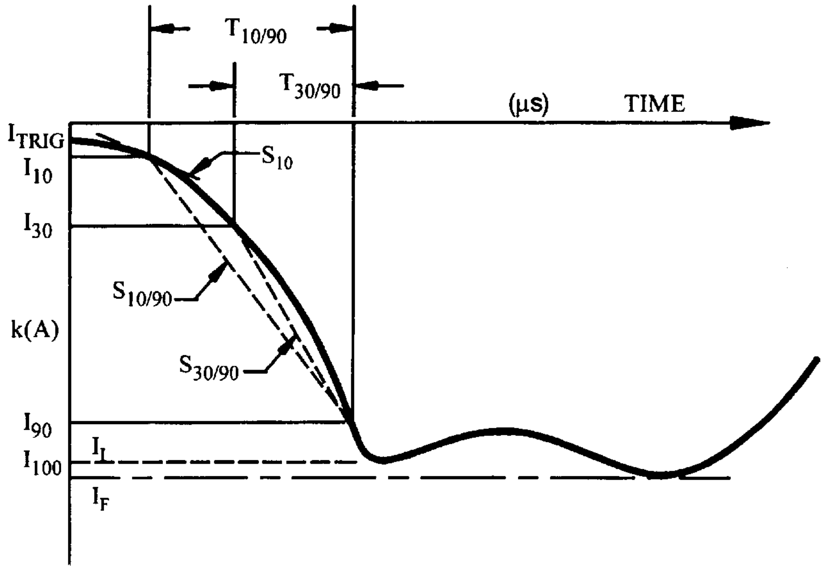

Figure 3—Description of lightning waveform parameters

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:

a) Direct strikes

b) 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):

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

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where

h is the pole height (m),
b is the structure width (m),
N_g is the ground flash density (flashes/km^2/yr),
N is the flash collection rate (flashes/100 km/yr).

For most distribution lines, the structure width factor b is negligible ($b \approx 0$).

From Equation (5), 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 × H model, which was used for several years. In the 4 × 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 that otherwise would have hit a line. The shielding factor, Sf, is defined as the per-unit portion of the distribution line shielded by nearby objects. The number of strikes to the line is then shown in Equation (6):

$$N_S = N(1 - \mathrm{Sf}) \tag{6}$$

A shielding factor of 0.0 means the distribution line is in the open terrain 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 and located on one side of it. This could represent a continuous row of trees or buildings paralleling the distribution line.

Figure 4 may also be used for objects on both sides of the distribution line if the shielding factors for the left and right sides are summed (if the sum of the shielding factors is greater than one, then the total shielding factor is equal to one). As an example, consider a 10 m tall overhead distribution line with the following rows of buildings on each side:

a) A 7.5 m tall row of buildings, 30 m from the left side of the distribution line ($\mathrm{Sf}_{\mathrm{left}} = 0.23$)
b) A 15 m tall row of trees, 40 m from the right side of the distribution line ($\mathrm{Sf}_{\mathrm{right}} = 0.4$)

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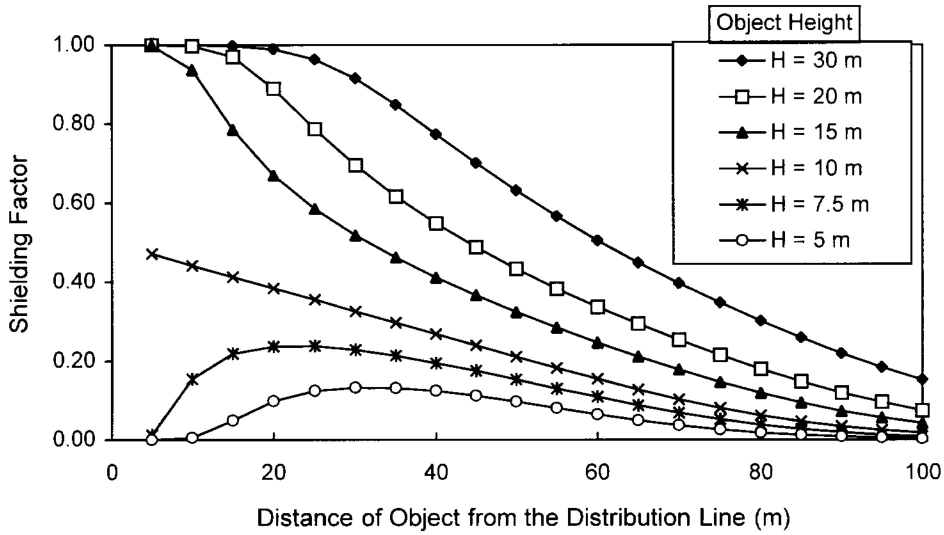

Figure 4—Shielding factors due to nearby objects of different heights for a 10 m tall distribution line

If the GFD is 1 flash/km^2/yr, the number of direct hits to the overhead distribution line in open ground would be 11.15 flashes/100 km/yr [from Equation (5)]. With the rows of buildings and trees, the number of direct hits would reduce to, as shown in Equation (7):

$$N_S = N[1-(\mathrm{Sf}_{\mathrm{left}} + \mathrm{Sf}_{\mathrm{right}})] \quad (7)$$

$$= (11.15\ \mathrm{flashes/100km/yr})[1-(0.23+0.4)]$$

$$= 4.12\ \mathrm{flashes/100km/yr}$$

Unless distribution-line insulation is protected with a shield wire or arresters, all direct lightning strikes will cause flashovers regardless of insulation level, conductor spacings, or grounding. Therefore, to estimate the number of flashovers due to direct lightning flashes, use Equation (5) for a distribution line in open ground, or Equation (5) and Equation (6) for a partially shielded line. It is assumed that all flashovers will cause faults on the distribution circuit (see 6.4).

5.2 Induced-voltage flashovers

According to Rusck [B71], assuming a return stroke speed of 1.2 × 10^8 m/s, and a step like waveshape for the lightning current, the maximum voltage that is induced in a power line at the point closest to the strike may be estimated by

$$V_{\max} = 38.8\frac{I_o h_a}{y}[kV] \quad (8)$$

where

I_o is the lightning-peak current,
h_a is the average height of the line over the ground level,
y is the closest distance between line and the lightning stroke.

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Equation (8) is used for an infinitely long, single conductor above a perfectly conducting ground. Such an equation has been inferred by Rusck from the more general model he proposed in Rusck [B70].

A grounded neutral wire or overhead shield wire will reduce the voltage across the insulation by a factor, which depends on grounding and proximity of the grounded conductor to the phase conductors. This factor is typically between 0.6 and 0.9.

Induced-voltage flashover frequency may dramatically increase for low levels of insulation. Figure 5 presents the frequency of flashover as a function of the critical flashover (CFO) voltage of the line. Figure 5 shows results for two grounding configurations. The ungrounded circuit does not have a grounded neutral wire or shield wire such as a three-wire ungrounded or four-wire unigrounded circuit. The results for a grounded circuit are for a circuit with a grounded neutral wire or overhead shield wire. The grounded circuit has fewer flashovers for a given CFO because the grounded conductor reduces the voltage stress across the insulation. Ungrounded and unigrounded circuit structures, however, may tend to have a higher phase-to-ground CFO than an equivalent multigrounded circuit structure due to the absence of the grounded neutral wire. The values are normalized for a GFD of 1 flash/km^2/yr and a distribution-line height of 10 m. The results may be scaled linearly with respect to length and GFD.

The results shown in Figure 5 are for a distribution line in open ground with no nearby trees or buildings. The number of induced flashovers depends on the presence of nearby objects that may shield the line from direct strokes. This may increase the induced-voltage flashovers because there are more nearby strokes.

As a point of reference, a 10 m tall distribution line in open ground with GFD = 1 flash/km^2/yr will have approximately 11 flashes/100 km/yr due to direct strokes, using Equation (5). In open ground, induced voltages will only be a problem for lines with very low insulation levels and/or above a poor conducting ground. For example, for the case of an overhead line above a perfectly conducting ground, the number of induced-voltage flashovers will exceed the number of direct-stroke flashovers for an ungrounded circuit only if the CFO is less than 75 kV (from Figure 5). However, if the ground conductivity is poor, the number of lightning-induced flashover can be over 10 times greater than for the case of an ideal ground (Borghetti and Nucci [B9]). In shielded areas, induced-voltage flashovers are more of a concern. Typically, an assumption used for distribution lines is that if the CFO is 300 kV or greater, induced flashovers will be eliminated.

Another factor to consider is that most distribution lines have distribution transformers protected by arresters, which will also provide some degree of induced-voltage flashover reduction (see 8.2). However, this reduction may be small in rural and suburban areas.

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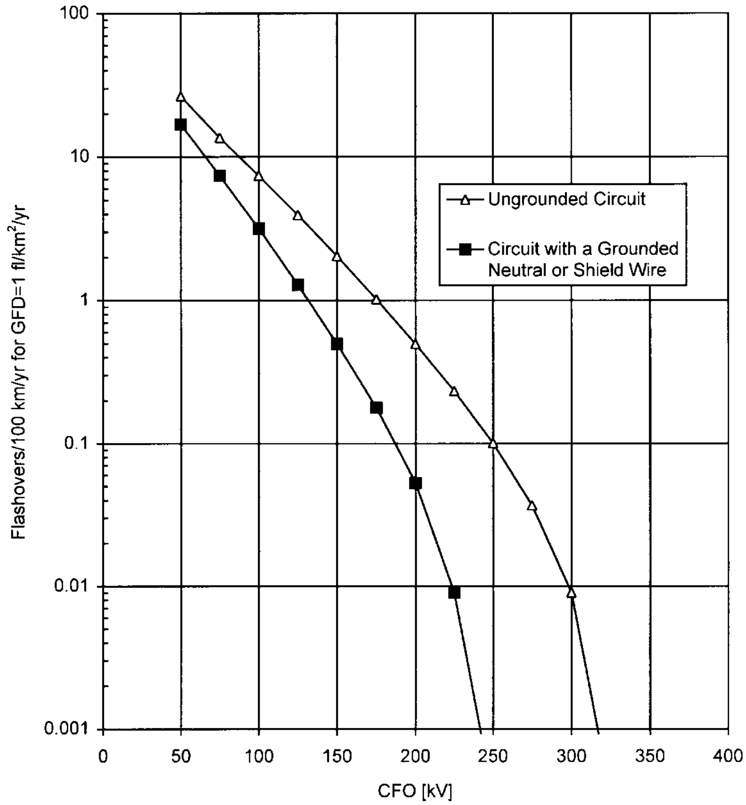

Figure 5—Number of induced-voltage flashovers versus distribution-line insulation level

NOTE—In Figure 5, the distribution-line height is 10 m (see B.2 for modeling details).

6. Distribution-line insulation level

This design guide is an attempt to assist the distribution-system design engineer to optimize the lightning insulation capabilities of overhead distribution lines. Most overhead construction utilizes more than one type of insulating material for lightning protection.

The more common insulating components used in overhead distribution-line construction are porcelain, air, wood, polymer, and fiberglass. Each element has its own insulation strength. When the insulating materials are used in series, the resulting insulation level is not the summation of those levels associated with the individual components, but is somewhat less than that value.

The following factors affect the lightning-flashover levels of distribution lines and make it difficult to easily estimate the total insulation level:

a) Atmospheric conditions, including air density, humidity, rainfall, and atmospheric contamination

b) Polarity and the rate of rise of the voltage

c) Physical factors, such as insulator shape, shape of metal hardware, and insulator configuration (mounted vertically, horizontally, or at some angle)

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If wood is in the discharge path of the lightning stroke, the stroke's effect on the insulation strength may be quite variable, dependent primarily upon the moisture on the surface of the wood. The insulation strength depends to a lesser degree on the physical dimensions of the wood.

Even though the design engineer may be more familiar with the basic impulse insulation level (BIL) of a given combination of insulating materials, the results of this guide are given in terms of the CFO of these combinations. The CFO is defined as the voltage level at which statistically there is a 50% chance of flash-over and a 50% chance of withstand. This value is a laboratory-definable point. If a Gaussian distribution of flashover data is assumed, then any specific probability of withstand may be statistically calculated from the CFO value and the standard deviation.

As the laboratory data became available, various methods were studied in an attempt to develop a procedure for use in determining the expected CFO of a given combination of insulating components. The *insulation-strength-added* approach may be the most practical.

This method was adopted from a similar procedure used earlier in transmission-line design but has been expanded in its application to multiple insulating components used in distribution-line construction. It utilizes the CFO of the basic- or primary-insulation element and adds to that value the increase in CFO offered by an added component (keeping in mind that the added insulation strength is always less than that of the single added element).

6.1 CFO voltage of combined insulation

From the earliest times, electrical engineers have been constructing distribution lines using wooden crossarms and poles in series with basic insulators to increase the lightning-impulse strength of the distribution-line insulation. In the early 1930s, a number of papers presented the results obtained when insulators were tested in combination with wood. A question arose as to how much lightning-voltage insulation the wood added to the primary insulation (the insulator). A partial answer came through research in many laboratories, and some results were published in the 1940s and 1950s (Clayton and Shankle [B18]). A general summary of previous works on CFO was presented in the 1950 AIEE Committee Report [B2], and an extended report (AIEE Committee Report [B3]) in 1956. However, these results applied mostly to transmission lines and not to distribution-line construction. On overhead distribution lines, the weakest insulation is generally at a pole structure rather than between conductors through the air.

More recently, research continued on multi-dielectric combinations used in electrical power systems. These investigations were concerned with distribution and transmission lines and the withstand level of the wood when subjected to lightning, switching, and steep-front impulses (Darveniza et al. [B21], Grzybowski and Jacob [B38], Jacob et al. [B46], [B47], Pigini et al. [B60], Ross and Grzybowski [B66], Shwehdi [B74], Schwehdi and El-Kieb [B76]). Recently, polymer insulators and fiberglass crossarms have been introduced to distribution lines (Cherney et al. [B15], Elrod and Menzel [B31], Grzybowski and Jenkins [B39], Schwehdi [B73], Shwehdi and El-Hadri [B75]).

6.2 Determining the CFO voltage of structures with series insulation

Studies have indicated that 1 m of wood or fiberglass adds approximately 330–500 kV to the impulse strength of the total insulation (Grzybowski and Jacob [B38], Grzybowski and Jenkins [B39]). For longer lengths, the lightning insulation strength of the wooden or fiberglass crossarm and insulator combination is determined mainly by the wooden or fiberglass crossarm alone. The alternating-voltage insulation is obtained by the insulator alone, and the wooden or fiberglass crossarm is considered only as additional insulation for lightning overvoltage.

When the lightning-surge path to the ground does not include a wooden or fiberglass crossarm but involves two or more types of insulators in series, the CFO of the combination is not obtained by merely adding the

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individual CFOs of the components. The CFOs of these combined insulations are controlled by a number of different factors, each of which requires individual analysis. Today, there are many different combinations and configurations in use by the operating companies.

The extended CFO-added method may be used to estimate the total CFO of a distribution structure by

a) Determining the contribution of each additional insulation component to the total CFO of the combination
b) Estimating the total CFO of the combination knowing the CFO of the insulation components

This may be done using either tables or curves that display the experimental data available, and utilizing these data to relate the effect of one insulating material added to another. This procedure relies on the CFO characteristic data of the basic insulation and an additional set of composite data given as the CFO voltage added by a specific component.

In configurations where two components are involved, the CFO of the combination is much lower than the sum of the individual CFOs. The insulator is considered the primary or basic insulation. The CFO obtained for configurations consisting of two components is calculated as the CFO of the basic component plus the added CFO of the second component.

Total calculated CFO voltage for two components is shown in Equation (9):

$$\mathrm{CFO}_T = \mathrm{CFO}_{\mathrm{ins}} + \mathrm{CFO}_{\mathrm{add.sec}} \tag{9}$$

where

$\mathrm{CFO}_{\mathrm{ins}}$ is the CFO of the primary component,
$\mathrm{CFO}_{\mathrm{add.sec}}$ is the CFO added by the second component.

Total calculated CFO voltage of three and more components is shown in Equation (10):

$$\mathrm{CFO}_T = \mathrm{CFO}_{\mathrm{ins}} + \mathrm{CFO}_{\mathrm{add.sec}} + \mathrm{CFO}_{\mathrm{add.third}} + \ldots + \mathrm{CFO}_{\mathrm{add.nth}} \tag{10}$$

where

$\mathrm{CFO}_{\mathrm{add.third}}$ is the CFO added by the third component,
$\mathrm{CFO}_{\mathrm{add.nth}}$ is the CFO added by the nth component.

The most commonly used individual CFO and CFO-added components are given in Table 2, Table 3, and Table 4.

Table 2—Primary insulation ($\mathrm{CFO}_{\mathrm{ins}}$)

Insulators		kV
Pin	ANSI 55-4	105
	ANSI 55-5	120
	ANSI 55-6	140
Porcelain suspension	1-10.2 cm (4 in)	75
	2-10.2 cm (4 in)	165
	3-10.2 cm (4 in)	250

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Table 2—Primary insulation (CFO_{ins}) *(continued)*

Insulators	kV
Insulation	**kV/m**
Air	600
Wooden pole	330
Wooden crossarm	360
Fiberglass standoff	500

Table 3—CFO-added second components ($CFO_{add.sec}$)

Second component	With first component of	kV/m
Wooden crossarm	Vertical pin insulator	250
Wooden crossarm	Vertical suspension insulator	160
Wooden crossarm	Horizontal suspension insulator	295
Wooden pole	Vertical pin insulator	235
Wooden pole	Suspension insulator	90
Fiberglass crossarm	Insulator	250
Fiberglass standoff	Insulator	315

Table 4—CFO-added third component ($CFO_{add.third}$)

Third component	kV/m
Wooden pole	65
Fiberglass standoff	200

NOTES FOR TABLE 2, TABLE 3, AND TABLE 4

1—All values are wet CFO levels.

2—Values are the minimum of the negative and positive polarity values.

3—Insulators are shown as examples only. Refer to manufacturer's data for more exact values.

The values given in the tables refer to wet conditions, which is recommended for estimating CFO. For CFO values under dry conditions obtained from the manufacturer or from laboratory impulse tests, multiply the dry CFO values by 0.8 to obtain an estimate of wet condition CFO. Wet condition CFO is typically between 0.7 and 0.9 of the dry-condition CFO.

For components not given in Table 3 or Table 4, the total CFO may be estimated by reductions for the second and third components as shown in Equation (11):

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$$CFO_{add.sec} = 0.45 \times CFO_{ins} \tag{11}$$

$$CFO_{add.sec} = 0.2 \times CFO_{ins}$$

Use of the extended CFO-added method and Table 2, Table 3, and Table 4 in this guide will usually give answers within a ±20% error. More accurate estimates are available with the following methods:

a) Perform laboratory impulse tests of the structure in question under wet conditions. This method will give the most accurate results.

b) Perform impulse tests under dry conditions, and multiply the values obtained by 0.8 to estimate the wet condition CFO.

c) Use more detailed component CFOs given in Jacob et al. [B46], [B47], and Shwehdi [B74].

d) Reference other test results of distribution structures found in Armstrong et al. [B6], Darveniza [B22], and Darveniza et al. [B24].

6.3 Practical considerations

Equipment and support hardware on distribution structures may severely reduce CFO. These *weak-link* structures may greatly increase flashovers from induced voltages. The following are descriptions of several situations.

6.3.1 Guy wires

Guy wires may be a major factor in reducing a structure’s CFO. For mechanical advantage, guy wires are generally attached high on the pole in the general vicinity of the principal insulating elements. Because guy wires provide a path to the ground, their presence will generally reduce the configuration’s CFO. The small porcelain guy-strain insulators (often called *johnny balls*) that are often used provide very little in the way of extra insulation (generally less than 30 kV of the CFO).

A fiberglass-strain insulator may be used to gain considerable insulation strength. A 50 cm fiberglass-strain insulator has a CFO of approximately 250 kV.

6.3.2 Fuse cutouts

The mounting of fuse cutouts is a prime example of unprotected equipment that may lower a pole’s CFO. For 15 kV class systems, a fuse cutout may have a 95 kV BIL. Depending on how the cutout is mounted, it may reduce the CFO of the entire structure to approximately 95 kV (approximately because the BIL of any insulating system is always less than the CFO of that system).

On wooden poles, the problem of fuse cutouts may usually be improved by arranging the cutout so that the attachment bracket is mounted on the pole away from any grounded conductors (guy wires, ground wires, and neutral wires). This is also a concern for switches and other pieces of equipment not protected by arresters.

6.3.3 Neutral wire height

On any given line, the neutral wire height may vary depending on equipment connected. On wooden poles, the closer the neutral wire is to the phase wires, the lower the CFO.

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6.3.4 Conducting supports and structures

The use of concrete and steel structures on overhead distribution lines is increasing, which greatly reduces the CFO. Metal crossarms and metal hardware are also being used on wooden pole structures. If such hardware is grounded, the effect may be the same as that of an all-metal structure. On such structures, the total CFO is supplied by the insulator, and higher CFO insulators should be used to compensate for the loss of wooden insulation. Obviously, trade-offs should be made between lightning performance and other considerations such as mechanical design or economics. It is important to realize that trade-offs exist. The designer should be aware of the negative effects that metal hardware may have on lightning performance and attempt to minimize those effects. On wooden pole and crossarm designs, wooden or fiberglass brackets may be used to maintain good insulation levels.

6.3.5 Multiple circuits

Multiple circuits on a pole often cause reduced insulation. Tighter phase clearances and less wood in series usually reduces insulation levels. This is especially true for distribution circuits built underneath transmission circuits on wooden poles. Transmission circuits will often have a shield wire with a ground lead at each pole. The ground lead may cause reduced insulation. This may be improved by moving the ground lead away from the pole with fiberglass spacers.

6.3.6 Spacer-cable circuits

Spacer-cable circuits are overhead-distribution circuits with very close spacings. Covered wire and spacers (15–40 cm) hung from a messenger wire provide support and insulating capability. A spacer-cable configuration will have a fixed CFO, generally in the range of 150–200 kV. Because of its relatively low insulation level, its lightning performance may be lower than a more traditional open design (Powell et al. [B61]). There is little that may be done to increase the CFO of a spacer-cable design.

A spacer-cable design has the advantage of a messenger wire that acts as a shield wire. This may reduce some direct-stroke flashovers. Back flashovers will likely occur because of the low insulation level. Improved grounding will improve lightning performance.

6.3.7 Spark gaps and insulator bonding

Bonding of insulators is sometimes done to prevent lightning-caused damage to wooden poles or crossarms, or it is done to prevent pole-top fires. Spark gaps are also used to pre-vent lightning damage to wooden material [the use of spark gaps was a practice suggested by the Rural Utilities Service (RUS) distribution specifications (Rural Electric Association [B69]), but it is no longer a suggested practice]. In some parts of the world, spark gaps are also used instead of arresters for equipment protection.

Spark gaps and insulator bonds will greatly reduce a structure’s CFO. If possible, spark gaps, insulator bonds, and pole-protection assemblies should not be used to prevent wood damage. Better solutions for damage to wood and pole fires are local insulator-wood bonds at the base of the insulator as discussed in 6.5.

6.4 Arc-quenching capability of wood

Wood poles and crossarms have shown the capability to quench the lightning-caused arc and prevent it from forming a power-frequency fault (Armstrong et al. [B6], Darveniza [B22], Darveniza et al. [B24]).

The arc-quenching capabilities of wood are predominantly a function of the instantaneous power-frequency voltage across the arc at the instant of the lightning-caused flashover. If the voltage is near a zero crossing, the arc is much more likely to extinguish without causing a fault. If the nominal voltage along the wooden crossarm is maintained below a certain level, the chance of a fault developing may be greatly reduced.

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If multiple flashovers occur, arc quenching is much less likely (see Figure 6). Most distribution lines will suffer multiple flashovers from a direct strike. On distribution structures that have RMS voltage gradients across wood greater than 10 kV/m of wood, arc quenching may not provide a significant benefit. For example, a 13.2 kV distribution line with 0.5 m of wood between the phase insulator and the neutral wire has an RMS voltage gradient across the wood of 13.2 kV/ (√3 x 0.5 m) = 15.2 kV/m. For this voltage, if wooden spacings of 1 m are achieved between all phase conductors and all grounded objects on the pole, then arc quenching may become a significant factor. This may be readily achieved on circuits with high insulation levels and long distances of wood. For this guide, a conservative assumption is made that all flashovers cause faults.

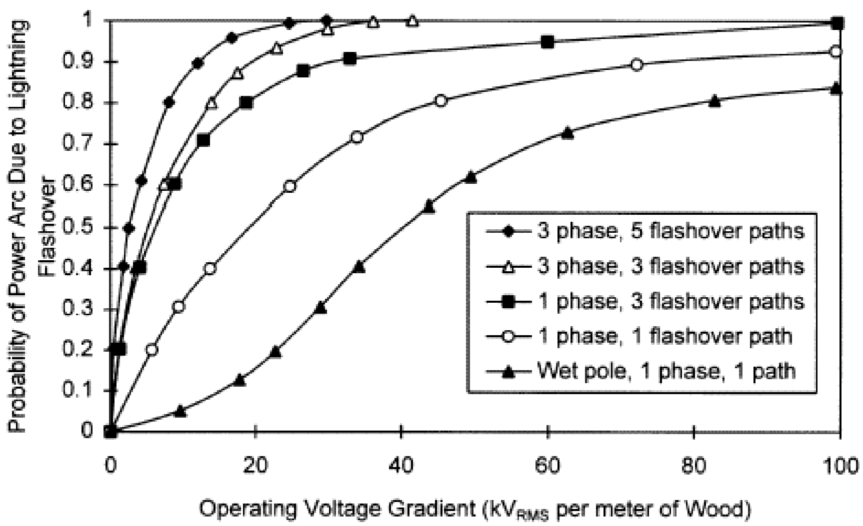

Figure 6—Probability of a power arc due to a lightning flashover over a wet wooden crossarm (Darveniza et al. [B24])

6.5 Wood damage caused by lightning

Service experience indicates that damage to poles or crossarms due to lightning is relatively rare (Darveniza [B22]). Nevertheless, in high-lightning areas it may be a concern under certain conditions. The probability of damage due to lightning depends on many factors, especially the moisture content and aging of the wood. Damage and shattering occurs when the breakdown is internal to the wood rather than along the surface of the wood. If the wood is green, it is more likely to breakdown internally.

If historical records show that wood damage is a problem, the wood may be protected by bonding the insulators. However, this short circuits the insulation capability provided by the wood. A better solution may be to use surface electrodes fitted near the insulator pin. This may include wire-wraps, bands, or other metal extensions attached near the insulator in the likely direction of flashover. This encourages breakdown near the surface rather than internally.

Preventative measures for lightning damage to wood will also reduce the likelihood of pole-top fires. Pole-top fires are the result of leakage-current arcs at metal-to-wood interfaces (Darveniza [B22], Ross [B67]). Local bonding, using wire bands or wraps, will bridge the location where fires are most likely to start at poor metal-to-wood contacts. This is preferable to completely bonding the insulators (see 6.3).

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7. Shield-wire protection of distribution lines

Shield wires are grounded conductors placed above the phase conductors to intercept lightning strokes that would otherwise directly strike the phases. Lightning current is diverted to ground through a pole ground lead. To be effective, the shield wire is grounded at every pole.

Lightning-surge current flowing through the pole ground impedance causes a potential rise, resulting in a large voltage difference between the ground lead and the phase conductors. The voltage difference may cause a back flashover across the insulation from the ground lead to one of the phase conductors.

The back flashover phenomenon is a substantial constraint to shield-wire effectiveness in distribution-line applications. Shield wires may provide effective protection only if

a) Good insulation design practices are used to provide sufficient CFO between the ground downlead and the phase conductors, and

b) Low pole ground resistances are obtained.

Figure 5 may be used to estimate the number of induced flashovers for a shield-wire design. For three-wire distribution circuits, adding a shield wire will reduce the number of induced flashovers. Since the shield wire is grounded, it will suppress the voltages on the phase conductors through capacitive coupling. The closer the phase wires are to the shield wire, the better the coupling, and the smaller the induced voltages will be (although this may reduce the CFO, as discussed in 6.3). Note that adding a grounded wire below the phase conductors will have approximately the same effect as an overhead shield wire.

On a four-wire, multigrounded system, replacing the underbuilt neutral wire with an overhead shield wire will not reduce the number of induced flashovers. However, having both a shield wire and a neutral wire will improve performance to some degree.

The cost of including a shield wire in a distribution-line design may be substantial. In addition to the cost of the conductor, pole grounds, and additional insulation, the pole height must be greater to support the shield wire such that there is a sufficient shielding angle between the shield wire and the outer phase conductors. The greater structure height attracts more direct strokes, and this slightly offsets some of the flashover rate reduction provided by the shielding. Despite the cost and design difficulties, shield wires have been used by some utilities with great success.

7.1 Shielding angle

To ensure that most lightning strokes terminate on the shield wire rather than on the phase conductors, a shielding angle (as shown by Figure 7) of 45° or less is recommended. This guideline is only valid for lines less than 15 m tall with conductor spacings under 2 m. Taller lines require smaller shielding angles.

For more information, refer to IEEE Std 1243™-1997 [B42] and its references. Most of the shielding angle curves are drawn for transmission circuits, starting with a critical current of 5 kA to cause a shielding failure flashover. It must be recognized that critical currents for distribution circuits would be lower, with a range of 2–3 kA accepted as the minimum lightning stroke current. This would act to reduce the required shielding angle. Recent lightning-detection network measurements in North America indicate the possibility of lower median current values (Cummins et al. [B20]); this would also reduce the required shielding angle for a target shielding failure flashover rate. The electro-geometric models that form the basis of shielding angle recommendations are also under continuous review.

In areas where distribution lines with a 45° shielding angle perform well, this practice may continue. For newer construction or design standards, a smaller shielding angle of 30° should be considered.

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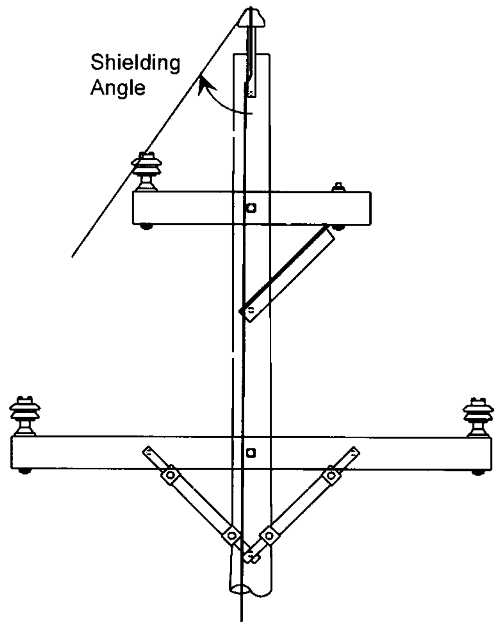

Figure 7—Shield-wire shielding angle

7.2 Insulation requirements

Shield-wire effectiveness in distribution lines depends greatly on the insulation provided between the ground lead and the phase conductors. If the ground lead is in contact with the pole for its entire height, it is difficult to provide adequate insulation. On a wooden pole, it is usually necessary to isolate the ground lead from the pole in the vicinity of the phase insulators and crossarms. This may be accomplished with fiberglass rods or standoffs mounted horizontally on the pole to hold the ground wire 30–60 cm away from the pole. The CFO from the ground lead to the closest phase is the most limiting value from several paths. Care should also be taken to insulate guy wires to obtain the necessary CFO.

A CFO in excess of 250–300 kV is necessary to make shield-wire application effective. By using ground-lead standoffs, it is not difficult to achieve this insulation level on distribution lines.

7.3 Effect of grounding and insulation level

Shield-wire effectiveness is highly dependent on grounding. For a shield-wire design to be effective, ground resistances must be less than 10 Ω if the CFO is less than 200 kV. If attention is given to insulation level and the CFO is 300–350 kV, a ground resistance of 40 Ω will provide similar performance. The shield wire should be grounded at every pole for effective results. Figure 8 shows the direct-stroke performance and effect of grounding with an example computer simulation of a shield wire with CFOs of 175 kV and 350 kV. Triggered-lightning studies of the behavior of grounding electrodes under actual lightning surge conditions are presented in Rakov et al. [B63].

7.4 Distribution underbuild

Distribution lines underbuilt on transmission structures may be especially susceptible to back flashovers. Greater structure heights and larger right-of-ways will draw more direct strikes to the structures. Care must be taken to maintain high insulation levels to avoid unnaturally high flashover rates.

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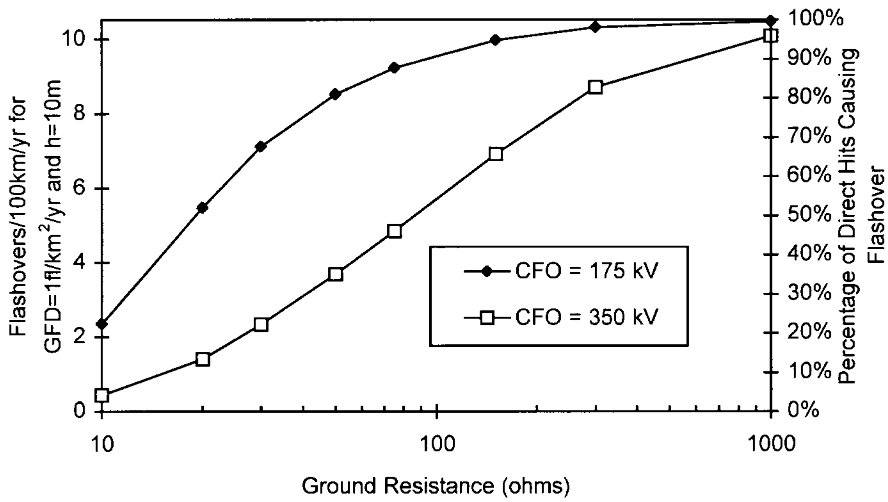

Figure 8—Effect of grounding resistance on shield-wire performance (direct strikes)

NOTE—In Figure 8, the span length is 75 m (see B.3 for modeling details).

In addition, the voltage stress developed to cause a back flashover is higher on the distribution circuit than on the transmission circuit. This occurs because the distribution conductors are further from the shield wire, and therefore, have a lower coupled voltage and a higher voltage across the insulation compared to any of the transmission conductors. The insulation strength on the distribution underbuild is also usually less than on the transmission circuit. The distribution conductors will back flashover first and will then help the transmission circuit's performance by increased coupling to those conductors.

Care must be taken to maintain low ground resistance and high insulation levels to avoid unnaturally high flashover rates on the distribution circuits. Line arresters on every pole should also be considered for underbuilt circuits. These arresters can help even if installed on just one phase, by increasing the coupled voltage on the other phases.

7.5 Shield wires and arresters

To virtually eliminate flashovers, arresters on every pole and every phase may be used in conjunction with a shield wire. The arresters will protect the insulation from back flashover. The shield wire will divert most of the current to the ground, so the arresters are not subject to much energy input. The arresters make the shield-wire design less dependent on insulation level and grounding.

8. Arrester protection of lines

Distribution arresters are used effectively to protect equipment insulation such as transformers and regulators. These arresters function as high impedances at normal operating voltages and become low impedances during lightning-surge conditions. The arrester conducts surge current to the ground while limiting the voltage on the equipment to the sum of the discharge voltage of the arrester plus the inductive voltage developed by the discharge current in arrester line and ground leads.

Arresters may be used to protect distribution-line insulation to prevent flashovers and circuit interruptions. Several different types of arresters are available (e.g., gapped silicon carbide, gapped or non-gapped metal-oxide). From the point of view of protection of distribution-line insulation, all perform in a similar manner. Differences in discharge voltage characteristics will cause only a small difference in the protection of

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insulation, since there is considerable margin. Several studies have investigated the effectiveness of different arrester spacings (McDaniel [B53], Paolone et al. [B59], Short and Ammon [B72]). Triggered-lightning studies of the performance of arresters on distribution lines are presented in De la Rosa et al. [B30], Fernandez et al. [B35], [B37], and Mata et al. [B50], [B51], [B52].

For selection of arrester rating, refer to IEEE Std C62.22-1997 or the manufacturer's guidelines. For equipment protection (especially underground cables), it is sometimes necessary to select an arrester with the lowest possible protective level. However, for line-insulation protection, this is not usually necessary because the arrester protective level is generally considerably lower than the line-insulation level.

When applying arresters for protection, the failure rate of the added arresters should be considered along with the line-flashover improvement obtained by adding the arresters.

8.1 Arrester lead length considerations

Arrester leads that connect the distribution line and ground terminals of arresters to the equipment they protect contain a small amount of inherent inductance. This inductance causes L(di/dt) voltage drops to appear across the leads that conduct lightning-surge currents. Any voltage drop across an arrester lead will add to the arrester discharge voltage. This will increase the voltage appearing across the device(s) protected by the arrester.

The effect of the line-lead length on the protection of the distribution-line insulation is not as significant as it is with equipment protection. For overhead equipment, the margin is generally very high. Also, line insulation level is generally much larger than standard equipment BIL. Of course, it is always good practice to keep arrester distribution line and ground leads as short and straight as possible. Refer to IEEE Std C62.22-1997 for more information on arrester lead lengths.

8.2 Flashovers from nearby strikes

Arresters may greatly reduce the flashover rate due to induced voltages from nearby strokes. Figure 9 shows results for an insulation level of 150 kV for an ungrounded circuit. Note that even relatively wide arrester spacings may reduce induced-voltage flashovers significantly (8 spans yields at least a 25% reduction). On many distribution circuits with frequent transformers, the arresters used to protect the transformers may provide significant protection from induced flashovers. The technical assumptions are described in Annex B.

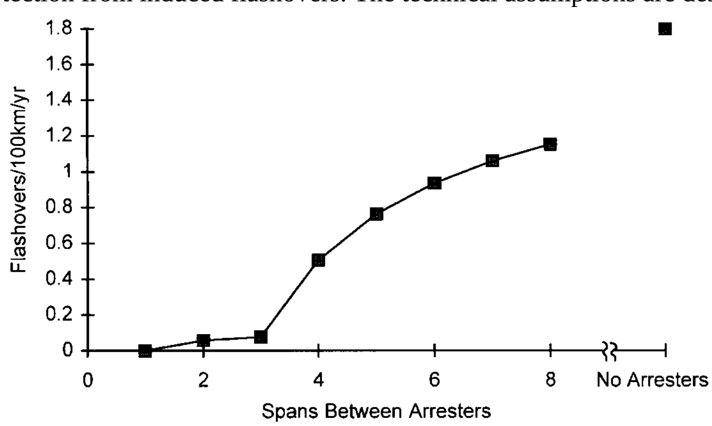

Figure 9—Arrester spacing for flashovers from induced voltages

NOTE—In Figure 9, CFO = 150 kV, h = 10 m, N_g = 1 flash/km^2/yr, span length = 75 m.

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Arresters may be even more effective at reducing induced flashovers if they are used to protect poles with poor insulation levels. These weak links may include cutouts, dead-end poles, or crossover poles. Placing arresters on these poles may be more cost-effective than improving the insulation level.

8.3 Flashovers from direct strokes

Protecting against direct strokes is difficult because of the high surge currents, steep rates of rise, and large energy content in lightning flashes. In theory, arresters may effectively protect against direct strikes, but they must be used at very close intervals (virtually every pole). Figure 10 shows flashover estimates for various arrester spacings to protect against direct strokes (see the Annex B for details and assumptions). The analysis in Figure 10 assumes that the neutral wire is grounded at every pole. The high number of flashovers may be misleading according to Figure 10, where the neutral wire is not grounded except at poles where arresters are applied to all phases, and the neutral-to-ground insulation level is high.

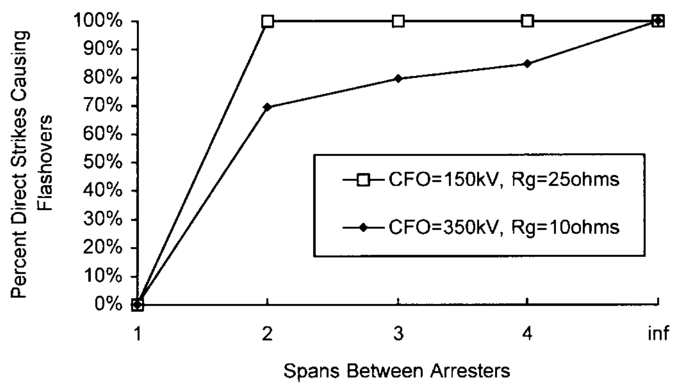

Figure 10—Arrester spacing for direct-stroke protection

NOTE—In Figure 10, the span length is 75 m.

8.3.1 Top-phase arrester protection

If the top-phase conductor is situated such that it will intercept all lightning strokes, arresters may be applied to the top phase that make it act like a shield wire. Upon being struck, the top-phase arrester will conduct the surge to ground. The circuit will be protected if the arrester ground resistance is low enough and the insulation on the unprotected phases is high enough. Like a shield wire, care should be taken to maintain high insulation level on the unprotected phases. The curves for a shield wire (see Figure 8) may be used to estimate the effectiveness of a top-phase arrester design. The arresters should be used on virtually every pole or tower to achieve optimum protection.

8.3.2 Arrester direct-stroke capability

In exposed applications (e.g., a distribution line in the open without a shield wire), distribution-class metal-oxide arresters may suffer occasional failures due to direct strokes. McDermott et al. [B54] has shown that a significant percentage of direct lightning strikes may cause arresters to absorb energy in excess of both the manufacturer’s published capability and the 4/10 µs discharge test wave. This is tempered by the fact that metal-oxide blocks have been shown to have appreciably more surge-energy absorption capability than the published capability (Ringler et al. [B64]). Another failure mechanism of some metal-oxide arrester designs is the occurrence of flashovers around the blocks when the arrester is subjected to multiple-stroke events (Darveniza et al. [B25]). Surface flashovers due to multiple strokes are much less likely for arresters without air spacings such as polymer-housed arresters (Darveniza et al. [B27]). Several studies, both field and laboratory, have evaluated arrester performance due to both single-stroke and multiple-stroke events (Darveniza and Saha [B23], Darveniza et al. [B26], Fernandez et al. [B36]).

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Annex A

(informative)

Examples of guide usage

A.1 Example 1—A 15 kV wooden crossarm design

Problem: A utility is performing a review of its standard 15 kV class, three-wire distribution-line design (see Figure A.1). The utility is in a moderate lightning area with a keraunic level of 40 thunderstorm days per year. Insulators are ANSI-class 55-4, porcelain-pin insulators. Assume that the crossarm braces are conducting and steel insulator pins are used. Guy wires have porcelain-strain insulators (ANSI-class 54-4). The standard pole size is 12.2 m with a planting depth of 2 m. The goal is to estimate the lightning performance level of the current design and investigate improvements.

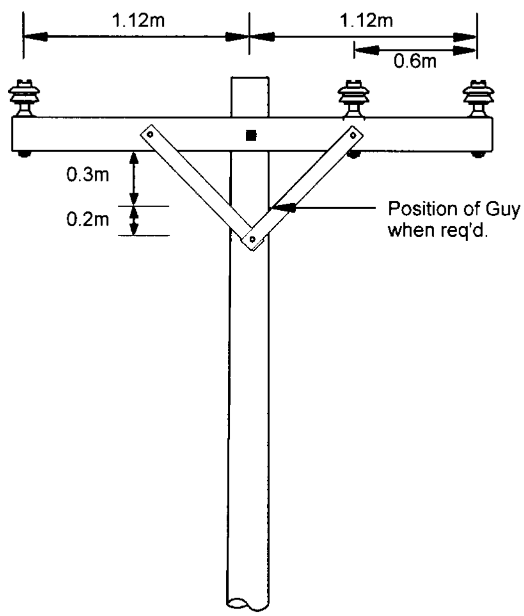

Figure A.1—A 15 kV class wooden crossarm design

Insulation level. The CFO for several possible flashover paths are shown in Table A.1.

Direct strokes. The GFD may be estimated from the keraunic level, from Equation (1):

$$N_g = 0.04 \times (40)^{1.25} = 4 \text{ flashes/km}^2\text{/yr}$$

The top conductor height is 10.2 m with a structure width of 2.24 m. From Equation (5), the number of direct flashes in open ground is

$$N = 4\ [28 \times (10.2)^{0.6} + 2.24]/10 = 46 \text{ flashes/100 km/yr}$$

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Table A.1—CFO calculations for several possible flashover paths for the 15 kV pole design

From	To	Flashover path	Total CFO (kV)
Middle phase	Guy wire	Insulators (105 kV) to 0.2 m wooden pole (47 kV) to guy insulator (0 kV)	152
Outer phase	Guy wire	Insulator (105 kV) to 0.6 m wooden crossarm (150 kV) to 0.2 m wooden pole (13 kV) to guy insulator (0 kV)	268
Right phase	Middle phase	Insulator (105 kV) to 0.6 m wooden crossarm (150 kV) to second insulator (20 kV)	275
Right phase	Middle phase	Air (0.6 m)	360

Assuming a 0.75 shielding factor and that all direct strokes will cause a flashover, the estimated number of direct-hit flashovers are

Direct-hit flashovers = 11.5 flashovers/100 km/yr

Induced flashovers. The number of induced flashovers in open ground may be estimated from Figure 5 using the lowest CFO path of 152 kV and scaling by the GFD, as follows:

Induced flashovers (open ground) = (4)2 flashes/100 km/yr

= 8 flashovers/100 km/yr

Because much of the distribution line is shielded (bordered by tall structures, e.g., Sf = 0.75), larger magnitude strokes can terminate close to the line, without striking the distribution line directly. This will cause more induced flashovers. The number of induced-voltage flashovers should be somewhere between the number of indirect flashovers in open ground (in this case, 8 flashes/100 km/yr) and the number of direct hits in open ground (in this case, 46 flashes/100 km/yr). As an estimate, we will assume that the induced-voltage flashovers are two times the induced flashovers in open ground.

Induced flashovers = 16 flashovers/100 km/yr

All flashovers are assumed to cause faults, as shown by

Total faults = direct + induced = 27.5 faults/100 km/yr

Improvement options to consider. It has been decided to consider changes that are relatively inexpensive and easy to implement. Insulation changes to reduce induced-voltage flashovers are the primary consideration with a goal of a 300 kV CFO.

a) Use 50 cm fiberglass guy-strain insulators. This will increase the middle phase-to-guy CFO to 310 kV [0.5 m fiberglass guy-strain insulator (250 kV) + insulator (0.45 × 105 kV = 47 kV) + 0.2 m wooden pole (0.2 m × 65 kV/m = 13 kV)]. This virtually eliminates induced-voltage flashovers. Note: Because the fiberglass strain insulator has an individual CFO much higher than any of the other elements, it is taken first, rather than the insulator.

b) Use wooden crossarm braces. This will add a significant amount of wood to the middle phase-to-guy flashover path. The CFO along this path would be approximately 255 kV [insulator (105 kV) + wooden crossarm (0.52 m × 250 kV/m = 130 kV) + wooden pole (0.3 m × 65 kV/m = 20 kV)]. This reduces the number of induced-voltage flashovers to less than 0.8 flashovers/100 km/yr.

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Other structure designs such as dead-end, angle, and crossover should also be examined. Improvement options may then be cost-compared to the existing design and against the improvement in service reliability and power quality.

A.2 Example 2—A 35 kV distribution line with a shield wire

Problem: A utility is considering using a shielded distribution-line design for its 35 kV four-wire multigrounded neutral circuits (see Figure A.2). The line will be built in an area with a shielding factor of 0.5 provided by nearby objects and a keraunic level of 60 thunderstorm days per year. The design provides a shielding angle of 24°. The phase insulators are ANSI-class 57-2, porcelain-post insulators on steel brackets. The shield wire is supported by an ANSI-class 55-5, pin-porcelain insulator. The distribution line uses 15.24 m wooden poles, and every pole is grounded with a ground resistance of 10 Ω or less.

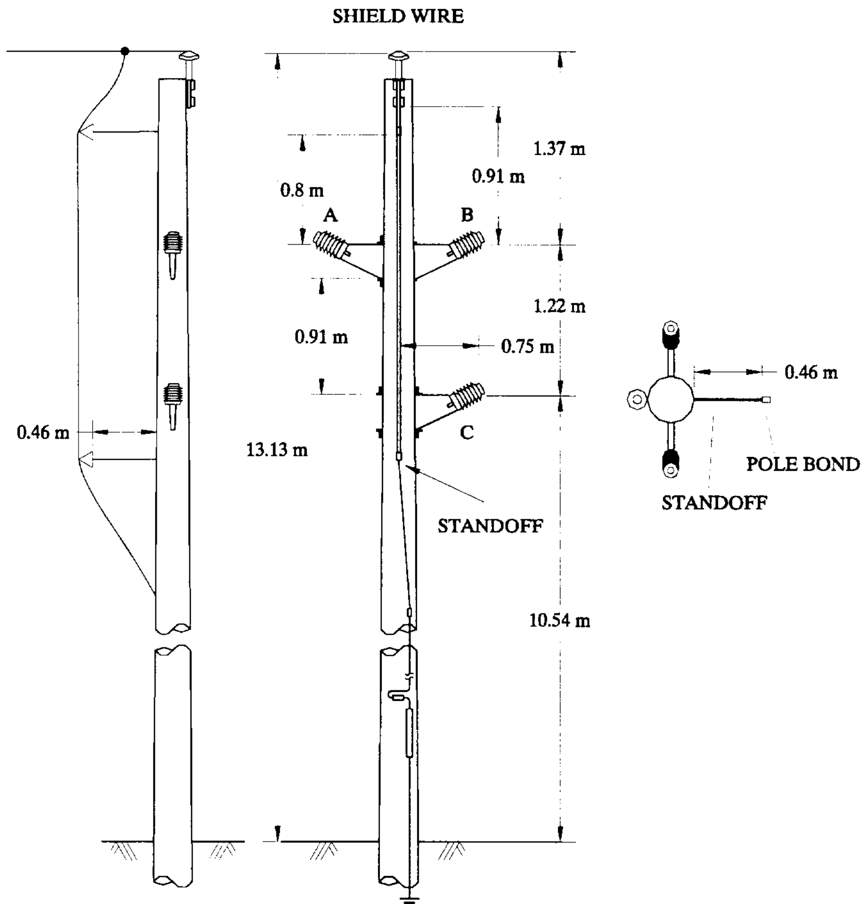

Figure A.2—A 35 kV shield-wire wooden pole structure

From the CFO calculations in Table A.2, it is obvious that the fiberglass ground-lead standoffs are needed. The pole ground lead wire is offset with a 0.46 m fiberglass standoff insulator, and it is attached to the pole 0.49 m below the bottom phase conductor. Without the standoffs, the CFO would be 180 kV, which would lead to induced-voltage flashovers, and the shield wire would not be effective at preventing direct-stroke flashovers. Although the lowest CFO path is 261 kV, the paths of most concern are the phase-to-ground

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Table A.2—The 35 kV shield-wire CFOs

From	To	Flashover path	Total CFO (kV)
Ground wire	A, B, C	Post insulator (with no ground-wire standoff)	180
Static	A, B	Post insulator (180 kV) to 0.91 m wooden pole (214 kV) to pin insulator (24 kV)	418
Static	C	Post insulator (180 kV) to 2.13 m wooden pole (501 kV) to pin insulator (24 kV)	705
A	B	First post insulator (180 kV) to second post insulator (81 kV)	261
A, B	C	First post insulator (180 kV) to 0.91 m wooden pole (214 kV) to second post insulator (36 kV)	430
Pole ground lead	C	Post insulator (180 kV) to standoff (145 kV)	325
Pole ground lead	A, B	Post insulator (180 kV) to 0.8 m wooden pole (188 kV) to standoff (92 kV)	460
Pole ground lead	A, B, C	0.75 m air (450 kV)	450

flashover paths, because the voltage for a stroke to the shield wire and induced voltages are phase-to-ground voltage stresses. The lowest phase-to-ground flashover path is 325 kV from phase C to the pole ground lead.

Direct hits. The GFD may be estimated from the keraunic level in the following, from Equation (1):

$$N_g = 0.04(60)^{1.25} = 6.68 \text{ flashes/km}^2\text{/yr}$$

The shield-wire height is 13.13 m, the width of the phase conductors is 1.22 m. From Equation (5), the number of direct flashes in open ground is

$$N = 6.68[(28 \times 13.13^{0.6})/10] = 87.7 \text{ flashes/100 km/yr}$$

The estimated hits using a shielding factor of 0.5 is

Direct hits to the distribution line = 43.8 flashes/100 km/yr

Because the distribution line is grounded at every pole and the shielding angle is less than 45°, all flashes to the distribution line are assumed to strike the shield wire. The number of flashovers may be determined from Figure 8 with a ground resistance of 10 Ω using the 350 kV CFO curve:

Direct-hit flashovers = (43.8 flashes/100 km/yr)(4% flashover rate)

= 1.8 flashovers/100 km/yr

Induced flashovers. With a CFO of 325 kV, the structure may be assumed to be immune from induced-voltage flashovers (see Figure 5).

All flashovers are then due to direct strokes, and all flashovers are assumed to cause faults, as shown by

Total faults = direct = 1.8 faults/100 km/yr

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Improvement options to consider. The design shown in Figure A.2 has very good flashover performance. One concern is that the design goal of 10 Ω grounding resistance may be difficult to achieve in practice. Figure 8 may be used to estimate the reduction in performance due to the footing resistance. For example, if the footing resistance is 50 Ω, the flashover rate will increase to 35% of direct hits (15.3 faults/100 km/yr).

An improvement option to consider would be using fiberglass insulator brackets instead of the steel brackets specified. This would increase the phase-to-phase and phase-to-ground CFO.

When comparing this design to nonshielded designs, the increase in construction cost should be weighed against the mitigated cost of the power interruptions caused by flashovers.

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Annex B

(informative)

Technical modeling and assumptions

B.1 Shielding

An electro-geometric model may be used to estimate the shielding factor for a specific portion of a distribution line. An electro-geometric model is based on the idea that a distribution line or other object has a certain attractive radius that increases with height, and also the attractive radius is dependent on the current magnitude in the lightning flash. Although several models have been proposed, the equation used for the calculation of the striking distances is the equation adopted by the IEEE Working Group Report [B44], given by Equation (B.1).

$$r_s = 10 \times I_o^{0.65} \qquad \text{(B.1)}$$

$$r_g = 0.9 r_s$$

where

r_s is the striking distance to the conductor (m),
r_g is the striking distance to the ground (m),
I_o is the lightning-peak current (kA).

This electro-geometric model is used for the shielding-factor calculations shown in Figure 4 and for the induced-voltage flashover estimations (see B.2). The electro-geometric model may also be used to estimate the number of direct flashes to a distribution line. This is an alternate approach to the Eriksson formula given in Equation (5). This electro-geometric model gives results for direct flashes that are close to the Eriksson formula for line heights below 15 m. For larger distribution-line heights, the difference is much greater. Different line performances are estimated by adopting different lateral striking distance expressions. Such a difference, however, tends to decrease as the ground resistivity increases (Borghetti et al. [B13], Guerrieri et al. [B40]).

B.2 Induced-voltage flashovers

The theoretical calculation of the number of flashovers to distribution lines produced by close lightning has been described in several works (e.g., Borghetti and Nucci [B9], Chowdhuri [B16], IEEE Working Group Report [B43]). This guide uses the method of the IEEE Working Group Report [B43], based on the Rusck simplified formula for the calculation of the lightning-induced voltages and on the work of Chowdhuri [B16] concerning the statistical approach. The basic parameters considered in the IEEE Working Group Report [B43] are the GFD N_g, the striking distance r_s, and the source term, which in this model, is the lightning-peak current. It is worth reminding that a more general method has been proposed by Borghetti and Nucci [B9] that can be applied to overhead lines above a lossy ground with multiple groundings of the ground wire (e.g., Borghetti et al. [B12], [B13]).

A comparison between the results obtained by adopting the two above-mentioned approaches has been presented in Borghetti et al. [B11].

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Given the random nature of lightning, any calculation has to be kept within probabilistic bases, and as such, probabilistic distributions of the involved parameters have to be used. In this work we adopt the distribution described by Equation (4) for lightning-peak currents, assuming that it is not biased by the so-called *tower effect* (e.g., Borghetti et al. [B10], Rizk [B65]), namely that it is the distribution for lightning-peak current at ground level.

The striking distance concept, which has to be considered here in order to determine the distance from the distribution line beyond where lightning will not strike the line, is that given in Equation (B.1).

Detailed models for estimating the induced voltage have been derived (Agrawal et al. [B1], De la Rosa [B29], Master and Uman [B49], Nucci [B56], [B57], Nucci et al. [B58]). Efforts have been made to formulate a complete model that takes into account soil effects on the peak amplitude and waveshape of the induced voltage.

Several induced-voltage models are available, and all are very dependent on several parameters, including electro-geometric model, stroke-current model, return-stroke velocity, and current waveform characteristics. The Rusck model [B71] is chosen for induced voltages because of its simplicity, because it has shown to be mathematically correct, and because it has been shown to be somewhat consistent with experimental results. The Rusck model has been shown to be equivalent to more complicated models with some simplifying assumptions (Cooray [B19], Rubinstein and Uman [B68]). However, to take into account the effect of the ground resistivity, which in some cases can enhance the induced-voltage amplitude, the use of improved models is recommended (De la Rosa [B29], Guerrieri et al. [B40], Ishii et al. [B45], Rachidi et al. [B62]).

B.2.1 Induced voltage

According to the simplified Rusck formula [B71], the maximum voltage that is induced in a power line in the point closest to the strike is given by Equation (B.2):

$$\mathrm{v}_{\max} = \frac{Z_o I_o h}{y}\left(1 + \frac{1}{\sqrt{2}}\frac{v}{v_o}\frac{1}{\sqrt{1 - \frac{1}{2}\left(\frac{v}{v_o}\right)^2}}\right) \tag{B.2}$$

where

- Z_o is $1/(4\pi)\sqrt{\mu_o/\varepsilon_o}$,
- I_o is the lightning-peak current,
- h is the average height of the distribution line over the ground level,
- y is the closest distance between the lightning strike and the line,
- v is the return-stroke velocity,
- v_o is the velocity of light in free space.

The value for Z_o is 30 Ω, and the measured return stroke speed for natural lightning varies between 0.29×10^8 m/s and 2.4×10^8 m/s (Idone and Orville [B41]). For the simplified expression given in this guide, the return-stroke velocity is assumed as 1.2×10^8 m/s.

B.2.2 Frequency of indirect lightning flashovers

To estimate the flashover frequency, the procedures described in the IEEE Working Group Report [B43] and in De la Rosa [B28] are considered. The range of the lightning-peak current 1–200 kA is divided in intervals of 1 kA, and the probability of current peak to be within that interval is calculated from Equation

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(4). This is found as the difference between the probability for current to be equal or larger than the lower limit and the probability for current to reach or exceed the higher limit.

The maximum distance y_{max} for every peak current interval at which lightning may produce an insulation flashover in the distribution line is then calculated. This is obtained by solving Equation (B.2) for y, by taking I_o as the lower current limit of the interval, and taking V_{max} = 1.5 × CFO. The 1.5 factor is an approximation that accounts for the turnup in the insulation volt-time curve. This approximation is used for induced voltage, shield wire, and arrester-spacing calculations. These voltages are assumed to have much shorter duration waveshapes than the standard 1.2/50 µs test wave.

The minimum distance y_{min} for which lightning will not divert to the line is calculated from Equation (B.3), as proposed in the IEEE Working Group Report [B43]. For this, r_s and r_g are calculated by taking the upper limit of the current interval. This is shown graphically in Figure B.1.

$$y_{min} = \sqrt{r_s^2 - (r_g - h)^2} \tag{B.3}$$

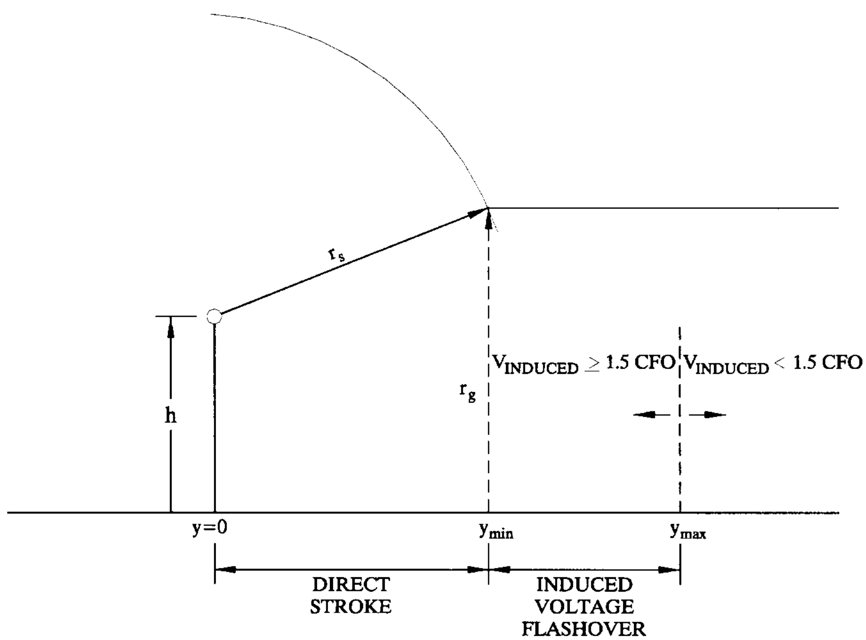

Figure B.1—Use of the electro-geometric model and the Rusck model for determining a direct stroke or induced-voltage flashover

For instance, following the described procedure, with CFO = 150 kV, for a current interval 49–50 kA, y_{max} and y_{min} result in 84.6 m and 72.5 m, respectively. In open ground, the three following scenarios may occur:

a) If the stroke comes down between $y = 0$ and $y = y_{min}$ = 72.5 m, the stroke will hit the line.

b) If the stroke comes down between $y = y_{min}$ = 72.5 m and $y = y_{max}$ = 84.6 m, the stroke will hit the ground and cause an induced-voltage flashover.

c) Beyond $y = y_{max}$ = 84.6 m, the stroke will hit the ground and not cause a flashover.

Finally, the number of insulation flashovers per km of distribution line and per year, F_p, is obtained as the summation of the contributions from all intervals considered, as expressed by Equation (B.4):

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$$F_p = 2 \times \sum_{i=1}^{200} (y_{i\ max} - y_{i\ min}) \times N_g \times P_i \times 0.001 \quad (B.4)$$

B.2.3 Experimental comparison

The method described here provides a simplified way to determine the expected number of flashovers to a distribution line produced by close lightning.

Field tests and triggered-lightning tests have provided some indication of the accuracy of this model. Natural lightning recorded to a 200 m tall smoke stack, 200 m from the line, showed several measurements with very good correlation with this model (although several also had poor correlation) (Yokoyama et al. [B77]). Rocket triggered-lightning measurements performed at a distribution line 145 m from the lightning flash found that the measurements were 63% higher than the modeled voltages (Barker et al. [B7]). Eriksson et al. [B34] showed results with good correspondence to the Rusck model.

B.2.4 Effect of shielding

The results given in Figure 5 pertain to a distribution line in open ground. This model compares favorably with experimental results discussed in B.2.3. A circuit with nearby trees or buildings will not have as many direct strokes, but there will be more of an opportunity for induced-voltage flashovers because the nearby objects will allow strokes closer to the line. The Rusck model for a distribution line shielded by nearby objects gives unrealistic estimates of distribution-line performance, as shown in the top curve of Figure B.2. This model assumes that nearby objects will cause strokes to be evenly distributed at distances from the distribution line using y_{max} to determine the number of flashovers.

$$F_p = 2 \times \sum_{i=1}^{200} y_{i\ max} \times N_g \times P_i \times 0.001 \quad (B.5)$$

This model is unrealistic in that it gives far too many flashovers for circuits with large CFOs. The 1/*y* model predicted by Rusck may break down for very close strokes. Also, most of the verification of the Rusck model has been done for lines in the open or for strokes beyond 100 m.

B.3 Shield-wire modeling

The estimation of shield-wire performance is modeled using a similar approach adopted by the Working Group on Estimating the Lightning Performance of Transmission Lines and used in the FLASH program (Anderson [B4], IEEE Std 1243-1997 [B42], IEEE Working Group Report [B44]). The tighter pole spacings of distribution lines prevent accurate modeling with the existing algorithm, so some modifications are necessary for distribution lines.

Because of shorter span lengths on distribution lines, reflections from adjacent poles will greatly reduce the insulator voltage. Reflections from adjacent poles will reduce both the peak voltage and the tail of the wave-shape. For calculation of the peak voltage, only the adjacent poles need to be considered. For calculation of tail voltages, additional poles need to be considered (the FLASH model neglects towers beyond the adjacent span).

The FLASH model performs voltage calculations at 2 μs and 6 μs. For distribution lines, only a 2 μs voltage will be calculated. It is assumed that reflections from adjacent poles will quickly reduce the tail, so that the 2 μs point determines the flashover point.

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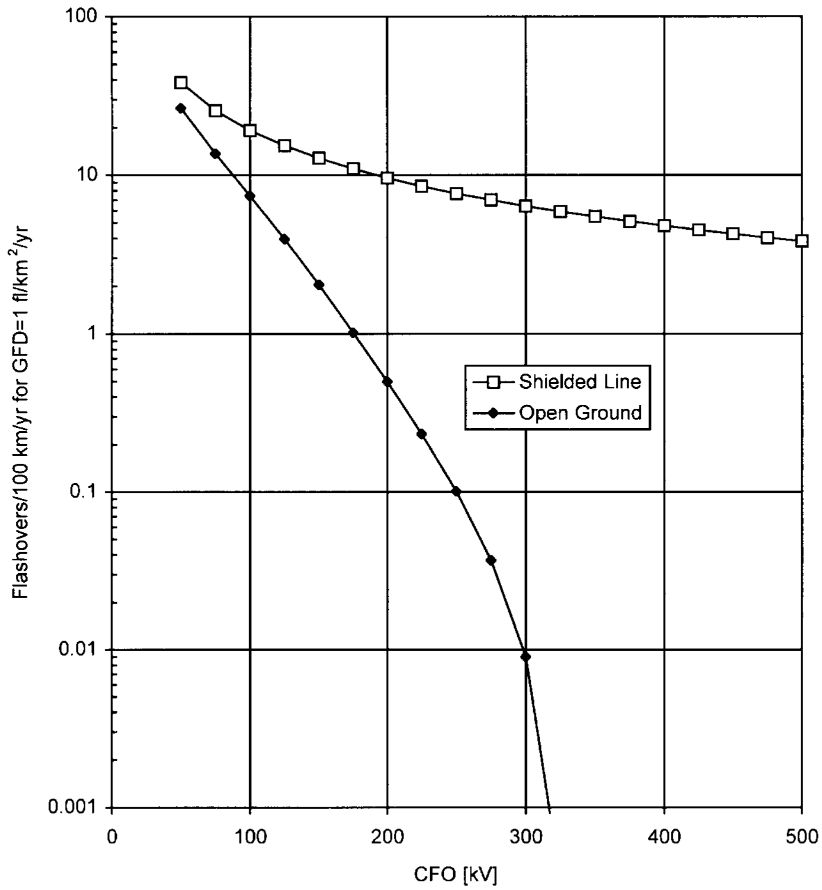

Figure B.2—Induced-voltage flashovers based on the Rusck model for a circuit in open ground and for a circuit shielded by trees and/or buildings

Power-frequency voltages may be ignored. Although this may affect which phase(s) flash over, power-frequency effects will not change the overall flashover rate.

Pole-surge impedance and travel time do not significantly contribute to increased voltages near the front of the wave, due to smaller pole heights. Therefore, pole effects may be ignored.

The simplified model considered is shown in Figure B.3, with adjacent pole grounds modeled. Z_s is the self-surge impedance of the shield wire.

An expression for the voltage, including reflections from adjacent poles, is solved at t = 2 μs as shown in Equation (B.6). The derivation is given in Appendix 12.4 of Anderson [B4] for an analogous problem. The voltage from phase-to-ground across the insulation is equal to $V\ (1 - c_n)$, where c_n is the coupling coefficient.

$$V = \frac{I_R}{2}t\left[Z_I - \frac{Z_w(1-\psi^N)}{1-\psi}\right] + I_R \tau Z_W\left[\frac{(1-\psi^N)}{(1-\psi)^2} - \frac{N\psi^N}{1-\psi}\right] \tag{B.6}$$

$$Z_w = \frac{2R_i^2 Z}{(Z+R_i)^2}\frac{(Z-R_n)}{(Z+R_n)}$$

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$$Z_I = \frac{R_i Z}{Z + R_i}$$

$$\psi = \frac{(Z - R_i)(Z - R_n)}{(Z + R_i)(Z + R_n)}$$

where

N is the largest value that the wave number can reach (the largest whole number ≤ t/2τ).

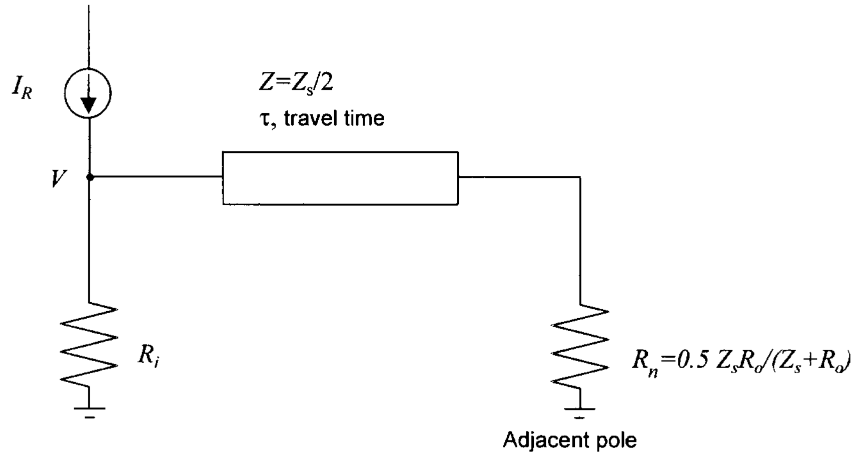

Figure B.3—Simplified model of a direct stroke to a shield wire for distribution lines

A nonlinear ground given by Equation (B.7) is used for the ground of the pole struck (Mousa [B55]), as follows:

$$R_i = \frac{R_o}{\sqrt{1 + i_R/I_g}} \tag{B.7}$$

$$I_g = \frac{E_g \rho}{2\pi R_o^2}$$

$$i_R = I_R \frac{R_o Z}{R_o + Z}$$

where

- R_i is the pole footing resistance that is a function of the current through the footing resistance,
- R_o is the normally measured low-current resistance,
- E_g is the soil ionization gradient, assumed at 300 kV/m (Mousa [B55]),
- ρ is the soil resistivity in Ω-m,
- I_R is the peak stroke current.

Because much less current will flow through the adjacent pole grounds, the low-current resistance, R_o, is used for the adjacent pole grounds.

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At 2 µs, the volt-time insulation curve is assumed to have a turnup of 1.5 times the CFO. This is somewhat lower than the volt-time curve for insulator lengths used in the FLASH model (which is 1.68 times the CFO at 2 µs). This model is iterated to find a critical current used to find a probability of flashover using Equation (4). The remainder of the assumptions for shield-wire modeling are the same as the FLASH model.

For the shield-wire results shown in Figure 8, c_n = 0.35, Z_s = 400 Ω, ρ = 1000 Ω-m, span length = 75 m, and τ = 0.25 µs.

B.4 Arrester spacing

B.4.1 Direct strikes

If a direct lightning strike hits midspan between a pole with arresters and a pole without arresters, the voltage that may develop on the unprotected pole is determined by the separation distance between the lightning strike and the pole with arresters. This is determined by the separation distance to the next pole with arresters (L/2), the arrester-discharge voltage level, V_{IR}, the wave velocity, c (3×10^8 m/s), the line surge impedance, Z_o and the rate of rise of the voltage ($\frac{IZ_o}{2T_f}$ where T_f is the risetime), as shown in Equation (B.8):

$$V = \left(V_{IR} + \frac{L}{c}\frac{IZ_o}{2T_f}\right) \tag{B.8}$$

The peak-stroke current required to cause a flashover may be found by setting V = 1.5 × CFO and solving for I, as shown in Equation (B.9):

$$I_{\text{midspan}} = \frac{2cT_f(1.5 \times CFO - V_{IR})}{LZ_o} \tag{B.9}$$

The 1.5 factor approximates the turnup in the insulation volt-time curve.

Assuming a T_f = 2 µs, CFO = 350 kV, Z_o = 400 Ω, L = 75 m, and V_{IR} = 40 kV, the percentage of flashovers may be calculated by:

I_{midspan} = 19.4 kA

The probability of exceeding this current, given by Equation (4), gives the probability of flashover as

P_{midspan} = 77.2%

If a direct hit strikes a pole with phases not protected by arresters, it is assumed to flashover 100% of the time. If a direct hit strikes a pole protected by arresters, the probability of a flashover at the next pole is determined by the CFO of the unprotected pole and the ground resistance at the pole with arresters, as shown in Equation (B.10):

$$I_{\text{pole}} = \frac{1.5 \times CFO - V_{IR}}{R_o} \tag{B.10}$$

The probability of flashover may be calculated from the critical current I_{pole} with V_{IR} = 40 kV.

If R_o = 25 Ω, and CFO = 150 kV, then

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I_{pole} = 7.4 kA, P_{pole} = 98%

If R_o = 10 Ω, and CFO = 350 kV, then

I_{pole} = 48.5 kA, P_{pole} = 24%

Using the probabilities of a flash-to-poles with arresters, those without arresters, and midspan between poles (assuming 50% of the time it hits midspan), it is possible to create a table of flashovers versus arrester spacing as shown in Table B.1.

Table B.1—Direct-stroke flashovers for different spans to the next arrester

Spans between arresters	Percent flashover R_o = 25 Ω, CFO = 150 kV	Percent flashover R_o = 10 Ω, CFO = 350 kV
1	0	0
2	100	70
3	100	80
4	100	85
Infinite	100	100

With 2 spans between arresters and R_0 = 10 Ω and CFO = 350 kV, use the following to arrive at the number in the table:

Assume: 50% hit midspan (use P_mid = 77.2%), 25% hit a pole with arresters (use P_pole = 24%), 25% hit an unprotected pole (100% of these flash), so

Probability = 0.25 + 0.25 · P_pole + 0.50 · P_mid = (0.25 + 0.25 · 24 + 0.5 · 77.2) = 70%

For 3 spans between arresters use:

3/6 + 1/6 · P_pole + 2/6 · P_mid

For 4, use:

5/8 + 1/8 · P_pole + 2/8 · P_mid

B.4.2 Induced-voltage flashovers

Rusck's model is assumed for voltages induced by nearby lightning. If lightning strikes the ground perpendicular to the location of a pole with arresters, it is assumed that flashovers will not occur. If lightning strikes perpendicular to the location of a pole without arresters, the voltage that develops on that pole will be determined by the separation distance to the next pole with arresters (L), the arrester discharge level (V_{IR}), the wave velocity (c), and the rate of rise of the induced voltage (V_{pk}/T_f), as shown in Equation (B.11):

$$V = V_{IR} + \frac{2LV_{pk}}{T_f c} \quad \text{(B.11)}$$

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The induced voltage required to cause a flashover may be found by setting $V = 1.5 \cdot \text{CFO}$ (the 1.5 is a factor representing the turnup on the volt-time flashover curve), as shown in Equation (B.12):

$$V_{pk} = (1.5 \times CFO - V_{IR})\left(\frac{T_f c}{2L}\right) \qquad \text{(B.12)}$$

If $V_{pk}/1.5$ is used as an equivalent CFO, the number of flashovers per year may be estimated for that pole. This is found by looking up the number of flashovers for a CFO equal to $V_{pk}/1.5$ on the induced-voltage flashover curve (Figure 5, ungrounded curve). For CFO = 150 kV, V_{IR} = 40 kV, T_f = 1 µs, and L = 75 m, the results are given in Table B.2.

Table B.2—Equivalent number of induced flashovers for different spans to the next arrester

Spans until next arrester	Voltage required to cause flashover Vpk (kV)	Equivalent number of flashovers/100 km/yr
0	Infinite	0
1	247	0.11
2	150	1.8
3	150	1.8

By averaging the above numbers for different arrester spacings, the arrester-spacing results shown in Table B.3 are obtained. Even relatively wide arrester spacings perform fairly well (every 300 m cuts flashovers down to 28% of the value without arresters).

Table B.3—Induced flashovers for various arrester spacings (CFO = 150 kV)

Spans between arresters	Number of flashovers/100 km/yr GFD = 1 flash/km^2/yr
1	0
2	0.06
3	0.08
4	0.51
5	0.76
6	0.94
No arresters	1.79

Using a separation distance equation for induced voltages is not correct, since it is not strictly a traveling wave. The inducing fields actually travel from the lightning stroke channel along the hypotenuse of the triangle rather than taking the corner. Voltage starts developing at the adjacent pole before an equivalent traveling wave would have gotten there. This makes the separation distance method more conservative.

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Annex C

(informative)

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