VERDOLIN SOLUTIONS INC.

HIGH VOLTAGE POWER ENGINEERING SERVICES

Lightning Protection and Transient Overvoltage

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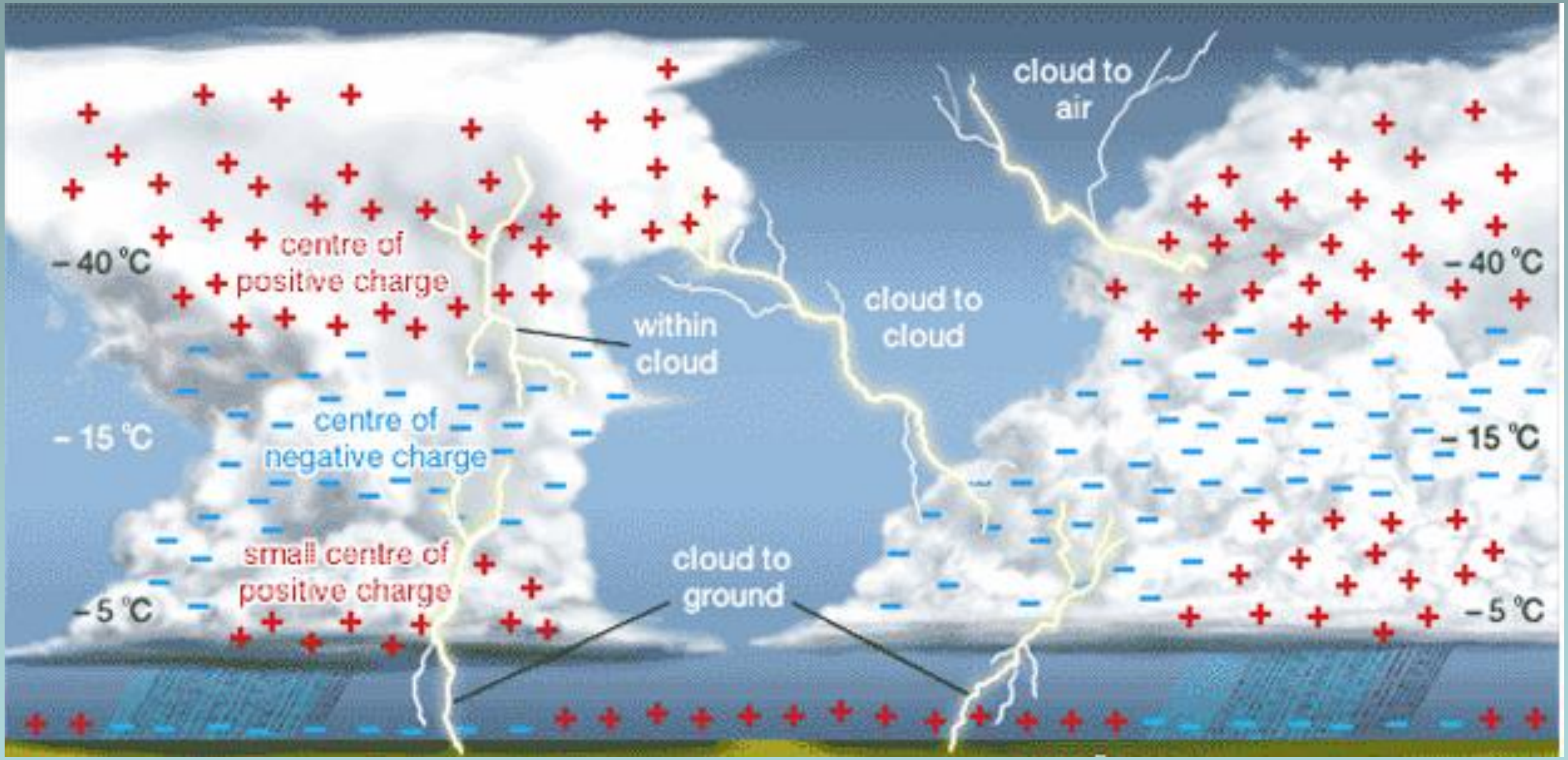
Agenda

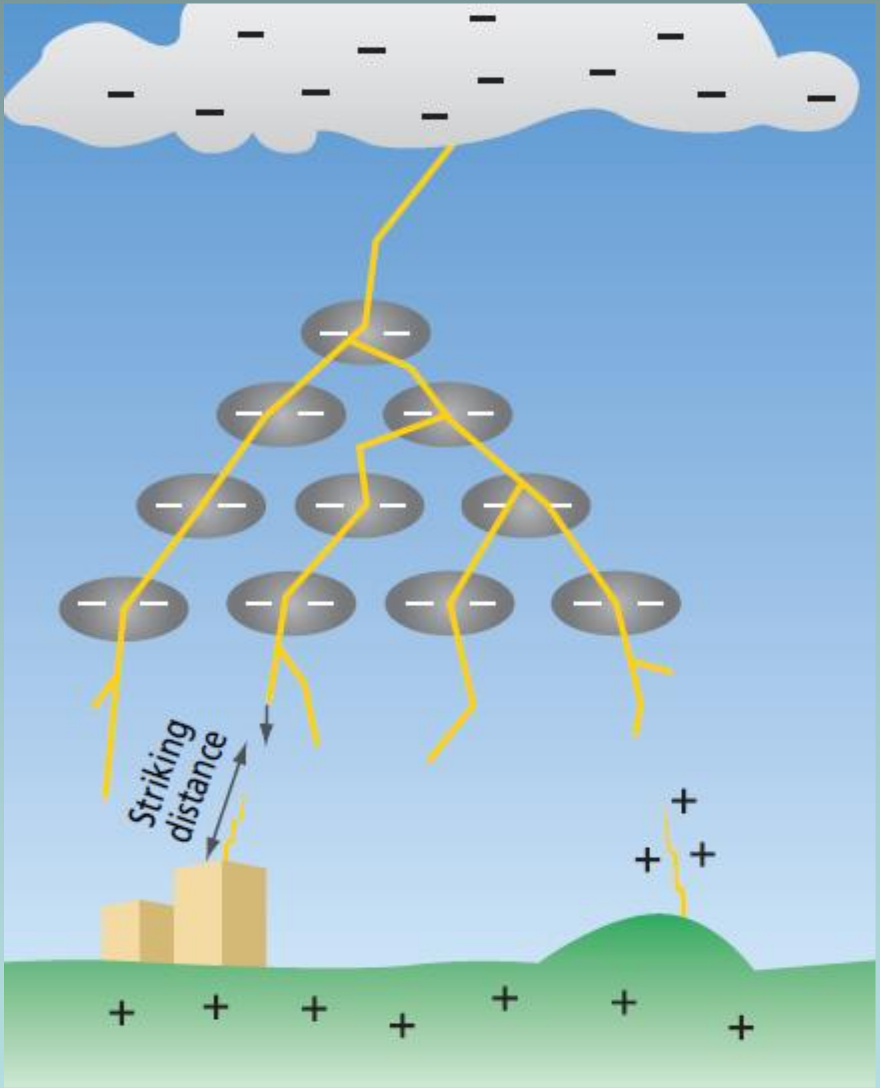
- **WHAT IS LIGHTNING**
- **STRIKING DISTANCE**
- **GROUND FLASH DENSITY**
- **STATISTICS ON LIGHTNING OCCURRENCE**
- **LIGHTNING PROTECTION**
- **EMPIRICAL METHODS**
- **ELECTROGEOMETRIC MODEL (EGM)**
- **ROLLING SPHERE METHOD**
- **FAILURE PROBABILITY**
- **FAILURE RATE**
- **LIGHTNING PROTECTION OF TRANSMISSION LINES**
- **INDUSTRIAL APPLICATION**
- **TRANSIENT OVERVOLTAGE**
- **LIGHTNING OVERVOLTAGES**
- **SWITCHING OVERVOLTAGES**
- **SURGE ARRESTERS**
- **CONCLUSIONS**

WHAT IS LIGHTNING

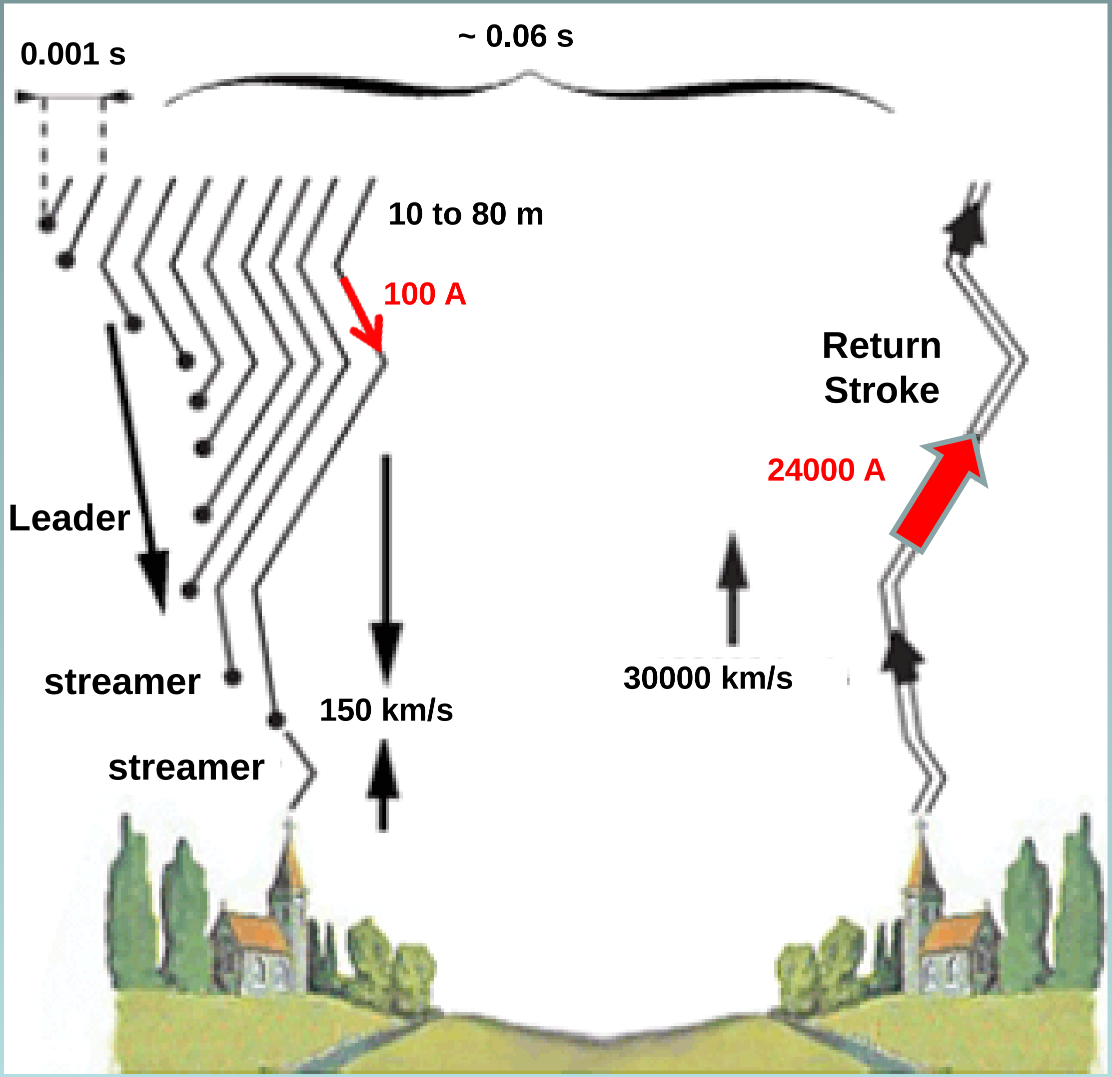
Thundercloud Charge Structure



Thundercloud Charge Structure



Stroke Formation

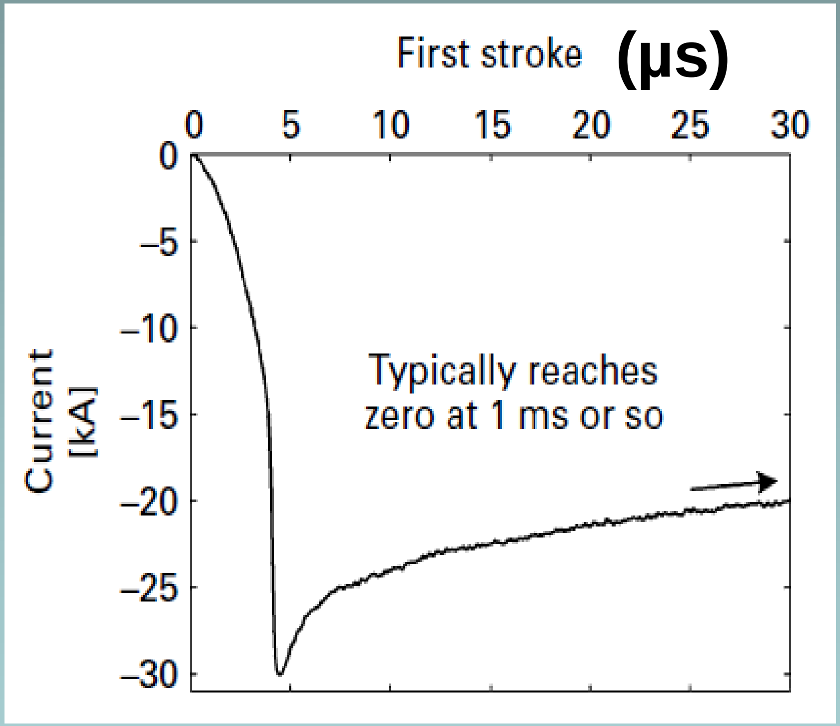


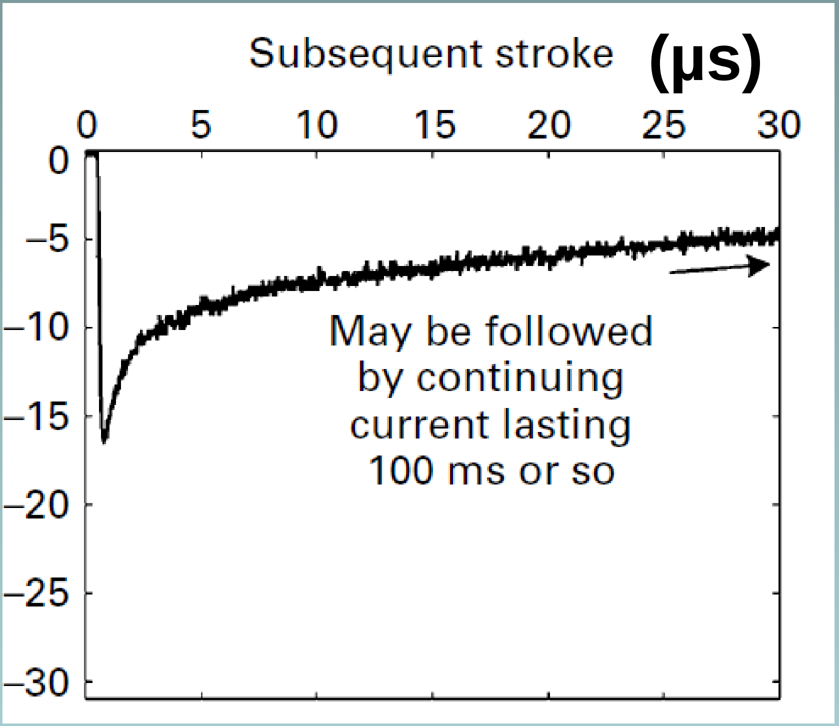
High Definition Refresh Rate Camera

Effects of Direct Stroke on Substations

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

Lightning Return Stroke Current





STRIKING DISTANCE

Striking Distance

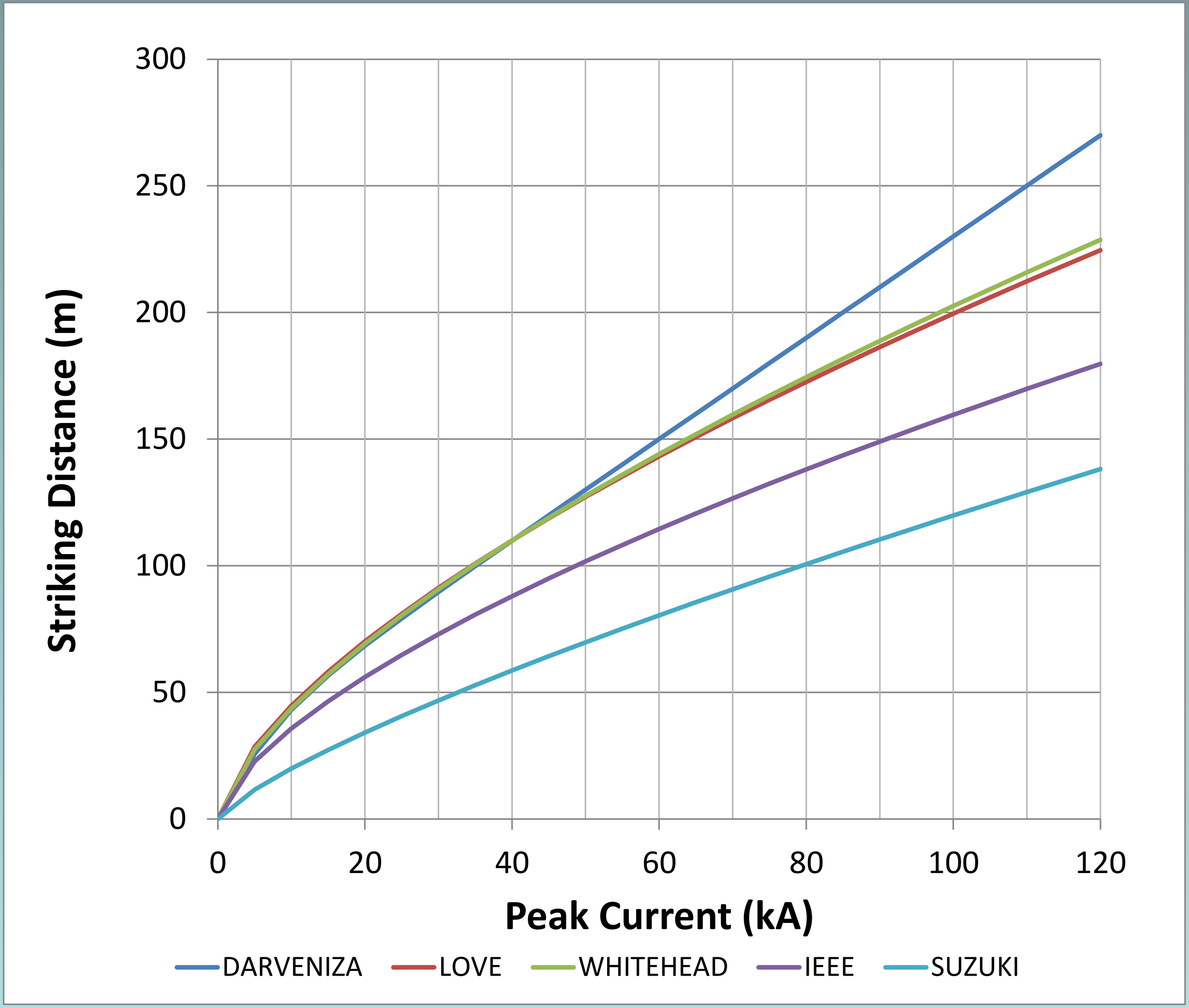
$$S = 2\,I + 30\,(1 - e^{-I/6.8})$$

$$S = 10\,I^{0.65}$$

$$S = 9.4\,I^{2/3}$$

$$S = 8\,I^{0.65}$$

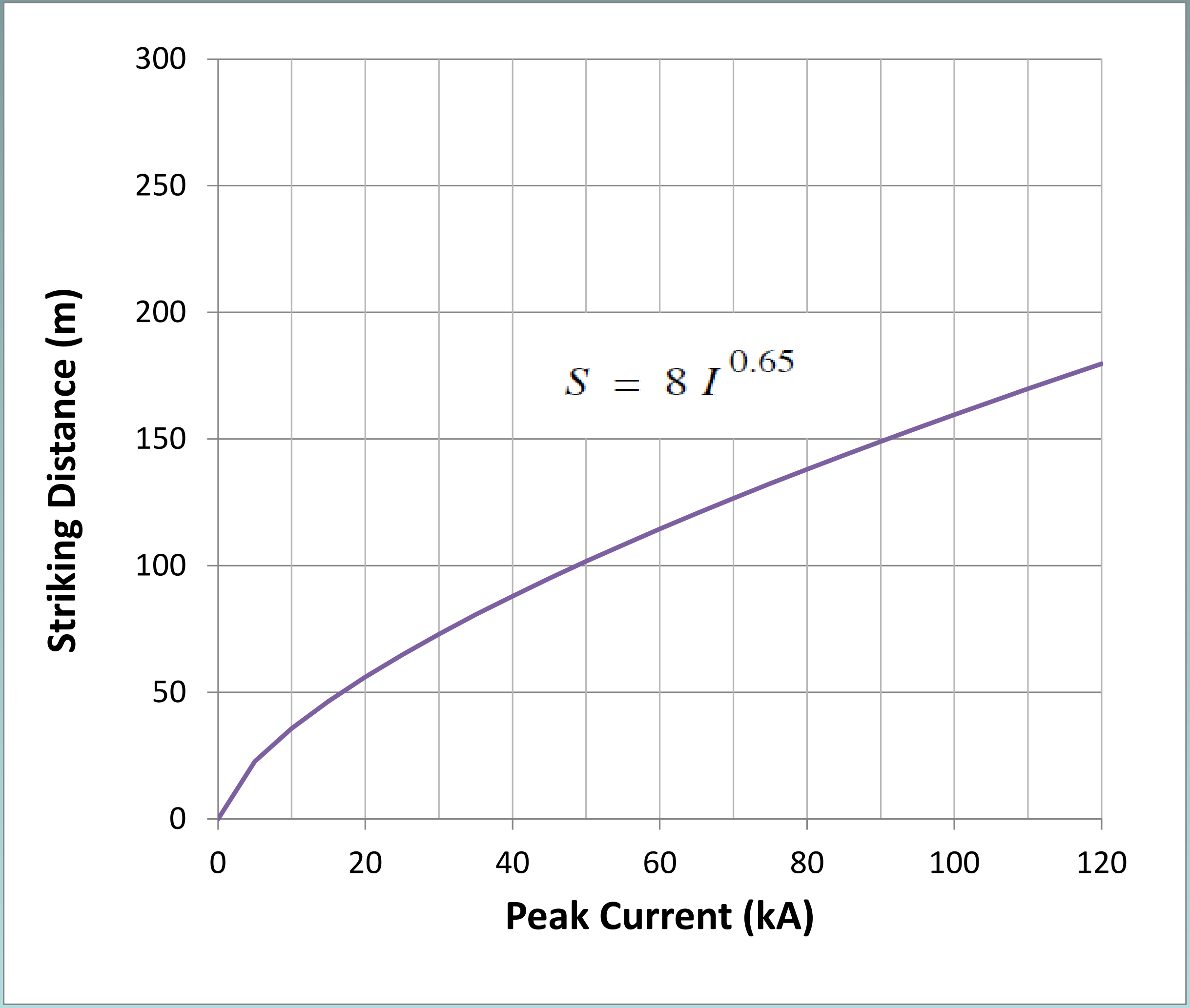
$$S = 3.3\,I^{0.78}$$



Striking Distance – IEEE Equation

$$S = 8\,I^{0.65}$$

$$I = 0.041\,S^{1.54}$$



GROUND FLASH DENSITY

Ground Flash Density (GFD)

- **Ground flash density (GFD)** is defined as the average number of **strokes per unit area per unit time** at a particular location.
- N_k is the number of **flashes to earth/km²/per year**
- T_d is the average annual keraunic level, **thunderstorm days**

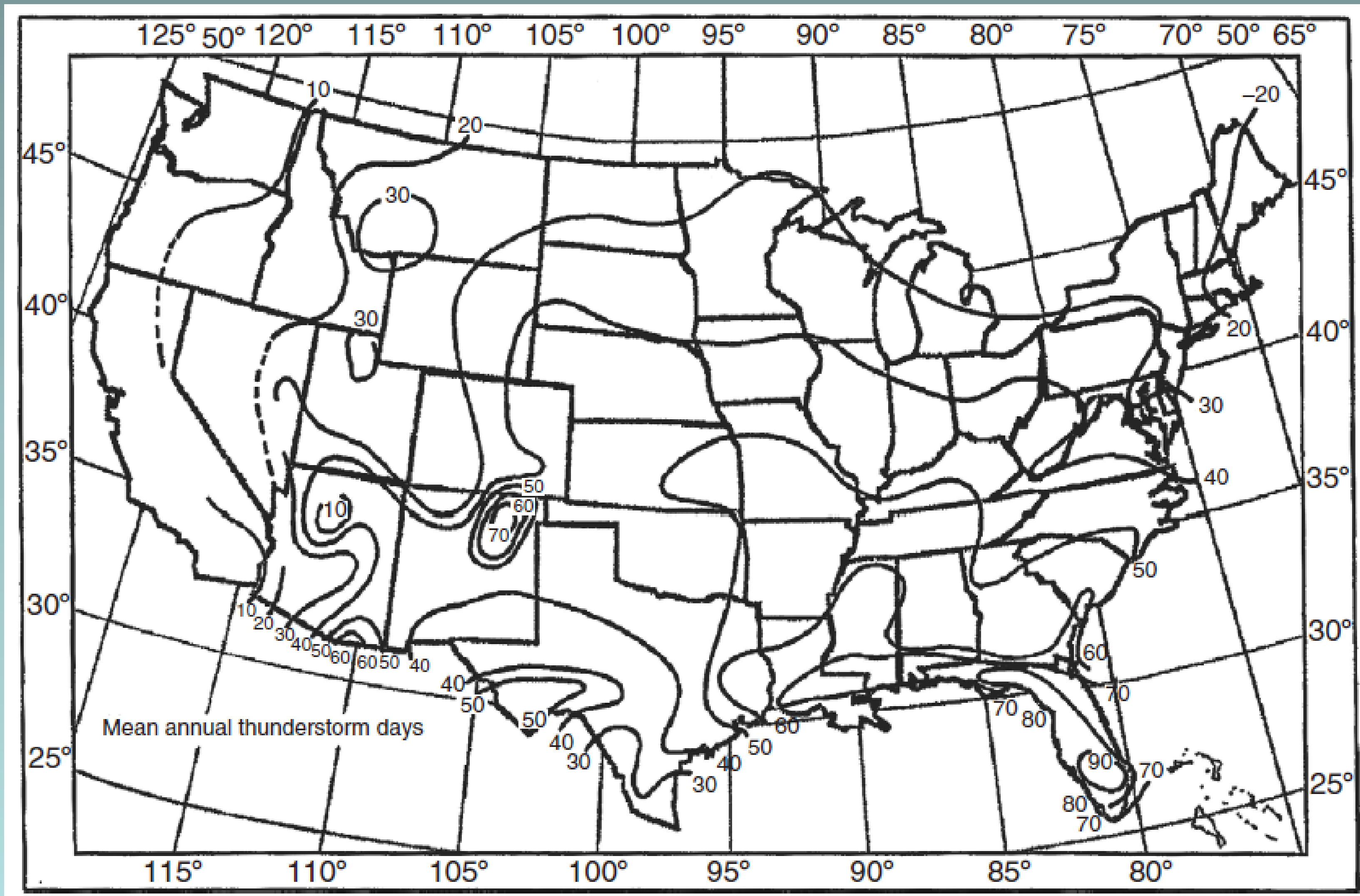
$$N_k = 0.12 \cdot T_d$$

Ground Flash Density (GFD)

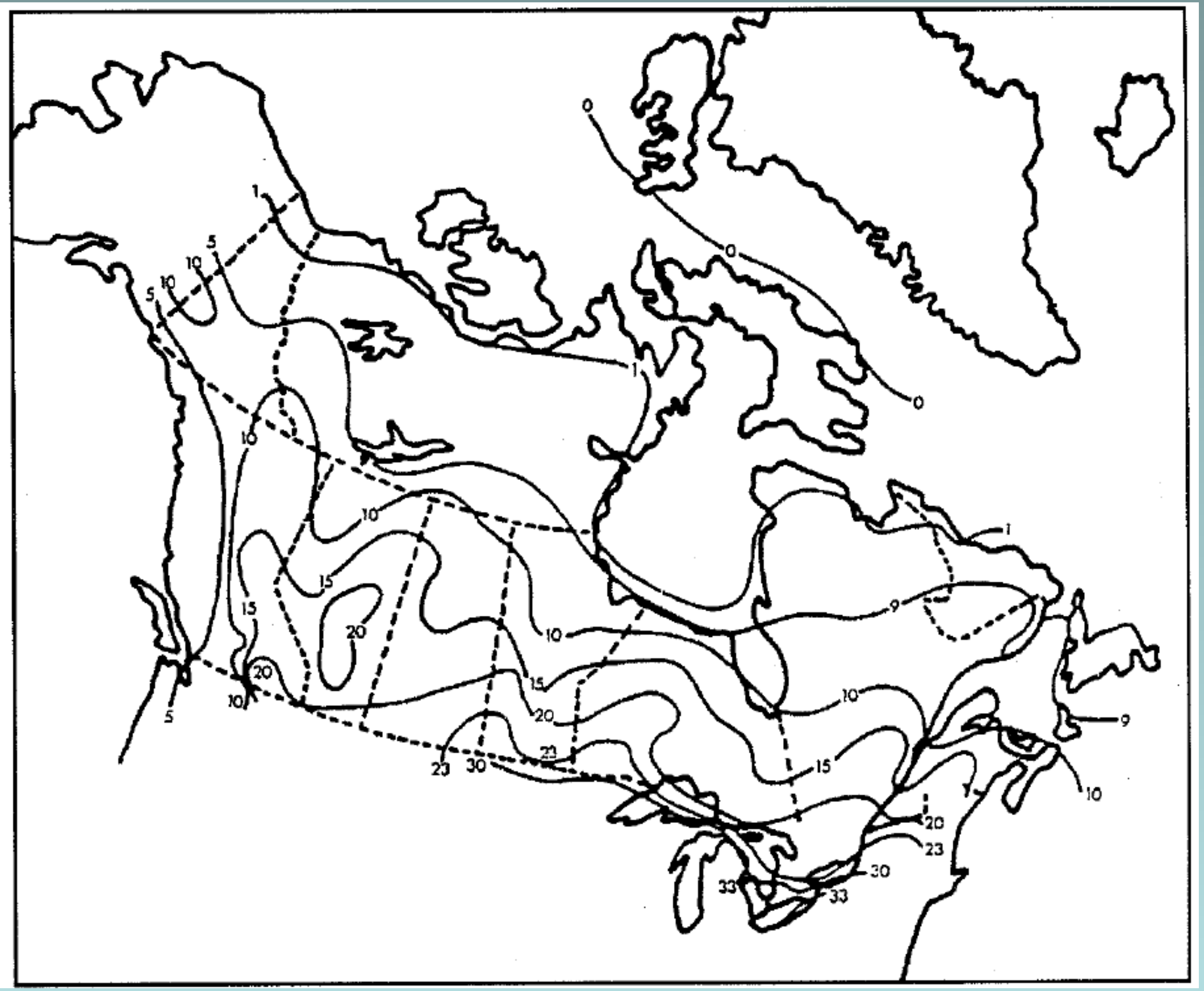
- N_k is the number of **flashes to earth/km²/per year**
- T_h is the average annual keraunic level, **thunderstorm hours**

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

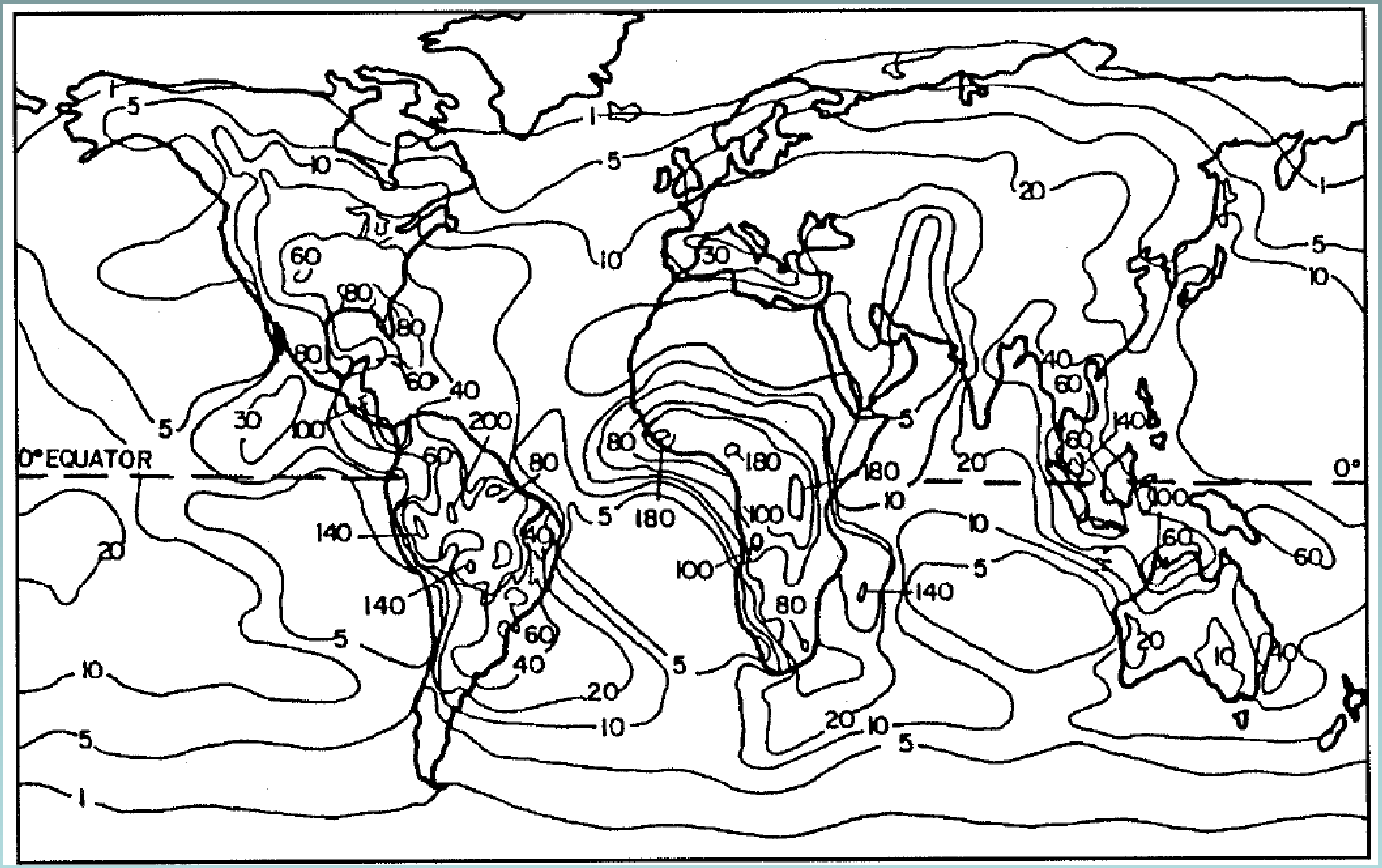
Mean Annual Thunderstorm Days (T_d) - US



Mean Annual Thunderstorm Days (T_d) - Canada



Mean Annual Thunderstorm Days (T_d) - World



LIGHTNING PROTECTION

STANDARDS

- **IEEE Guide for Direct Lightning Stroke Shielding of Substations - IEEE Std 998-2012**
- **IEEE Guide for Improving the Lightning Performance of Transmission Lines - IEEE Std 1243-1997**
- **IEEE Guide for Improving the Lightning Performance of Electric Power Overhead Distribution Lines-IEEE Std 1410-2011**
- **IEC 62305-Protection against lightning – 2013**
- **NFPA 780: Standard for the Installation of Lightning Protection Systems-2014**

LIGHTNING PROTECTION OF SUBSTATIONS

THE DESIGN PROBLEM

The Design Problem

- **The unpredictable, probabilistic nature of lightning.**
- **The lack of data due to the infrequency of lightning strokes in substations.**
- **The complexity and economics involved in analyzing a system in detail.**
- **No known practical method of providing 100% shielding.**

Four-Step Approach

- **Evaluate the importance and value of the facility being protected. (Risk Assessment)**
- **Investigate the severity and frequency of thunderstorms in the area of the substation facility and the exposure of the substation.**
- **Select an appropriate design method (Shielding and Surge Arresters)**
- **Evaluate the effectiveness and cost of the design.**

EMPIRICAL METHODS

Empirical Design Methods

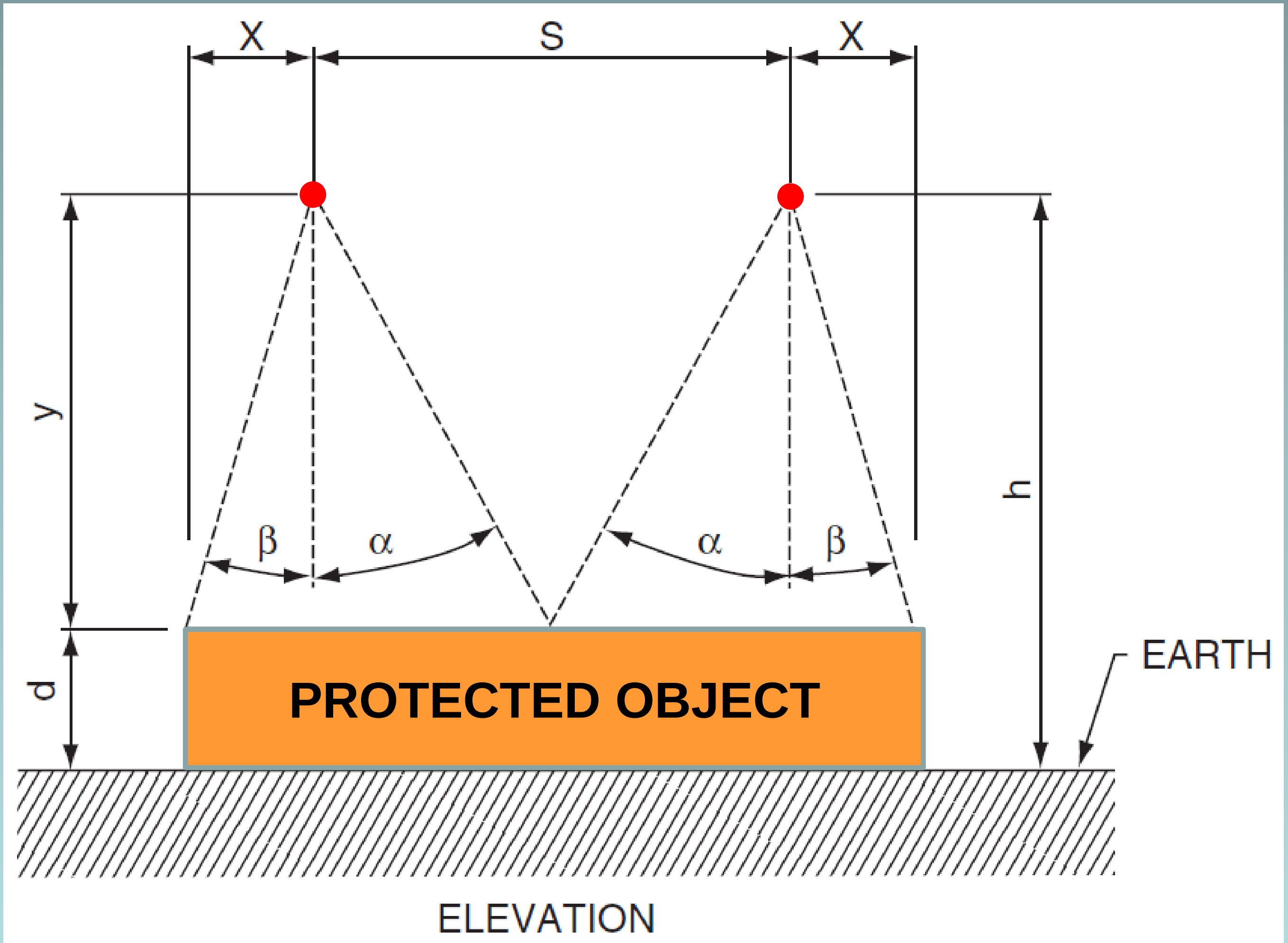
- **Fixed angles**
- **Empirical curves**

FIXED ANGLES

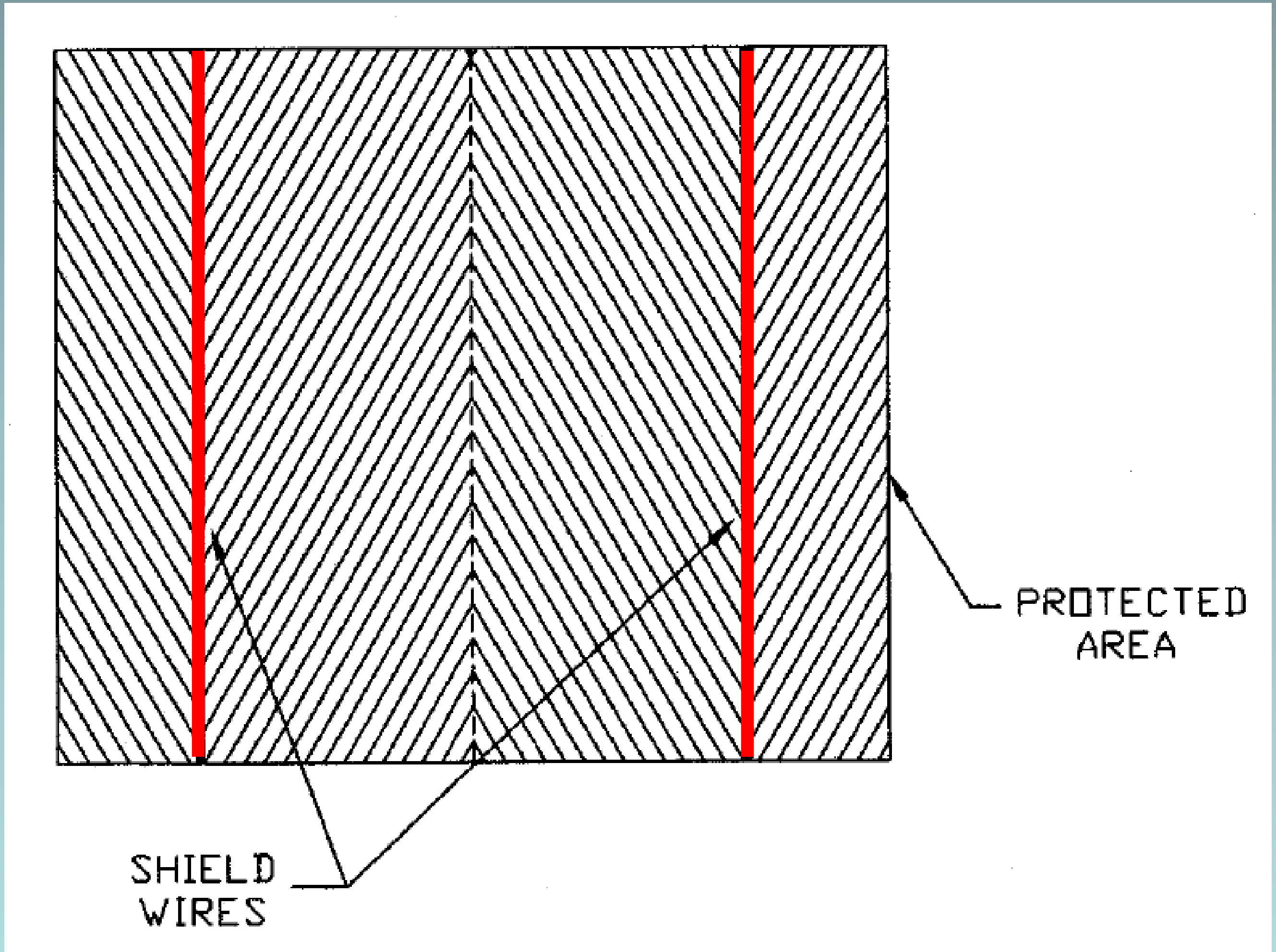
Fixed Angles for Shielding Wires

$\alpha = 45°$

$\beta = 30°$ or $45°$



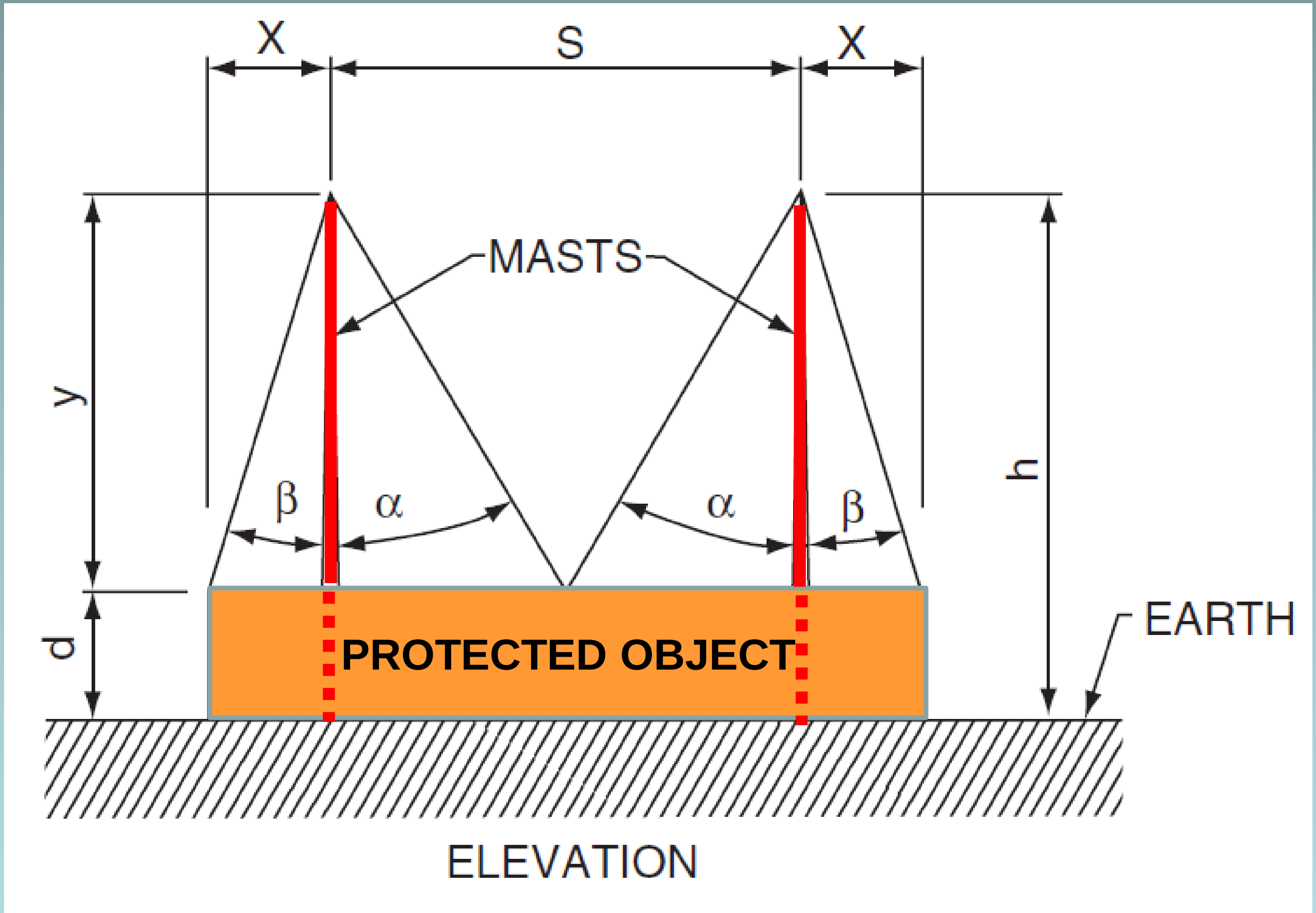
Fixed Angles for Shielding Wires



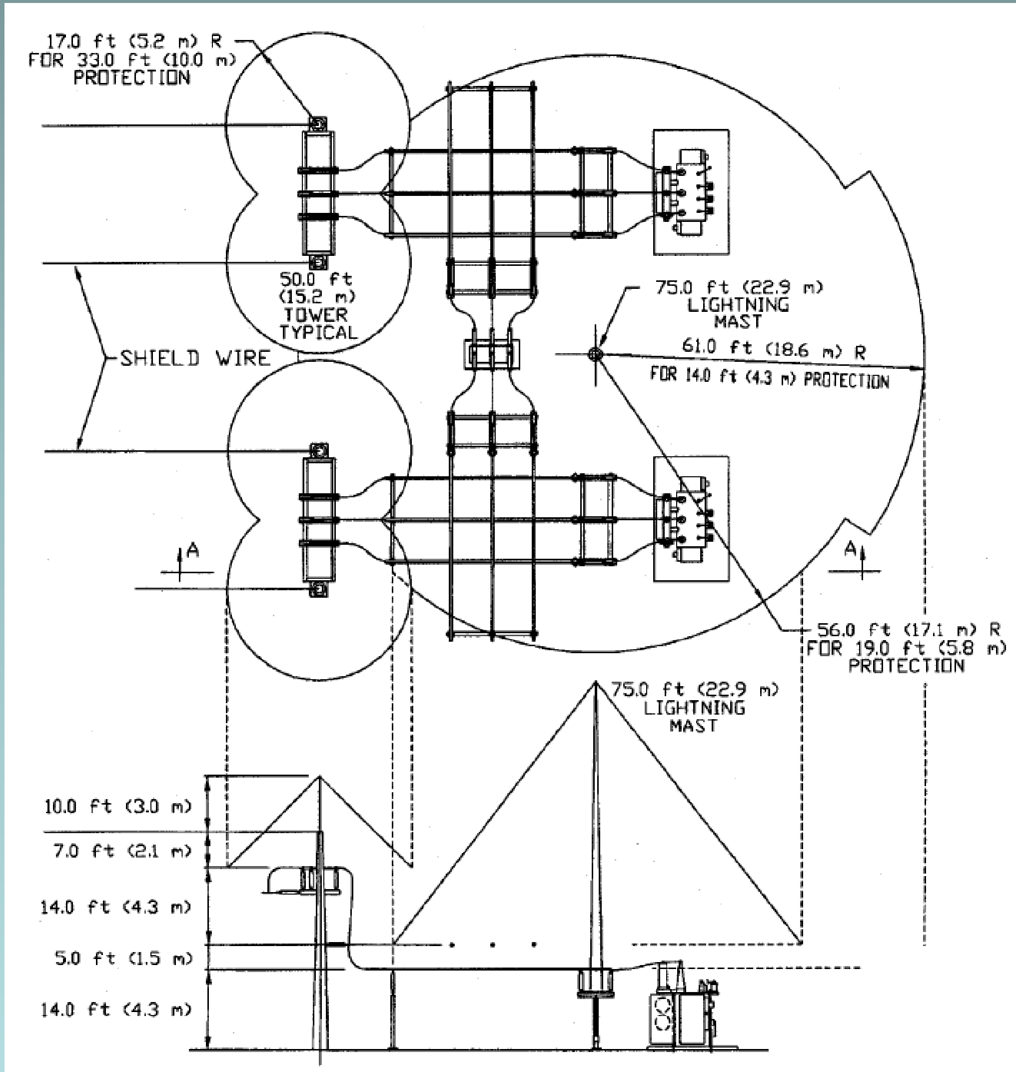
Fixed Angles for Masts

α = 45°

β = 30° or 45°



Fixed Angle Method – Example 69kV



Fixed Angle Method (Summary)

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

- **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 Distribution Substation design.**
- **Has been in use since 1940's.**
- **For 69 kV and below produces very good results.**

EMPIRICAL CURVES

Empirical Curves

- **Developed in 1940's (Experimental)**
- **Assumptions:**
- **Based on "Scale Model" tests.**
- **Independent of Insulation Level (BIL), Surge Impedance, Stroke Current Magnitude, and the Probability of Lightning Occurrence.**
- **Designed for different shielding failure rates.**
- **A failure rate of 0.1% is commonly used.**

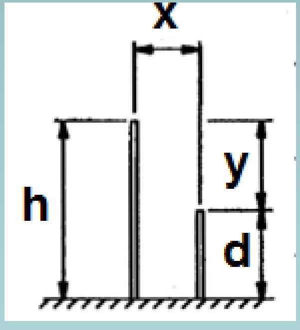
Single Lightning Mast

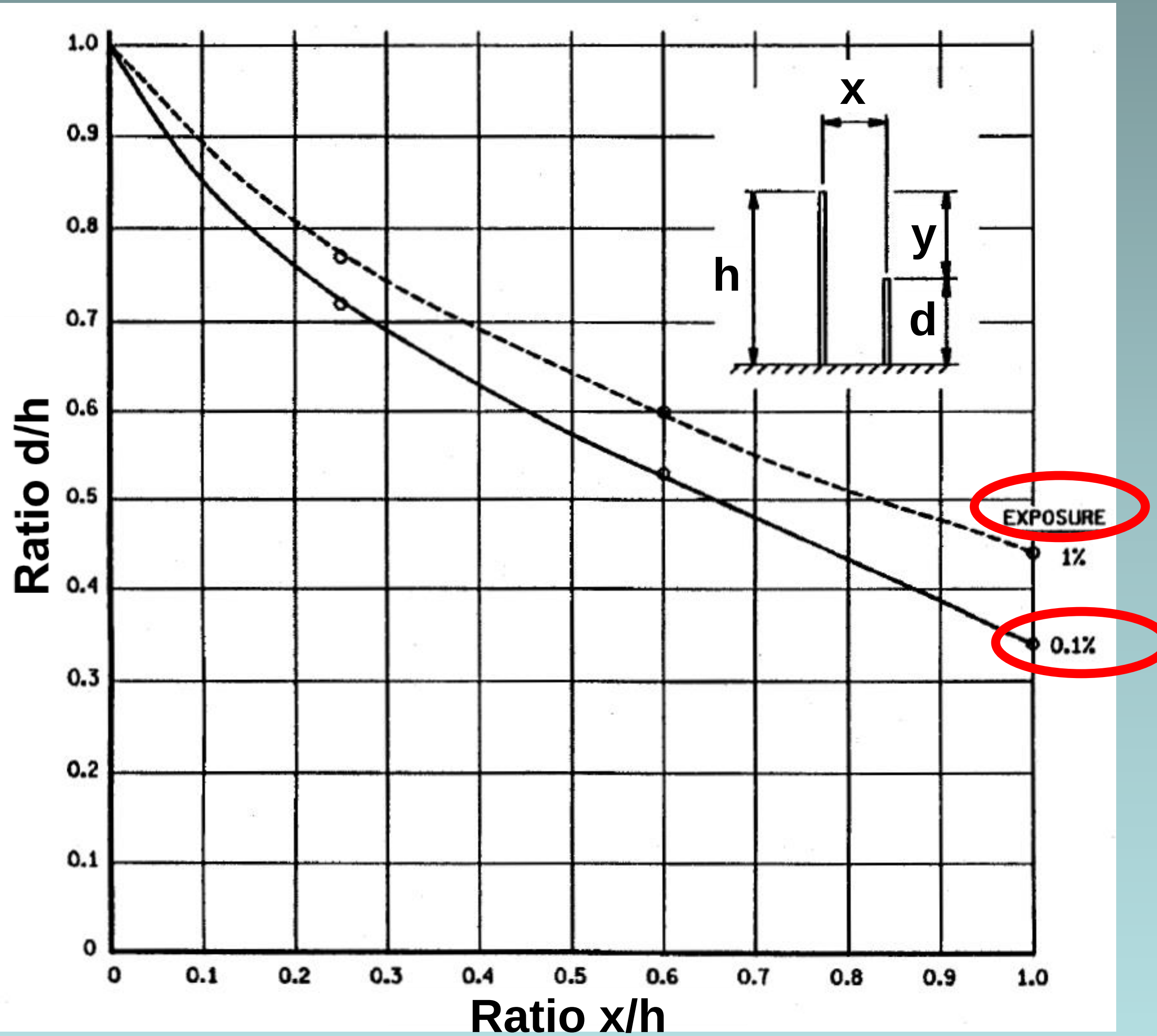
d= height of the protected object

h= height of the mast

x= horizontal separation

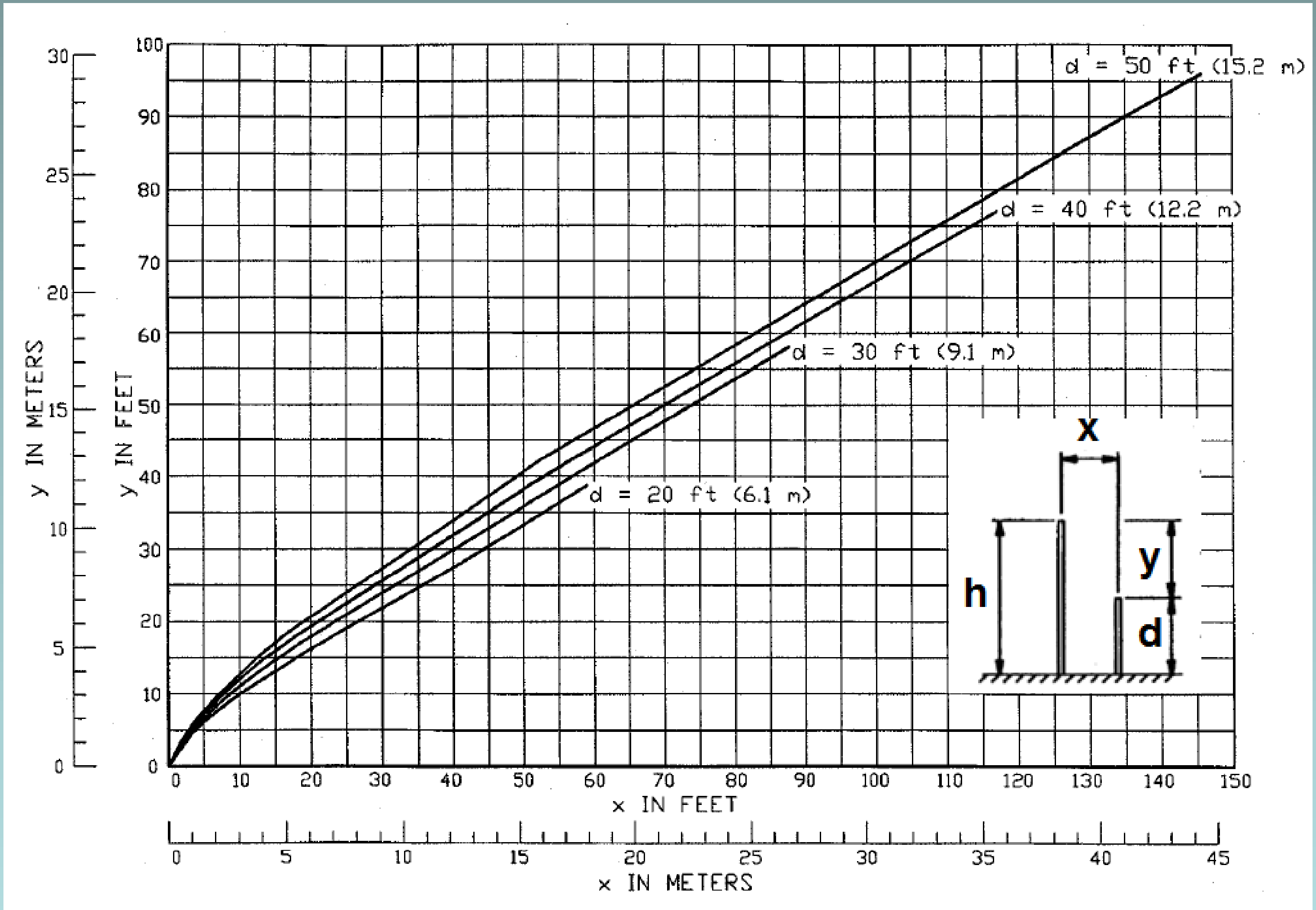
y= h-d





Single Lightning Mast

0.1% Exposure



Empirical Curve Method (Summary)

- **Limited Applications Capabilities.**
- **Not Very User Friendly, time consuming and used by very few.**
- **Not recommended design practice for EHV Substations.**

ELECTROGEOMETRIC MODEL (EGM)

EGM: Procedure

- **Calculate bus Surge Impedance Z_s from the geometry. For two heights, use the higher level heights.**
- **Determine the value of CFO (or BIL). For higher altitude use correction factor for BIL.**
- **Calculate the value of I_s.**
- **Calculate the value of the striking distance (or radius of the rolling sphere)**
- **Use two or more striking distance values based on BIL voltage levels in a substation with two or more different voltages.**

EGM: Design Parameters

Recommended for EHV Transmission

Substation and Switching Station

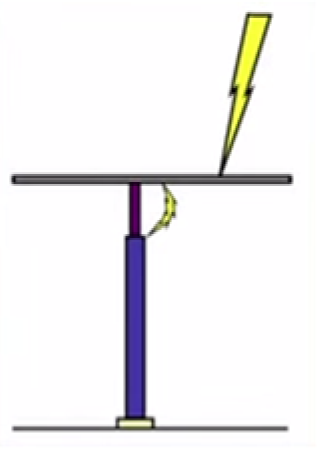
- **Ground Flash Density (GFD)**
- **Stroke Current**
- **Strike Distance**

Electrogeometric Model

Allowable Stroke Current (I_s):

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

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



I_s	-	Allowable stroke current (kA)
BIL	-	Basic lightning impulse insulation level (kV)
Z_s	-	Surge impedance (Ω)
CFO	-	Negative polarity critical flashover voltage (kV)

Surge Impedance of a Transmission Line

$$Z_s = 60 \cdot \sqrt{ln\left(\frac{2 \cdot h}{R_c}\right) \cdot ln\left(\frac{2 \cdot h}{r}\right)}$$

$$R_c \cdot ln\left(\frac{2 \cdot h}{R_c}\right) - \frac{V_c}{E_0} = 0$$

h - Average height of the conductor (m)
R_c - Corona radius (m)
r - Conductor radius (m)
V_c = BIL (kV)
E_0 = Limiting corona gradient = 1500kV/m

Basic Lightning Impulse Insulation Level (BIL)

Vm (rms)	BIL (kVp)
72.5	325
123	450 550
145	450 550 650
170	550 650 750
245	650 750 850 950 1050
300	850 950 1050

Vm (rms)	BIL (kVp)
362	950 1050 1175
420	1050 1175 1300
525	1175 1300 1425 1550
765	1675 1800 1950 2100

EGM – Strike Distance

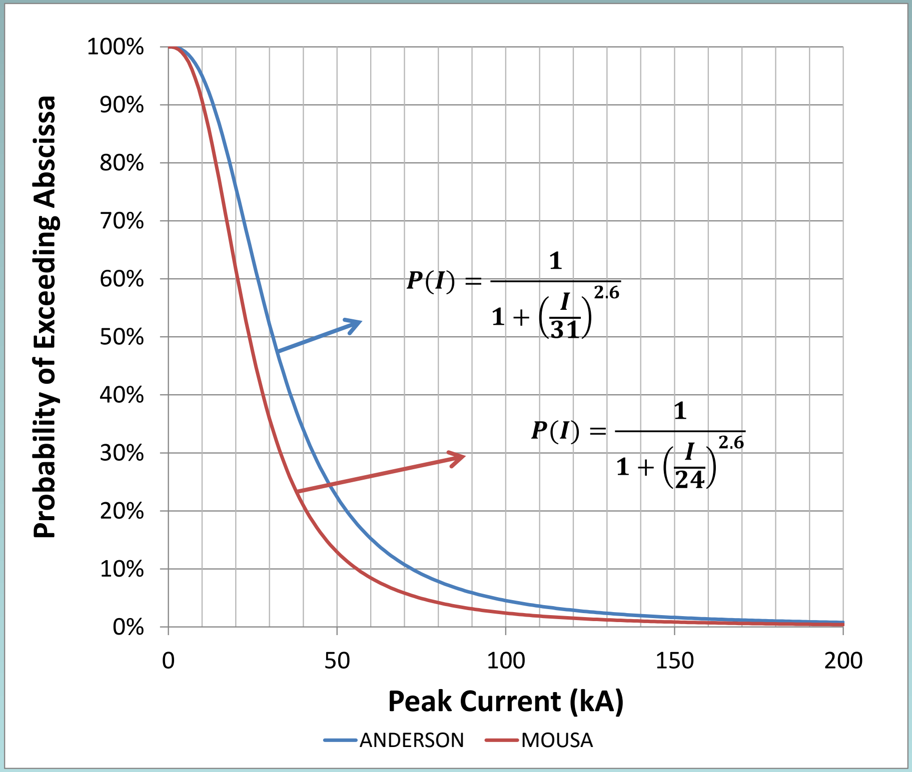
$$S_m = 8 \cdot k \cdot I^{0.65}$$

$$S_f = 26.25 \cdot k \cdot I^{0.65}$$

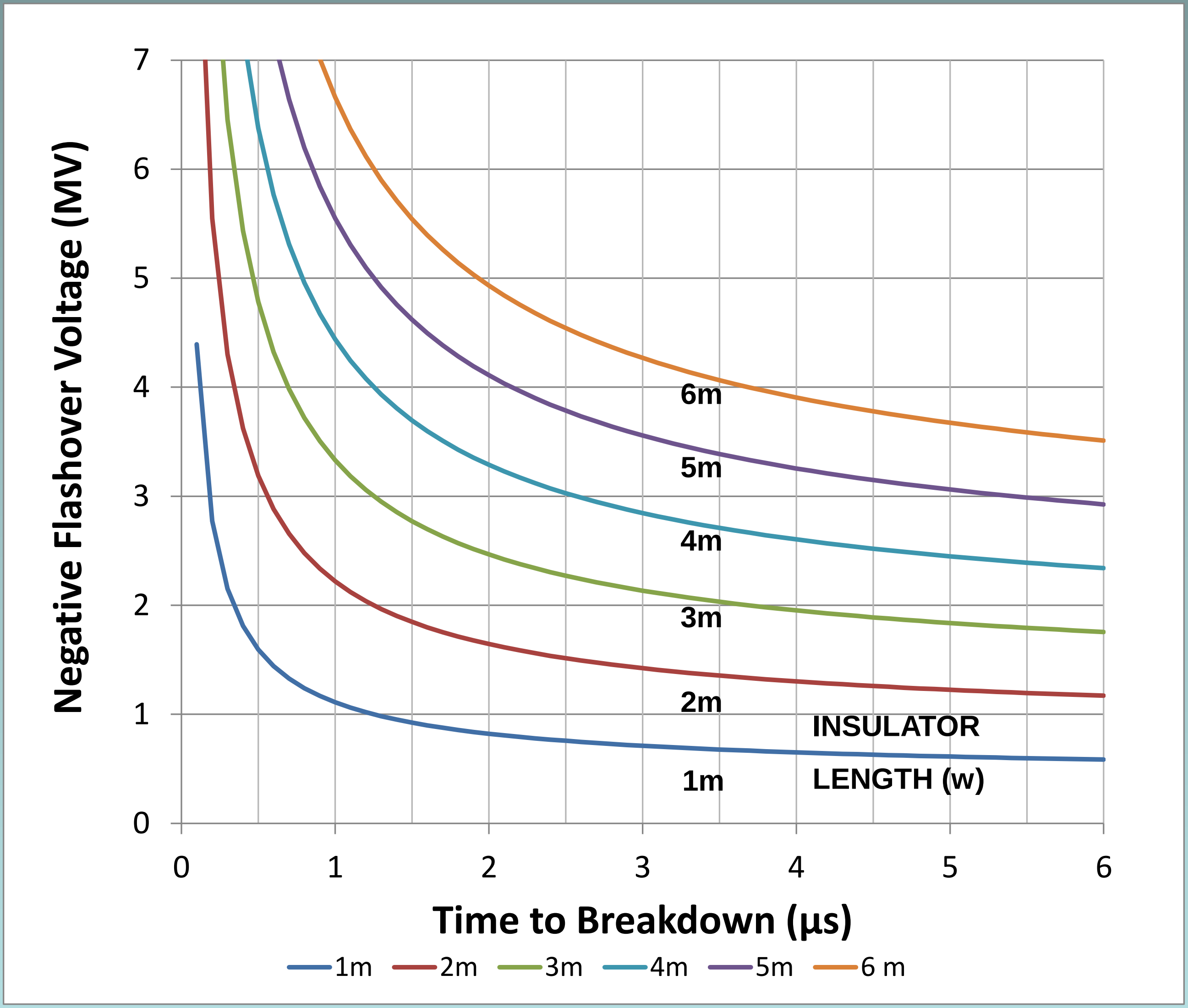
- **Where:**
- S_m **is the strike distance in meters**
- S_f **is the strike distance in feet**
- I **is the return stroke current in kA**
- $k = 1$ **for strokes to wires or the ground plane**
- $k = 1.2$ **for strokes to a lightning mast**

Electrogeometric Model – BIL<350kV

$$I_s = 2kA$$



Voltage-Time Curves for Insulator Strings (CFO)

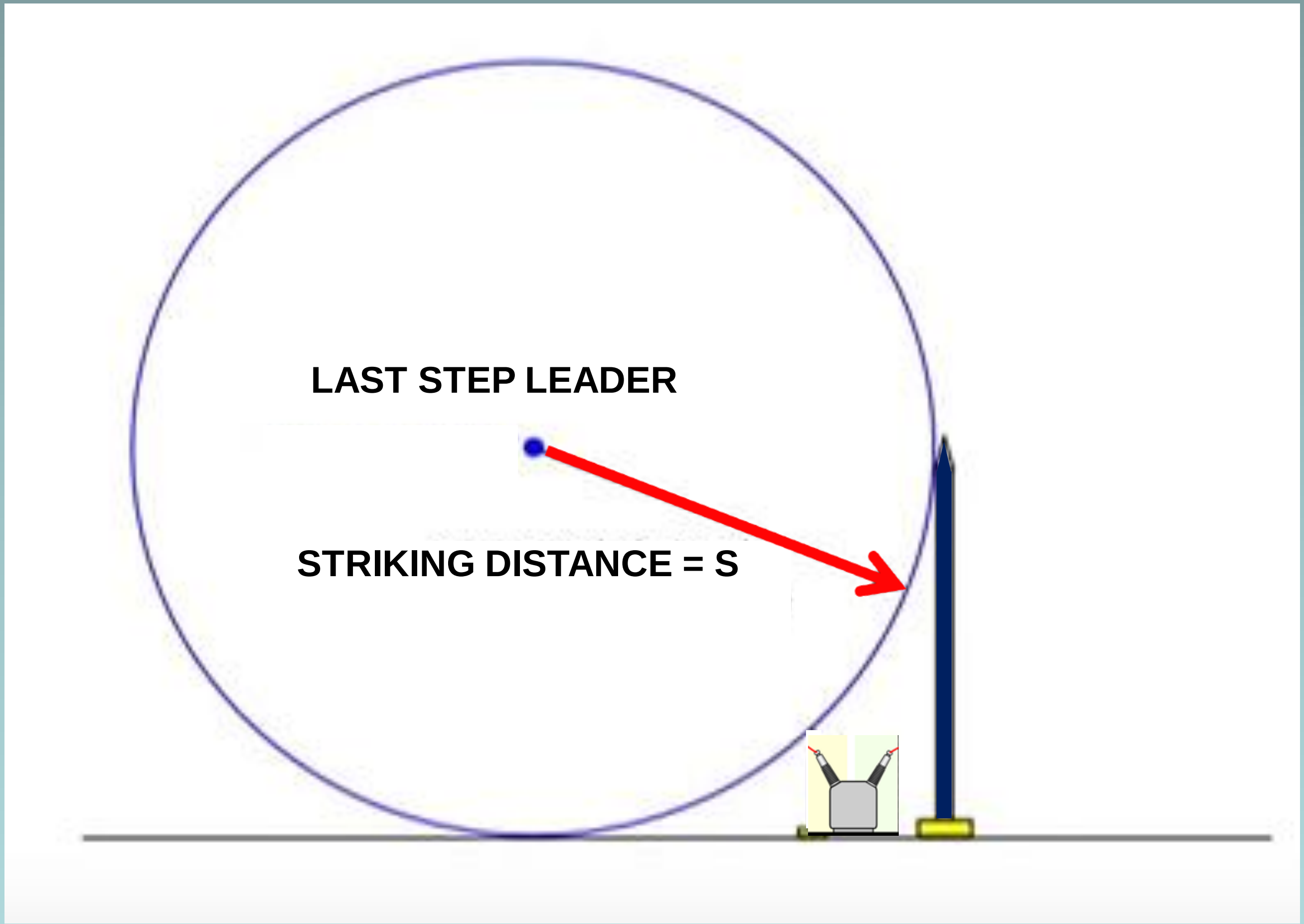


ROLLING SPHERE METHOD

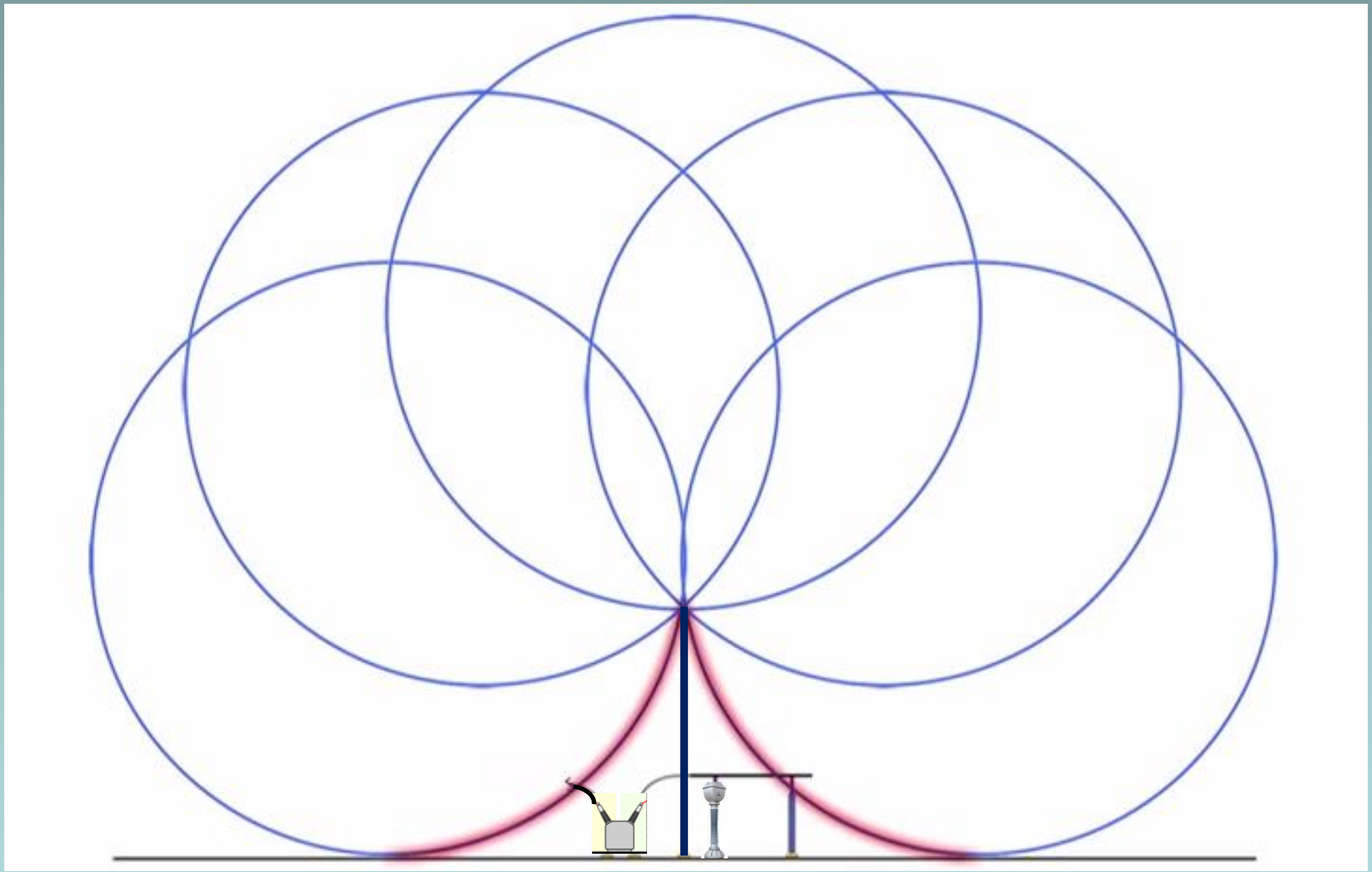
Rolling Sphere Method

- **Use an imaginary sphere of radius S over the surface of a substation.**
- **The sphere rolls up and over (and is supported by) lightning masts, shield wires, substation fences, and other grounded metallic objects that can provide lightning shielding.**
- **A piece of equipment is said to be protected from a direct stroke if it remains below the curved surface of the sphere.**

Principle of Rolling Sphere

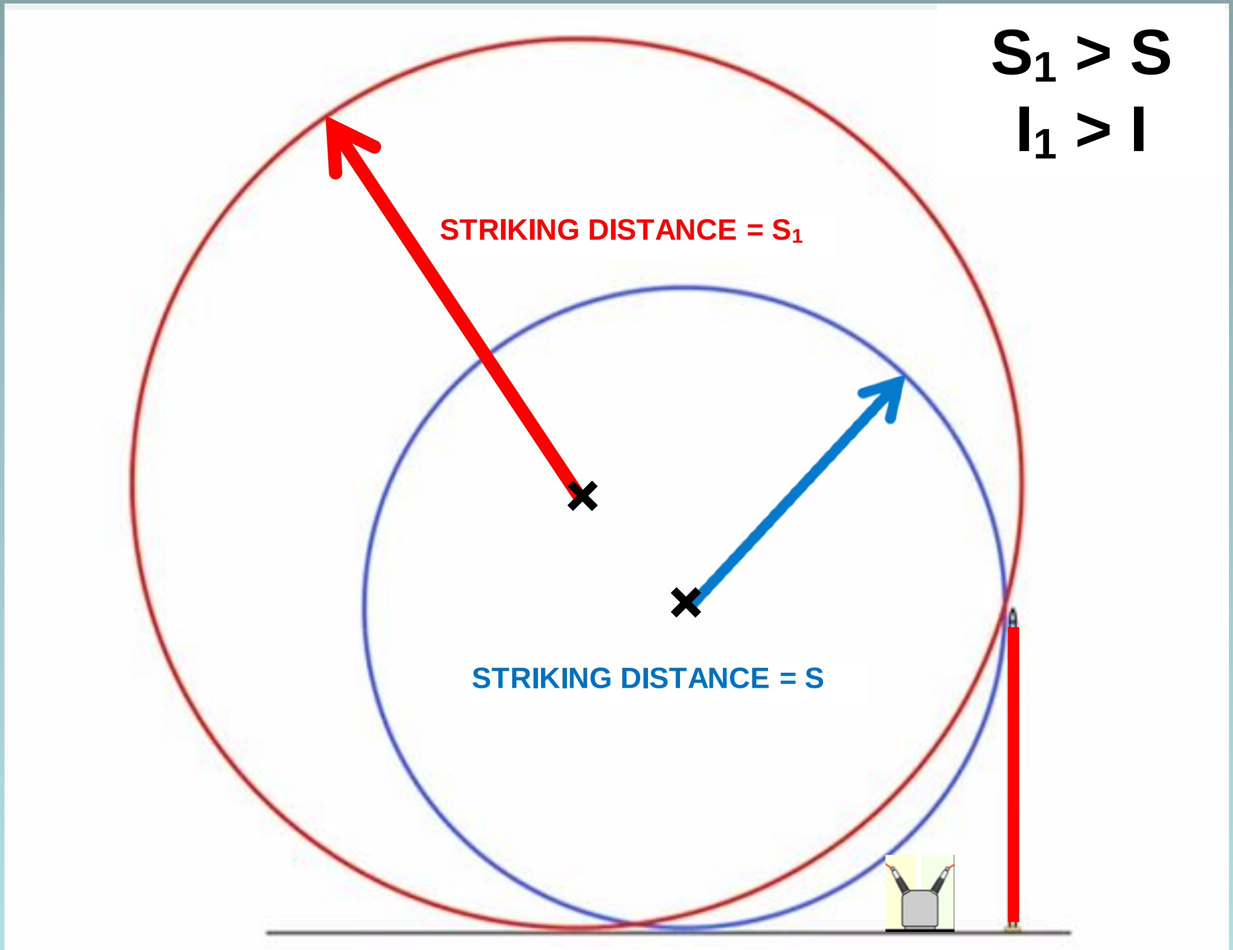


Principle of Rolling Sphere

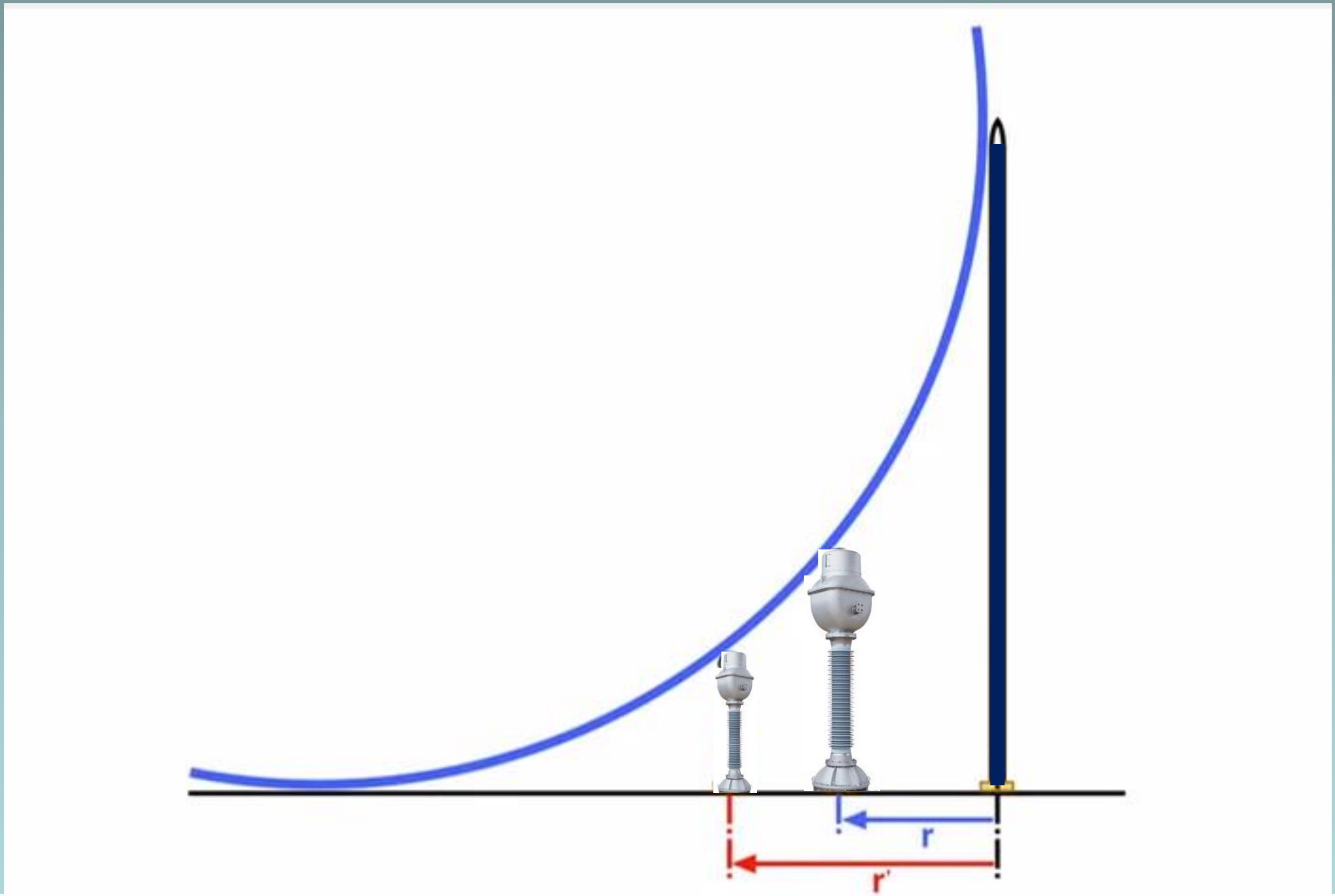


Principle of Rolling Sphere

$$S_m = 8 \cdot k \cdot I^{0.65}$$

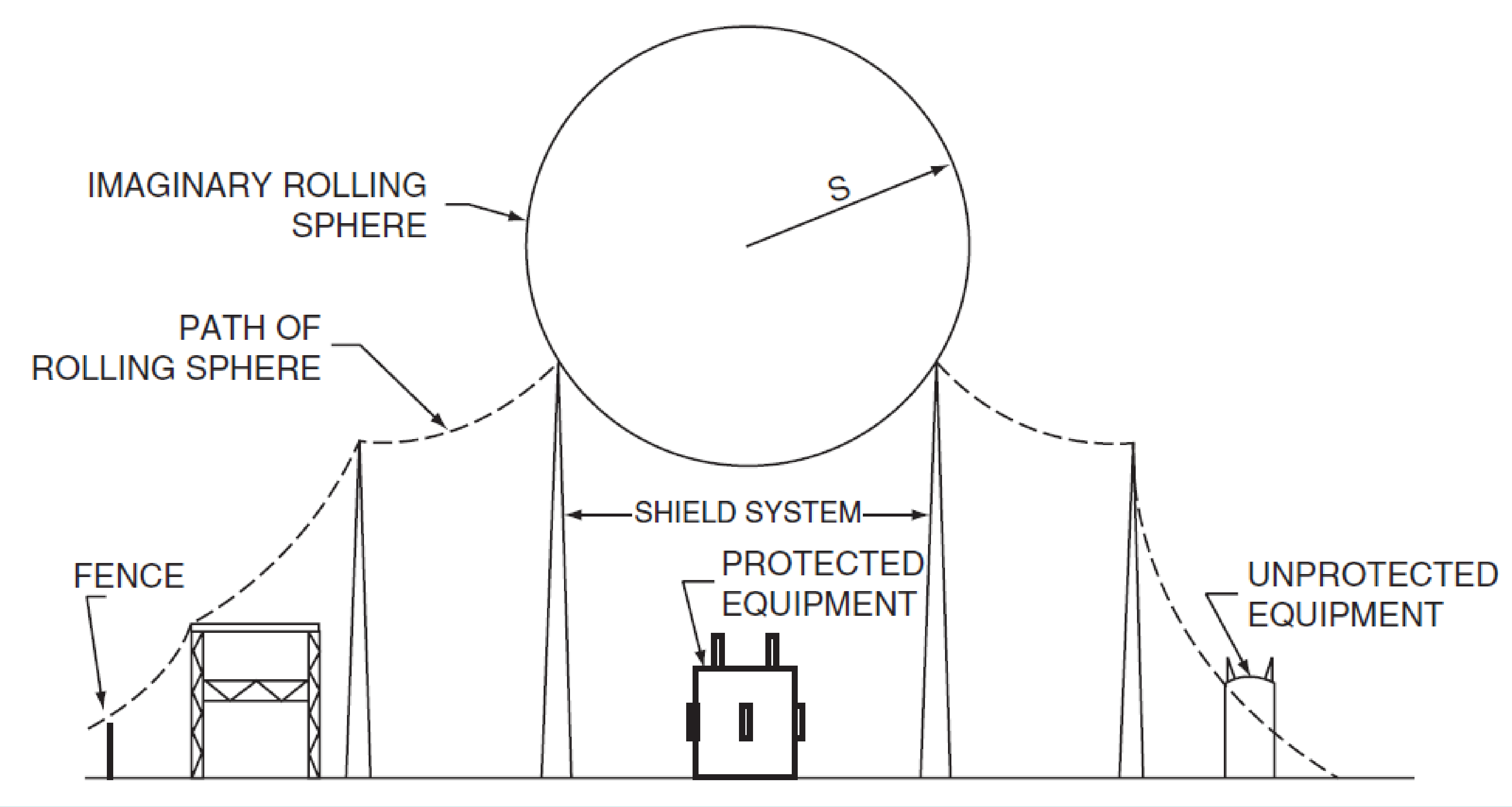


Radius of Protection – Single Mast

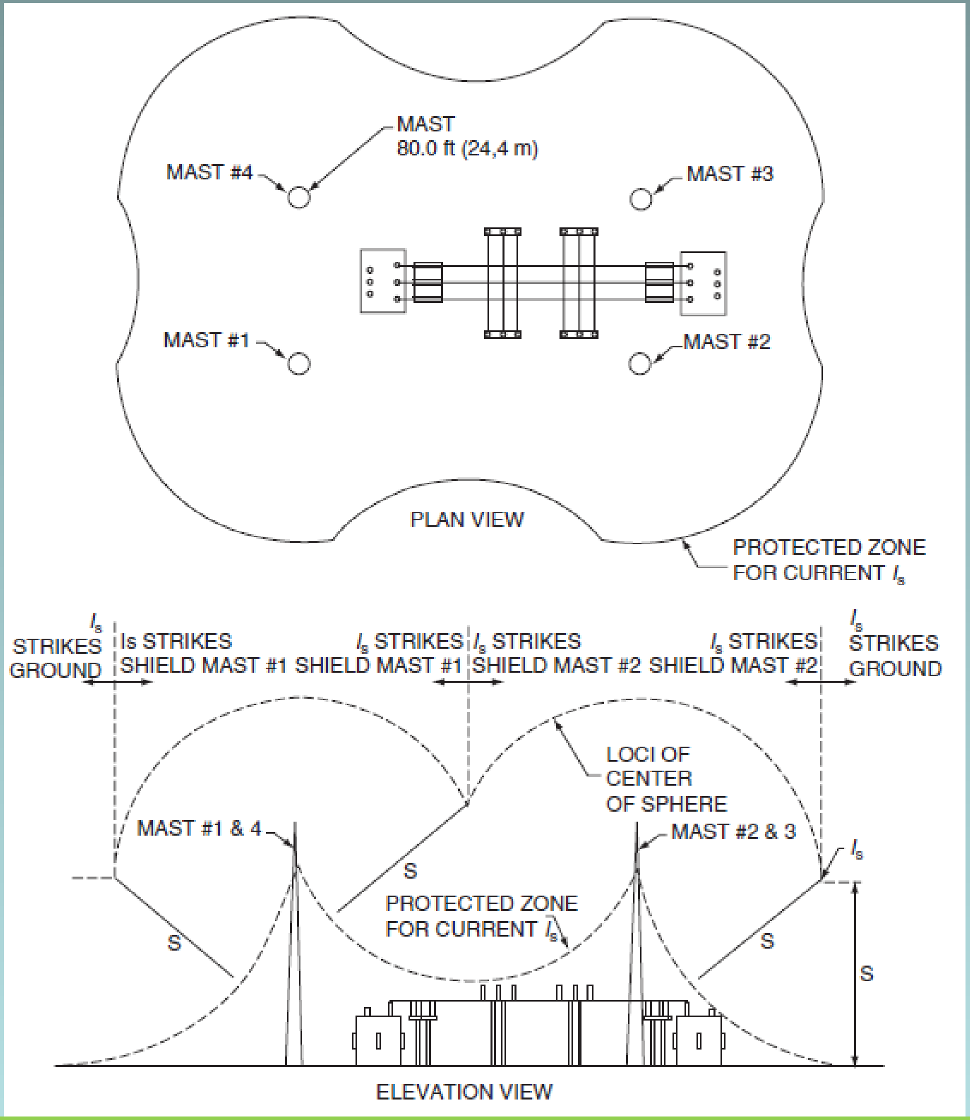


Height of the equipment affects radius of protection

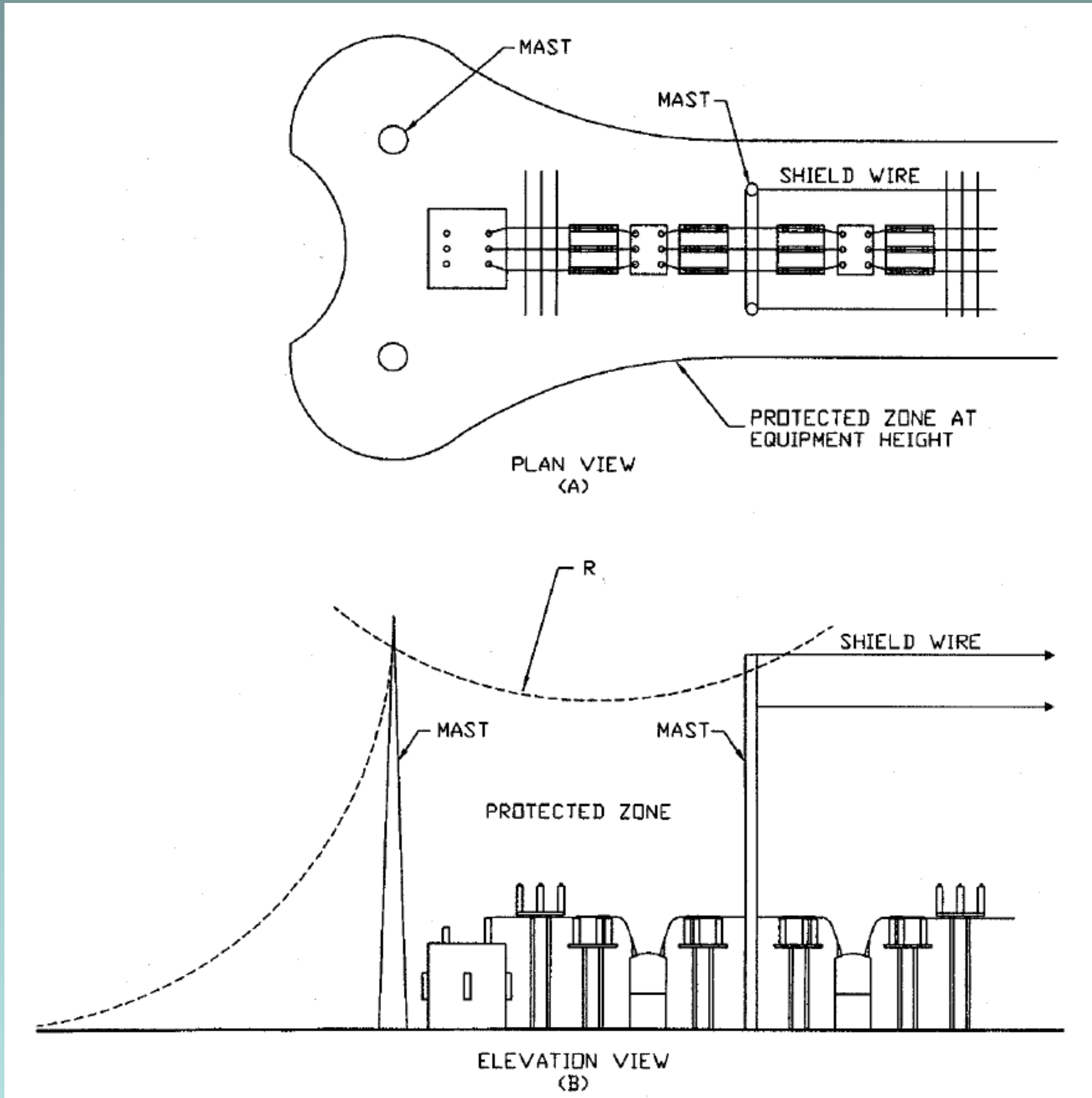
Principle of Rolling Sphere



Multiple Shielding Electrodes

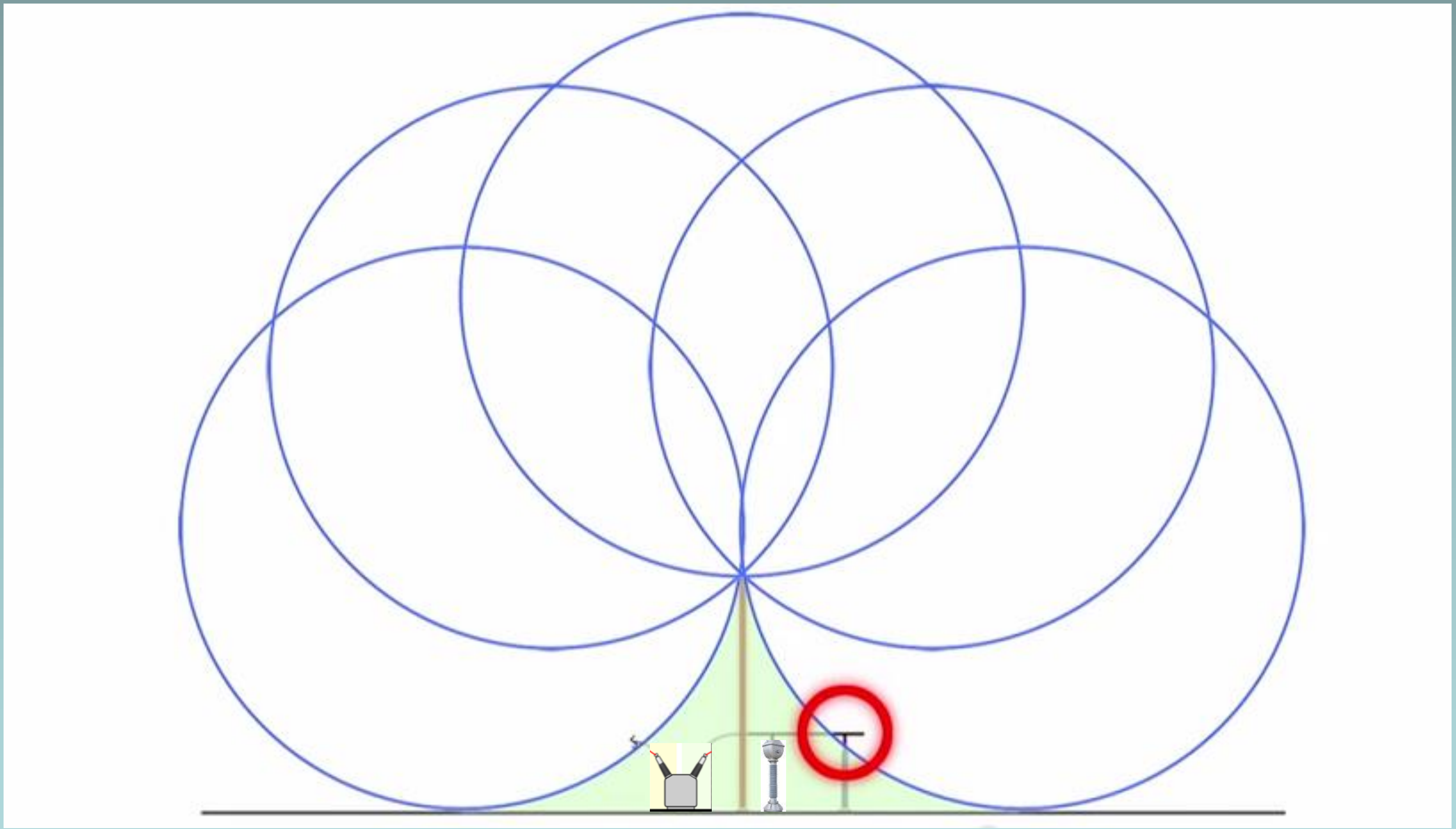


Protection by Shield Wires and Masts

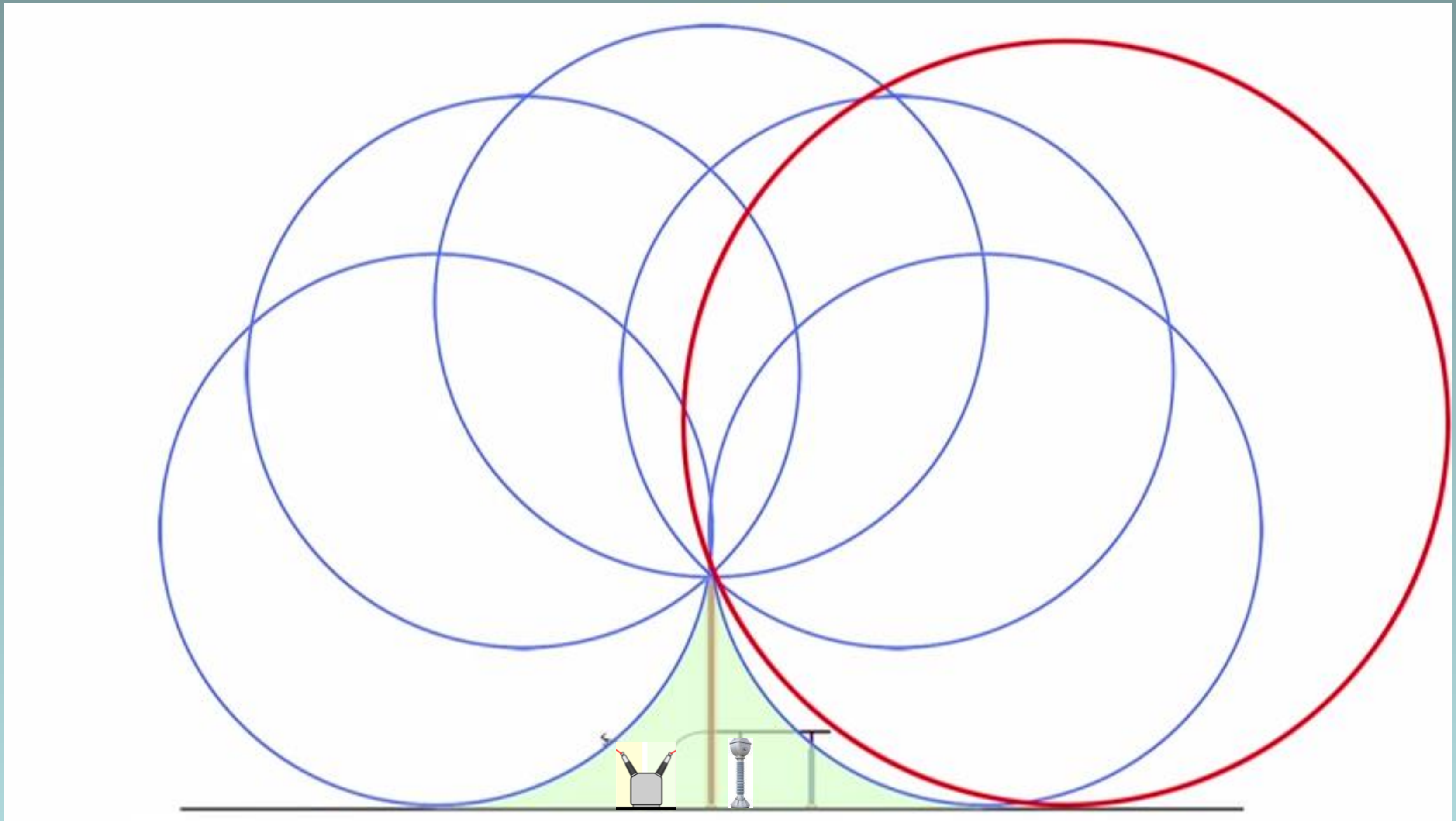


FAILURE PROBABILITY

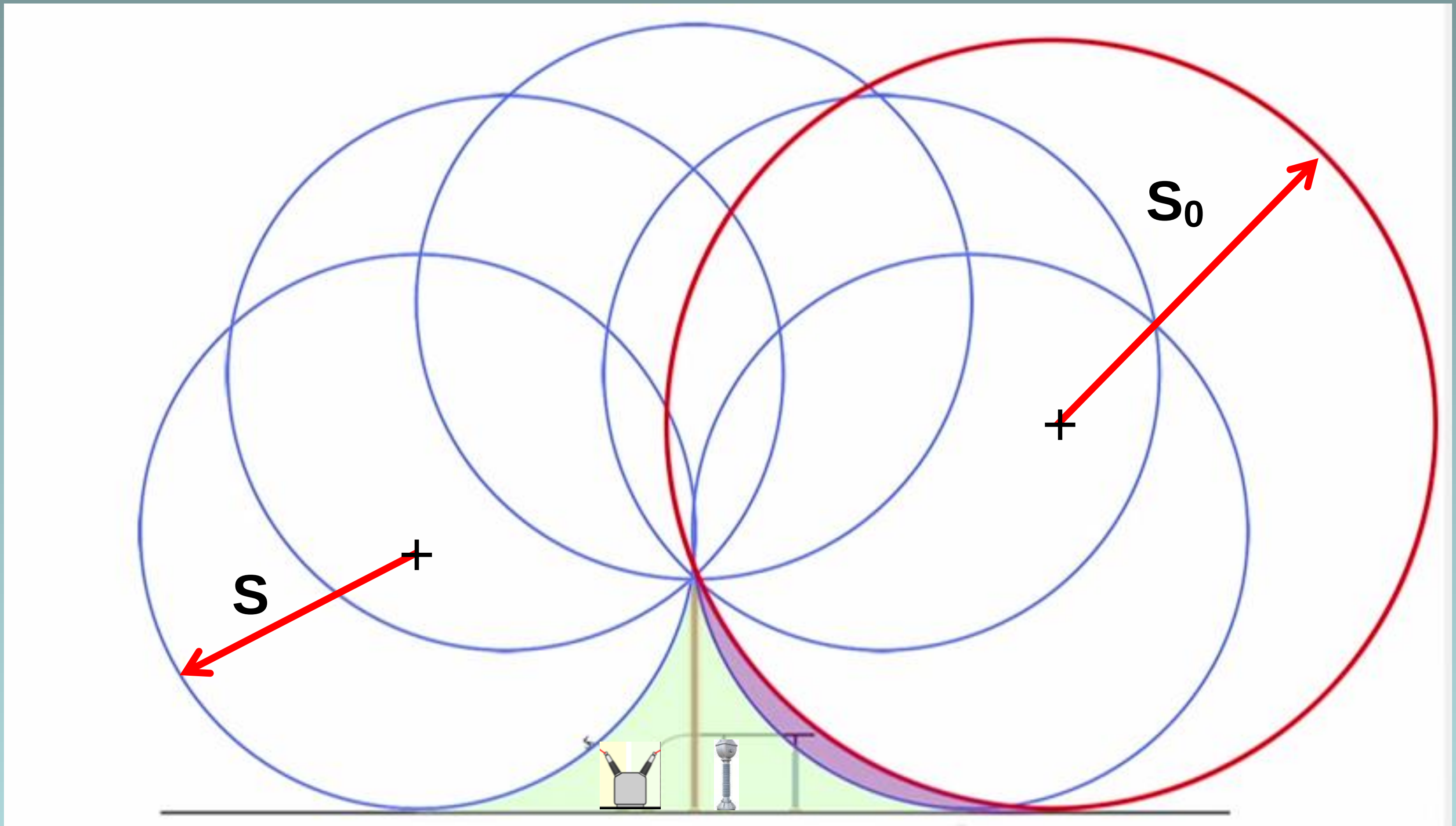
Failure Probability



Failure Probability

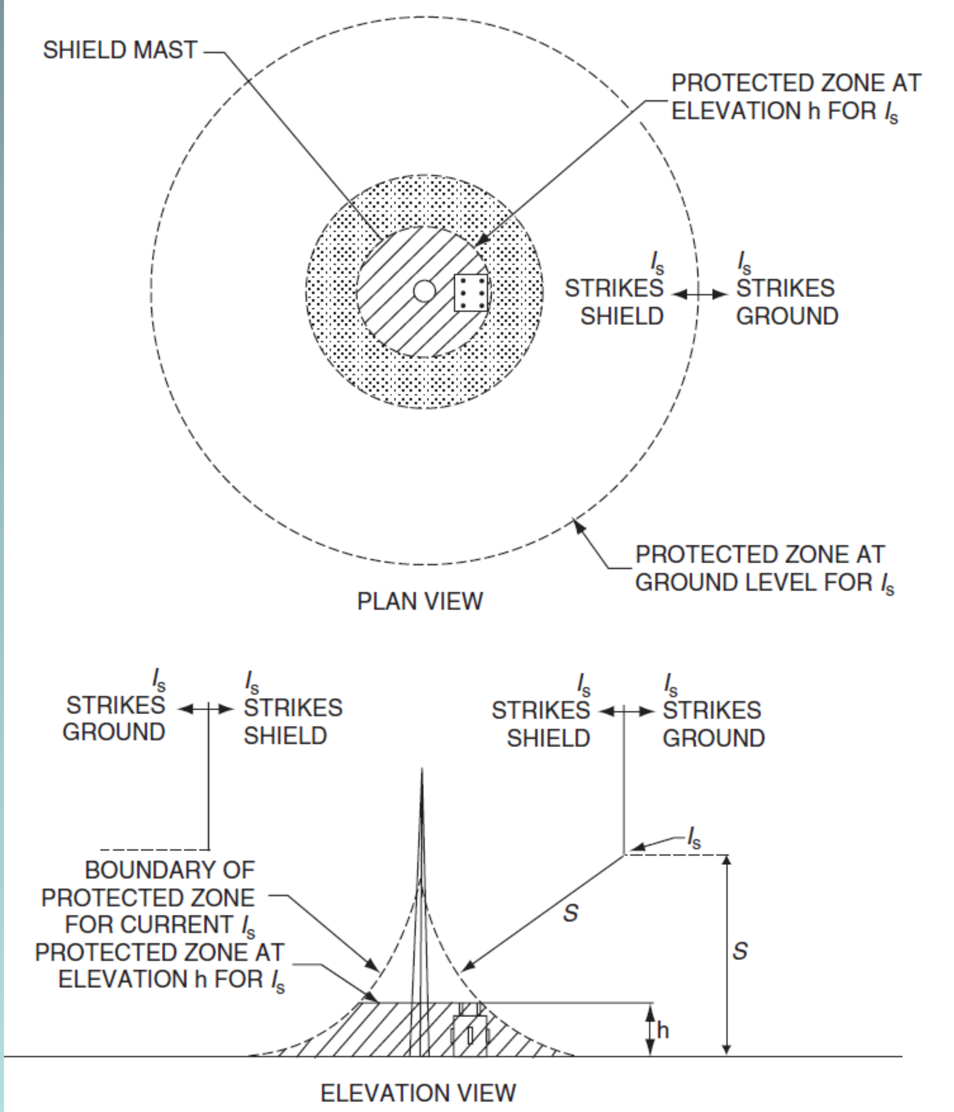


Failure Probability



$$P(f) = P(I_s) - P(I_{s0})$$

Failure Probability

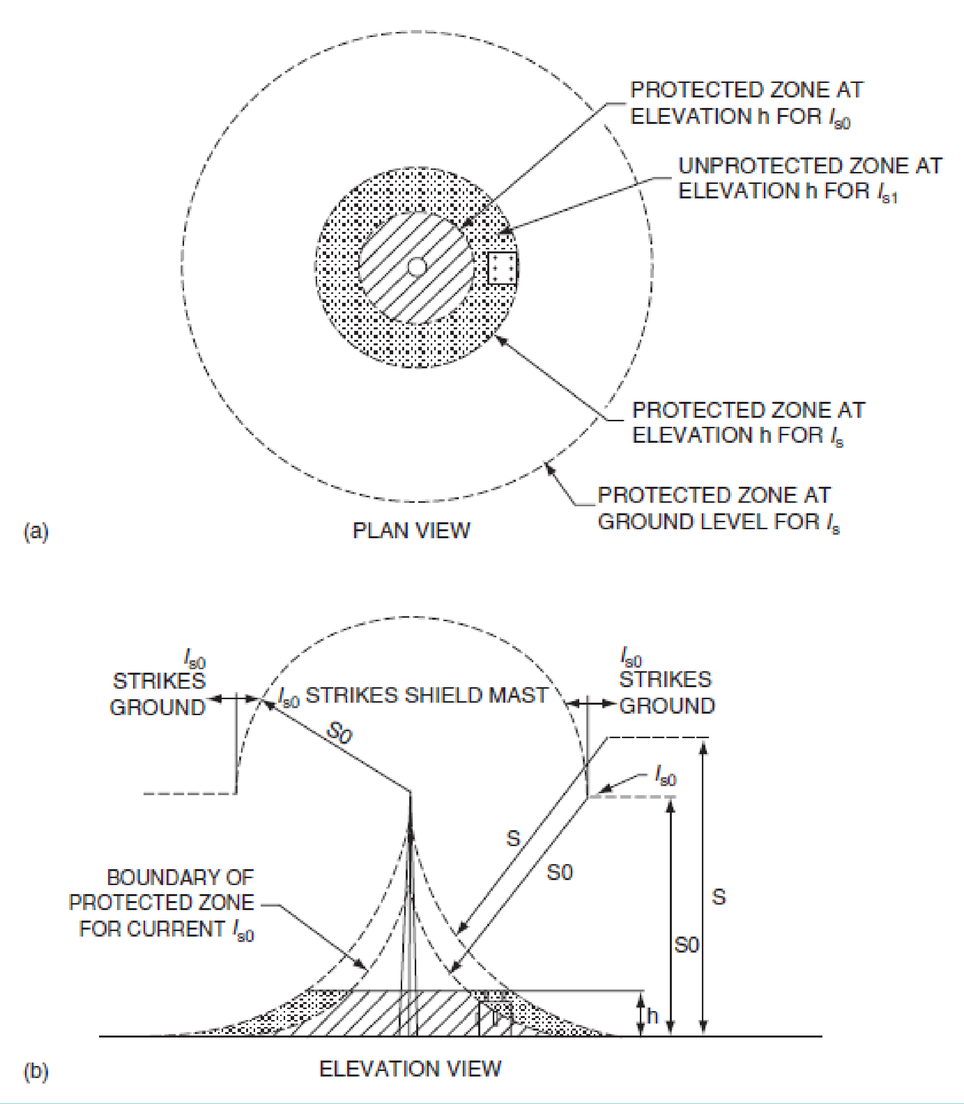


Failure Probability

$$I_s = \frac{2.2 \cdot BIL}{Z_s}$$

$$S = 8 \cdot k \cdot I_s^{0.65}$$

$$S > S_0$$
$$I_s > I_{s0}$$



Failure Probability

Example: Vm=145kV, BIL=650kV, Z=355Ω

$$I_s = \frac{2.2 \cdot BIL}{Z_s}$$

$$I_s = \frac{2.2 \cdot 650}{355} = 4.03kA$$

$$I_{s0} = 4.03 \text{ kA}$$

$$S_0 = 8 \cdot k \cdot I_s^{0.65} = 20\, m$$

Assume the strike distance, S, above which protection is provided, is 40 m

$$S = 40\, m$$

$$I_s = 11.89 \text{ kA}$$

$$4.03\, kA < I < 11.89 \text{ kA (Unprotected Zone)}$$

Failure Probability - Example

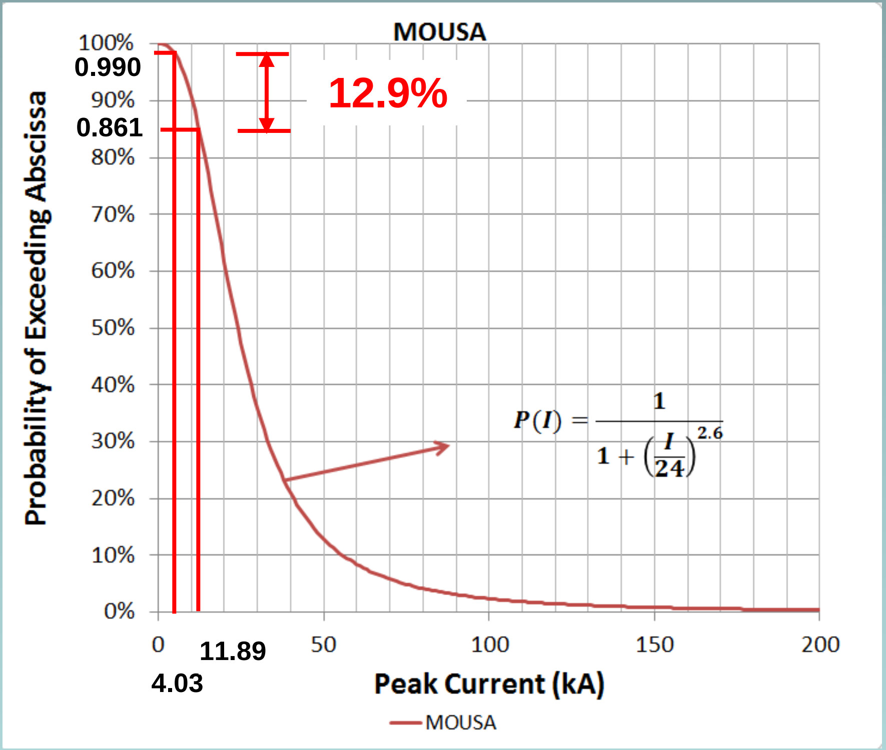
The probability that a stroke current will exceed I_{s0} and I_s

$$P(I) = \frac{1}{1+\left(\frac{I}{24}\right)^{2.6}}$$

$$P(I > 4.03) = 0.990$$

$$P(I > 11.89) = 0.861$$

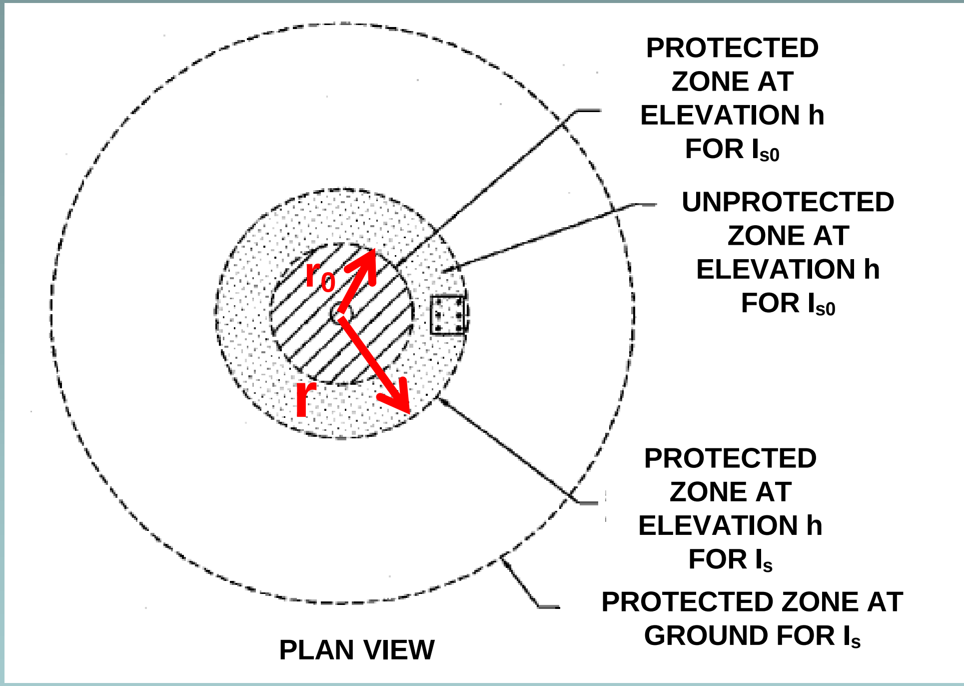
$$P(f) = P(I_{s0}) - P(I_s)$$



$$P(f) = 0.990 - 0.861 = 0.129 = 12.9\%$$

FAILURE RATE

Failure Rate - Example



$$r_0 = 22\ m$$

$$r = 35\ m$$

$$UNPROTECTED\ AREA = \pi\left[\left(35^2\right) - \left(22^2\right)\right] = 0.002328 km^2$$

Failure Rate - Example

Assume the isokeraunic level is 50 thunderstorm-days per year (T_d = 50)

$$N_k = 0.12 \cdot T_d$$

$$N_k = 0.12 \cdot 50 = 6\ strokes\ per\ km^2 per\ year$$

The annual number of strokes expected to descend into the unprotected area is:

$$6 \cdot 0.002328 = 0.01397\ strokes\ per\ year$$

Failure Rate - Example

The annual expected number of equipment failures due to direct lightning strokes, using the 12.9% probability

0.01397 x 0.129 = 0.00180 failures/year
= 556 years between failure

If the utility company has 30 substations

556/30= 18.5 years between failure

Electrogeometric Method: Summary

- **Major difference (Fixed-Angle and Empirical Methods): Shielding design is based on the BIL (CFO), Surge Impedance, Lightning current probability distribution, and lightning strike propagation.**

Electrogeometric Method: Summary

- **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.**

Electrogeometric Method: Summary

- **Direct stroke shielding complemented by appropriately selected surge arrester provides the necessary protection.**

LIGHTNING PROTECTION OF TRANSMISSION LINES

Route Selection

- **Many factors play an important role in route selection.**
- **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.**

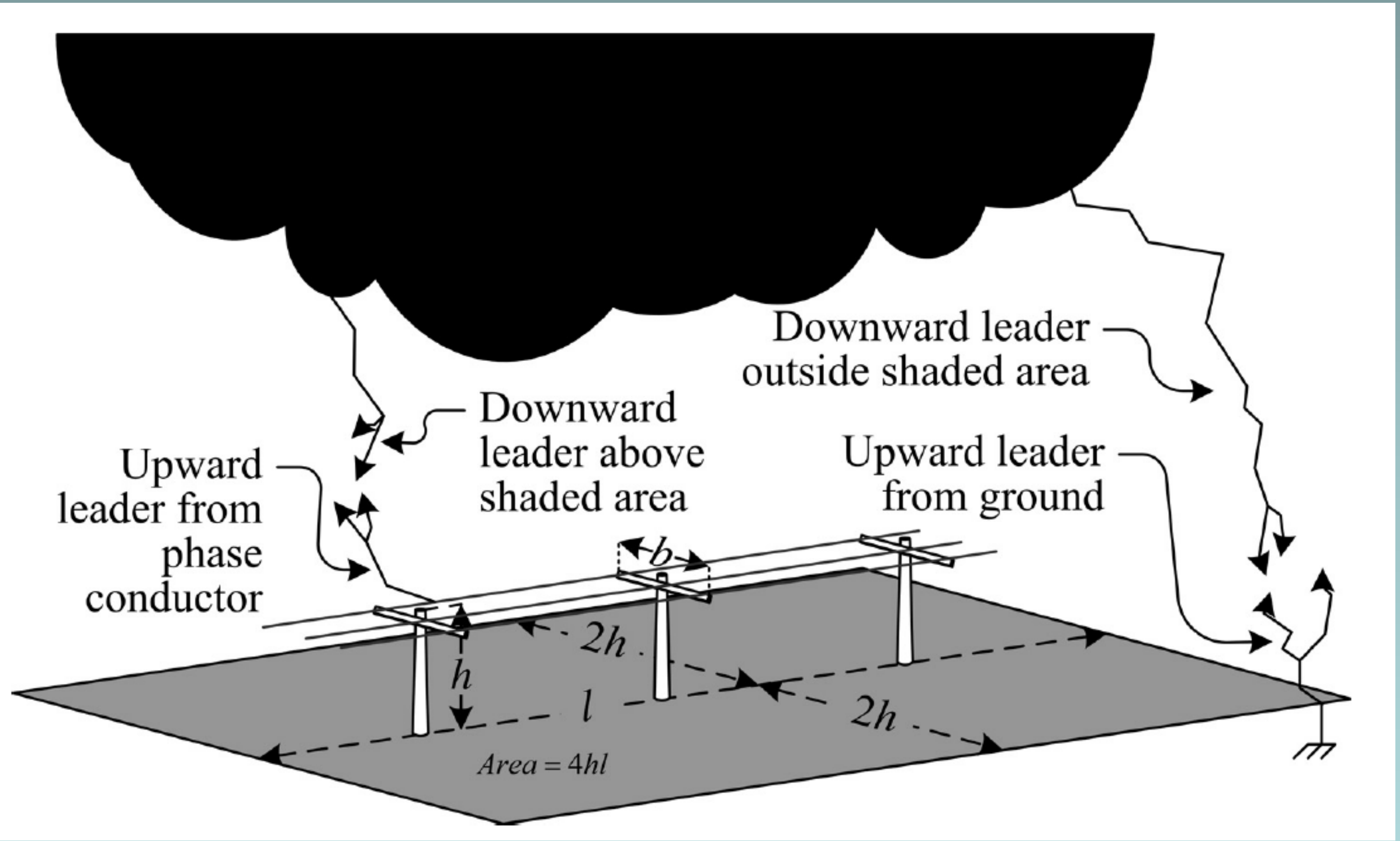
Route Selection

- **Lightning location systems and flash-counter networks (GFD maps).**
- **Structures located along the top of mountains, ridges, or hills will be likely targets for lightning strikes.**
- **It is preferable to locate structures along mountain sides.**
- **Soil resistivity may be different for alternate routes.**

Route Selection

- **High structure footing impedances cause increased voltages and more lightning outages for a given lightning exposure.**
- **One way to prevent structures from being a target for lightning is to take advantage of surrounding forestation.**
- **Route the line next to existing transmission line structures.**

Structure Height



Structure Height

The first factor of a line route that affects lightning performance is structure height

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

h - Tower height (m)
b - OHGW separation distance (m)
N_g - GFD (flashes/km^2/yr)
N_s - flashes/100km/yr

If the tower height is increased by 20%, the flash rate to the line would increase by 12%

Soil Resistivity

- **The ground electrode sizes and shapes will depend on the range of soil conductivities.**
- **High footing impedance occur in rocky terrain**
- **Methods of improving footing impedance: large ring or radial crowfoot installation.**

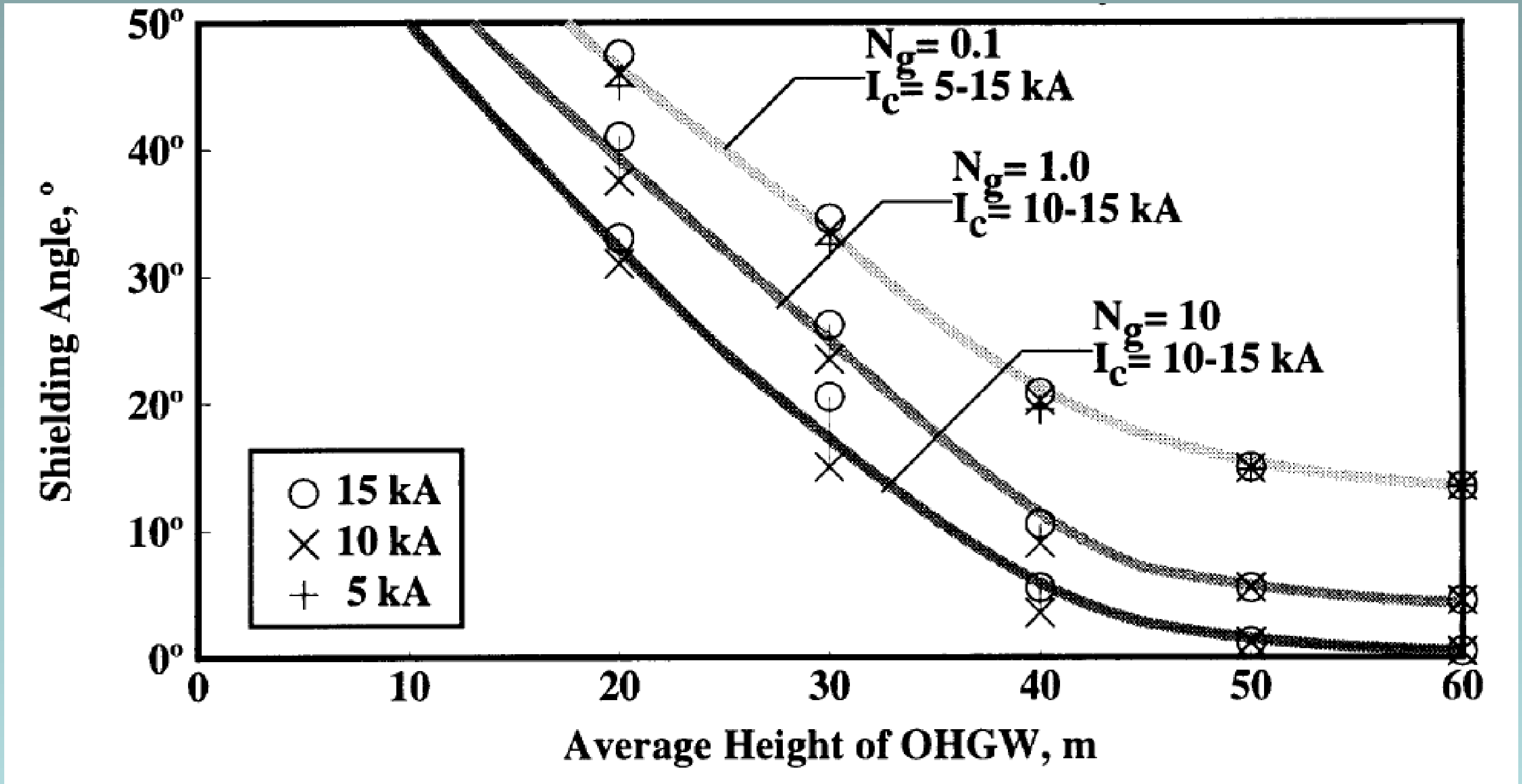
Shielding Angle - Transmission Lines

Height of earth wire in m	Shielding failure/100 km per year with protective angle: 15°	20°	25°	30°	35°	40°	45°
10	0	0	1.1E-4	0.0087	0.0383	0.1032	0.2286
15	0	6.4E-5	0.0068	0.0351	**0.0982**	**0.2182**	0.4483
20	8.3E-6	0.0026	0.0214	**0.0711**	**0.1695**	0.3466	0.6903
25	0.0011	0.0087	0.0404	**0.1123**	0.2468	0.4819	0.9429
30	0.0035	0.0170	**0.0620**	**0.1565**	0.3275	0.6208	1.2008
35	0.0069	0.0269	**0.0853**	**0.2024**	0.4100	0.7616	1.4608
40	0.0109	0.0378	**0.1096**	0.2494	0.4936	0.9035	1.7214
45	0.0155	0.0493	**0.1345**	0.2969	0.5776	1.0462	1.9820
50	0.0204	**0.0612**	**0.1598**	0.3447	0.6619	1.1892	2.2423

0.1 - 0.2 shielding failure/100km/year is recommended

Shielding Angle

Shielding Failure Flashover Rate (SFFOR) = 0.05 flashover/100km-year

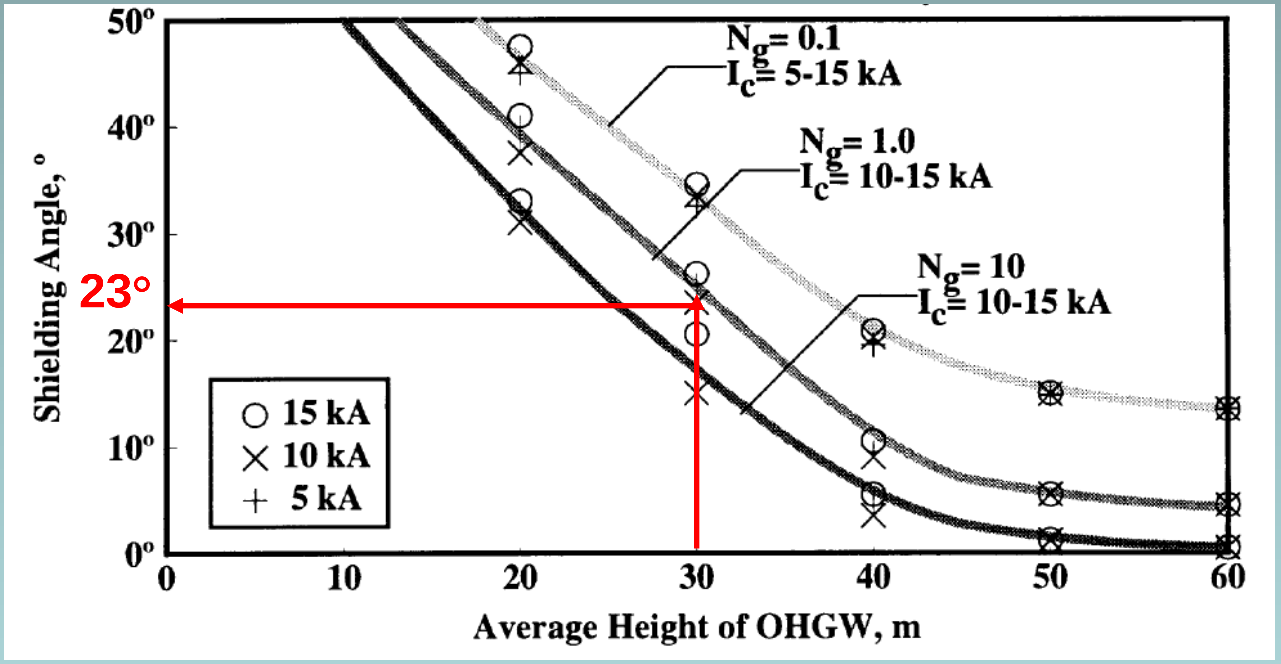


N_g = GFD

Shielding Angle

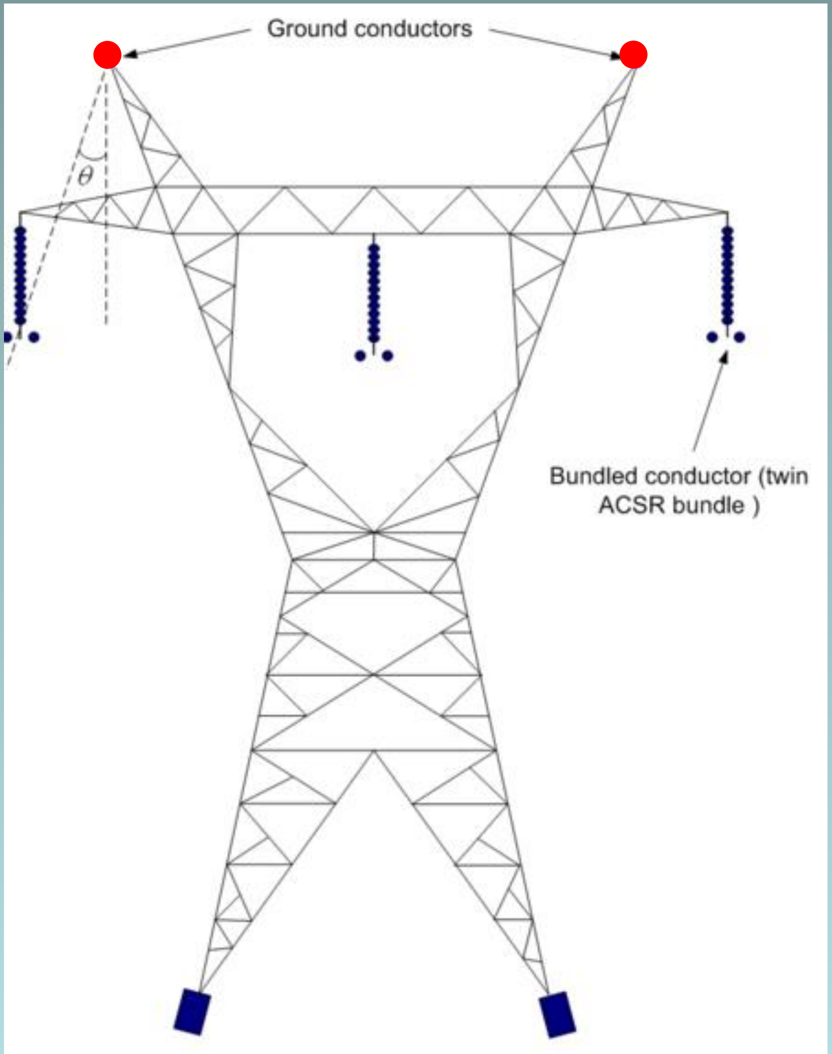
Shielding Failure Flashover Rate (SFFOR) = 0.05 flashover/100km-year

Example:
N_g = 1 flashes/km^2/yr
OHGW height = 30 m
I_c = 10 kA
Shielding Angle = 23°

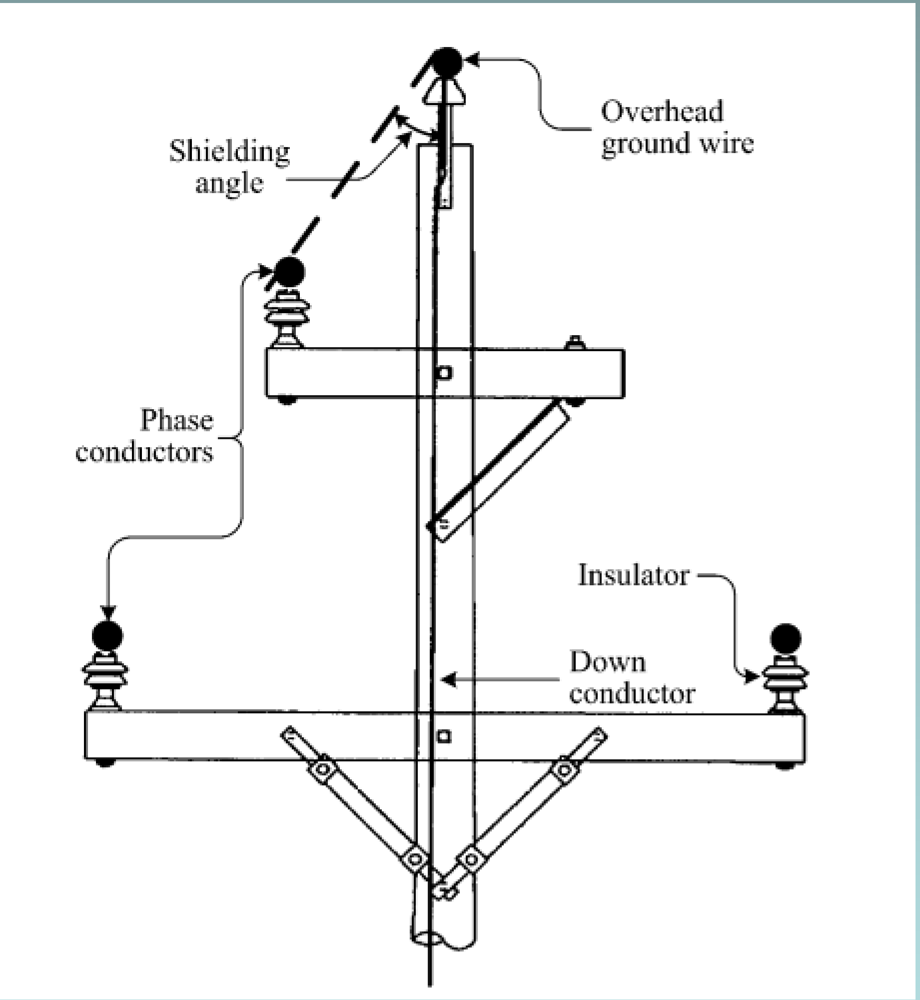


Lightning Protection – Transmission Line

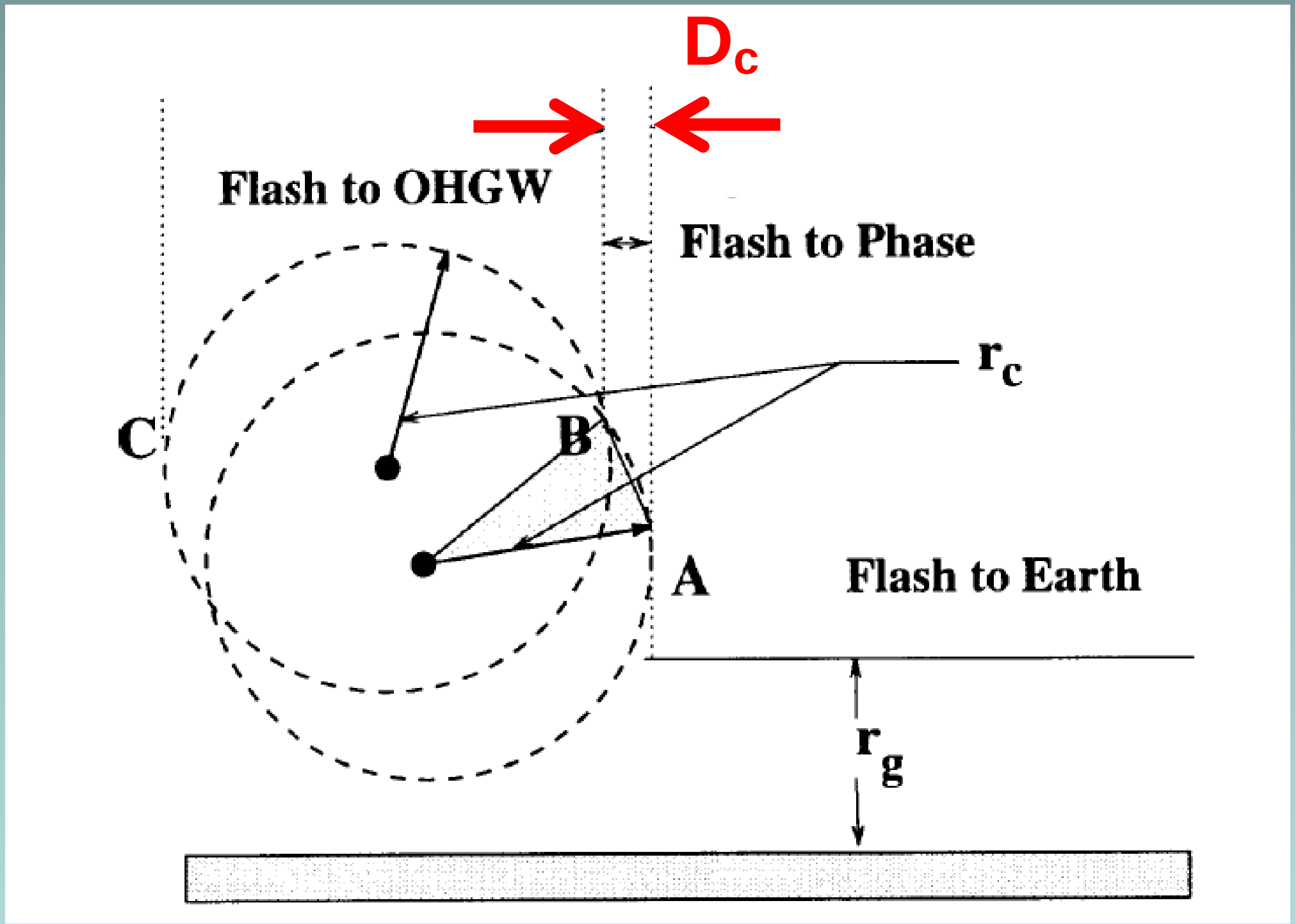
Shielding Angle



Lightning Protection – Distribution Line

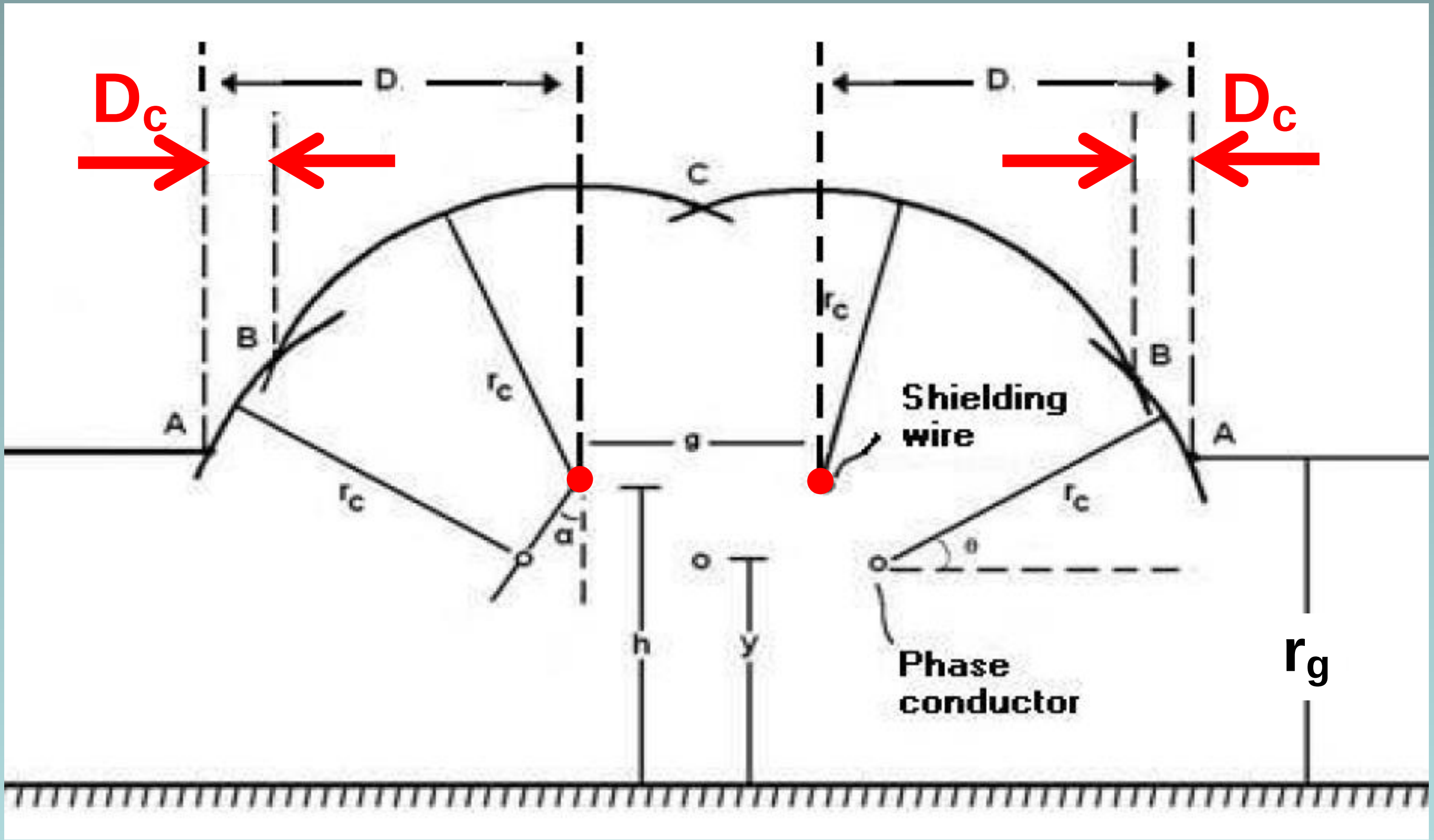


Exposed Distance for Final Jump in EGM



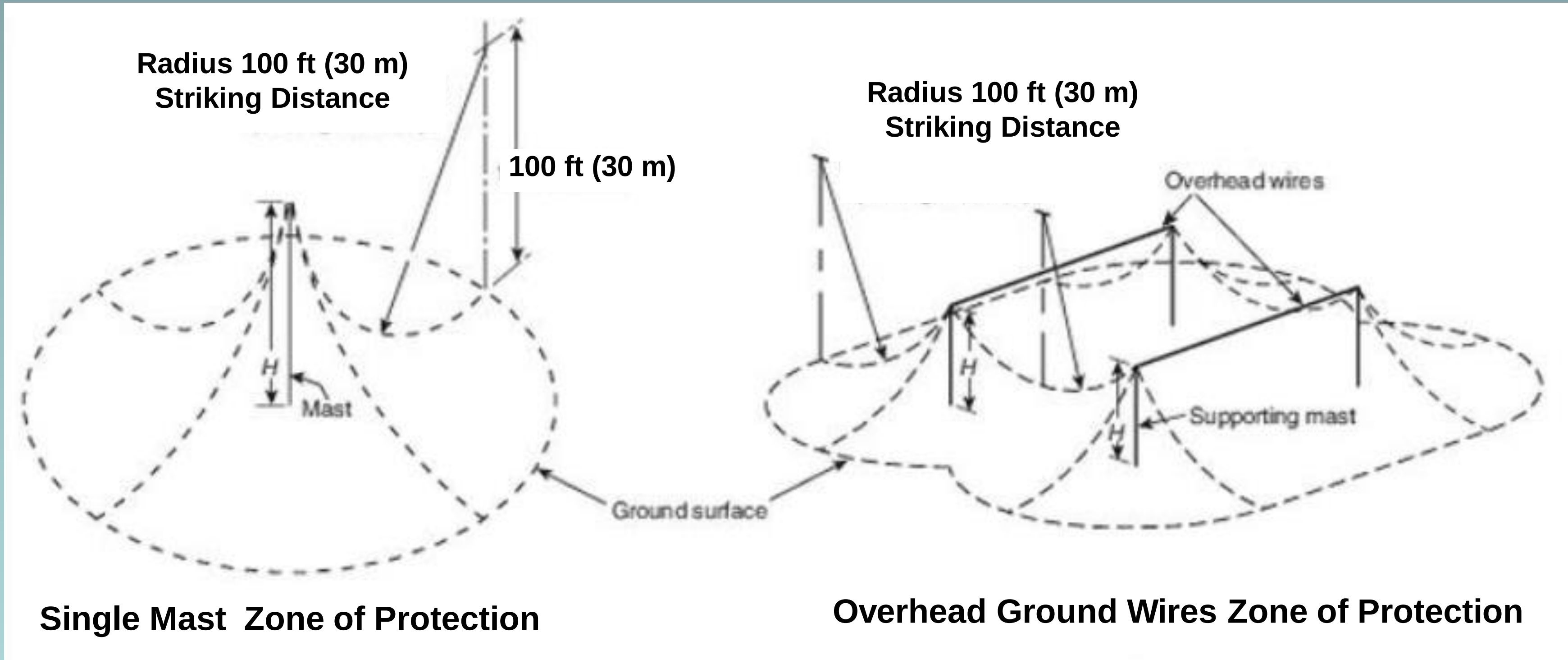
D_c - Exposure Distance for a shielding failure

Lightning Protection – Transmission Line



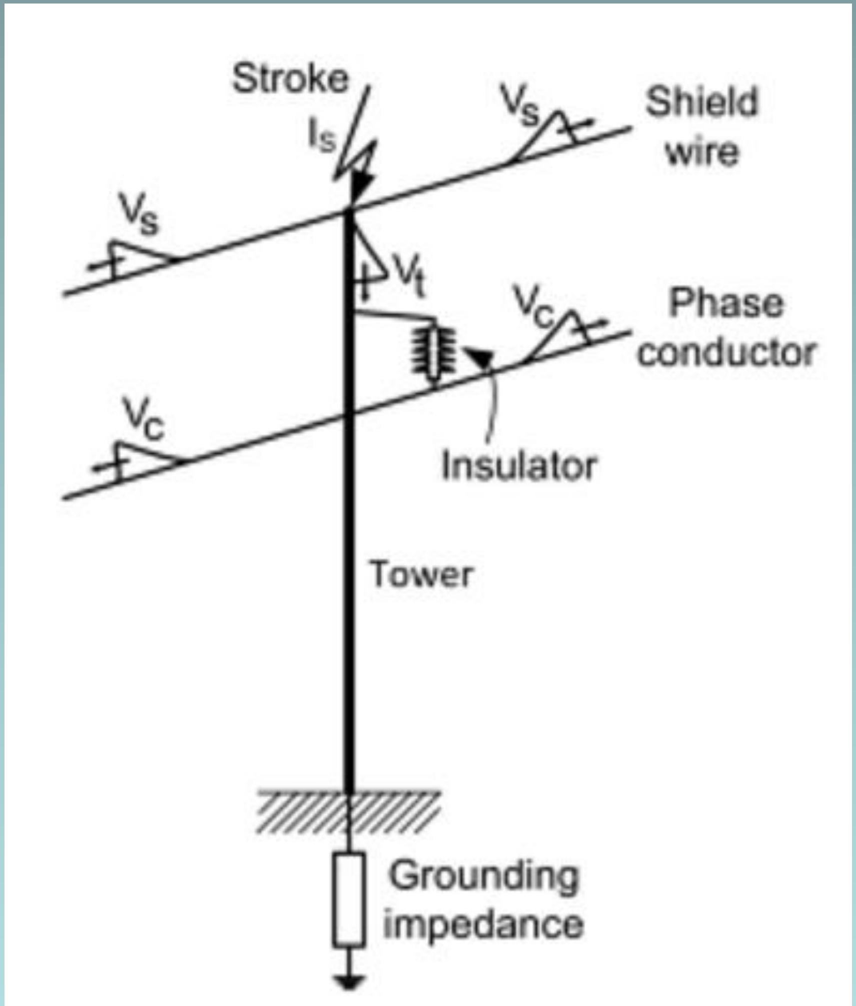
INDUSTRIAL APPLICATION

Structures Containing Flammable Products



GROUNDING

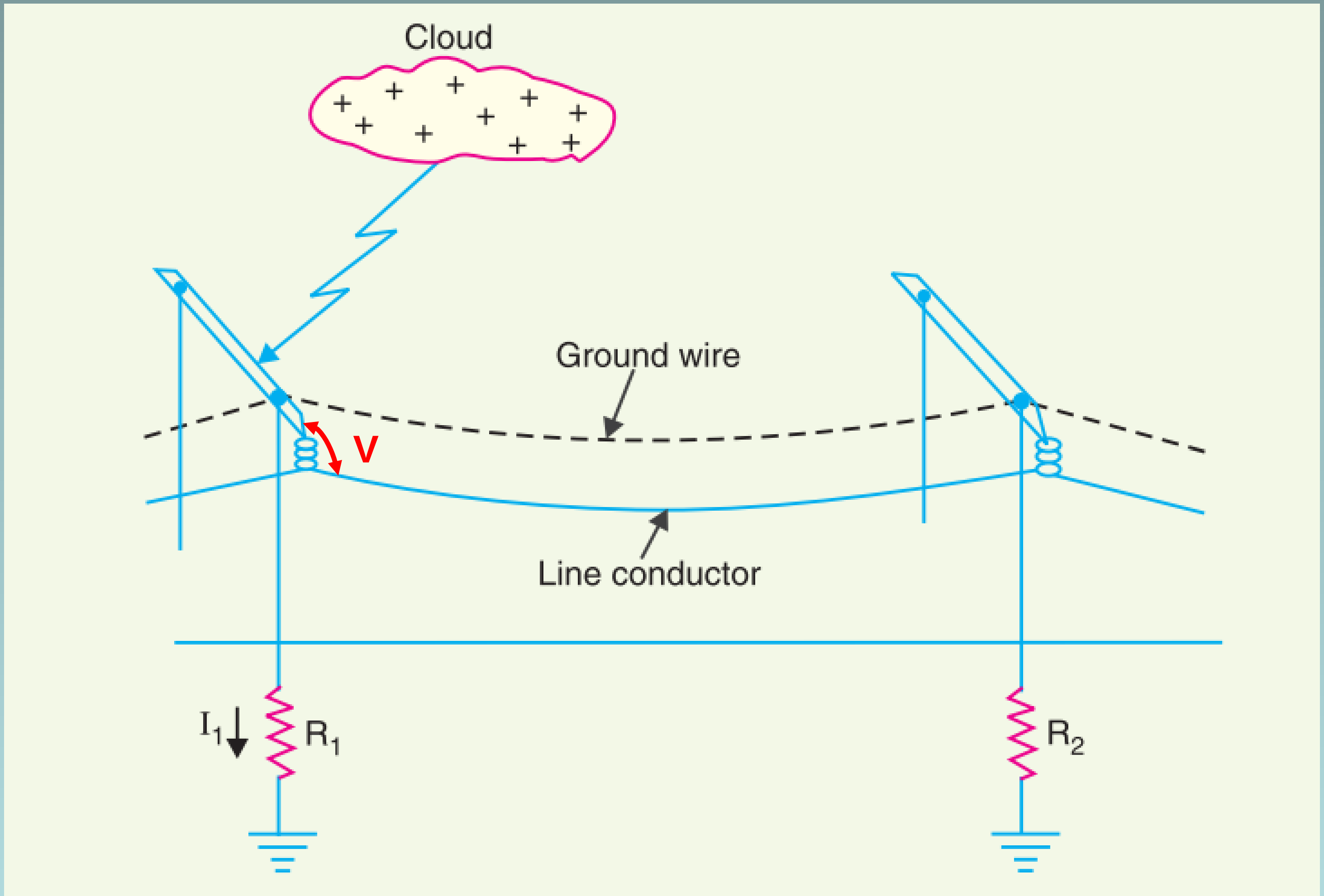
Grounding Impedance



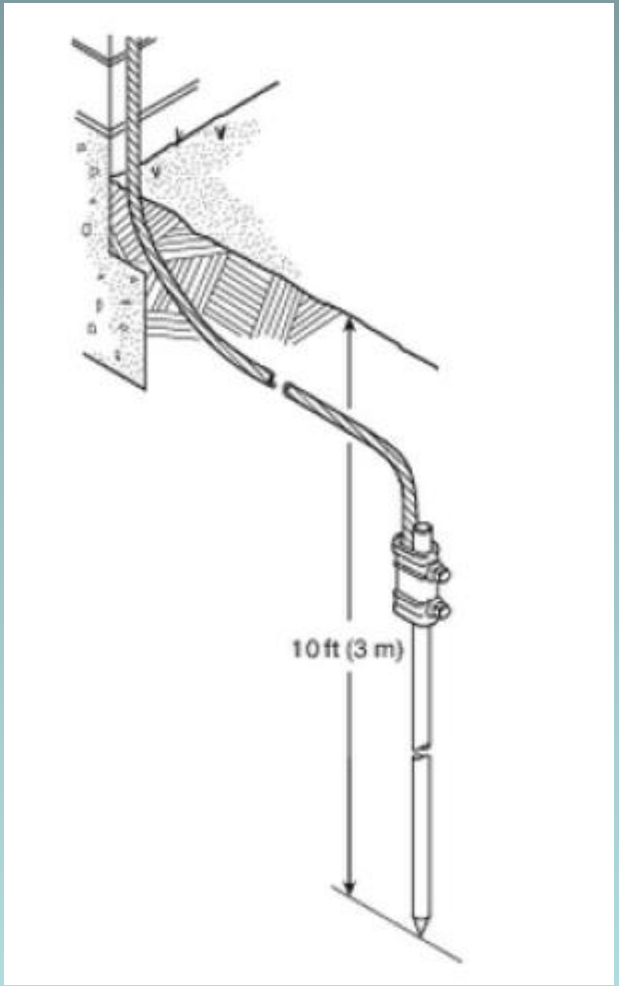
Classes of Overvoltages

I_1 = 50kA
R_1 = 50 Ω
V_t = 2500 kV

I_1 = 50kA
R_1 = 10 Ω
V_t = 500 kV



Typical Single Ground Rod Installation



Ground Rods

- **Ground rods shall be not less than ½ in (12.7 mm) in diameter and 8 ft (2.4 m) long.**
- **Rods shall be free of paint or other nonconductive coatings.**
- **The ground rods shall extended vertically not less than 10 ft (3 m) into the earth.**
- **The earth shall be compacted and made tight against the length of the conductor and ground rod.**
- **Where multiple connected ground rods are used, the separation between any two ground rods shall be at least the sum of their driven depths, where practicable.**
- **Ground rods shall be copper-clad, solid copper, or stainless steel.**

Grounding

$$R = \frac{\rho}{2\pi s} ln\left(\frac{2s}{r}\right)$$

R - Resistance (Ω)
ρ - Earth resistivity (Ω.m)
s - Length of the rod in contact with the Earth
r - Rod radius (m)

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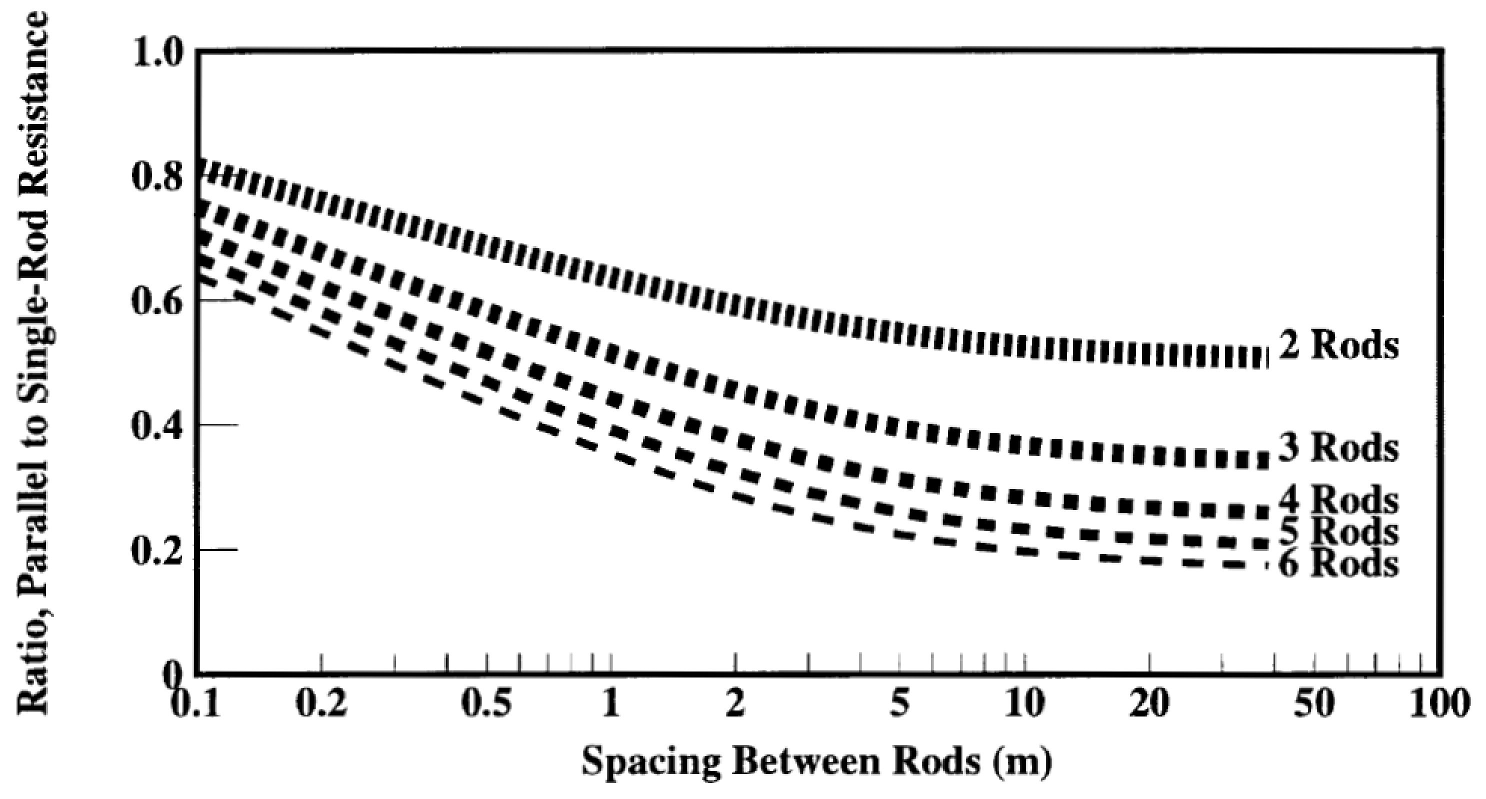
HIGH VOLTAGE POWER ENGINEERING SERVICES

Supplemental Grounding

Increasing the number of rods in parallel is also more effective.



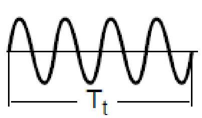
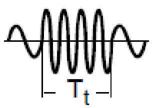
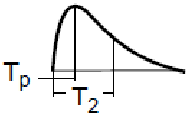
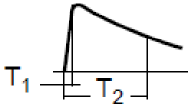
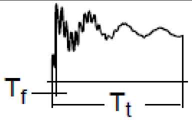
Rods are 20mm diameter, 3 m deep

TRANSIENT OVERVOLTAGE

Overvoltages

- **Lightning Overvoltages**
- **Switching Overvoltages**
- **Temporary System Overvoltage**

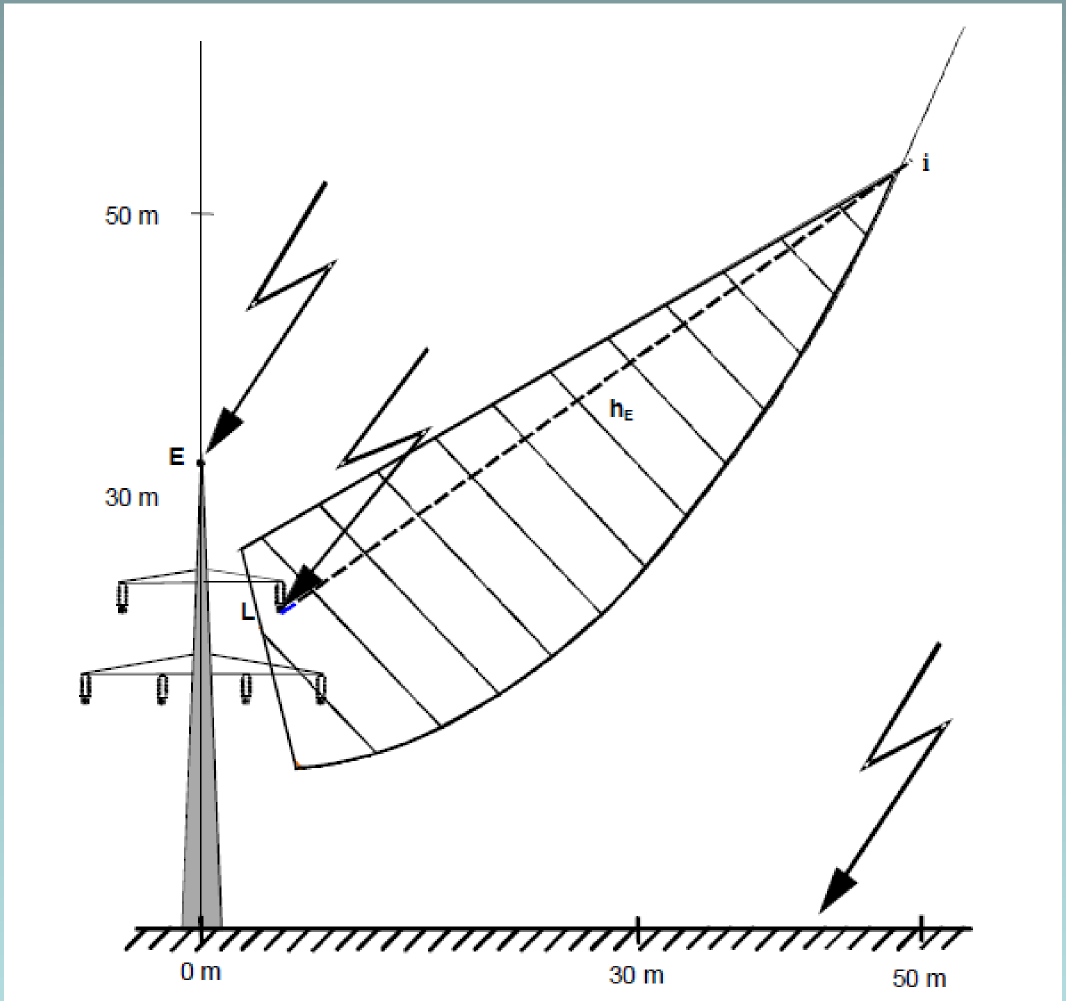
Classes of Overvoltages

overvoltage class	low frequency		transient		
	permanent	temporary	slow front	fast front	very fast front
shape					
shape range (frequency, rising front, term)	$f = 50$ or 60 Hz $T_t \geq 3{,}600$ s	$10 < f < 500$ Hz $3{,}600 \geq T_t \geq 0.03$ s	$5{,}000 > T_p > 20$ µs 20 ms $\geq T_2$	$20 > T_1 > 0.1$ µs 300 µs $\geq T_2$	$100 > T_f > 3$ ns $0.3 > f_1 > 100$ MHz $30 > f_2 > 300$ kHz 3 ms $\geq T_t$
standardised shape	$f = 50$ or 60 Hz T_t (*)	$48 \leq f \leq 62$ Hz $T_t = 60$ s	$T_p = 250$ µs $T_2 = 2{,}500$ µs	$T_1 = 1.2$ µs $T_2 = 50$ µs	(*)
standardised withstand test	(*)	short duration power frequency test	switching impulse test	lightning impulse test	(*)

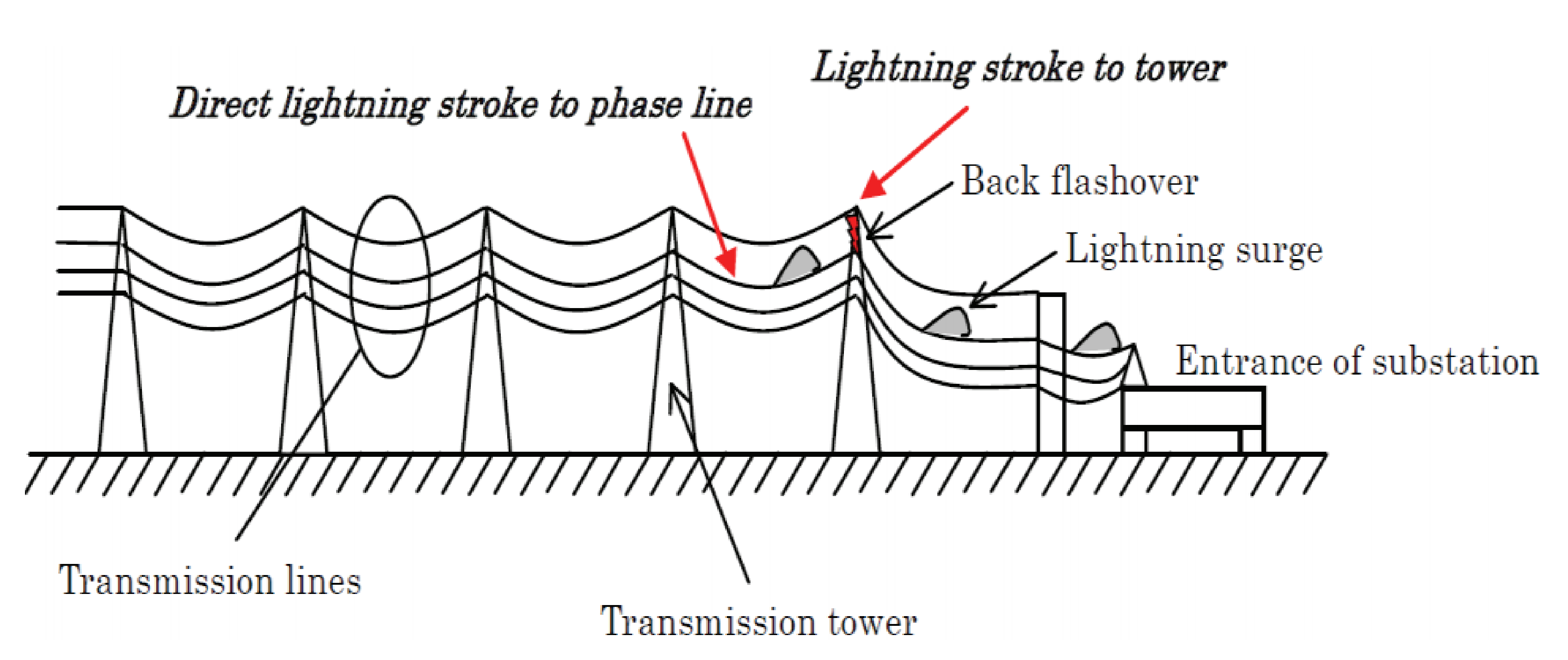
(*) to be specified by the relevant product Committee

LIGHTNING OVERVOLTAGES

Lightning Overvoltages



Lightning Overvoltages



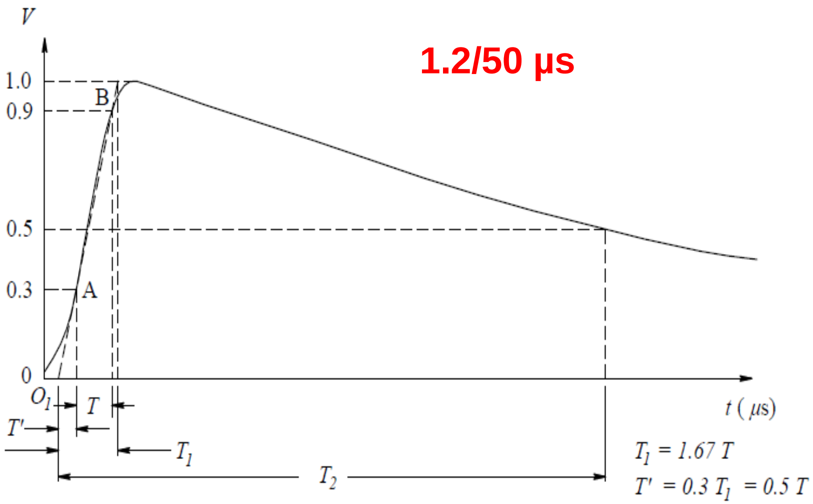
Impulse Voltage Generator

a) 3.2 MV, 320 kJ b) 3.0 MV, 300 kJ

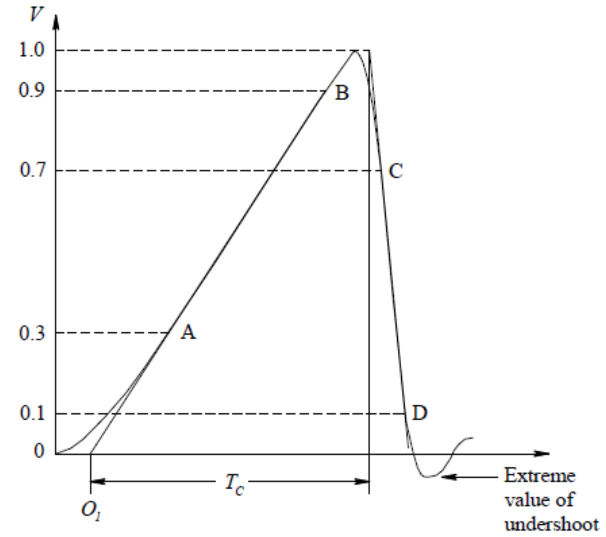
High Voltage Laboratory Insulation Transmission Line Test

Lightning Impulse Voltage

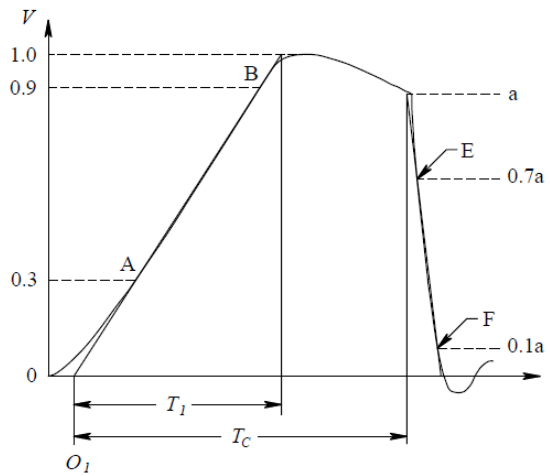
Full-wave Lightning Impulse Voltage



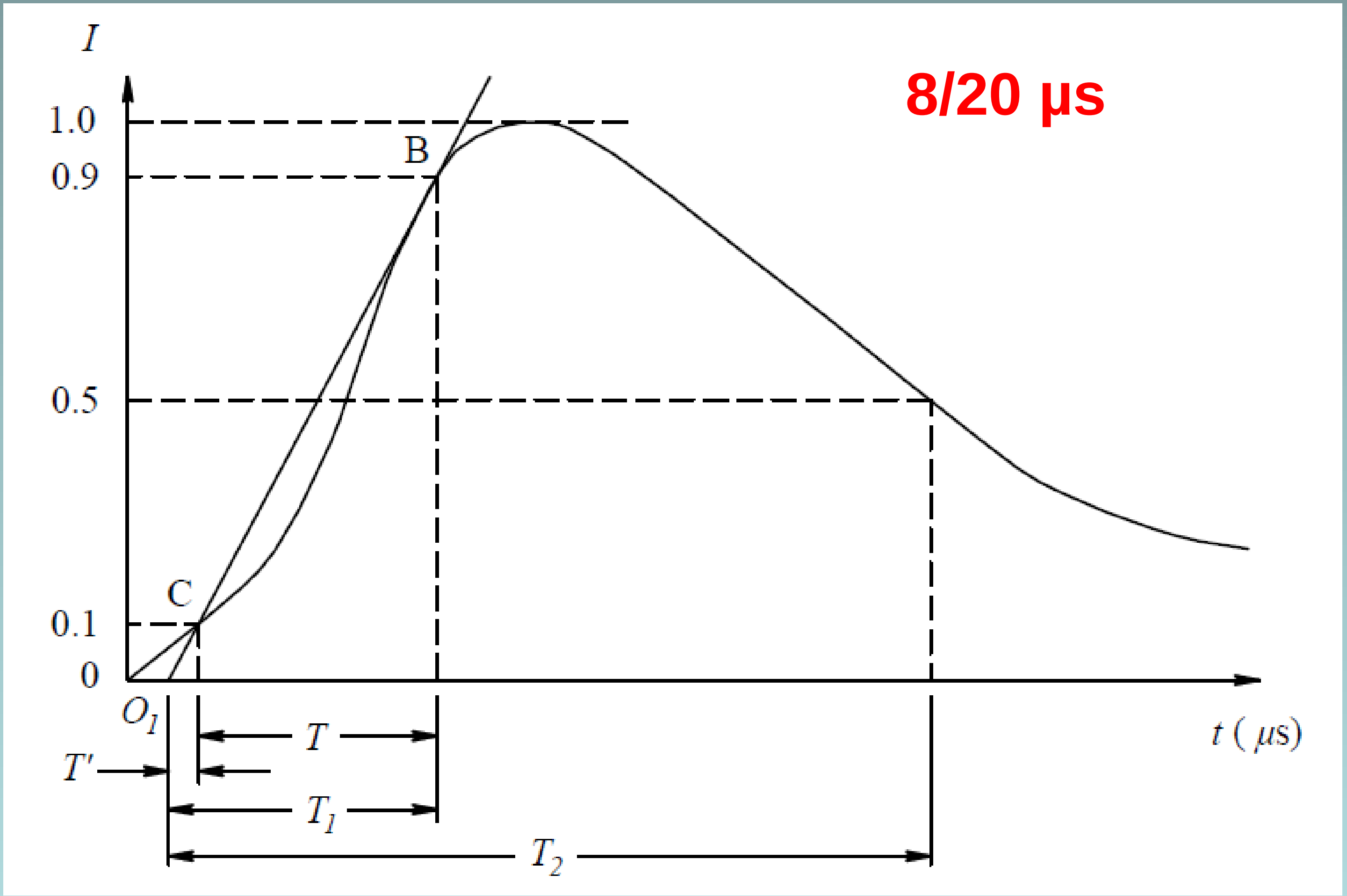
Front-chopped Lightning Impulse Voltage



Tail-chopped Lightning Impulse Voltage



Lightning Impulse Current



SWITCHING OVERVOLTAGES

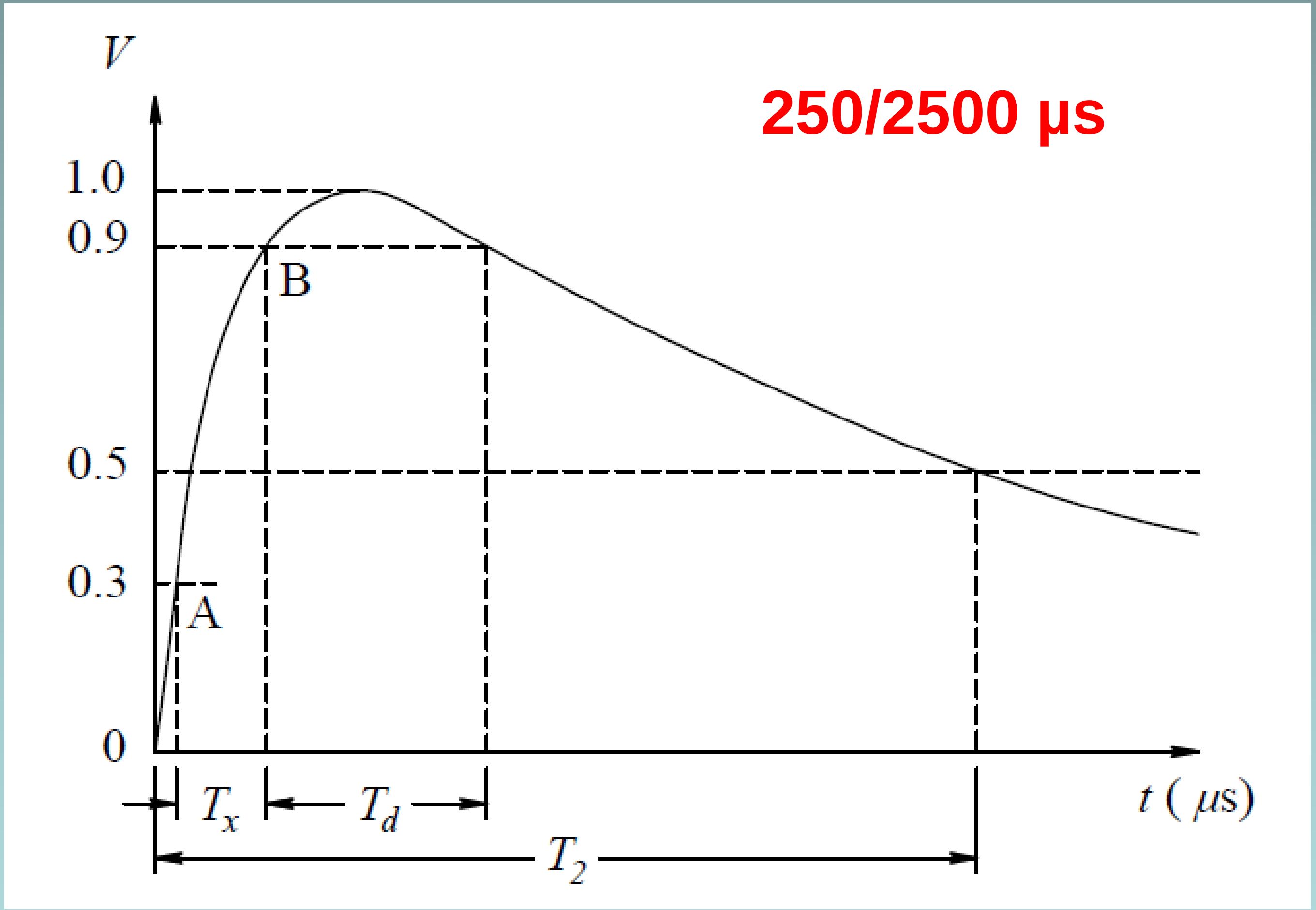
Switching Overvoltages

- **Line energization**
- **Faults and fault clearing**
- **Load rejections**
- **Switching of capacitive or inductive currents**

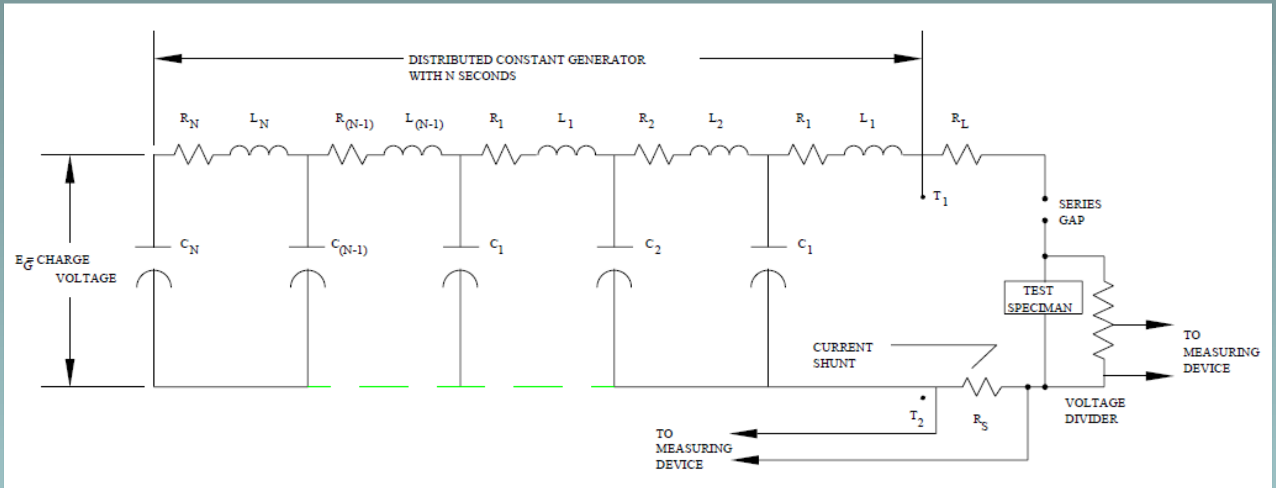
Switching Overvoltages - Mitigation

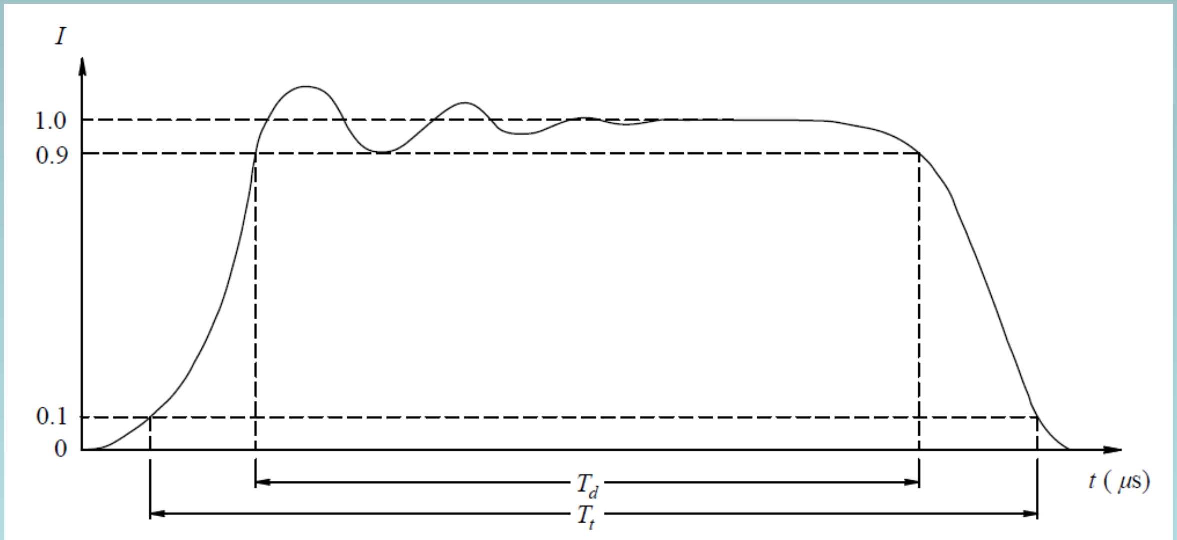
- **Preinsertion resistors or reactors**
- **Current-limiting reactors**
- **Surge arresters**
- **Controlled opening and closing of HVAC breakers**

Switching Impulse Voltage

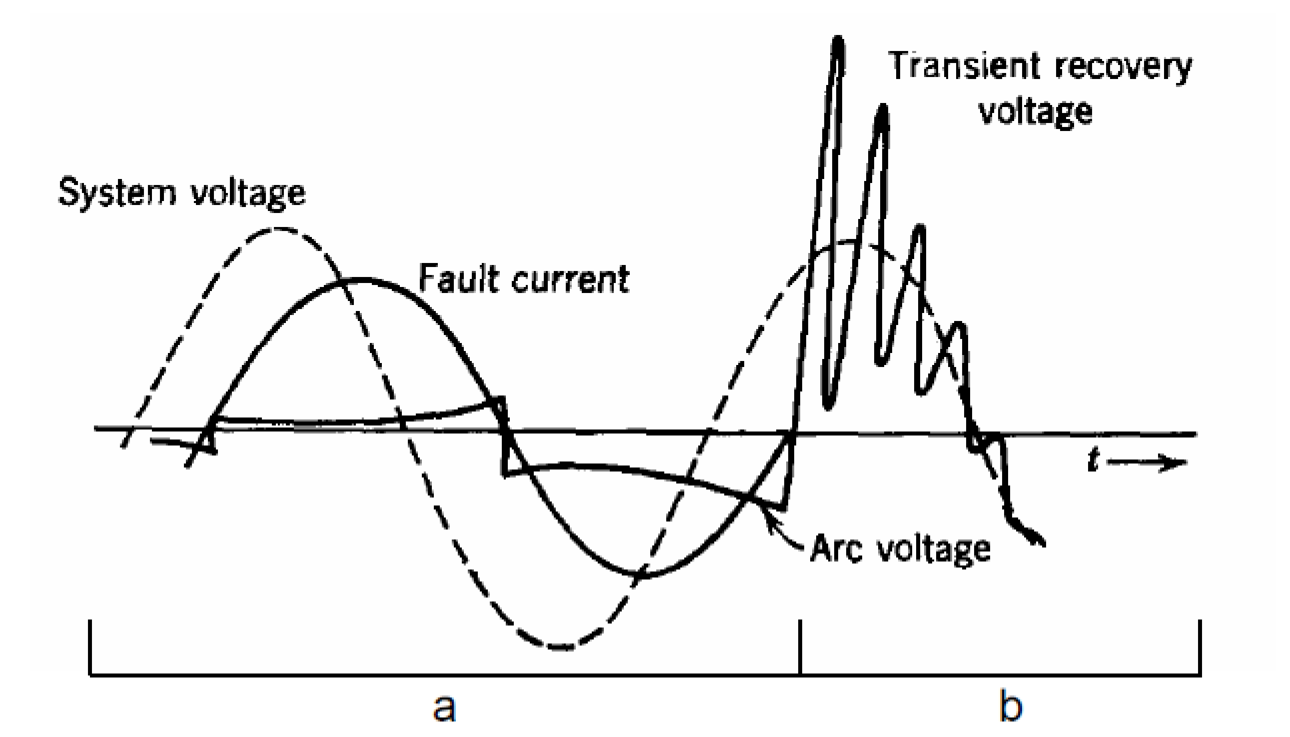


Rectangular Impulse Current

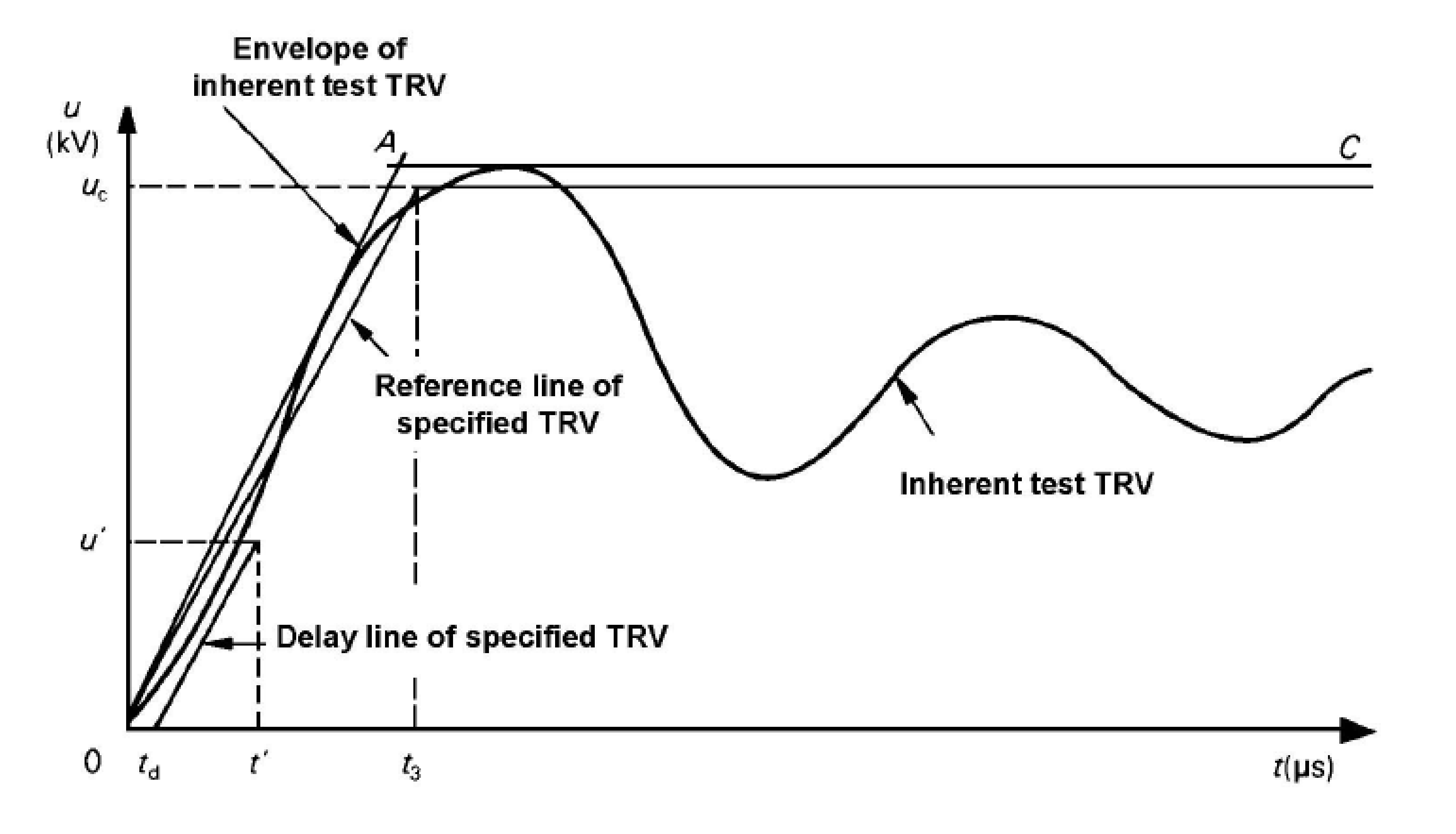




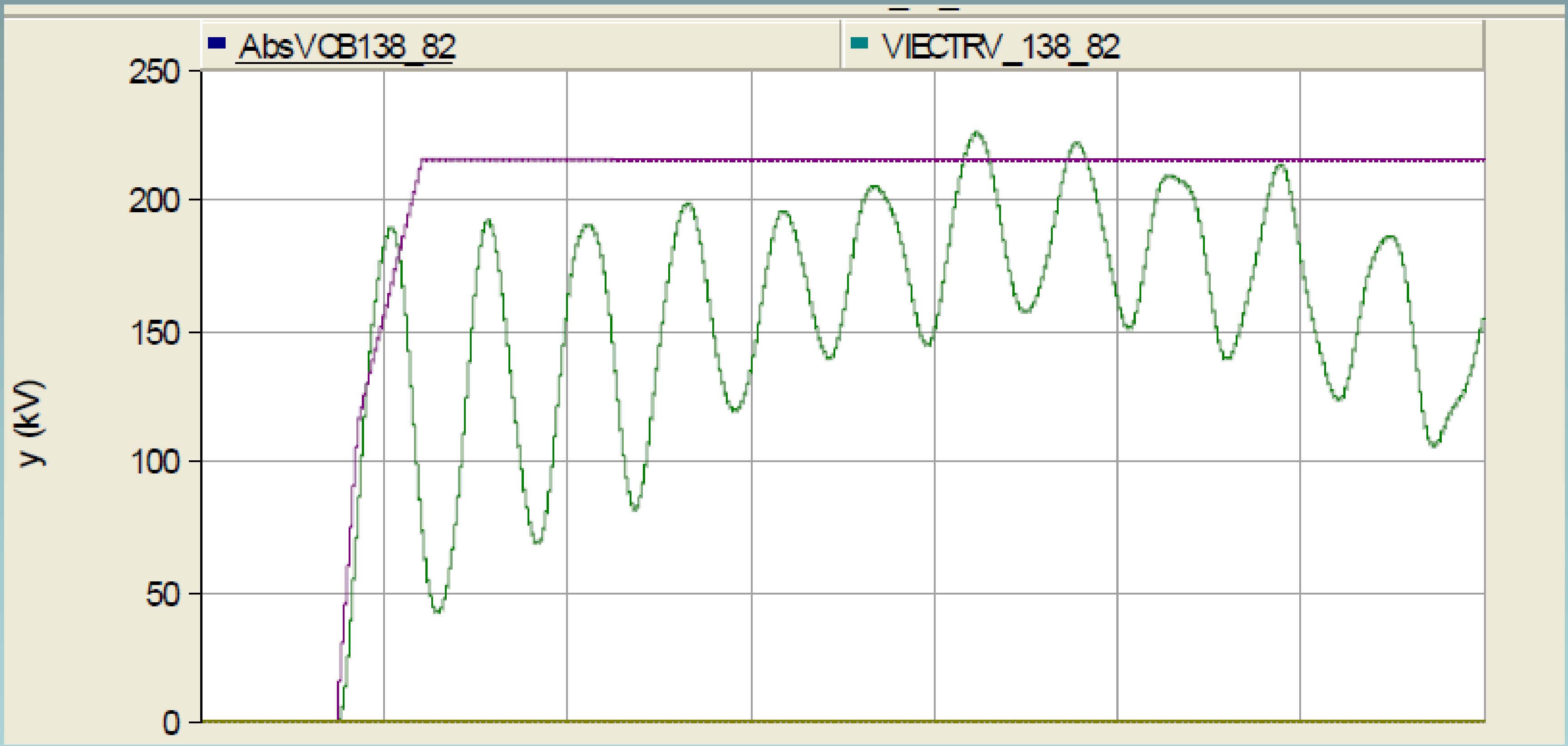
Transient Overvoltage



Transient Recovery Voltage (TRV)



Transient Recovery Voltage (TRV)

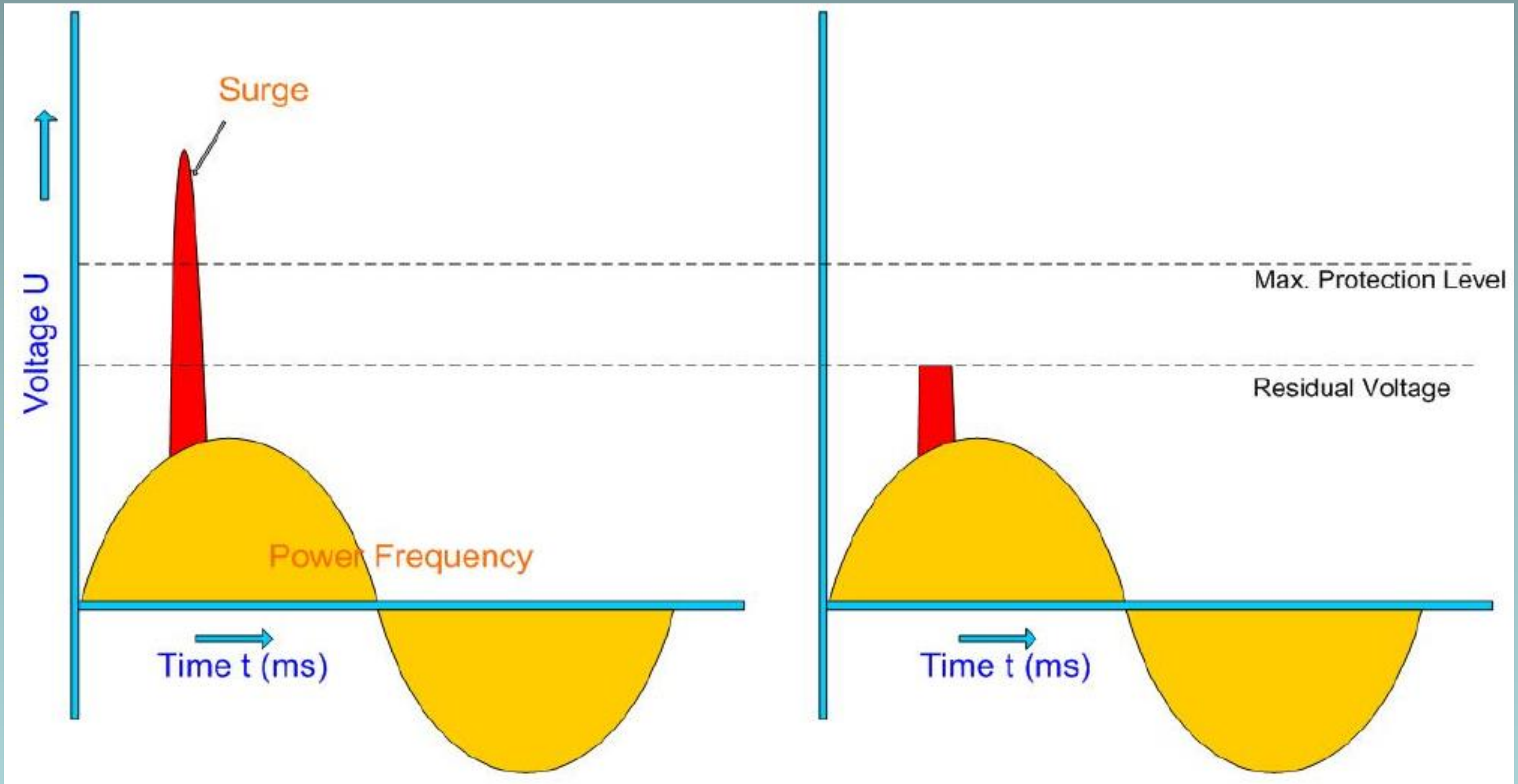


SURGE ARRESTERS

Function of an Arrester

- **Protect Equipment Against**
  - **Lightning**
  - **Switching Surges**
- **Capable of Withstanding Repeated Duty**
  - **Durability Tests**
- **Withstand System Conditions**
  - **System Voltage**
  - **Temporary Overvoltage (TOV)**
  - **Outdoor weathering**
  - **High voltage stress**
- **Assure Uninterrupted Service**

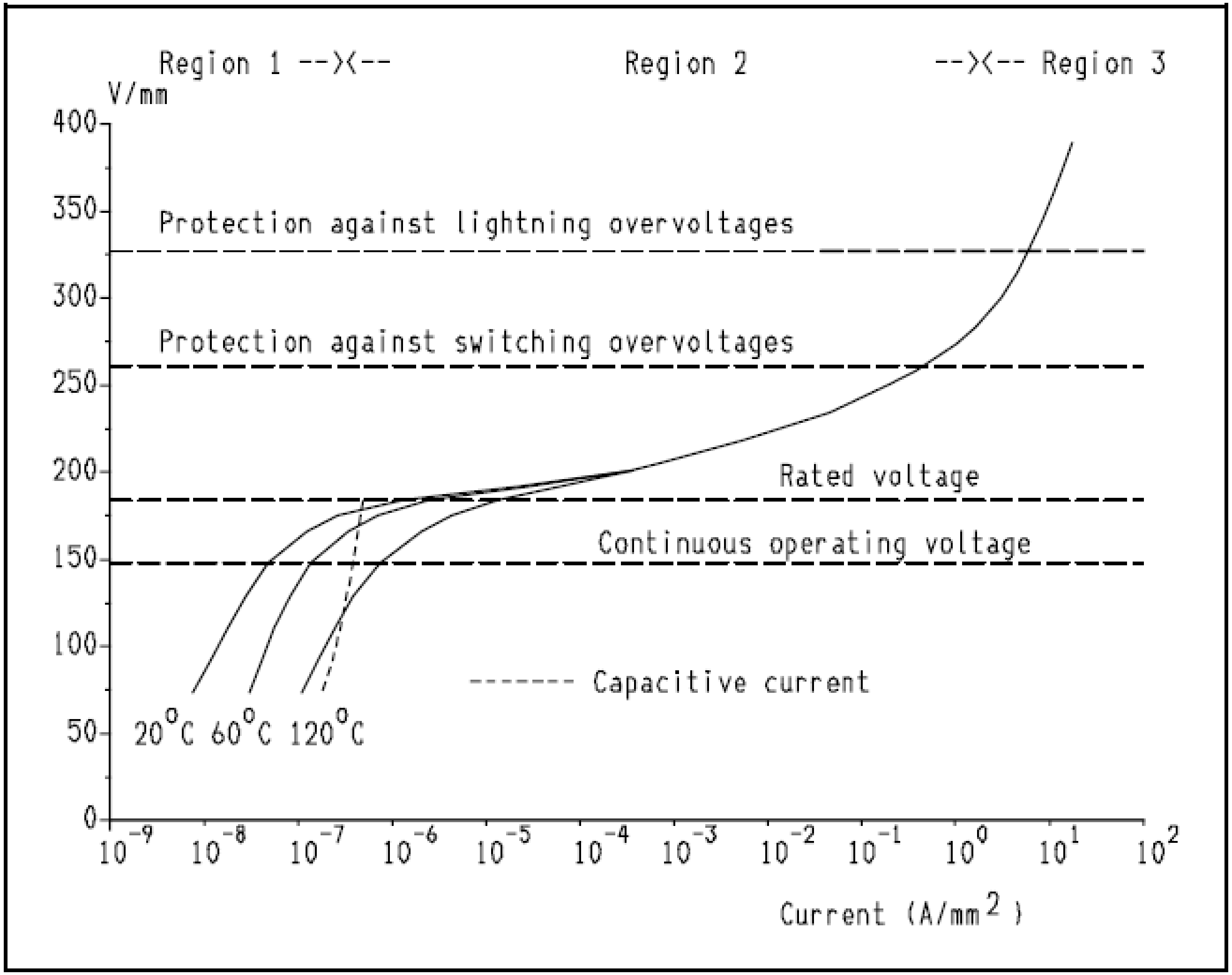
Transient Overvoltage



without protection

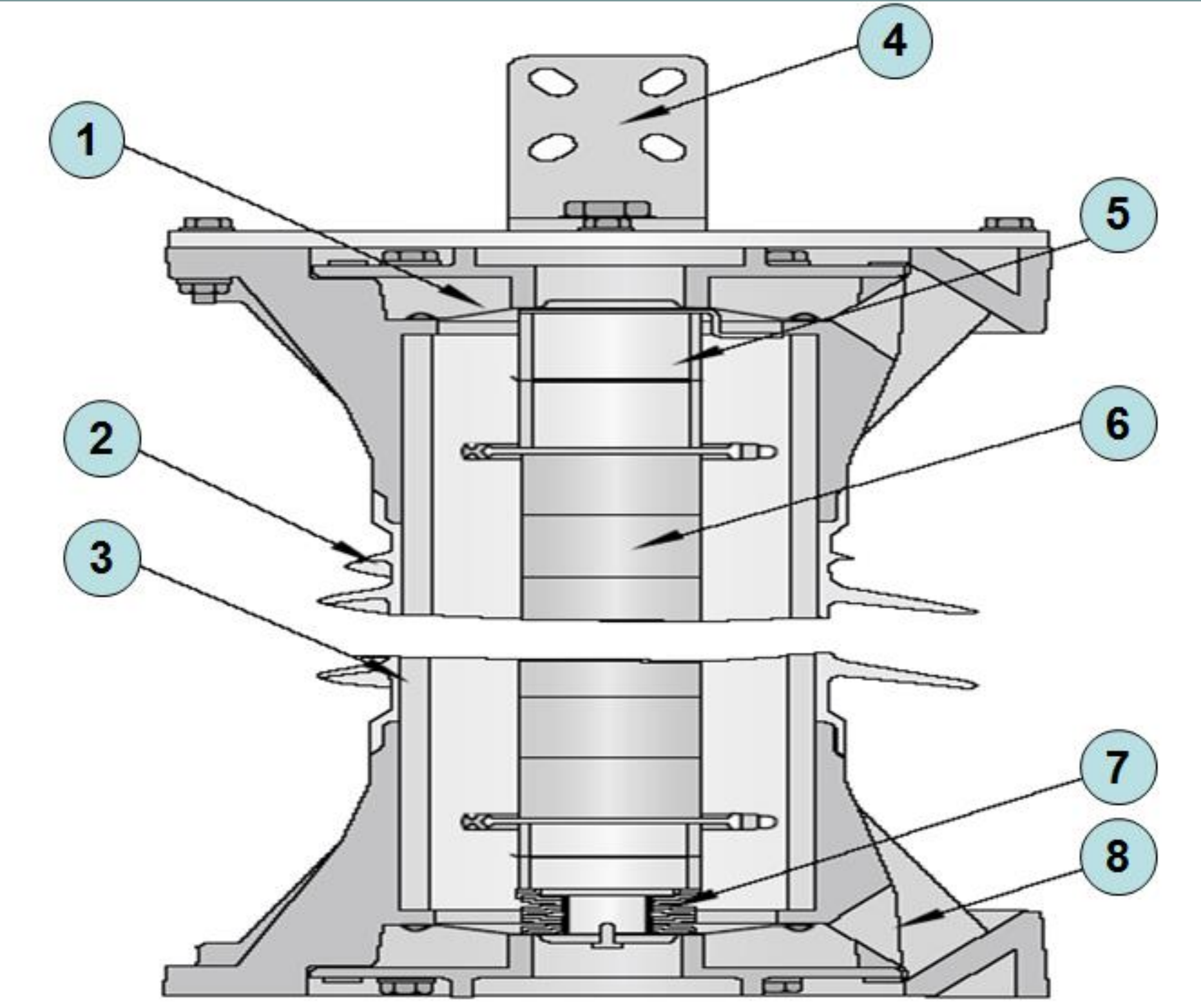
with surge arrester

V-I Characteristics of a Typical ZnO Arrester

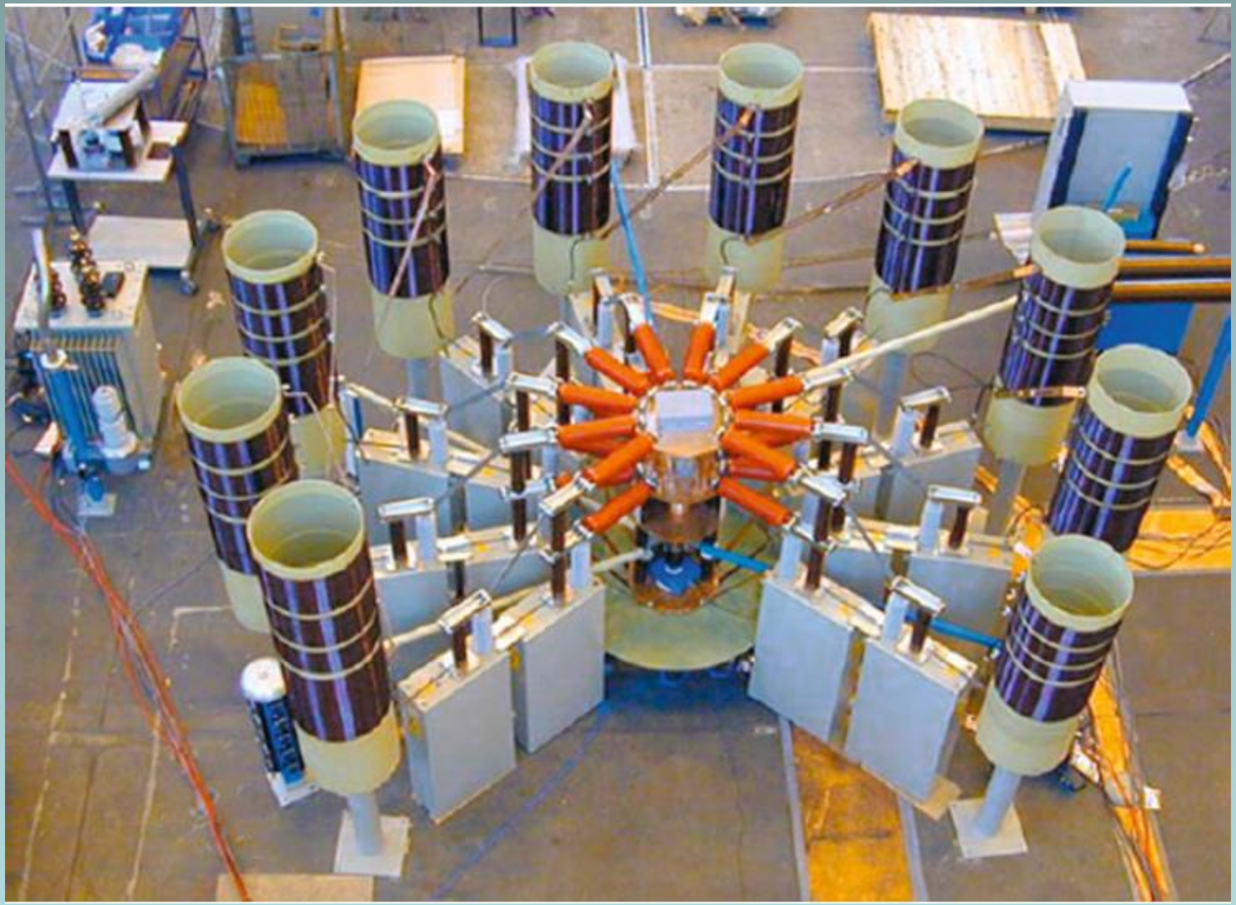


Cross-sectional – Polymer-house Arrester

1. **Sealing Cover**
2. **Silicone Rubber Insulator**
3. **Fiberglass Tube**
4. **Line Terminal**
5. **Spacers**
6. **ZnO Blocks**
7. **Spring**
8. **Venting Duct**

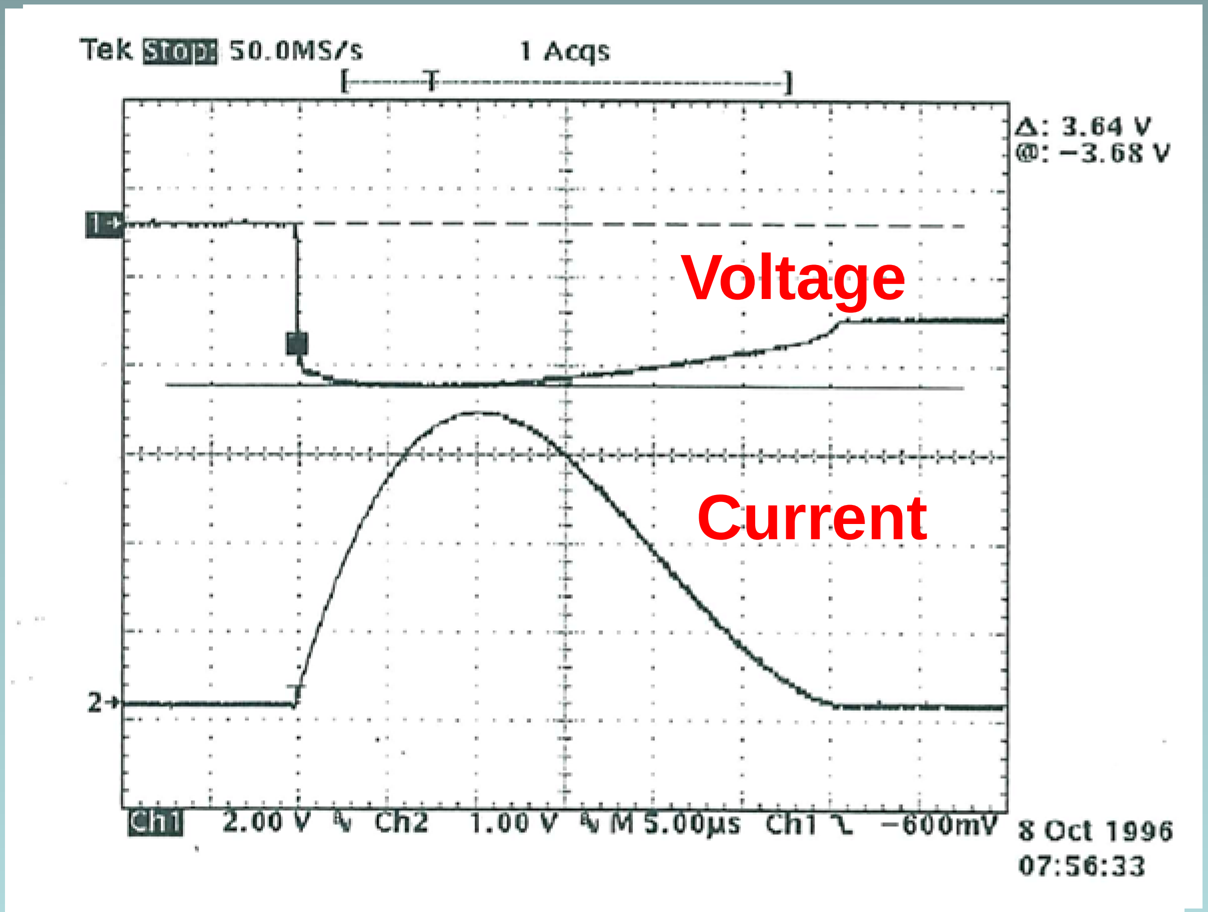


Impulse Current Generator



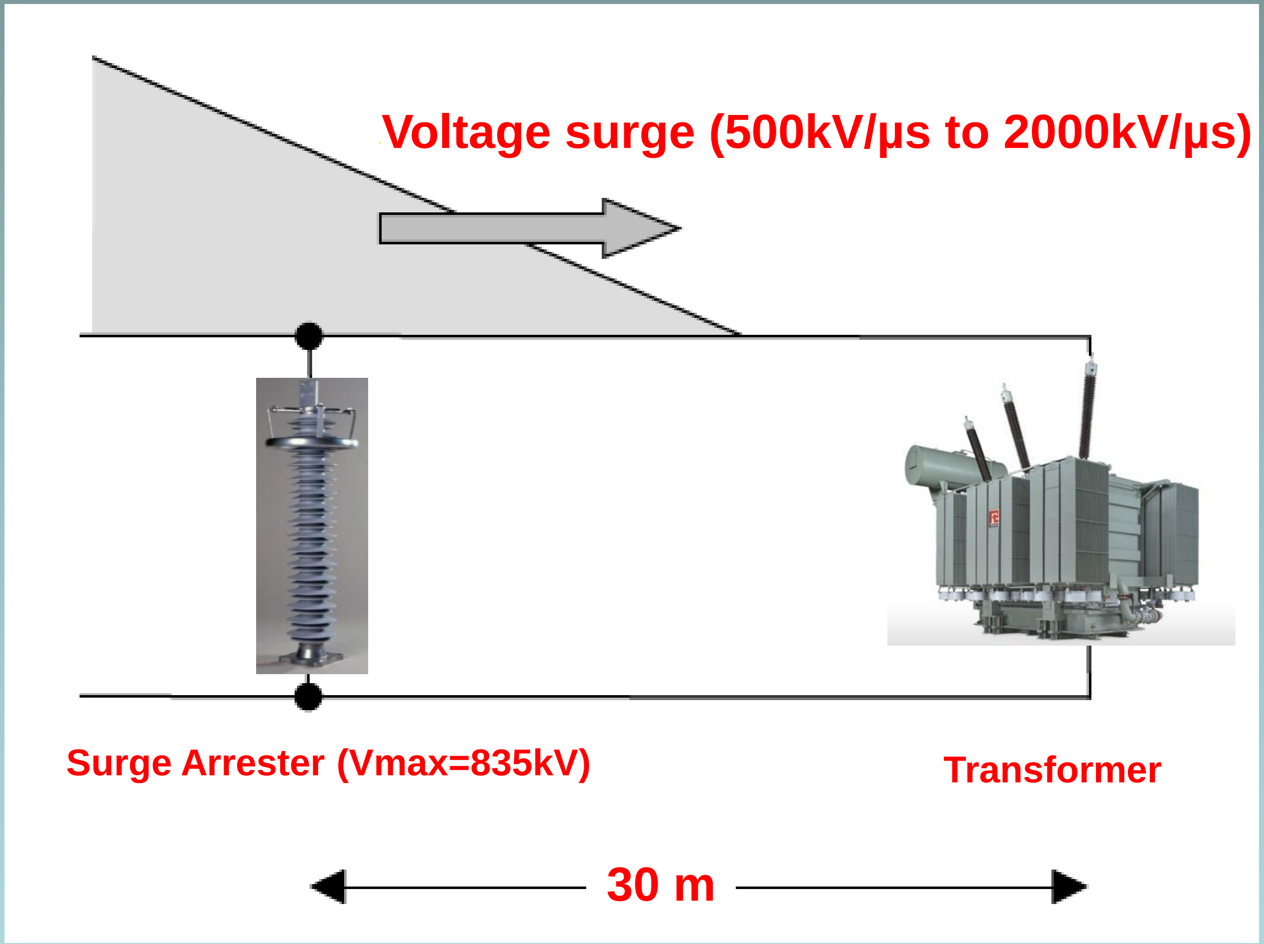
Lightning Impulse Current (8/20)

8 x 20 µs

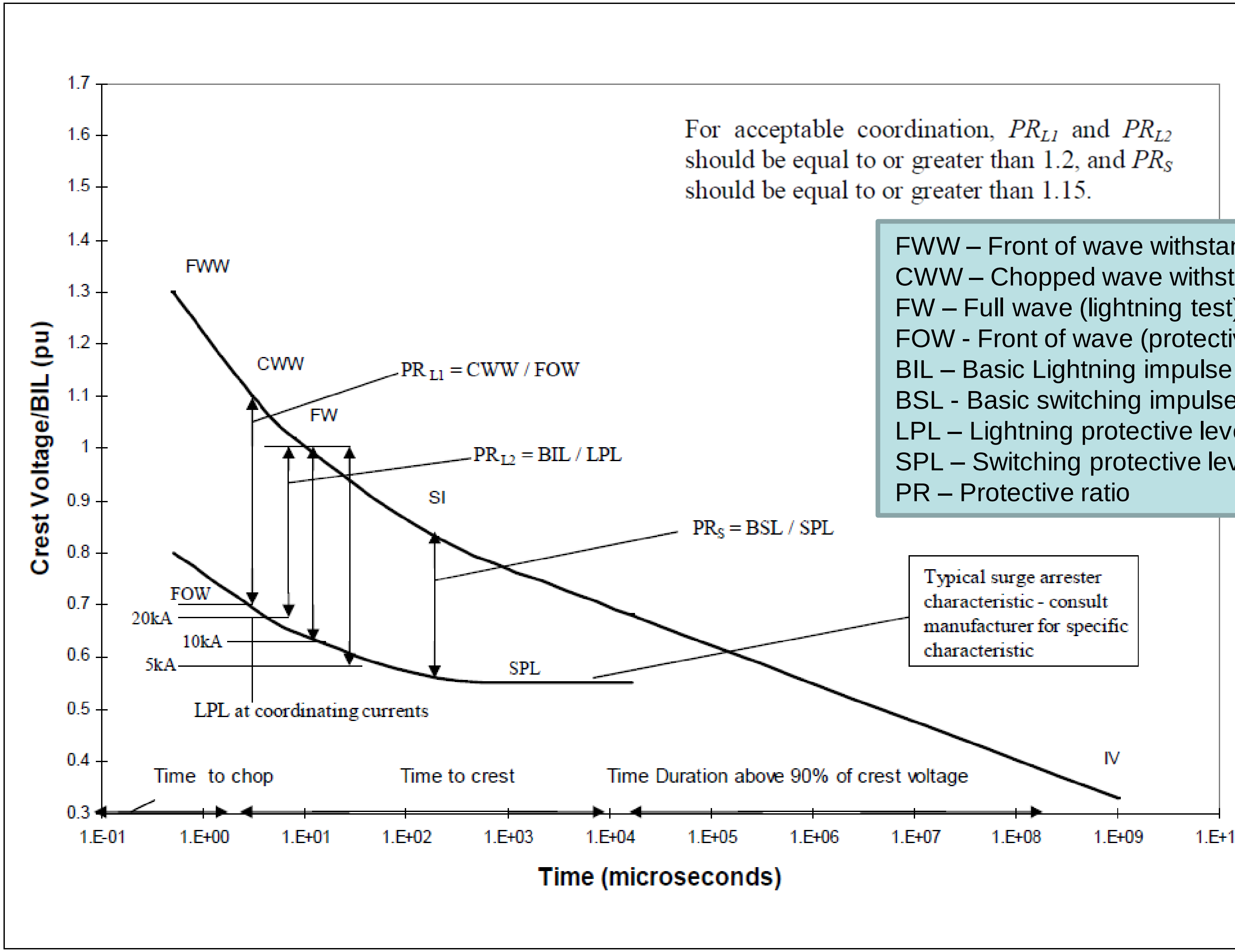


Laboratory Test Result

Separation Effect

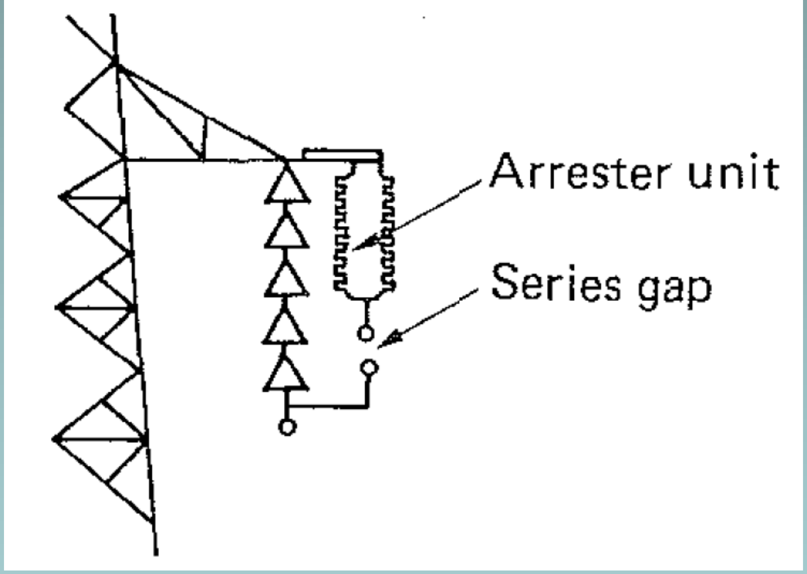


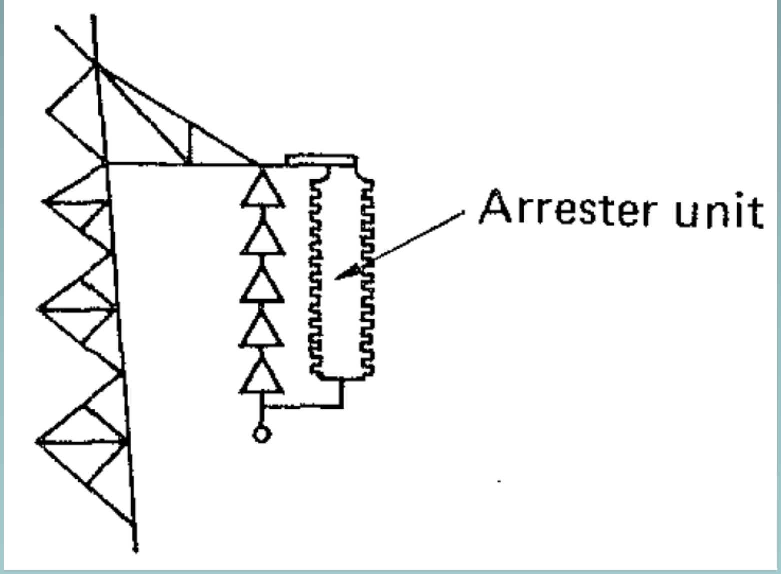
Typical Transformer and Arrester Volt-time Curves Protective Levels



- FWW – Front of wave withstand
- CWW – Chopped wave withstand
- FW – Full wave (lightning test)
- FOW - Front of wave (protective level)
- BIL – Basic Lightning impulse insulation level
- BSL - Basic switching impulse insulation level
- LPL – Lightning protective level
- SPL – Switching protective level
- PR – Protective ratio

Surge Arresters for Transmission Lines





CONCLUSIONS

Conclusions

- **Any design of Direct Lightning Stroke Shielding depends on the probabilistic nature of lightning phenomena.**
- **There is no method available to provide 100% shielding against direct lightning stroke of the substation equipment and bus structures.**
- **There are a number of other variables not addressed in the standards and not discussed in this presentation, such as, effects of altitude on BIL, state (cleanliness) of the insulators, aging effect of equipment on failure, and temperature variations.**

Conclusions

- **Fixed-angle design method is quite adequate for distribution substations.**
- **EGM method is more appropriate for large and important substations at 230kV and above.**
- **Proper grounding system design is also an integral part of the total solution and should be addressed during the design.**
- **In order to arrive at some practical solutions, many assumptions are made in the different design techniques.**
- **Surge arresters are added in strategic locations in a substation to provide coordinated protection for all major equipment.**

Conclusions

- **Power system transient simulation studies help in quantifying the maximum anticipated stress and determining the rating and location of overvoltage mitigating devices.**

References

- IEEE Guide for Direct Lightning Stroke Shielding of Substations - IEEE Std 998-2012;
- IEEE Guide for Improving the Lightning Performance of Transmission Lines - IEEE Std 1243-1997;
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- P.K. Sen, “Understanding Direct Lightning Stroke Shielding of Substations”, PSERC Seminar, Golden Colorado, November 6, 2001.

QUESTIONS?

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