

IEEE Application Guide for Surge Protection of Electric Generating Plants

Sponsor
**Surge-Protective Devices Committee
of the
IEEE Power Engineering Society**

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IEEE Standards Board

Abstract: This standard consolidates most electric utility power industry practices, accepted theories, existing standards/guides, definitions, and technical references as they specifically pertain to surge protection of electric power generating plants. Where technical information is not readily available, guidance is provided to aid toward proper surge protection and to reduce interference to communication, control, and protection circuits due to surges and other overvoltages. It has to be recognized that this application guide approaches the subject of surge protection from a common or generalized application viewpoint. Complex applications of surge protection practices may require specialized study by experienced engineers.

Keywords: electric utilities, electric power, electric generating plants, generating plants, power plants, surge protection

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Introduction

(This introduction is not a part of IEEE Std C62.23-1995, IEEE Application Guide for Surge Protection of Electric Generating Plants.)

The need for an application guide for surge protection of electric generating plants was indicated in 1979 when the US Nuclear Regulatory Commission published a draft regulatory guide and value/impact statement entitled, “Lightning Protection for Nuclear Power Plants.”

After meetings between IEEE Surge-Protective Devices Committee members and members of the US Nuclear Regulatory Commission, it was agreed that the task of writing an application guide for the surge protection of electric generating plants would be performed by a specially assigned working group of the IEEE Surge-Protective Devices Committee.

The first function of this working group was to publish a bibliography containing many standards and technical papers pertaining to the protection of all elements inside a power plant complex. The “Bibliography on Power Generating Plants Surge Protection” was published in *IEEE Transactions on Power Delivery*, vol. 6, no. 2, pp. 754–793, April 1991.

The working group also decided that this guide should not only cover nuclear power plants but that the method of surge protection is applicable to nuclear as well as all electric generating plants, and that no special differentiation should be made.

This guide is the result of efforts of the working group over a period of more than ten years. The working group is part of the application of Surge-Protective Devices Subcommittee, sponsored by the Surge-Protective Devices Committee of the IEEE Power Engineering Society. Comments were also solicited from the following groups:

- IEEE Power Engineering Society/Transmission and Distribution Committee
- IEEE Power Engineering Society/Power System Relaying Committee
- IEEE Power Engineering Society/Nuclear Power Engineering Committee
- IEEE Power Engineering Society/Substations Committee
- IEEE Power Engineering Society/Power System Communications Committee
- IEEE Power Engineering Society/Energy Development and Power Generation Committee
- IEEE Power Engineering Society/Electric Machinery Committee
- IEEE Industry Applications Society/Power Systems Engineering Committee

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At the time this guide was completed, the working group on surge protection of generating plants had the following membership:

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At the time this standard was published, it was under consideration for approval as an American National Standard. The Accredited Standards Committee on Surge Arresters, C62, had the following members at the time this document was sent to letter ballot:

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The final conditions for approval of this standard were met on January 18, 1995. This standard was conditionally approved by the IEEE Standards Board on December 13, 1994, with the following membership:

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IEEE Application Guide for Surge Protection of Electric Generating Plants

1. Overview

This application guide consolidates most electric utility power industry practices, accepted theories, existing standards/guides, definitions, and technical references as they specifically pertain to surge protection of electric power generating plants. Where technical information is not readily available, guidance is provided to aid toward proper surge protection and to reduce interference to communication, control, and protection circuits due to surges and other overvoltages. It has to be recognized that this application guide approaches the subject of surge protection from a common or generalized application viewpoint. Complex applications of surge protection practices may require specialized study by experienced engineers.

Surge overvoltages can cause equipment damage, system malfunction, or power interruptions at electric power generating plants if plants are not adequately protected against them. Excessive surge voltages have to, therefore, be controlled or reduced to permissible levels. These overvoltage surges in power generating plants may be generated by lightning or by system events such as switching, faults, load rejections, or by some combinations of these.

The subject of surge protection of power generating plants is very broad and complex, with many ramifications. To provide an understanding for consistent and comprehensive surge protection and to reduce interference, the power generating plant has been divided in this guide into four subareas: the power lines, the switchyard, the power plant, and the remote ancillary systems (see figure 1). Within each subarea, the “surge environment” in which the associated equipment and systems are required to operate is addressed in terms of the common overvoltage and electromagnetic interference sources identified below:

- Direct lightning strokes
- Incoming surges
- Internally generated surges
- Ground potential rise
- Electromagnetic interference

To evaluate each of these sources, the following questions are addressed:

- Is there a surge or interference problem from this source?
- How is surge protection accomplished?
- What standards and guides are available?
- How is surge interference initiated?

A typical power generating plant is illustrated by the one-line diagram in figure 2.

The subareas “switchyard” and “power lines” include the substation equipment, the incoming power and communication lines, and utilization power systems, as well as other plant switchyard systems. The “power plant” subarea includes the power equipment (distribution and utilization) and its associated communication, instrumentation, and protective/control equipment.

The “remote ancillary facilities” subarea includes all equipment pertaining to systems outside the power plant and switchyard, such as fuel handling facilities, the water intake building, the weather tower, outside plant monitoring facilities, etc.

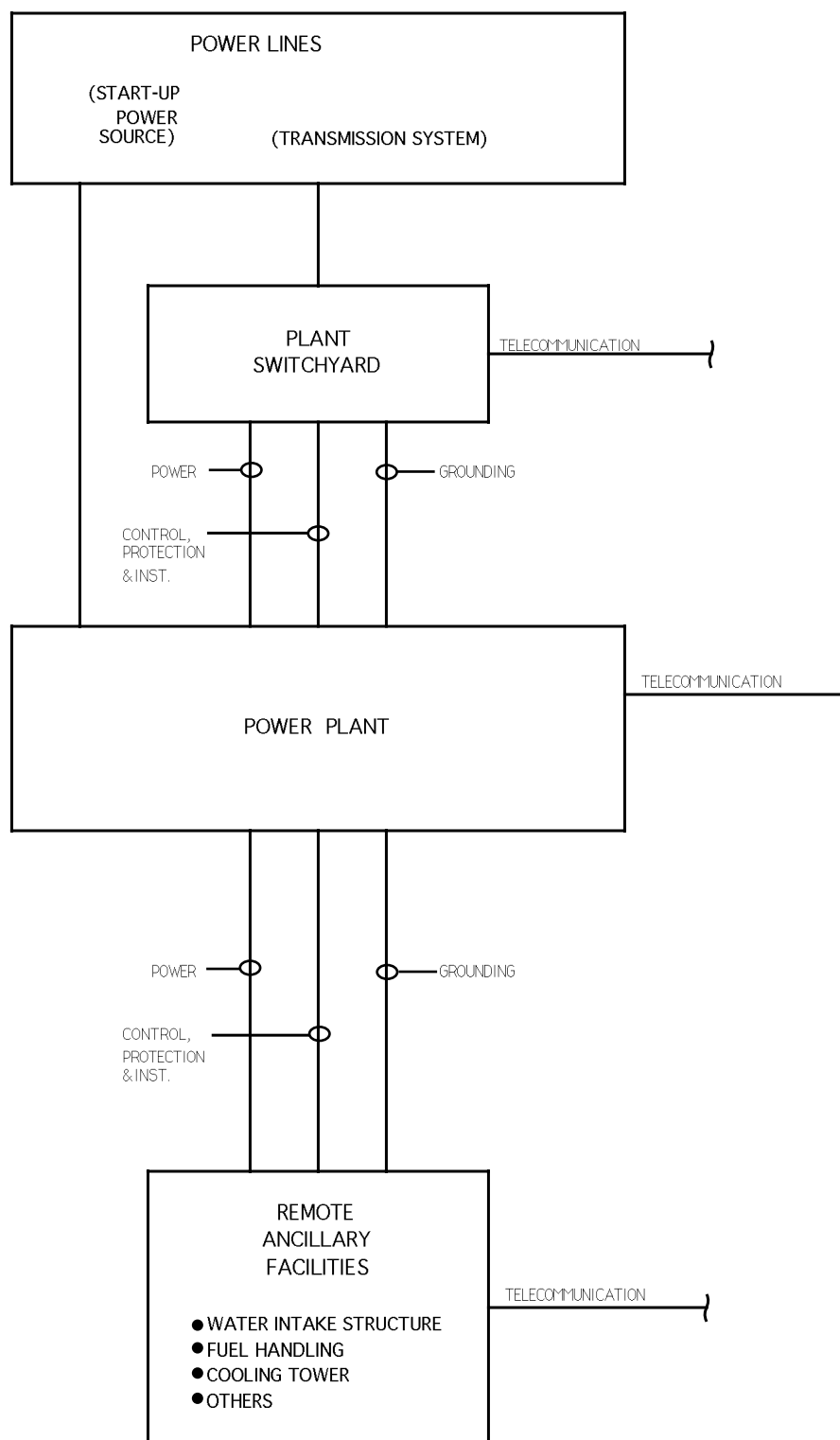


Figure 1—Power generating plant block diagram

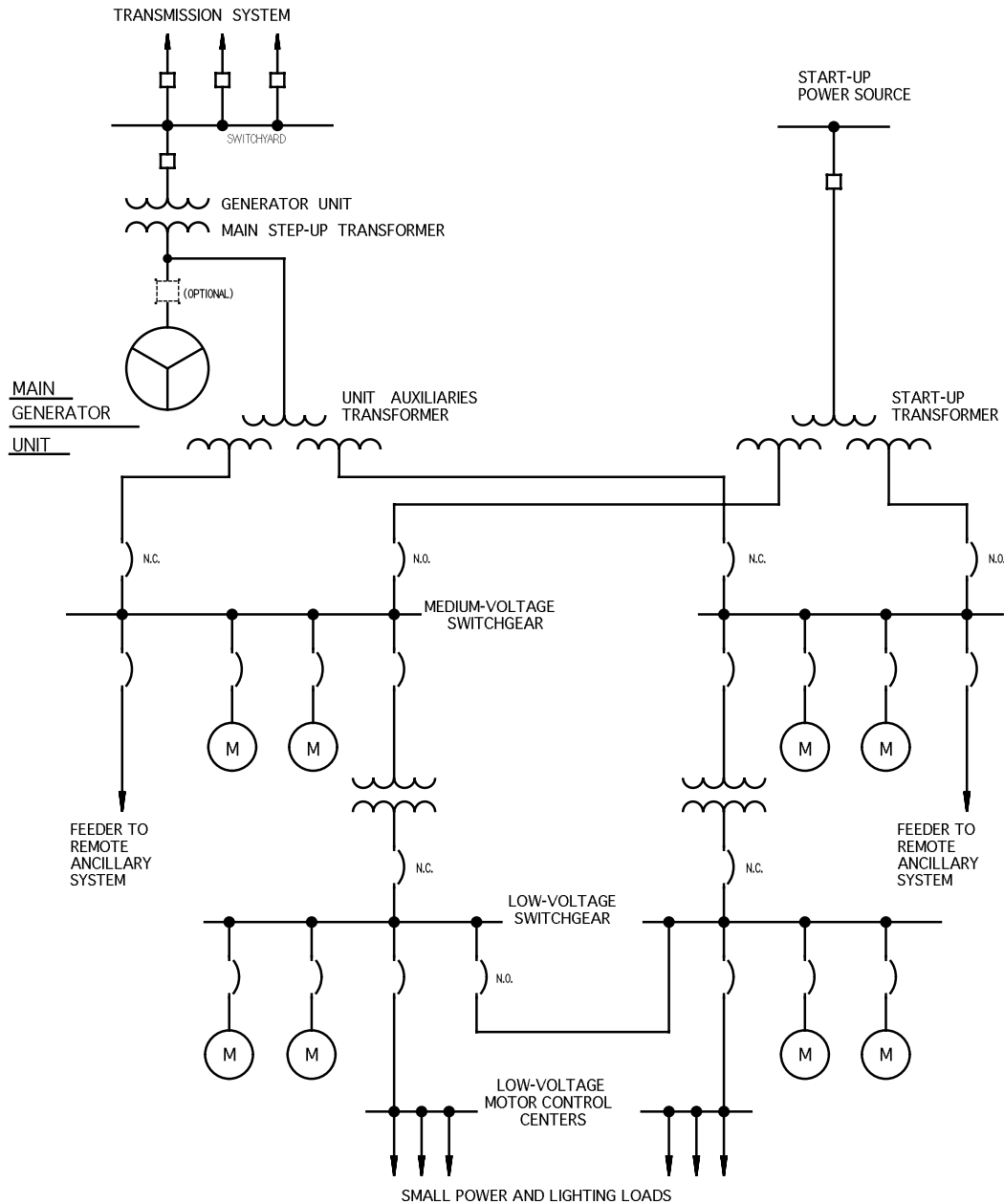


Figure 2—Power generating plant simplified one-line diagram

2. References

This guide shall be used in conjunction with the listed references applicable to the electrical system to be protected.

Accredited Standards Committee (ASC) C2-1993, National Electrical Safety Code.¹

ANSI C62.61-1993, American National Standard for Gas Tube Surge Arresters on Wire Line Telephone Circuits.

ANSI/NFPA 70-1993, National Electrical Code.²

ANSI/NFPA 780-1992, Lightning Protection Code.

IEEE Std 18-1992, IEEE Standard for Shunt Power Capacitors (ANSI).³

IEEE Std 141-1993, IEEE Recommended Practice for Electric Power Distribution for Industrial Plants (IEEE Red Book) (ANSI).

IEEE Std 142-1991, IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems (IEEE Green Book) (ANSI).

IEEE Std 367-1987, IEEE Recommended Practice for Determining the Electric Power Station Ground Potential Rise and Induced Voltage from a Power Fault (ANSI).

IEEE Std 368-1977, IEEE Recommended Practice for Measurement of Electrical Noise and Harmonic Filter Performance of High-Voltage Direct-Current Systems.⁴

IEEE Std 384-1992, IEEE Standard Criteria for Independence of Class 1E Equipment and Circuits.

IEEE Std 487-1992, IEEE Recommended Practice for the Protection of Wire Line Communications Facilities Serving Electric Power Stations (ANSI).

IEEE Std 518-1982 (Reaff. 1990), IEEE Guide for the Installation of Electrical Equipment to Minimize Noise Inputs to Controllers from External Sources (ANSI).

IEEE Std 519-1992, IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems (ANSI).

IEEE Std 525-1992, IEEE Guide for the Design and Installation of Cable Systems in Substations.

IEEE Std 643-1980 (Reaff. 1992), IEEE Guide for Power-Line Carrier Applications (ANSI).

IEEE Std 665-1987, IEEE Guide for Generating Station Grounding.⁵

IEEE Std 776-1992, IEEE Recommended Practice for Inductive Coordination of Electric Supply and Communication Lines (ANSI).

IEEE Std 1050-1991, IEEE Guide for Instrumentation and Control Equipment Grounding in Generating Stations (ANSI).

¹ASC C2-1993 is available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA..

²NFPA publications are available from Publications Sales, National Fire Protection Association, 1 Batterymarch Park, P.O. Box 9101, Quincy, MA 02269-9101, USA.

³IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

⁴IEEE Std 368-1977 has been withdrawn; however, copies can be obtained from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

⁵IEEE Std 665-1987 has been withdrawn; however, copies can be obtained from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

IEEE Std 1100-1992, IEEE Recommended Practice for Powering and Grounding Sensitive Electronic Equipment (IEEE Emerald Book) (ANSI).

IEEE Std 1143-1994, IEEE Guide on Shielding Practice for Low Voltage Cables.

IEEE Std C37.90-1989, IEEE Standard Relays and Relay Systems Associated with Electric Power Apparatus (Section 9, Surge Withstand Capability (SWC) Tests, and Appendix A) (ANSI).

IEEE Std C37.90.1-1989, IEEE Standard Surge Withstand Capability (SWC) Tests for Protective Relays and Relay Systems (ANSI).

IEEE Std C37.90.2-1987, IEEE Trial-Use Standard Withstand Capability of Relay Systems to Radiated Electromagnetic Interference from Transceivers (ANSI).

IEEE Std C37.99-1990, IEEE Guide for the Protection of Shunt Capacitor Banks (ANSI).

IEEE Std C37.109-1988 (Reaff. 1993), IEEE Guide for the Protection of Shunt Reactors (ANSI).

IEEE Std C57.13.3-1983 (Reaff. 1991), IEEE Guide for the Grounding of Instrument Transformer Secondary Circuits and Cases (ANSI).

IEEE Std C57.110-1986 (Reaff. 1992), IEEE Recommended Practice for Establishing Transformer Capability When Supplying Nonsinusoidal Load Currents (ANSI).

IEEE Std C62.22-1992, IEEE Guide for the Application of Metal-Oxide Surge Arresters for Alternating Current Systems (ANSI).

IEEE Std C62.33-1982 (Reaff. 1994), IEEE Standard Test Specifications for Varistor Surge-Protective Devices (ANSI).

IEEE Std C62.35-1987 (Reaff. 1993), IEEE Standard Test Specifications for Avalanche Junction Semiconductor Surge Protective Devices.

IEEE Std C62.36-1994, IEEE Standard Test Methods for Surge Protectors Used in Low-Voltage Data, Communications, and Signaling Circuits (ANSI).

IEEE Std C62.41-1991, IEEE Recommended Practice on Surge Voltages in Low-Voltage AC Power Circuits (ANSI).

IEEE Std C62.42-1992, IEEE Guide for the Application of Gas Tube Arrester Low-Voltage (Equal to or less than 100 Vrms or 1200 Vdc) Surge-Protective Devices (ANSI).

IEEE Std C62.47-1992, IEEE Guide on Electrostatic Discharge (ESD)—Characterization for the ESD Environment (ANSI).

NEMA ICS 1-1993, General Standards for Industrial Control and Systems.⁶

NEMA ICS 2-1993, Controllers, Contactors, and Overload Relays, Rated Not More Than 2000 Volts AC or 750 Volts DC.

NEMA ICS 3-1993, Factory Built Assemblies.

⁶NEMA publications are available from the National Electrical Manufacturers Association, 2101 L Street NW, Suite 300, Washington, DC 20037, USA.

3. Definitions

3.1 back flashover: 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 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 system of the towers or poles supporting the line.

3.3 coupling factor: The ratio of the induced voltage to the inducing voltage on parallel conductors.

For example, at the tower, the shield or coupling wires and tower crossarms are at practically the same potential (because of lightning stroke travel time). The stress across the insulator string is one minus the coupling factor multiplied by the tower top potential.

$$\text{Stress} = (1.0 - K_{fc}) \times V_{TT} \quad (1)$$

where

K_{fc} is the coupling factor
 V_{TT} is the tower top voltage

3.4 coupling wire: A conductor attached to the transmission line structure and below the phase wires, with proper clearance, and connected to the grounding system of the towers or the pole supporting the line.

3.5 ground potential rise: The voltage that a station grounding grid may attain relative to a distant grounding point assumed to be at the potential of remote earth.

3.6 overhead groundwire (lightning protection): 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.

3.7 remote earth (potential): The location outside the influence of local grounds. Always assumed to be at zero potential.

3.8 shielding angle: The angle between a vertical line through the overhead ground wire and a line connecting the overhead ground wire to the shielded conductor.

3.9 shield wire (electromagnetic fields): A wire employed to reduce the effects on electric supply or communication circuits from extraneous sources.

3.10 GPR: Acronym for **ground potential rise**. See: 3.5.

4. Power lines

4.1 Scope

The purpose of this clause is to guide the reader in understanding the nature of surges that can enter the power plant premises via transmission and distribution lines and to indicate methods to reduce their magnitudes. Overvoltage surges resulting from lightning strokes and line switching may stress the insulation of

power plant equipment, circuits, and systems. This provides information for evaluating line conditions as they affect the surges that may enter the switchyard and power plant.

4.2 Protection of transmission lines

Incoming surges to the switchyard or power plant can result from direct lightning strokes to the transmission lines, back flashovers, or switching surges initiated at remote substations and traveling on the transmission lines. Surges induced by nearby strokes usually do not exceed (and in any case are limited by) the withstand strength of the transmission line insulation (see [B4], [B30], and [B56]).⁷

A transmission line design involves the use of risk analysis technology to achieve a design that produces a level of performance suitable for its mission. Insulation coordination factors that have to be considered in the design are: switching surges, impulses caused by lightning, and the reduction of electrical strength caused by contamination of the insulators. Effects of insulator contamination are described in [B8]. The surge voltages, rather than the normal operating voltage, determine the transmission line insulation requirements. Lines can be designed to give a desired lightning performance by the proper use of overhead groundwires and a suitable combination of line insulation and tower footing resistance. Switching surge performance is determined primarily by the line insulation, which is selected to withstand a reasonably severe switching surge caused by line switching or reclosing. The objective is to determine each element in the line design to obtain the desired balance between performance and cost. The insulation design for any particular line will depend on its location, which determines the lightning exposure, and on system design, which determines the magnitude of switching surges (see [B103]).

The insulation design for a high-voltage (HV) or an extra-high-voltage (EHV) line may be dominated by either the switching surge or lightning requirements. For an ultra-high-voltage (UHV) line, switching surge is the dominant factor. Switching surges usually establish the insulation required on transmission lines 345 kV and above. Lightning surges may control the insulation design in areas of high ground resistance, high lightning incidence, or where use of breaker closing resistors or shunt reactors minimize switching surge amplitudes. In most cases, it is not advisable arbitrarily to neglect one or the other type of transient. Both need careful consideration (see [B103]).

4.2.1 Direct lightning strokes

Protection of a transmission line against lightning is dependent on (see [B20])

- Overhead groundwires located to shield the line conductors from direct lightning strokes
- Adequate clearance from the line conductor to ground points at the structure
- Clearance from the line conductor to the overhead groundwires at midspan
- Tower footing resistance, which should be as low as economically justified
- Number of overhead groundwires to be used
- Wave shape and magnitude of the stroke current (statistical quantities), and the resulting surge voltages on the phase and overhead groundwires
- Tower height and phase conductor configuration and spacing
- Span length
- Keraunic level of the area in which the transmission line is operating

Organizations have developed generalized curves for estimating the lightning performance of transmission lines from 69 kV to 800 kV. The American Institute of Electrical Engineers (AIEE) method applies to systems of 230 kV and below, while the IEEE, Edison Electric Institute (EEI), and Electric Power Research Institute (EPRI) methods deal with the higher voltage lines and their taller structures (see [B1], [B4], [B10], and [B103]).

⁷The numbers in brackets preceded by the letter B correspond to those in the bibliography in annex B.

With proper line design, flashovers of transmission lines due to lightning can be limited to about one per 161 km (100 miles) per year. One objective of line design for lightning performance is to reduce the impulse voltage across the line insulation to a value below the impulse flashover voltage of that insulation so that line outages are reduced. This will also reduce the magnitude of surges entering the switchyard. A suitable combination of line insulation and tower footing resistance minimizes line flashovers that result from lightning stroke currents. It is impractical, however, to provide sufficiently high impulse insulation levels to withstand the voltage developed when a phase conductor is struck by any but weak lightning strokes. An overhead groundwire is therefore used, where necessary, to improve the lightning performance by shielding the phase conductors from a direct lightning stroke and to divert the stroke currents to ground, as shown in figure 3.

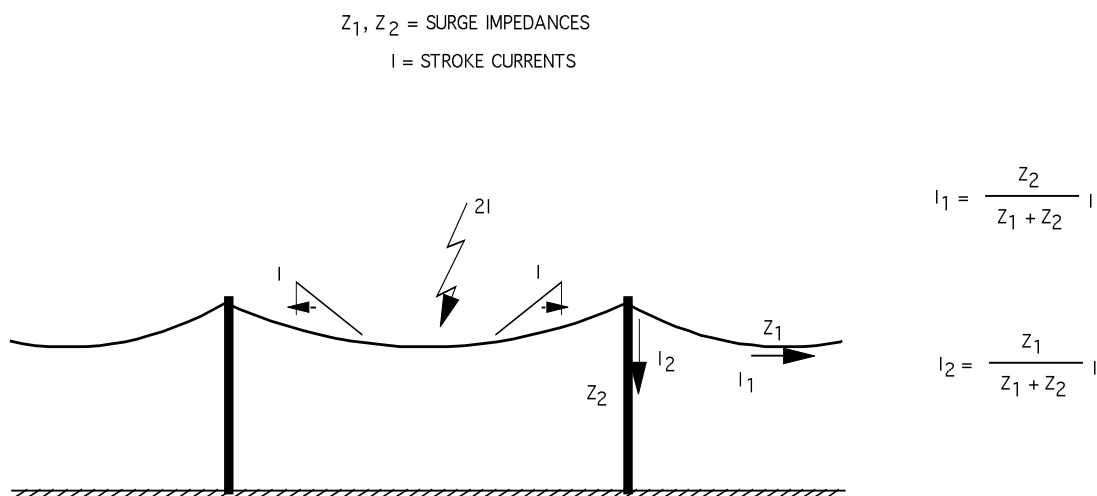


Figure 3—Stroke current diverted to ground

The different means of protection used to improve the line performance against lightning strokes is explained briefly in the following subclauses. The referenced material provides more detailed explanations (see [B1], [B4], [B10], [B47], [B49], [B56], [B87], and [B103]).

4.2.1.1 Overhead groundwires and coupling wires

Wires connected near the top of line structures or towers and properly located above the phase conductors provide shielding against lightning strokes. Shielding failures may occur, and line flashovers may occur if the voltage impressed on the line is greater than the critical flashover voltage (CFO) of the line insulation (see [B82]). Field data (see [B26] and [B62]) were published as the result of an EEI research project, “The Mechanism of Lightning” or “Pathfinder Project.” This project determined that insulator flashovers occur as the result of direct strokes to phase conductors; from shielding failures; and as the result of strokes to the tower or overhead groundwire(s), causing the back flashovers. Even with low tower footing resistance, the shielding failure mechanism predominates where large shielding angles and high towers exist. Back flash-over events predominate when high tower footing resistances are associated with low insulation levels and low tower heights.

For those lines participating in the “Pathfinder Project,” which demonstrated superior lightning performance, the average height of the overhead groundwire versus the average shielding angle formed with a phase conductor were plotted. Based on this field data, the plot shown in figure 4 was suggested as the design curve for selecting shielding angles to provide good lightning performance (see [B27]).

Shielding failure curves based on field data were reported in 1964 (see [B87]). The curves (figure 5) show the probability of shielding failures for a given stroke to a line as a function of tower height and shielding angle. The shielding angle curve of figure 4 would then provide shielding failure probabilities of less than

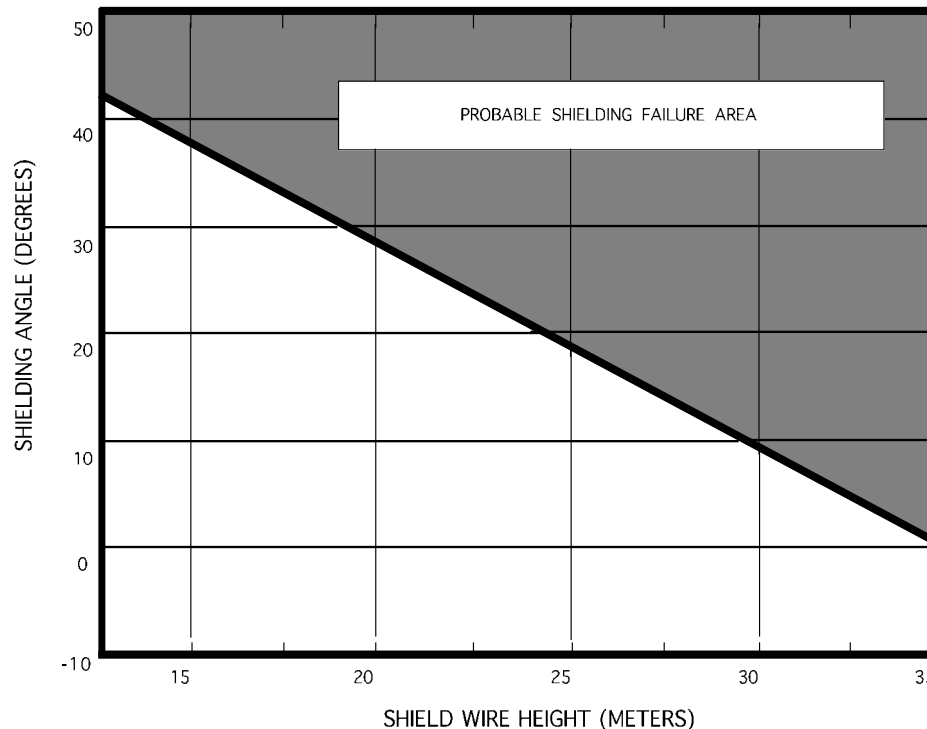


Figure 4—A guide for EHV line shielding angles proposed by Armstrong and Whitehead

0.01 based on the curves in figure 5. This is less than one shielding failure for every 100 strokes terminating on the overhead groundwire.

For double-circuit steel structures up to 42.7 m (140 ft) high (see figure 5), one overhead groundwire over each set of power conductors provides near-perfect shielding. In addition, the two wires lower the surge impedance to the lightning stroke, dissipating a greater portion of the stroke current along these wires to remote towers and a lesser portion down the nearby structures. The tower-top potentials will be lowered with two wires. The coupling factor is improved with two overhead groundwires versus one by approximately 20% for a 30.5 m (100 ft) steel pole. Adding a second overhead groundwire reduces overall outage rates by 30–35%; reduction in double-circuit outages of greater than 40% have been experienced (see [B40] and [B52]).

When double-circuit steel transmission structures are used, both circuits may be susceptible to tripouts caused by the same lightning stroke. Experience has shown that rates as high as 50% of tripouts, caused by lightning, can involve both circuits (see [B28], [B51], and [B52]). The rate depends on line design and tower footing resistance. To reduce the vulnerability of a line to tripouts, it is necessary to either reduce the potential of the tower struck, reduce the tower-to-conductor potential gradient, or both. The former is accomplished by the use of multiple overhead groundwires and a buried counterpoise. This results in a lower surge impedance to the lightning stroke current than the single overhead groundwire and, therefore, a lower tower potential for a given stroke current. Multiple overhead groundwires also reduce the tower-to-conductor potential gradient due to closer proximity and better coupling with the phase conductor than with a single overhead groundwire.

Better lightning performance can also be achieved by installing a coupling wire under the phase conductors. The phase conductors are thus essentially surrounded by conductors at tower potential. Coupling is as high

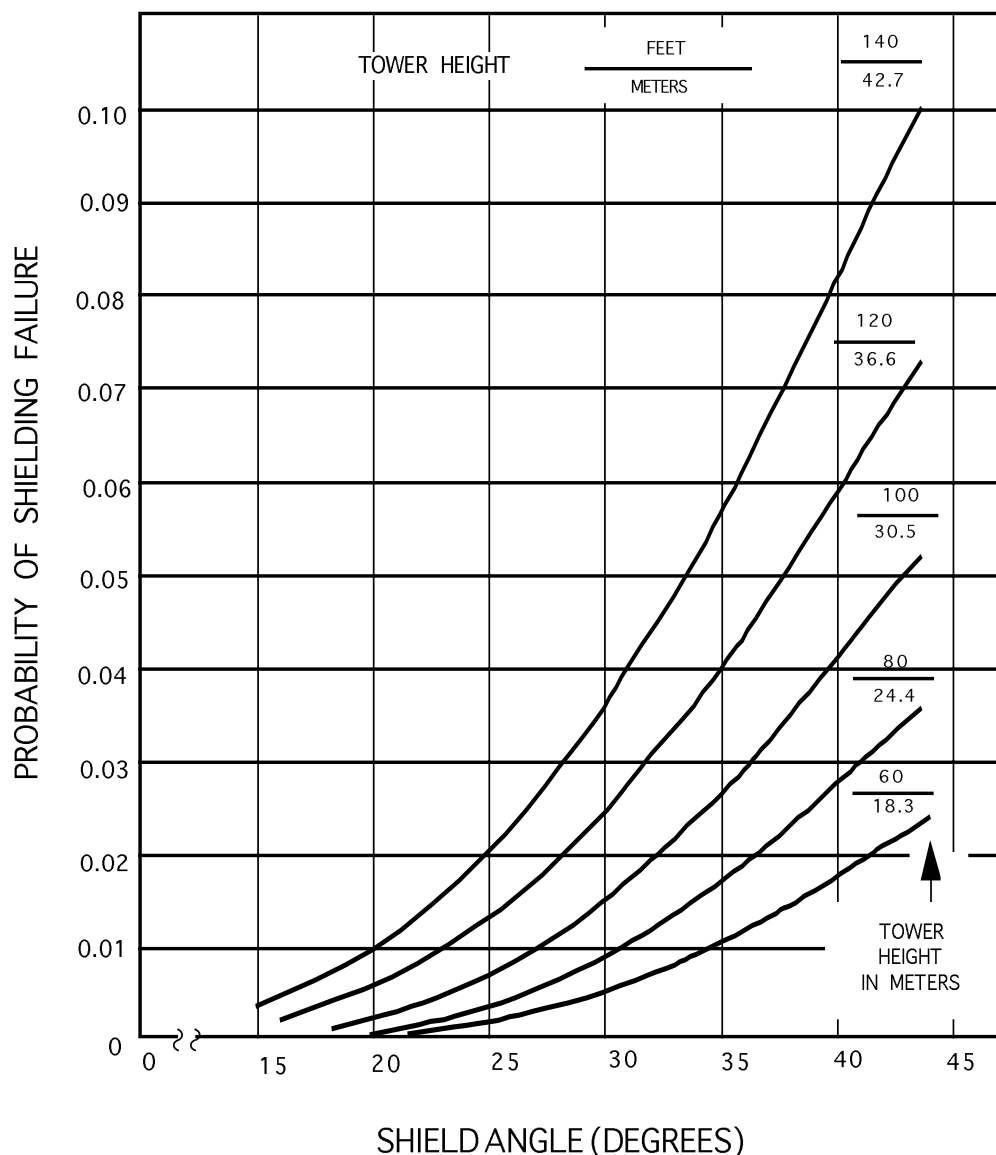


Figure 5—Probability of shielding failure versus shielding angle between grounds

as possible, and insulation stress is as low as possible. To improve reliability of the two circuits further and to decrease the probability of both circuits flashing over, it may be desirable to increase the insulation level of one circuit to a point where the other normally insulated circuit is most likely to flash over.

The merits of a ground (coupling) wire located under the phase conductors and overhead groundwires were discussed in [B83]. The improvement in coupling is calculated to be approximately 30% for the top phase and 80% for the bottom phase. Following a stroke to the structure or shield wires, increased coupling lowers the potential difference between phase conductors and grounded wires by raising the percentage of the ground wire potential impressed on the phase conductor. The result is less surge voltage stress across the insulation and less likelihood of flashover for a given stroke current.

The improvement in bottom-phase coupling is important for double-circuit steel structures. Indications are that the bottom phase is usually involved in double-circuit flashovers. It was calculated that without a cou-