

IEEE Guide for Improving the Lightning Performance of Transmission Lines

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

Keywords: grounding, lightning protection, overhead electric power transmission, shielding

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Introduction

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

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

The methods for estimating the lightning performance of transmission lines show several approaches to a real-life engineering problem that is ill-defined. Precise constants are rarely known and are often not really constant, input data is difficult to describe mathematically except in idealized ways, and outputs may be depictable only by probabilities or average values. By its nature, lightning is difficult to study and model. Lightning transients are so fast that air ionization time constants lead to a time- and waveshape-dependent insulation strength. Lightning peak currents may be ten times higher or lower than the median 31 kA value. Typical ground-flash densities are between 1 and 10 flashes/km², so a typical 100 km long strip of width 20 m should receive 2–20 flashes per year. A transmission line of normal height will receive ten times more flashes because it is tall. Structure footing impedances vary with soil characteristics, flash current, and time. Nonlinear corona and surge response effects change the waveshape and magnitude of stresses. As a further complication, lightning flash density varies widely from year to year and changes with location and season.

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

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

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

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

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

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IEEE Guide for Improving the Lightning Performance of Transmission Lines

1. Overview

1.1 Scope

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

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

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

1.2 Purpose

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

1.3 Disclaimer

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

2. References

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

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

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

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

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

3. Definitions and Acronyms

3.1 Definitions

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

3.2 Acronyms

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

4. Route selection

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

4.1 Lightning frequency of incidence

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

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

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

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

4.2 Route effects

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

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

4.3 Structure height

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

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

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

where

- h is the tower height (m);
- b is the OHGW separation distance (m);
- N_g is the GFD (flashes/km²/yr);
- N_s is the flashes/100 km/yr.

From Equation (1), if the tower height is increased by 20%, the flash rate to the line would increase by 12%. If a measured value of N_g is not available, it may be estimated [B18], [B29] using

$$N_g = 0.04T_d^{1.25} \quad (2)$$

$$N_g = 0.04T_h^{1.1} \quad (3)$$

where

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

T_h is the number of thunderstorm hours/yr.

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

4.4 Soil resistivity

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

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

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

4.5 Adjacent environment

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

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

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

5. Shielding

When lightning strikes a phase conductor, no other object shares in carrying the lightning current. Most flashes to an unprotected phase conductor are therefore capable of producing flashovers. OHGWs may intercept the stroke and shunt the current to the ground through the tower impedance and footing resistance if they are properly located. The resultant voltages across the transmission-line insulation, and the likelihood