

Understanding Direct Lightning Stroke Shielding of Substations

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**PSERC Seminar
Golden, Colorado
November 6, 2001**

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Understanding Direct Lightning Stroke Shielding of Substations

Presentation Outline:

- ☐ **Lightning Stroke Fundamentals**
- ☐ **Surge Protection and Surge Arresters**
- ☐ **Design Parameters**
- ☐ **Design Problem**
- ☐ **Design Methods**
- ☐ **Conclusions**

Main Reference

Recognized as an
American National Standard (ANSI)

IEEE Std 998-1996

IEEE Guide for Direct Lightning Stroke Shielding of Substations

Circuits and Devices

Communications Technology

Computer

*Electromagnetics and
Radiation*

IEEE Power Engineering Society

Sponsored by the
Substations Committee

Industrial App

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Committees*

IEEE Std 998-1996



Published by the Institute of Electrical and Electronics Engineers, Inc., 345 East 47th Street, New York, NY 10017, USA.

20 December 1996

SH94442

IEEE Std. 998 - 1996

Lightning Stroke Fundamentals (1)

Several Theories have been advanced regarding the:

- ❑ Formation of charge centers
- ❑ Charge separation within a cloud
- ❑ Ultimate development of lightning strokes

Types of Lightning Strokes:

- ❑ Strokes within clouds
- ❑ Strokes between adjacent clouds
- ❑ Strokes to tall structures
- ❑ Strokes terminating on the ground



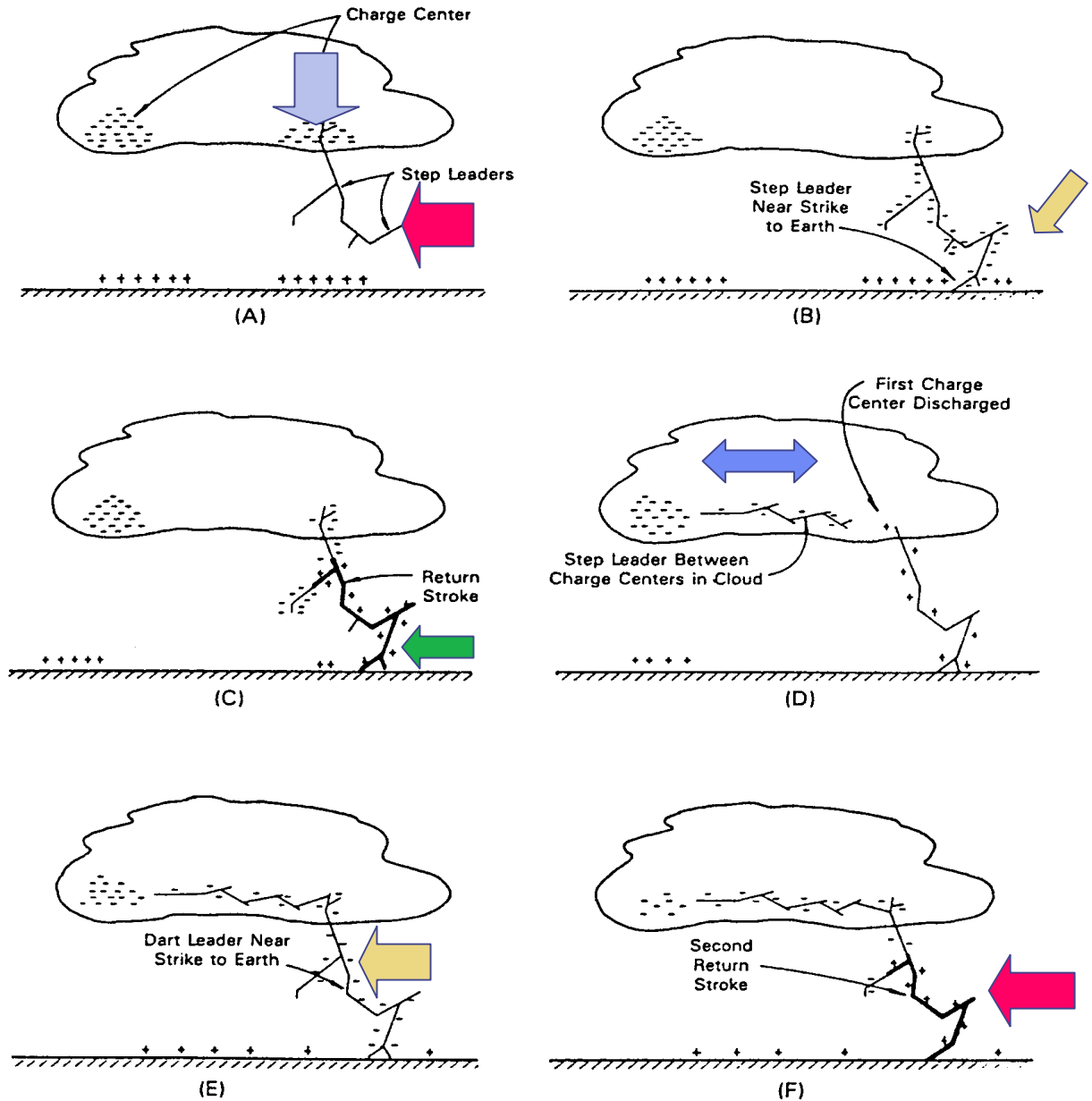
Lightning Stroke Fundamentals (2)

Stroke Development: (Two-Step Process)

1. Ionization (Corona breakdown) of the air surrounding the charge center and the development of “**Stepped Leaders.**”
2. Development of a lightning stroke called “**Return Stroke.**” The total discharge of current from a thundercloud is called a “**Lightning Flash.**”

Lightning Stroke Phenomena

Charge Distribution at Various Stages of Lightning Discharge



Adapted from: *Electrical Transmission and Distribution Reference Book*, by Central Station Engineers of the Westinghouse Electric Corporation, East Pittsburgh, Pennsylvania, Fourth Edition, 1964.

Ref: IEEE Std. 998-1996 (Figure 2-2)

Lightning Stroke Fundamentals (3)

Three Issues:

1. Usually the stroke consists of **negative charge** flowing from cloud to earth.
2. More than half of all lightning flashes consist of **multiple (subsequent) strokes**.
3. Leaders of subsequent strokes are called **Dart Leader**.

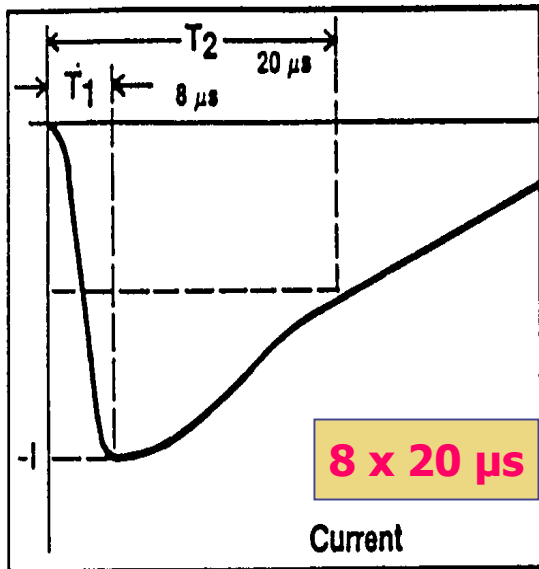
Effects of Direct Stroke on Substation

Assumptions: No Shielding and No Surge Protective Devices.

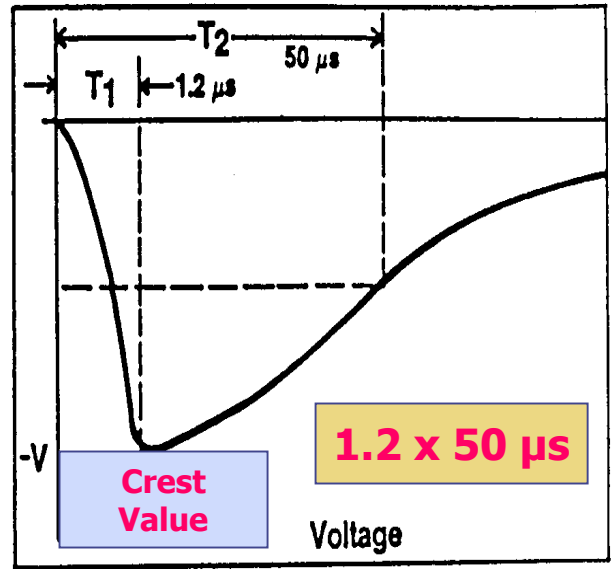
- **Possible Insulation Flashover (depends primarily on the stroke current magnitude)**
- **Damage (and possible failure) to Major Substation Equipment**
- **Substation Outage**
- **Cost**

Use of Direct Stroke Shielding and Surge Arresters to Minimize the Possibility of Damage of Equipment and Outage.

Surge Protection and Surge Arresters (1)



A



B

T_1 : Rise Time

T_2 : Time to Half value

**Standard Current and Voltage
Waveshapes to Define
Lightning for Laboratory Tests**

Surge Protection and Surge Arresters (2)

- **Standard Lightning Voltage Test Wave:**
1.2 x 50 μ sec
- **Standard Lightning Current Test Wave:**
8 x 20 μ sec
- **BIL (Basic Impulse Insulation Level):**
A specified insulation level expressed (in kV) as the crest value of a **standard** lightning impulse.
- **CFO (Critical Flashover Voltage):** Voltage (**negative**) impulse for a disruptive discharge around or over the surface of an insulator. BIL is determined statistically from the CFO tests.
- **Arrester Classes (Defined by Tests):**
 - **Distribution (Standard & Heavy Duty)**
 - **Intermediate**
 - **Station**

Surge Protection and Surge Arresters (3)

Metal Oxide Varistors (MOVs) **Important Characteristics:**

- **Maximum Continuous Operating Voltage (MCOV)**
- **Temporary Over Voltage (TOV)**
- **Lightning Discharge Voltage (IR)**
- **Protective Level: Maximum Crest Value of voltage that appears across its terminals under specified conditions.**
- **Volt-Time Characteristics**

Surge Protection and Surge Arresters (4)

Protective Margins:

Three Protective Margins (PMs) are normally calculated.

$$\text{PM}(1) = [(\text{CWW}/\text{FOW}) - 1] \times 100\%$$

$$\text{PM}(2) = [(\text{BIL}/\text{LPL}) - 1] \times 100\%$$

$$\text{PM}(3) = [(\text{BSL}/\text{SPL}) - 1] \times 100\%$$

Where:

CWW: Chopped Wave Withstand

FOW: Front-of-Wave

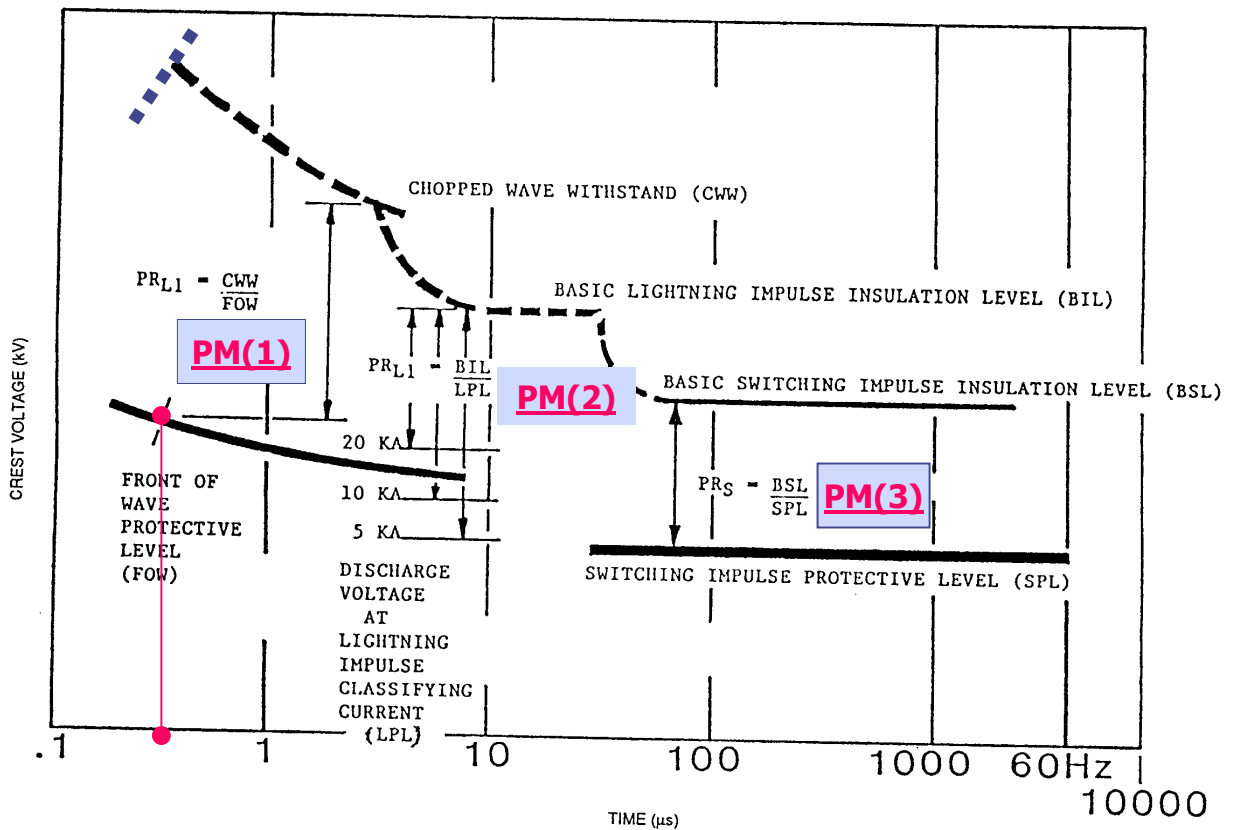
BIL: Basic Lightning Impulse Insulation Level

LPL: Lightning Impulse Classifying Current
(Also Called IR: Lightning Discharge Voltage)

BSL: Basic Switching Impulse Insulation Level

SPL: Switching Impulse Protective Level

Surge Protection and Surge Arresters (5)



Insulation Coordination

Ref: IEEE Std. C62.22-1991

Surge Protection and Surge Arresters (6)

Lead Length Voltage:

- For **standard** lightning surge current test waves (8 x 20 μ s) the value is approx. 1.6 kV/ft.
- For **actual** lightning current this value is between 6-10 kV/ft.

$$v(t) = L \frac{di(t)}{dt}$$

$$L = 0.4 \mu\text{H/ft.}$$

Effects of Direct Stroke on Substation

Assumptions:

Provide both Shielding and Surge Arresters.

- 1. Minimize the possibility of direct lightning strike to bus and/or major equipment in the substation and hence, the outage and possible failure of major electrical equipment.**
- 2. Shielding may allow some smaller strokes to strike the buswork and equipment. Even though these strokes may not cause flashover, they may damage internal insulation systems of transformers, etc., unless they have proper surge arresters mounted at their terminals.**

Effects of Direct Stroke on Substation

Assumptions:

Provide both Shielding and Surge Arresters (contd.).

- 3. Surge arresters will provide coordinated protection from lightning and switching surges for the internal insulation of power transformers, etc.**
- 4. Arresters cannot effectively absorb very large stroke currents (arresters may fail, or discharge voltage become too high).**
- 5. Arresters may not protect all of the buswork from lightning flashover, due to distance effect.**
- 6. Lightning shielding can reliably intercept the large strokes, and can generally protect buswork from lightning flashover.**

Design Parameters

- ☐ **Ground Flash Density (GFD)**
- ☐ **Stroke Current**
- ☐ **Strike Distance**

Design Parameters

Ground Flash Density (GFD)

Ground Flash Density (GFD): The average number of lightning strokes per unit area per unit time (year) at a particular location.

Approximate Relationships:

$$N_k = 0.12 T_d$$

$$N_m = 0.31 T_d$$

or

$$N_k = 0.054 T_h^{1.1}$$

$$N_m = 0.14 T_h^{1.1}$$

Where,

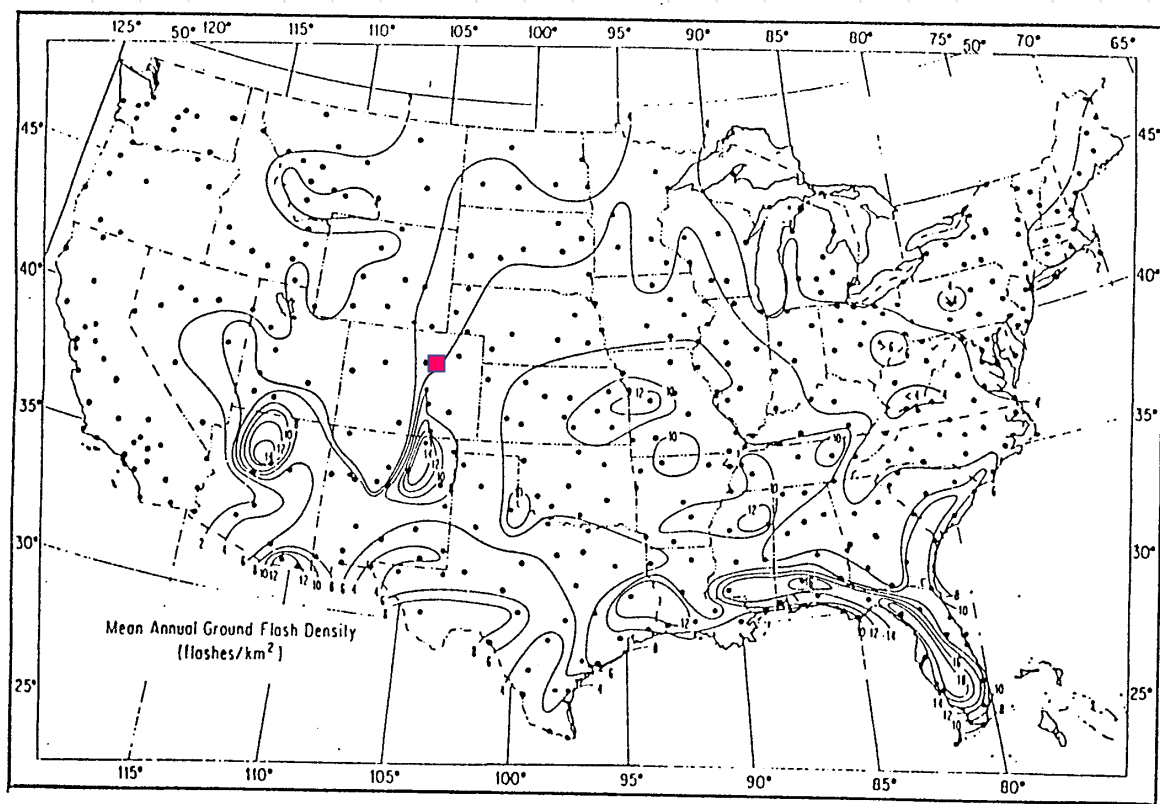
N_k = No. of Flashes in Earth per sq. km

N_m = No. of Flashes in Earth per sq. mile

T_d = Average Annual "keraunic level"
(thunderstorm-days)

T_h = Average Annual "keraunic level"
(thunderstorm-hours)

Mean Annual Ground Flash Density (GFD)



GFD (Flashes/km²/Year)

Denver, Colorado
GFD = 6 Flashes/km²/year

Mean Annual Ground Flash Density

Denver, Colorado

Thunderstorm-days (T_d) = 42

Thunderstorm-hours (T_h) = 70

$$\begin{aligned}(\text{GFD}) N_k &= 0.12 T_d \\ &= 0.12 \times 50 = 6\end{aligned}$$

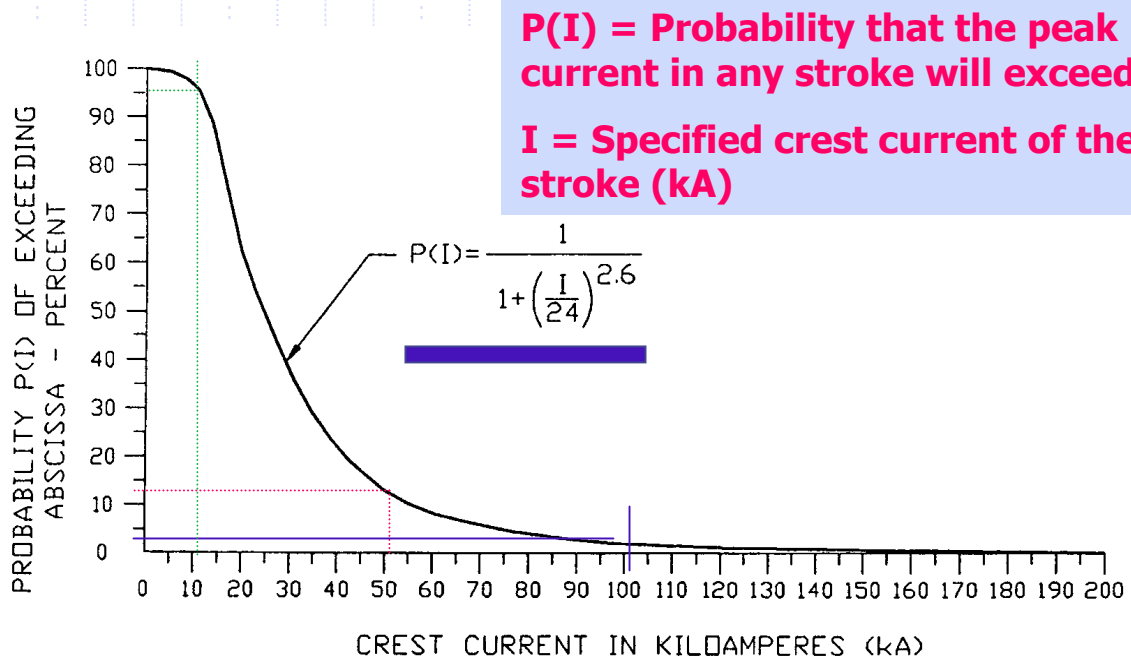
$$(\text{GFD}) N_k = 0.054 T_h^{1.1} = 5.8$$

From the Graph, (GFD)

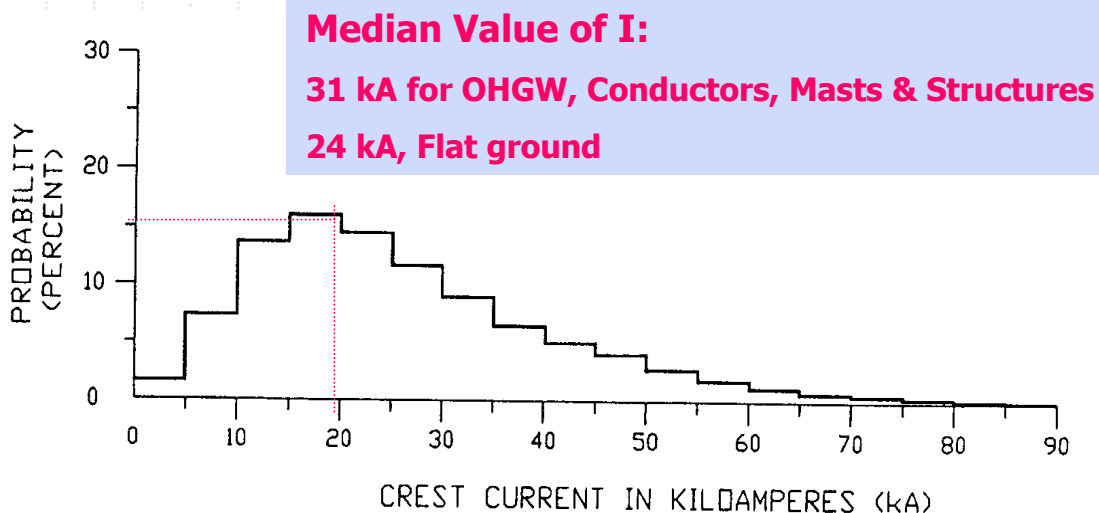
$$N_k = 6/\text{km}^2/\text{year}$$

(Compare to the value of 2 on NW corner of Colorado and a Value of 18 in Central Florida)

Stroke Current Magnitude and Distribution



Probability of Stroke Current Exceeding Abcissa for Strokes to Flat Ground



Stroke Current Range Probability for Strokes to Flat ground

Ref. IEEE Std. 998-1996

Design Parameters

Strike Distance

$$\begin{aligned} S_m &= 8 (k) I^{0.65} && (\text{m}) \\ S_f &= 26.25 (k) I^{0.65} && (\text{ft}) \\ I &= 0.041 S_m^{1.54} && (\text{kA}) \end{aligned} \quad \text{or}$$

Where,

S_m = Strike Distance in (meters)

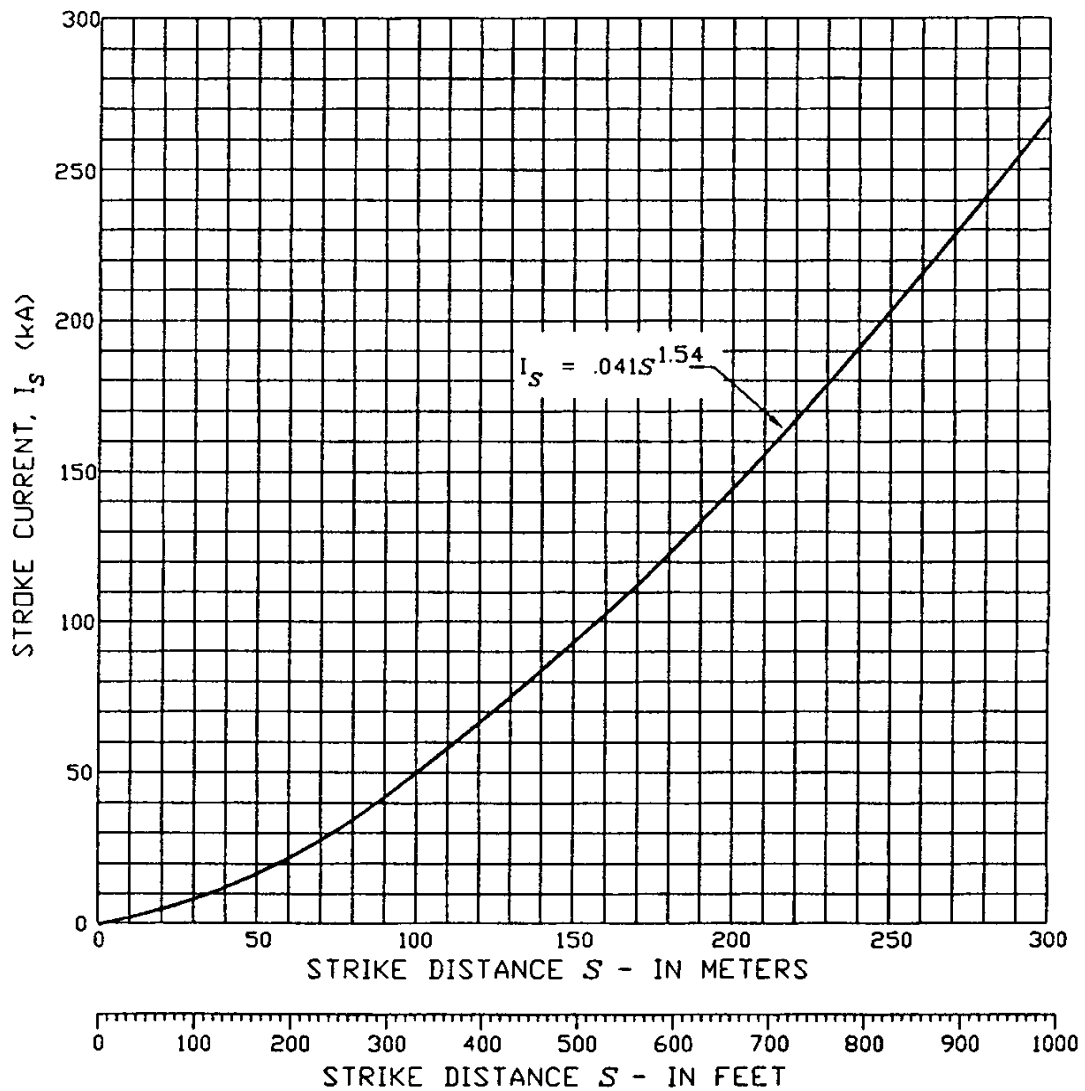
S_f = Strike Distance in (ft)

I = Return Stroke Current in (kA)

k = Constant (Introduced in Revised Model)
= 1, for strokes to wires or ground plane
= 1.2, for strokes to a lighting mast

Strike Distance is the length of the final jump (last step) of the stepped leader as its potential exceeds the breakdown resistance of this last gap; found to be related to the amplitude of the first return stroke.

Strike Distance vs. Stroke Current



Ref: IEEE Std. 998-1996

Design Problem

- ❑ Probabilistic nature of lightning
- ❑ Lack of data due to infrequency of lightning strokes in substations
- ❑ Complexity & economics involved in analyzing a system in detail
- ❑ No known practical method of providing 100% shielding
- ❑ **Lower Voltage (69 kV and Below) Facilities:**
Simplified Rules of Thumb
- ❑ **EHV (345 kV and Above) Facilities:**
Sophisticated (EGM) Study

Design Problem

Four-Step Approach:

- ❑ Evaluate the importance & value of the facility being protected and probable consequences of a direct lightning strike (**Risk Assessment**).
- ❑ Investigate the severity & frequency of thunderstorms in the area of the substation facility and the exposure of the substation.
- ❑ Select an appropriate design method (**shielding and SA's**).
- ❑ Evaluate the **effectiveness and cost** of the design.

Design Methods

(Commonly Used)

1. Empirical (Classical) Design

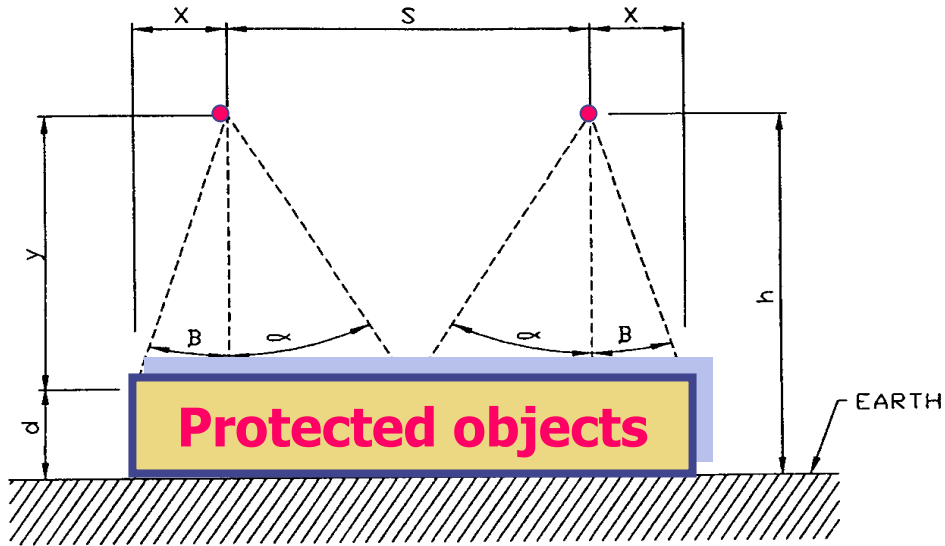
- a. Fixed Angles**
- b. Empirical Curves**

2. Electro-Geometric Model (EGM)

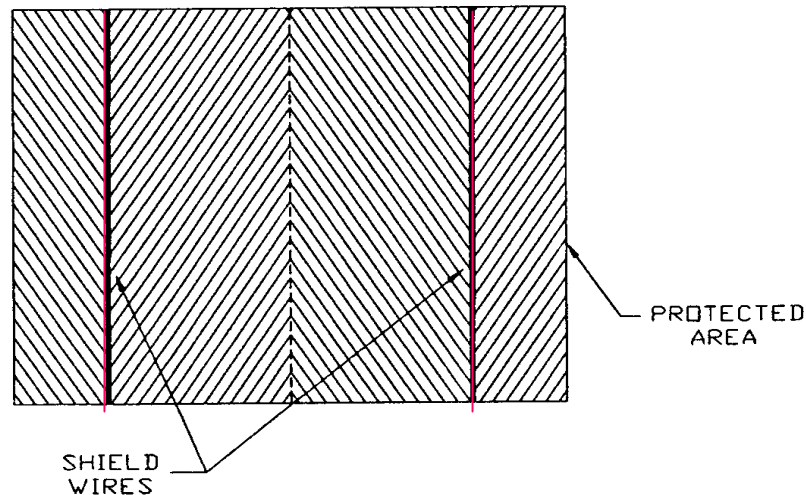
- a. Whitehead's EGM**
- b. Revised EGM**
- c. Rolling Sphere**

Fixed Angles Method (1)

(Examples)



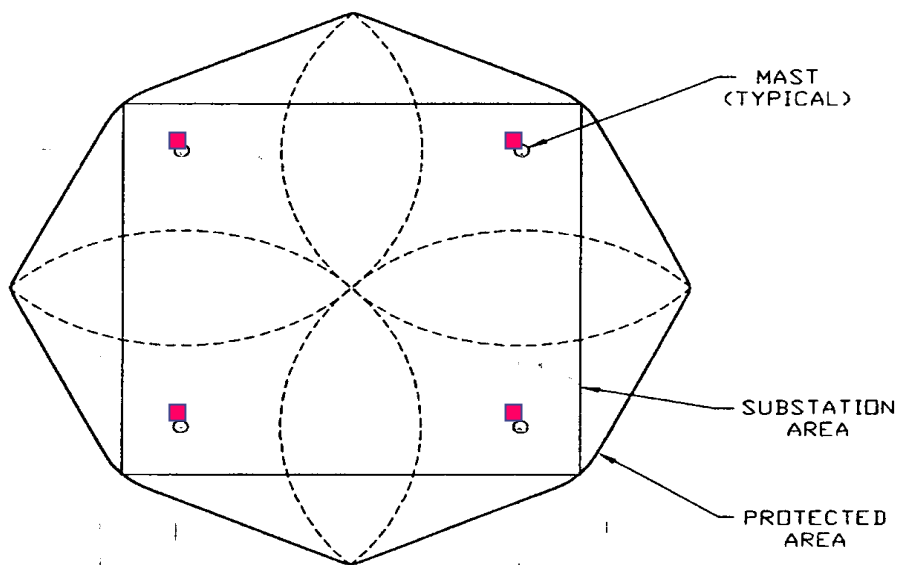
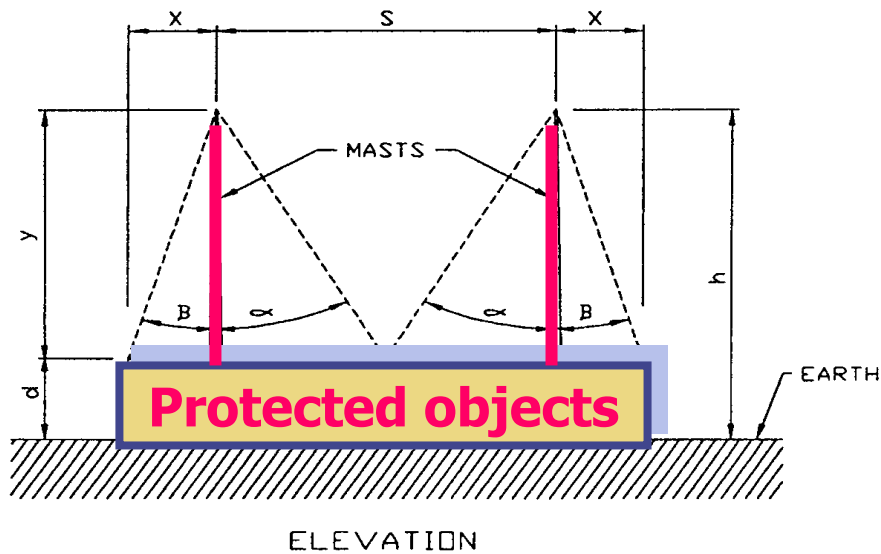
ELEVATION



Fixed Angles for Shielding Wires

Fixed Angles Method (2)

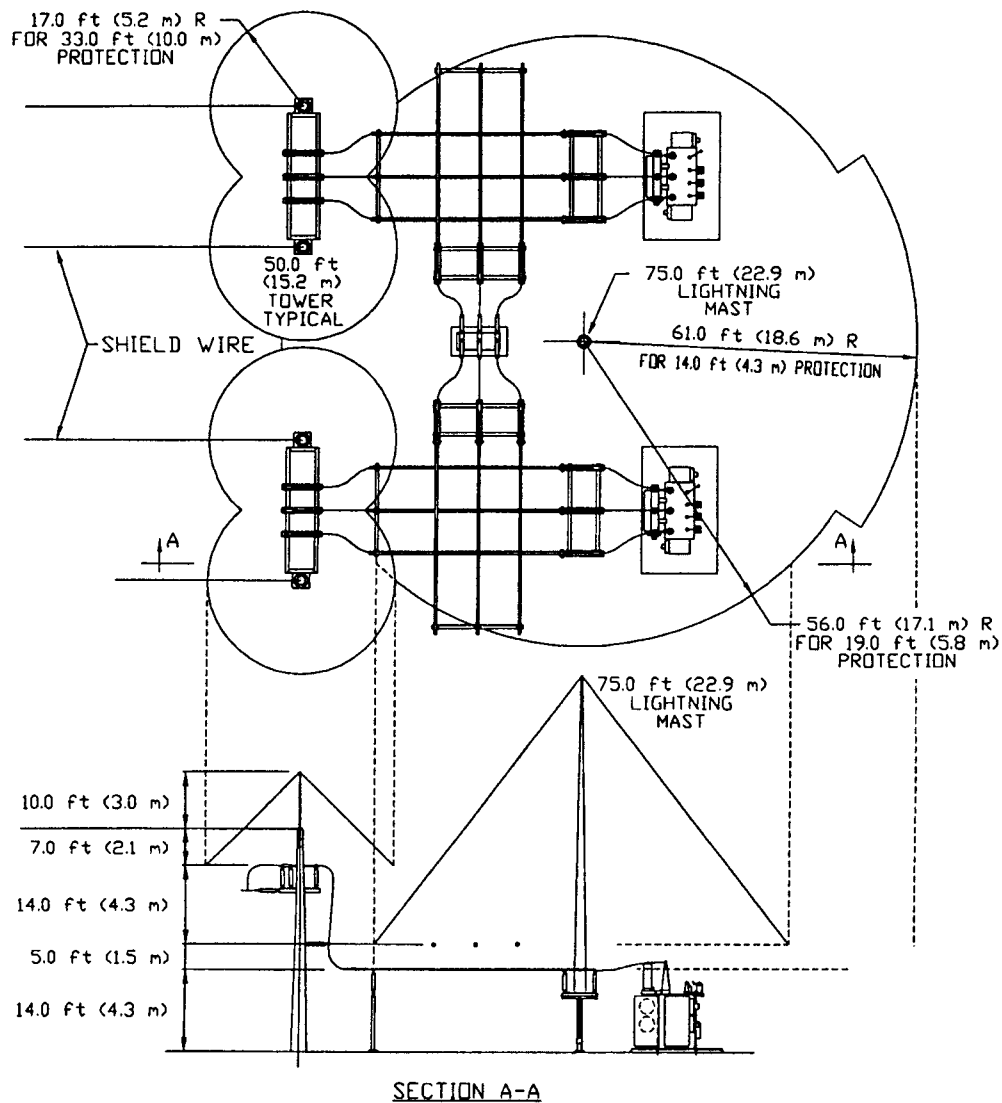
(Examples)



Fixed Angles for Masts

Fixed Angle Methods (3)

(Examples)



Shielding Substation with Masts Using Fixed Angle Method (Ref: IEEE 998, Fig. B.2-3)

Fixed Angles Method (4)

(Summary)

- 1. Commonly used value of the angle "alpha (α)" is 45°.**
- 2. Both 30° and 45° are widely used for angle "beta (β)".**

- 3. Notes:**
 - Independent of Voltage, BIL, Surge Impedance, Stroke Current Magnitude, GFD, Insulation Flashover Voltage, etc.**
 - Simple design technique and easy to apply.**
 - Commonly used in REA Distribution Substation design.**
 - Has been in use since 1940's.**
 - For 69 kV and below produces very good results.**

Empirical Curve Method (1)

Developed in 1940's (Experimental):

Assumptions:

- 1. All lighting strokes propagate vertically downward.**
- 2. The station is in a flat terrain.**
- 3. Thunderstorm cloud base is at 1000 ft. above ground.**
- 4. Earth resistivity is low.**

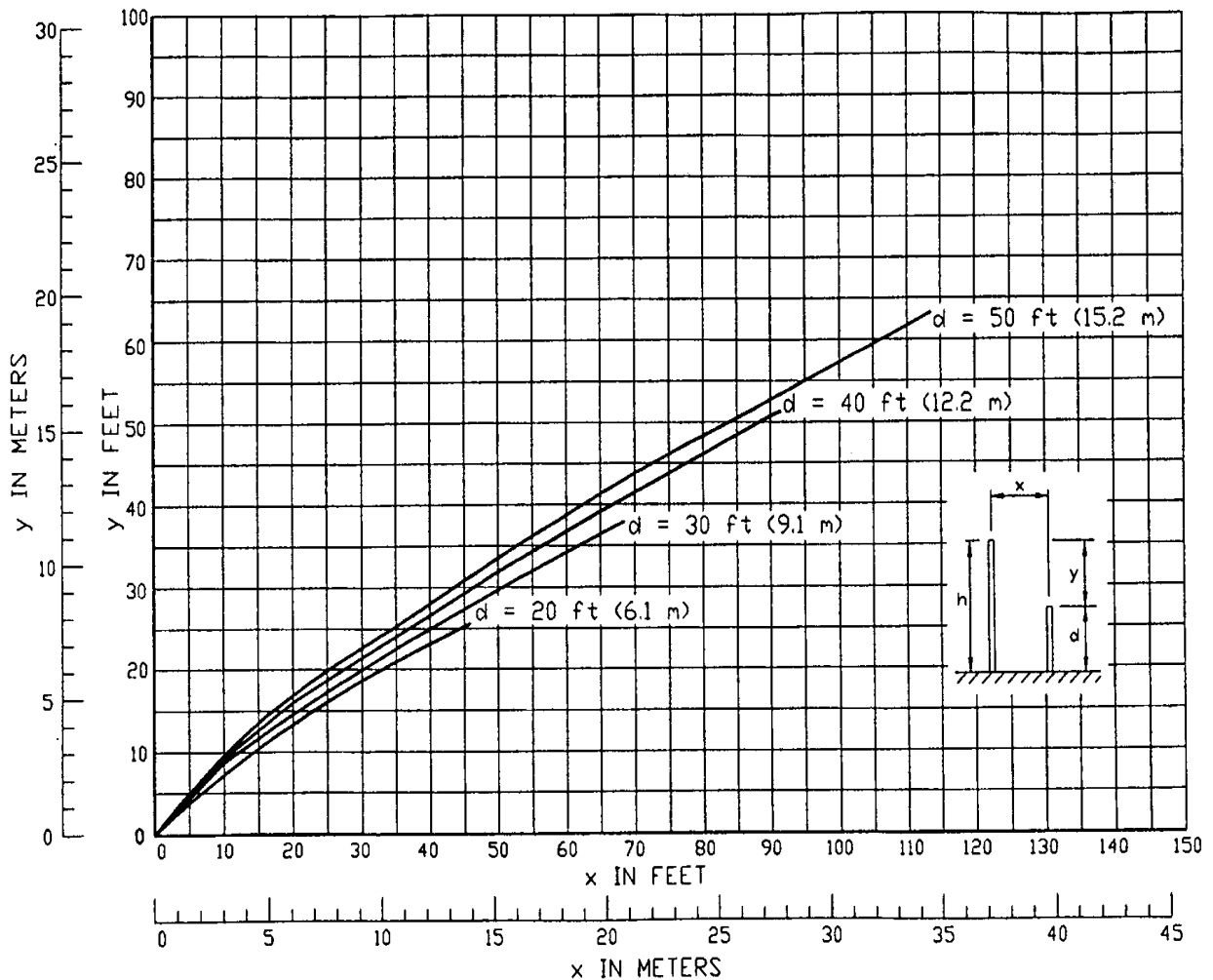
Empirical Curve Method (2)

Assumptions (contd.):

5. Based on “Scale Model” Tests.
6. Independent of Voltage Level.
7. Depends on the geometric relationship between the shield (or mast), the equipment, and the ground.
8. Independent of Insulation Level, Surge Impedance, Stroke Current Magnitude, and the Probability of Lightning Occurrence.
9. Designed for different shielding failure rates. A failure rate of 0.1% is commonly used.

Empirical Curve Methods (3)

(Examples)

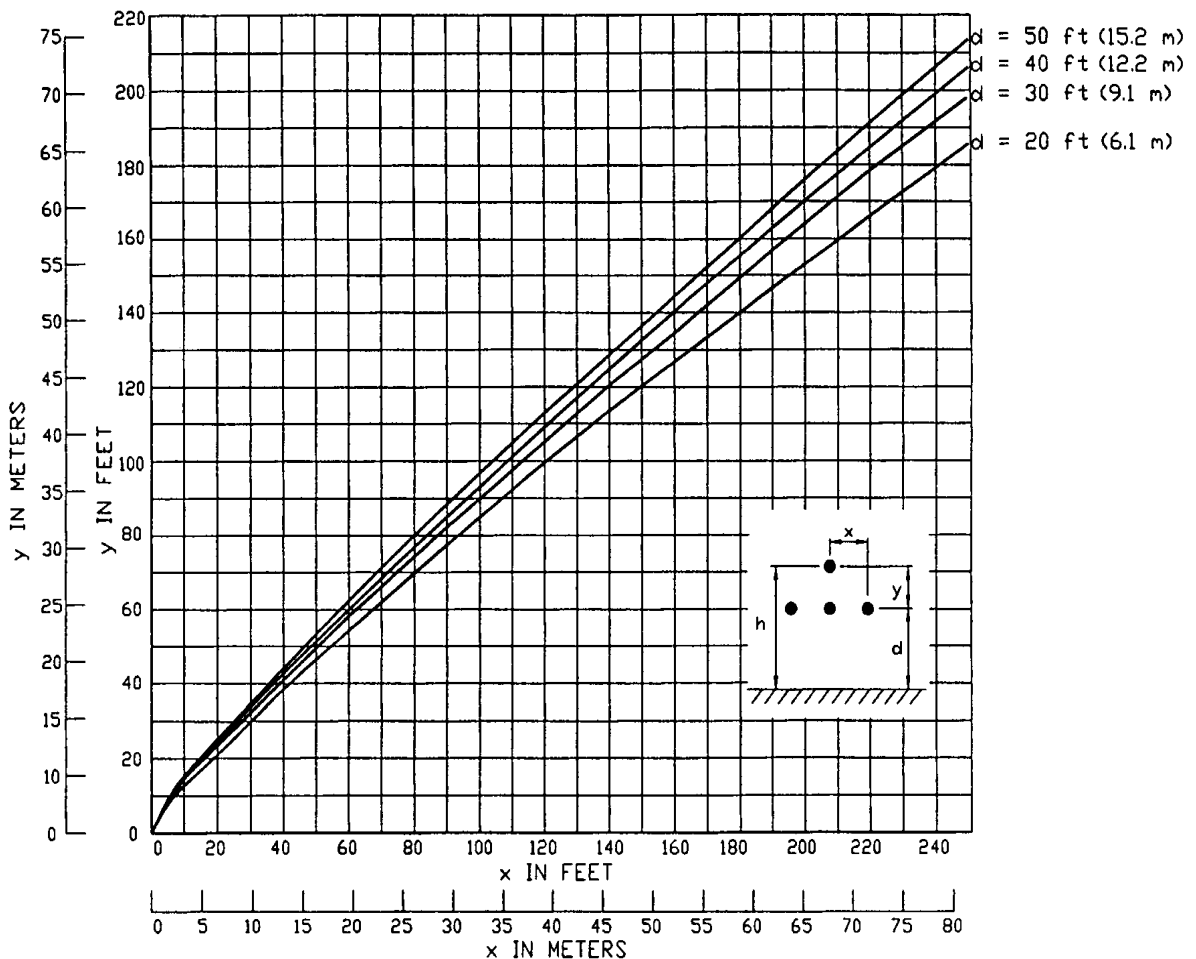


Single Mast Protecting Single Object

Derived from the Original Curves
published by Westinghouse Researchers

Empirical Curve Methods (4)

(Examples)



Single Shield Wire Protecting Horizontal Conductors

Derived from the Original Curves
published by Westinghouse Researchers

Empirical Curve Methods (5)

Summary :

- 1. Developed Experimentally in 1940's.**
- 2. Limited Applications Capabilities.**
- 3. Modified Curves Developed in the IEEE Std. 998-1996.**
- 4. Not Very User Friendly, Time Consuming and Used by Very Few.**
- 5. Not Recommended Design Practice for EHV Substations.**

Electrogeometric Method (1)

- 1. Whitehead's EGM Model**
- 2. Revised EGM Model**
- 3. Rolling Sphere Method**

Assumptions:

- a. The stroke is assumed to arrive in a vertical direction.**
- B. The differing strike distance (value of "k") to masts, wires, and the ground plane are taken into considerations.**

Electrogeometric Method (2)

(Recommended EHV Transmission Substation and Switching Station)

Allowable Stroke Current:

$$I_s = \frac{BIL \times 1.1}{\left(\frac{Z_s}{2}\right)} = \frac{2.2 (BIL)}{Z_s}$$

Or

$$I_s = \frac{0.94 \times CFO \times 1.1}{\left(\frac{Z_s}{2}\right)} = \frac{2.068 (CFO)}{Z_s}$$

Where,

I_s = Allowable Stroke Current in kA

**BIL = Basic Lightning Impulse Level
in kV**

**CFO = Negative Polarity Critical Flashover
Voltage of the Insulation in kV**

**Z_s = Surge Impedance of the Bus System
in Ohms**

Electrogeometric Method (3)

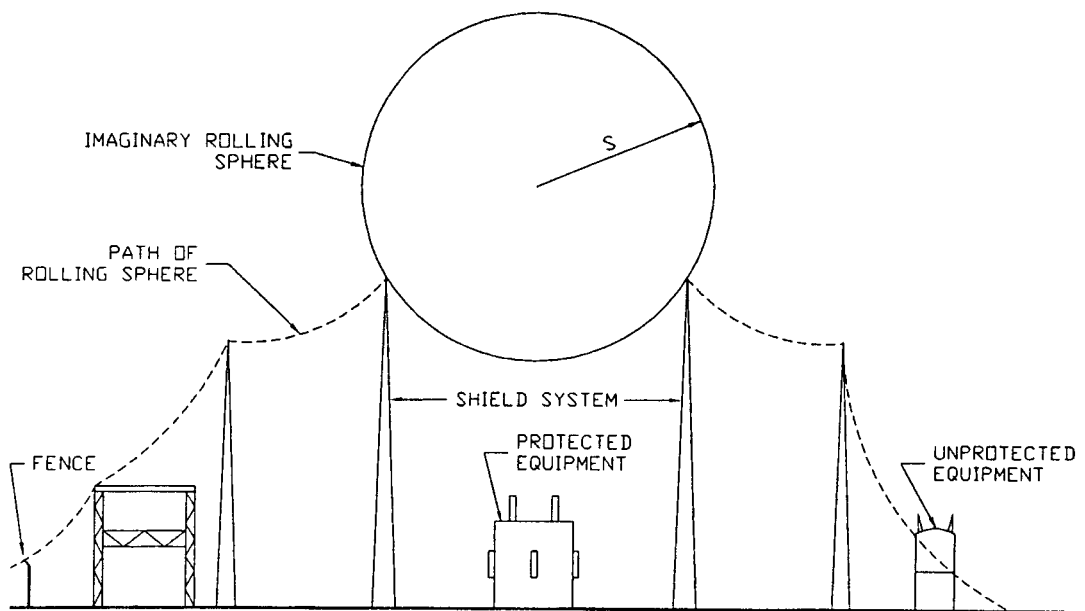
**(EHV Transmission Substation
and Switching Station)**

Procedure:

- 1. Calculate Bus Surge Impedance Z_s from the Geometry. For two heights, use the higher level heights.**
- 2. Determine the Value of CFO (or BIL). For higher altitude use correction factor for BIL.**
- 3. Calculate the Value of I_s .**
- 4. Calculate the Value of the Striking Distance (or Radius of the Rolling Sphere)**
- 5. Use Two or more Striking Distance Values based on BIL Voltage Levels in a Substation with two different voltages.**

Electrogeometric Method (4)

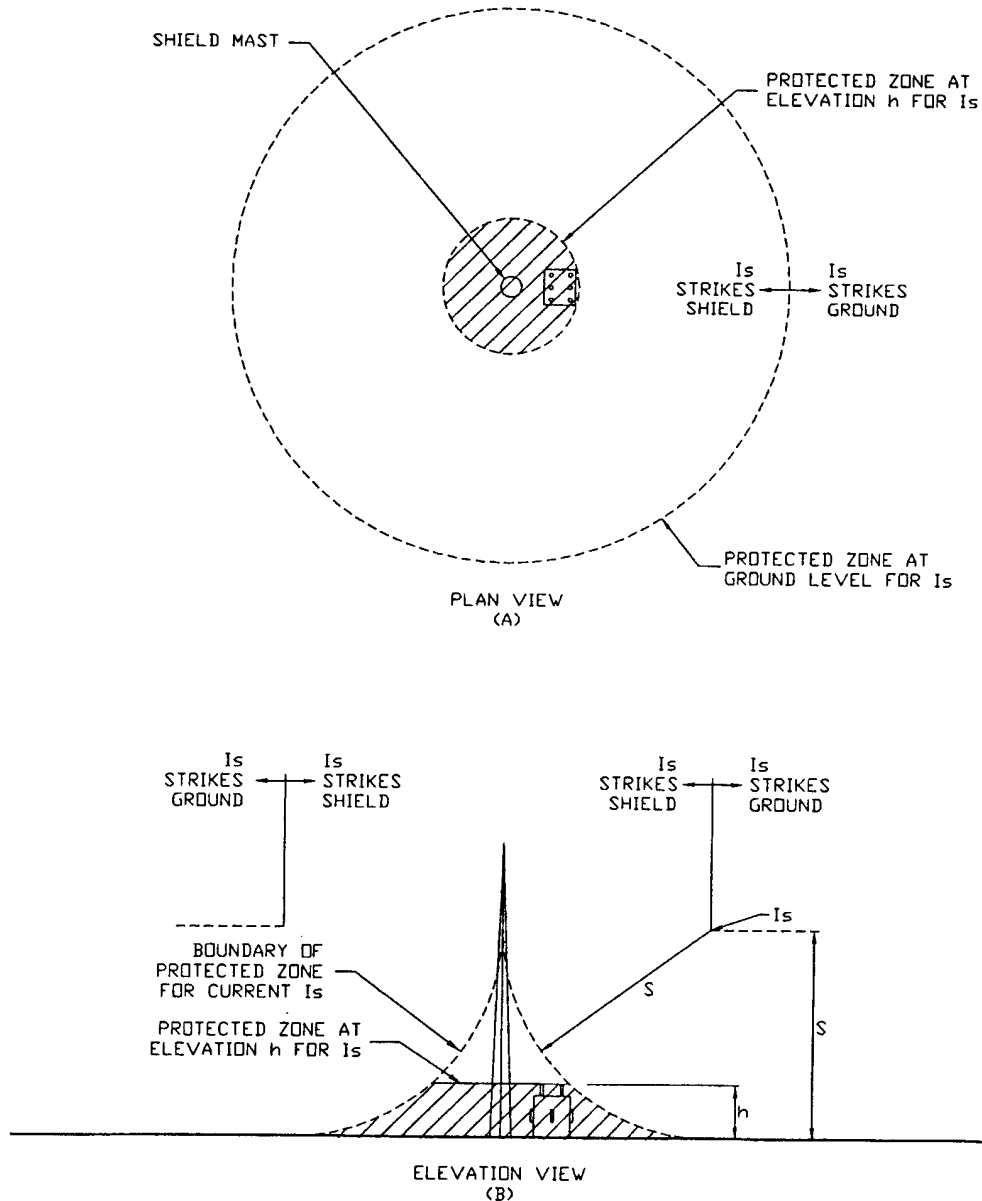
(Examples)



Principle of Rolling Sphere

Electrogeometric Method (5)

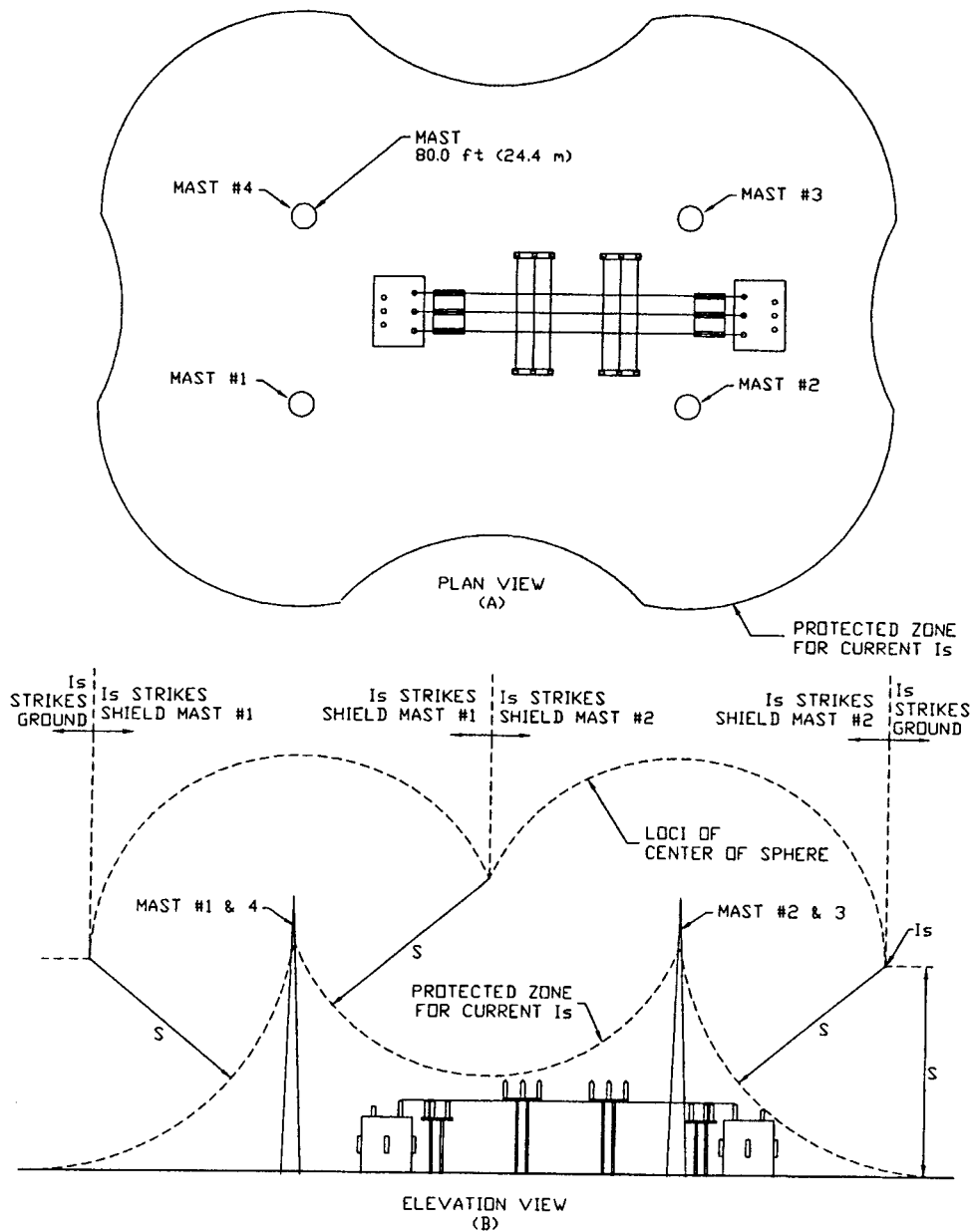
(Examples)



Shield Mast Protection for Stroke Current I_s

Electrogeometric Method (6)

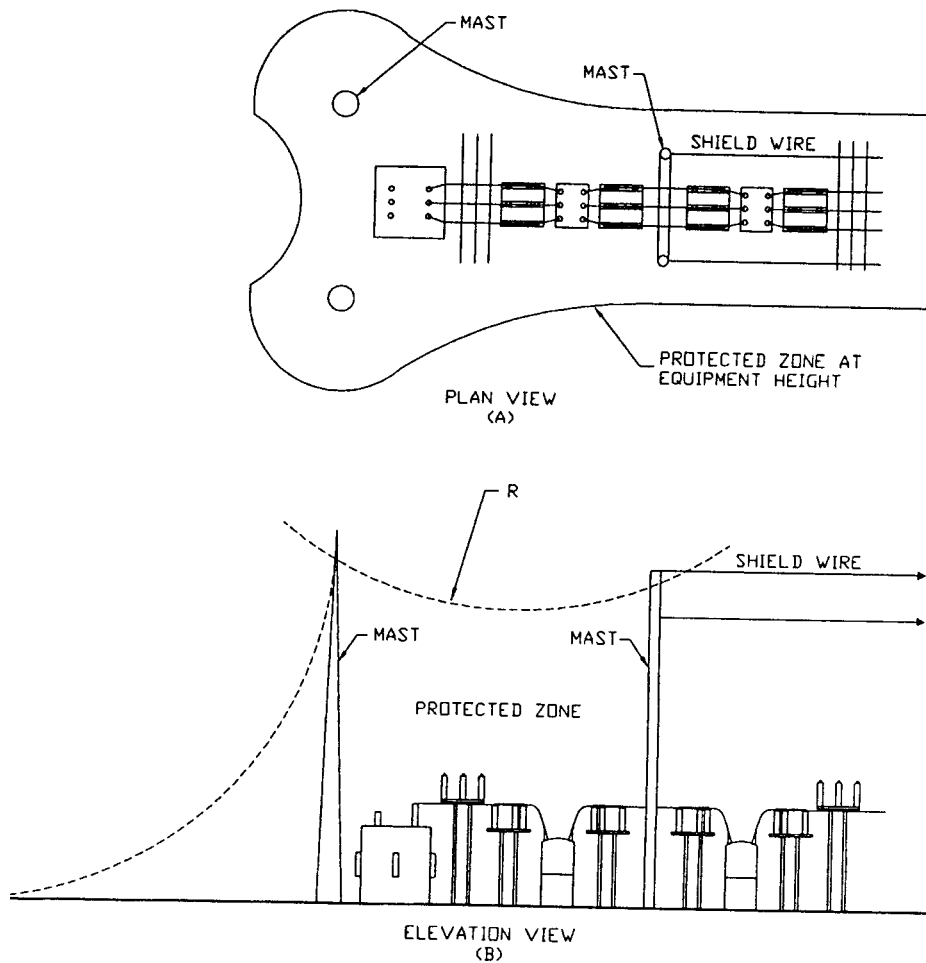
(Examples)



Multiple Shield Mast Protection for Stroke Current I_s

Electrogeometric Method (7)

(Examples)



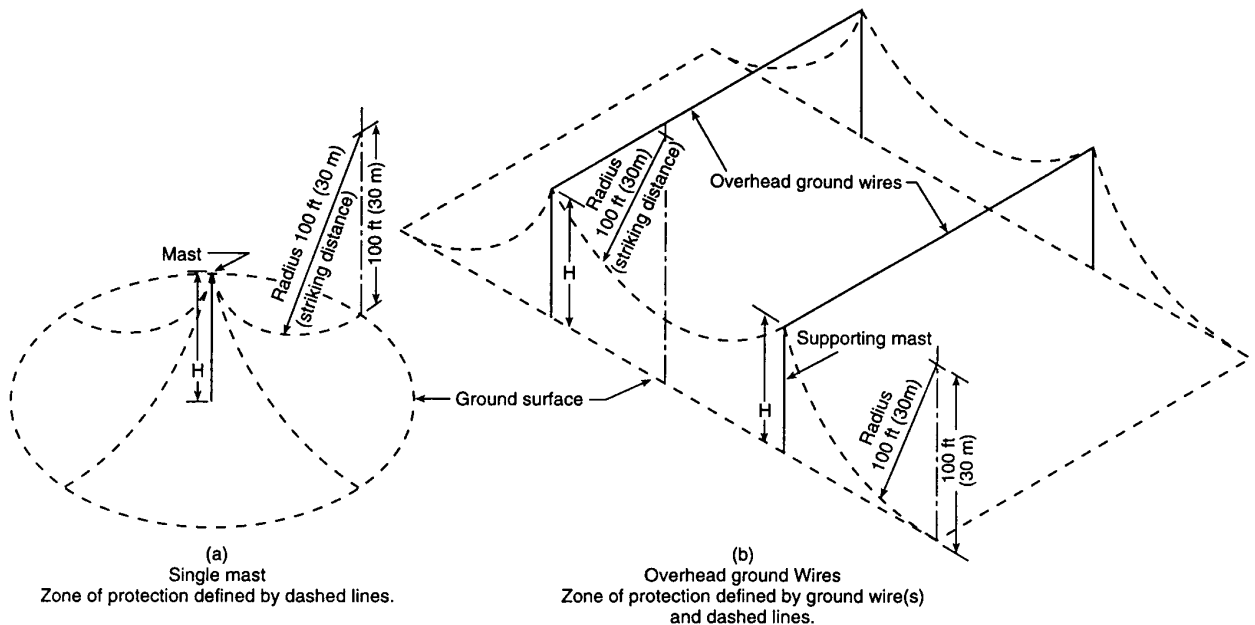
Protection by Shield Wires and Masts

Electrogeometric Method (8)

(Distribution Substation – Below 115 kV)

- ❖ Shield spacing becomes quite close (by EGM method) at voltages 69 kV and below.
- ❖ For Voltage 69 kV and below, Select a minimum Stroke Current of 2 kA (**also 3 kA has been recommended**).
- ❖ According to the data available 99.8% of all stroke currents exceed 2 kA. Lower possibility of flashover and lower consequences. Usually surge arrester will protect the transformer from any insulation damage.
- ❖ For, a 69 kV Design,
BIL = 350 kV, $Z_s = 360 \Omega$
Stroke Current (I_s) = 2.1 kA
- ❖ For, a 12.47 kV Design,
BIL = 110 kV, $Z_s = 360 \Omega$
Stroke Current (I_s) = 0.67 kA
- ❖ Striking (Radius) Distance:
 - $R_{sc} = 41 \text{ ft}$ (for 2 kA, $k = 1$)
 - $R_{sc} = 54 \text{ ft}$ (for 3 kA, $k = 1$)

Electrogeometric Method (Applied to Building)



Single Mast Zone of Protection

Overhead Ground Wires

Ref: NFPA 780, 1995

Electrogeometric Method (9)

(Summary)

- ☐ Originally, developed in the 1960's for EHV (345 kV) Transmission Line Design and later Modified to include EHV Substation and Switching Station Design.
- ☐ Major Difference (Fixed Angle and Empirical Methods) : Shielding design is based on the BIL (CFO), Surge Impedance, Lightning current probability distribution, lightning strike propagation, etc.
- ☐ The EGM method is based on more scientific research and well documented theoretical foundation.
- ☐ The basic EGM concept also has been modified and successfully adopted to protect building, power plant and other tall structures.
- ☐ This method is recommended for large EHV substations and switching Stations in an area with high GFD values. Also very effectively used in 230 kV switchyard design.
- ☐ Direct stroke shielding complemented by appropriately selected surge arrester provides the necessary protection.

Lightning Eliminating Devices **(Active Lightning Terminals)**

References

1. **IEEE Std. 998-1996**, Section 6, pp. 42-43.
2. **A.M. Mousa, The Applicability of Lightning Elimination Devices to Substations and Power Lines, IEEE Trans. on Power Delivery, Vol. 13, No. 4, October 1998, pp. 1120-1127.**
3. **D. W. Zipse, Lightning Protection Systems: Advantages and Disadvantages, IEEE Trans. On Industry Applications, Vol. 30, No. 5, Sept/Oct. 1994, pp. 1351-1361.**
4. **Many Others.**

Lightning Eliminating Devices

(Summary)

1. Ref [1]:

"There has not been sufficient scientific investigation to demonstrate that the above devices are effective, and these systems are proprietary, detailed design information is not available. It is left to the design engineer to determine the validity of the claimed performance for such systems. It should be noted that IEEE does not recommend or endorse commercial offerings."

2. Ref [2]:

"Natural downward lightning flashes cannot be prevented."

"The induced upward flashes which occur on structures having heights (altitude of the peak) of 300 m or more can be prevented by modifying the needle-like shape of the structure. Some charge dissipater designs inadvertently accomplish this and hence appear to "eliminate " lightning. Such an effect has little or nothing to do with the existence of multiple points on those devices."

"Charge dissipaters will have no effect, whether intended or inadvertent, on the frequency of lightning strikes to tall towers where the altitude of the site is such that the effective height of the tower is less than about 300 m.

"Charge dissipaters will have no effect whatsoever on the frequency of lightning strikes to substations and transmission towers since such systems do not experience upward flashes."

Lightning Eliminating Devices

(Summary)

3. Ref [3]

“NFPA has subdivided Standard 78 into two standards and has renumbered it. NFPA 780, entitled, “The Lightning protection Code,” and NFPA 781, “Lightning Protection Systems using Early Streamer Emission Air terminal,” are the new numbers and titles. NFPA 781 is under development and consideration.”

“As stated above, there is little factual data available to substantiate the claims being made for the system. Many installations have been made. The owners have not inspected the systems for direct strikes, nor have any systems been instrumented. The lack of viable and repeatable testing, when compared to the NASA and FAA studies and the multitude of experts in the lightning field who claim the system fails to function as advertised, casts doubt on the effectiveness of the multipoint discharge system to prevent lightning strikes.”

Conclusions (1)

- 1. Any design of Direct Lightning Stroke Shielding depends on the probabilistic nature of lightning phenomena.**
- 2. There is no method available to provide 100% shielding against direct lightning stroke of the substation equipment and bus structures.**
- 3. There are a number of other variables not addressed in the IEEE Std. 998-1996 and not discussed in this presentation, such as, effects of altitude on BIL, state (cleanliness) of the insulators, aging effect of equipment on failure, temperature variations, and so on.**
- 4. Fixed angle method of design is quite adequate for distribution substations. EGM method is more appropriate for large and important substations at 230 kV and above voltage level.**

Conclusions (2)

- 5. The applicability of Lightning Eliminating Devices to substation direct lightning stroke shielding requires additional data and research.**
- 6. Proper grounding system design is also an integral part of the total solution and should be addressed during the design.**
- 7. In order to arrive at some practical solutions, many assumptions are made in the different design techniques.**
- 8. Surge Arresters are added in strategic locations in a substation to provide coordinated protection for all major equipment.**