PART III - Substation Lightning Protection System – IEEE Std 998 – 1996

Scope
The scope of this guide is the identification and discussion of design procedures to provide direct stroke shielding of outdoor distribution, transmission, and generating plant substations.

Definitions
The definitions of terms contained in this document are not intended to embrace all legitimate meanings of the terms. They may only be applicable to the subject treated in this document. For additional definitions refer to IEEE Std 100-1992

Effective Shielding:
That which permits lightning strokes no greater than those of critical amplitude (less design margin) to reach phase conductors.
The zone of protection of a shielding system is the volume of space inside which equipment is considered adequately protected by the system. A shielding system allowing no more that 0.1 percent of the total predicted number of lightning strokes to terminate on the protected equipment is considered adequate for most situations.

Shielding System Grounding:
A shielding system cannot effectively protect substation equipment unless adequately grounded. Multiple low impedance connections from the shielding system to the substation ground grid are essential. It is beneficial to use at least two separate connections to ensure continuity and reliability. Whenever non-conducting masts or supports are used, install separate ground cables to establish a direct connection from the shield system to the substation ground system.

Surge impedance Z_s:
The ratio between voltage and current of a wave that travels on a conductor.

$$Z_s = 60 \times \sqrt{\ln\left(\frac{2 \times h}{R_c}\right) \times \ln\left(\frac{2 \times h}{r}\right)} \quad \text{(C.7)}$$

where
- h is the average height of the conductor
- r is the metallic radius of the conductor, or equivalent radius in the case of bundled conductors
- Rc is the corona radius (use Eq. C.1 for a single conductor or refer to IEEE Std. 998 – 1996 Annex – C as appropriate)

$$R_c \times \ln\left(\frac{2 \times h}{R_c}\right) - \frac{V_c}{E_0} = 0 \quad \text{(C.1)}$$

Lightning mast:
A column or narrow-base structure containing a vertical conductor from its tip to earth, or that is itself a suitable conductor to earth. Its purpose is to intercept lightning strokes so that they do not terminate on objects located within its zone of protection.

Shield wire (overhead power line or substation):
A wire suspended above the phase conductors positioned with the intention of having lightning strike it instead of the phase conductor(s). Synonyms :overhead ground wire (OHGW), static wire and sky wire.

Keraunic level:
The average annual number of thunderstorm days or hours for a given locality. (1) A daily keraunic level is called a thunderstorm-day and is the average number of days per year in which thunder is heard during a 24 h period. (2) An hourly keraunic level is called a thunderstorm-hour and is the average number of hours per year that thunder is heard during a 60 min period.

Ground Flash density (GFD):

The average number of lightning strokes per unit area per unit time at a particular location.
It is usually assumed that the GFD to earth, a substation, or a transmission or distribution line is roughly proportional to the keraunic level at the locality.
Various equations for GFD as developed by various researchers around the world, if thunderstorm days are to be used as a basis, it is suggested that the following equation be used

$$N_K = 0.12 \cdot T_d \quad (2\text{-}3A)$$

Where,

N_k is the number of flashes to earth per square kilometer per year

T_d is the average annual keraunic level, thunderstorm days

If thunderstorm hours are to be used as a basis, the following formula is recommended.

$$N_K = 0.054 \cdot T_d^{\ 1.1} \quad (2\text{-}4A)$$

Striking distance:

The length of the final jump 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.
Return stroke current magnitude and strike distance (length of the last stepped leader) are interrelated. A number of equations have been proposed for determining the striking distance. However, lightning investigators now tend to favor the shorter strike distances given by Equation 2-1D which will be used in this guide:

$$S_m = 8 \cdot I^{0.65} \quad (2\text{-}1D)$$

Equation 2-1D has been adopted for this guide. The equation may also be stated as follows:

$$I = 0.041 \bullet S^{1.54} \quad (2\text{-}1F)$$

This relationship is shown graphically in Figure 2-3. From this point on, the return stroke current will be referenced in this guide as the stroke current

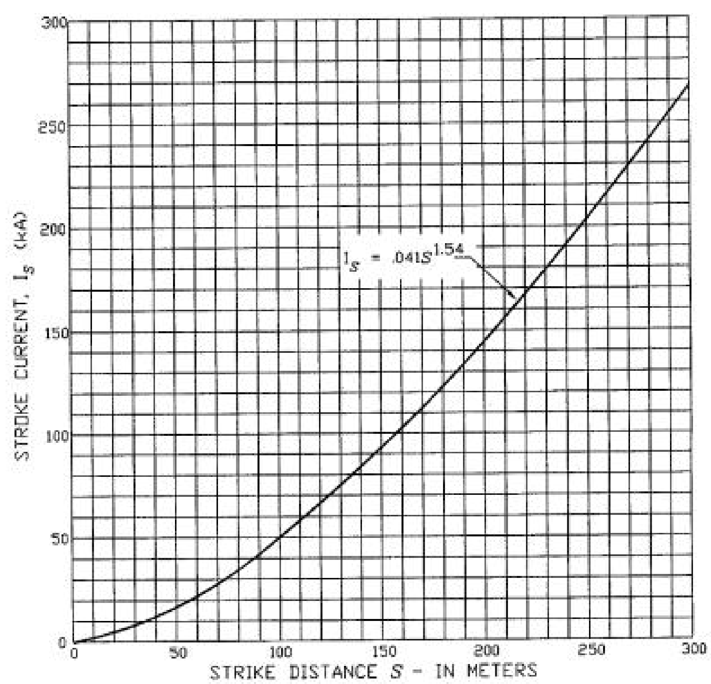


Figure 2-3 - Strike distance vs. stroke current

Stroke current magnitude :

Since the stroke current and striking distance are related, it is of interest to know the distribution of stroke current magnitudes.
The probability that a certain peak current will be exceeded in any stroke as follows:

$$P(I) = \frac{1}{1 + (\frac{I}{24})^{2.6}} \qquad (2\text{-}2B)$$

where

$P_{(I)}$ is the probability that the peak current in any stroke will exceed I.

I is the specified crest current of the stroke in KA.

Figure 2-4 is a plot of Eq. 2-2B.

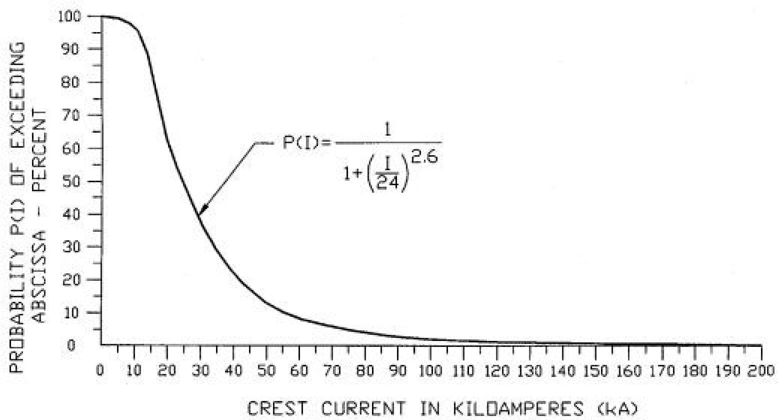


Figure 2-4 —Probability of stroke current exceeding abscissa for strokes to flat ground

General

Substation electrical equipment is subject to abnormal conditions as a result of direct lightning strokes, lightning surges, switching surges, and faults on the system. These abnormal conditions can cause overvoltages that may result in equipment flashover or insulation failure. To prevent equipment damage and/or system shutdown from overvoltages, protective devices are used to limit the overvoltages to reasonable levels. Application of these devices is usually a compromise between the costs of the devices

and the degree of protection desired.

The protection provided for substations and substation equipment can be broken into two main parts:

a) **Surge protection**, employed to protect the equipment from damaging overvoltages caused by lightning surges, switching surges, and system faults . Brief description is given in Annex – A .
b) **Direct stroke protection**, employed to protect the equipment from direct lightning strokes

Surge Protection

Surge arresters are used to protect equipment against overvoltages caused by incoming surges. The arresters function by discharging surge current to the ground system and then interrupt the current to prevent flow of normal power frequency follow current to ground.

Direct Stroke Protection :

The scope of this guide is the identification and discussion of design procedures to provide direct stroke shielding of outdoor distribution, transmission, and generating plant substations and to provide design information for the methods historically and typically applied by substation designers to minimize direct lightning strokes to equipment and bus work within substations. Information is provided on the following two methods of design procedure found to be widely used:

a) The classical empirical method
b) The electro-geometric model (EGM).

A third approach, which involves the use of active lightning terminals, is briefly reviewed below :

Active lightning terminals :

In the preceding methods a) & b) above and described clause 4&5 … , the lightning terminal is considered to be a passive element that intercepts the stroke merely by virtue of its position with respect to the live bus or equipment. Suggestions have been made that lightning protection can be improved by using what may be called active lightning terminals. Three types of such devices have been proposed over the years:

a) Lightning rods with radioactive tips. These devices are said to extend the attractive range of the tip through ionization of the air.
b) Early Streamer Emission (ESM) lightning rods . These devices contain a triggering mechanism that sends high-voltage pulses to the tip of the rod whenever charged clouds appear over the site. This process is said to generate an upward streamer that extends the attractive range of the rod.
c) Lightning prevention devices. These devices enhance the point discharge phenomenon by using an array of needles instead of the single tip of the standard lightning rod. It is said that the space charge generated by the many needles of the array neutralize part of the charge in an approaching cloud and prevent a return stroke to the device, effectively extending the protected area .

Direct Stroke Protection Methods:

1. **Shielding**: Since the effects of a direct lightning stroke to an unshielded substation can be devastating, it is recommended that some form of direct stroke protection be provided. Direct stroke protection normally consists of shielding the substation equipment by using lightning masts, overhead shield wires, or a combination of these devices. The types and arrangements of protective schemes used are based on the size and configuration of the substation equipment.
2. **Overhead Shield Wires**: Overhead shield wires are often used to provide direct stroke protection. The shield wires can be supported by the circuit pull-off structures, if conveniently located, to extend over the substation. Since these shield wires are located above substation buses and equipment, breakage could result in outage of and/or damage to equipment. To minimize possible breakage, the overhead shield wire systems are constructed from high-quality, high-strength materials. Sag has to be considered to ensure adequate clearance from energized equipment. A complete overhead shield wire system should include protection for overhead circuits entering or leaving the substation. In areas not employing transmission line shielding, substation shield wire systems should be extended at least 805 meters (one-half mile) away from the substation to limit the exposure of the phase conductors to direct strokes near the substation. Strokes occurring on the circuits beyond the shielding will usually be attenuated enough by the time they reach the substation to be discharged successfully by the surge arresters without causing equipment damage. For adequate protection, the circuit wire systems should be directly connected to the substation shield wire system.
3. **Shielding Masts**: Shielding masts can be used for nearly all types of substations to provide protection against direct lightning strokes. They are particularly useful in large substations and those of low-profile design. Shielding masts can be guyed or self-supporting steel poles or lattice-type towers and are usually made of steel. Other materials, such as precast concrete or aluminum, can also be used.

In some instances, shielding masts can also be used to provide support for substation lighting equipment.

Design Procedures :

a) Empirical design methods

Two classical design methods have historically been employed to protect substations from direct lightning strokes:

1. Fixed angles.
2. Empirical curves

The two methods have generally provided acceptable protection.

b) The electro-geometric model (EGM)

Only revised EGM will be discussed in this guide .

The two widely used methods for designing substation lightning protection are and will be discussed in this guide:

1. Fixed angle
2. Rolling sphere

a) Empirical design methods :

1. **Fixed angle method :**

The fixed angle design method uses vertical angles to determine the number, position, and height of shielding masts and wires. The shaded areas in Figure 4-17 illustrate the zones of protection afforded by single- and double-mast or shield wire systems. For a single mast, the zone of protection consists of a cone. For a single shield wire, the zone of protection is a wedge. When two or more masts or shield wires are used, the zones of protection of each overlap to provide complete coverage. Figure 4-17 also lists the ranges of angles that have been used for various shielding systems.

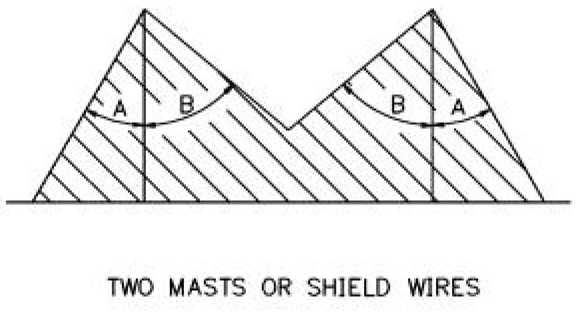


Figure 4-17**:** Zones of Protection for Masts and Shield Wires Using Fixed Angle Method

The angles used are determined by the degree of lightning exposure, the importance of the substation being protected, and the physical area occupied by the substation. The value of the angle alpha that is commonly used is 45º. Both 30º and 45º are widely used for angle beta.

Application on 69 KV Outdoor Substation :

a) Assume a mast height and location .

b) Determine coverage at different bus or equipment heights using 60° and 45° protective angles for the protective masts and dead end structures. Table B.2-1(b) gives the coverage (protected area) at bus height A for each mast height.

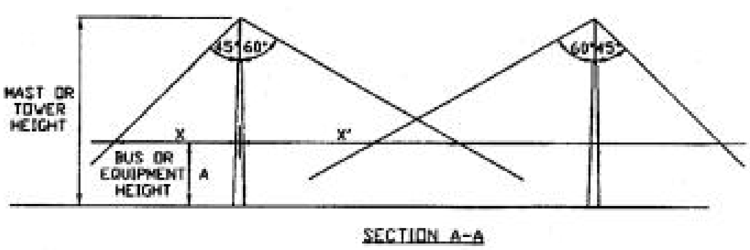


Figure B.2-2 —Coverage at height A, two masts

Protected Distance X at Bus Height = (Mast Height – Equipment Height) x Tan (the Angle).

$X = (H-A) \tan\beta = (H - A) \tan 45^{\circ}$

$X' = (H - A) \tan 60^{\circ}$

Table B.2-1(b) — Coverage at height A (m)

Ht. (m)	Coverage X (m)					
Bus or equip.	22.9 m mast		15.2 m twr.		12.2 m twr.	
	60° ∠	45° ∠	60° ∠	45° ∠	60° ∠	45° ∠
10.1	22.2	12.8	9.0	5.2	3.7	2.1
5.8	29.6	17.1	16.4	9.4	11.1	6.4
4.3	32.2	18.6	19.0	11.0	13.7	7.9

c) Draw arcs of coverage for buses on plan view of station as shown in figure B.2-3.

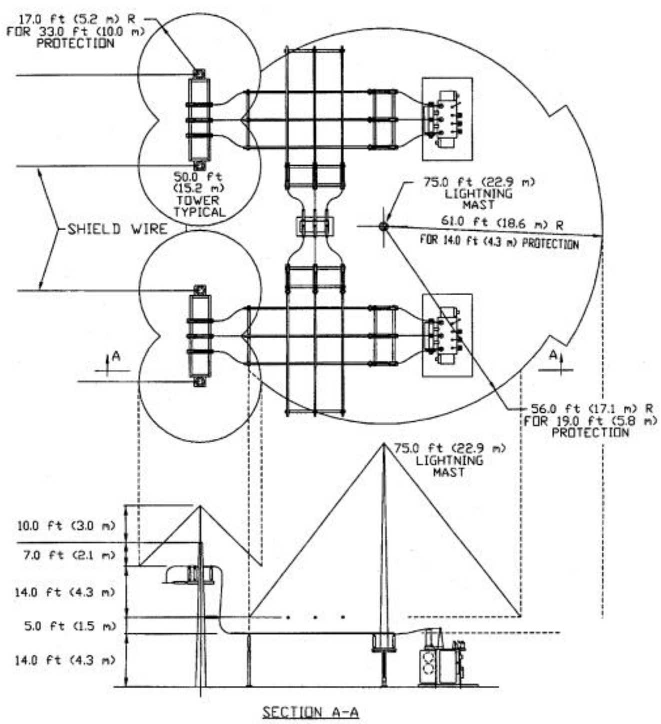


Figure B.2-3 — Shielding substation with masts using fixed angle method

d) Increase mast heights, relocate masts, and/or add masts as required to obtain complete coverage.

NOTE - 60° angle can only be used if two arcs overlap. Otherwise, the 45° angle coverage must be used.

1. Protection with Overhead earth wires

The protected zone, which should enclose all equipment and also the transformers, is determined as shown in Fig. 5-13 or from a diagram (Fig. 5-14).

The sectional plane of the protected zone is bounded by an arc along an overhead earth wire as shown in Fig. 5-13, whose midpoint M is equal to twice the height H of the earth wire both from ground level and from the overhead earth wire B. The arc touches the ground at a distance $\sqrt{3} \cdot H$ from the footing point of the overhead earth wire.

The sectional plane of the protected zone for two overhead earth wires, whose distance from each other is C $2 \cdot H$, is shown in Fig. 5-13b. The outer boundary lines are the same as with an overhead earth wire. The sectional plane of the protected zone between the two overhead earth wires B is bounded by an arc whose midpoint M1 is equal to twice the height 2H of the earth wire from ground level and is in the middle of the two overhead earth wires. The radius R is the distance between the overhead earth wire B and the midpoint M1 R = $\sqrt{\left(H^2 \pm \left[\frac{C}{2}\right]^2\right)}$

The angle between the tangents to the two bounding lines is 2 × 30° at their point of intersection. If an angle of around 2 × 20° is required in extreme cases, the distance 1.5H must be selected instead of the distance 2H.

The arrangement of the overhead earth wires for a 245 kV outdoor installation is shown in Fig. 5-13 c. The bounding line of the protected zone must be above the live station components.

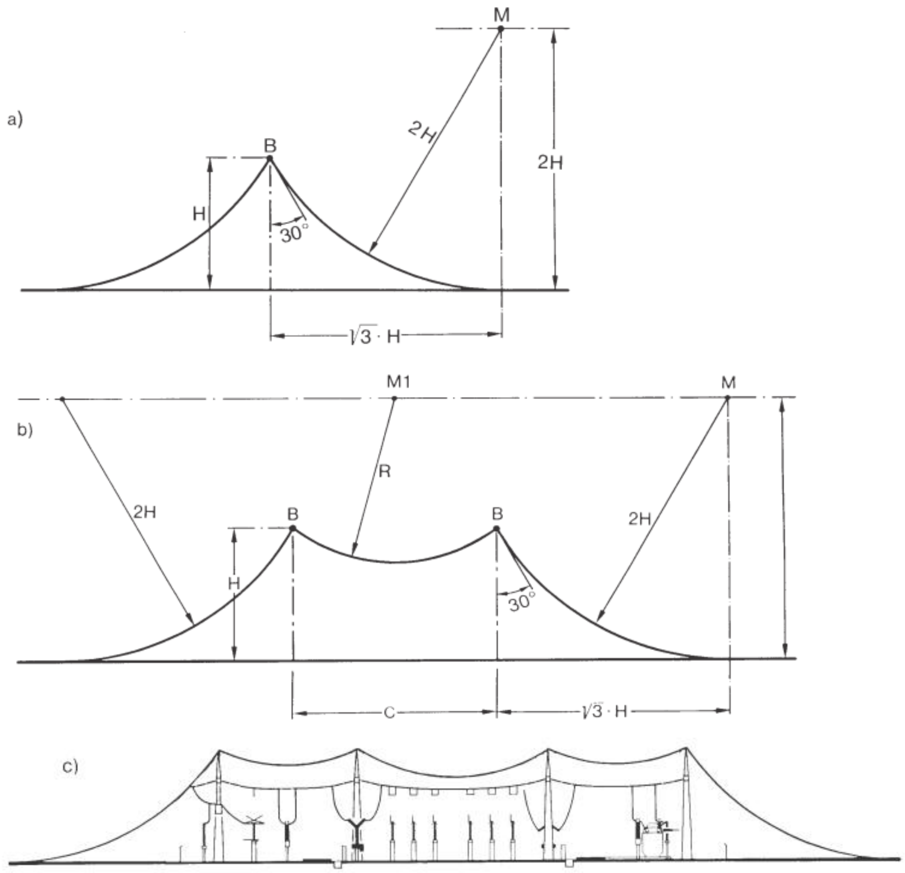


Fig. 5-13

Sectional plane of the protected zone provided by overhead earth wires as per the FGH recommendations:

a) sectional plane of the protected zone with one overhead earth wire,
a) sectional plane of the protected zone with two overhead earth wires,
c) arrangement of the overhead earth wires and protected zone of an outdoor switchgear installation.

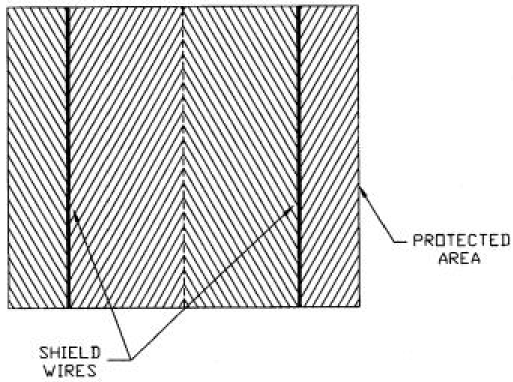


Figure 5-13A – Protected Area using Fixed angles for shielding wires

The height H of the overhead earth wire can be calculated from Fig. 5-14. The curves show the sectional plane of the protected zone one overhead earth wire.

Example: equipment is installed at a distance of L = 12.5 m from the overhead earth wire, with the live part at height h = 9.0 m above ground level: The overhead earth wire must be placed at height H = 23.0 m (Fig. 5-14).

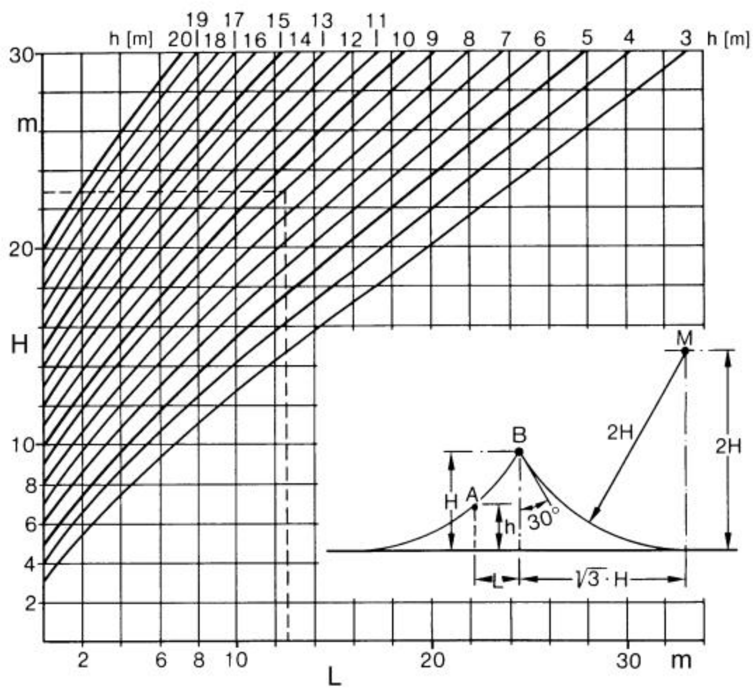


Fig. 5-14 Sectional plane of the protected zone for one overhead earth wire

2. Protection with Lightning rods

Experience and observation have shown that the protected zone formed by rods is larger than that formed by wires at the same height.

A lightning rod forms a roughly conical protected zone, which in the sectional plane shown in Fig. 5-15 a) is bounded by the arc whose midpoint M is three times the height H of the rod both from ground level and the tip of the lightning rod. This arc touches the ground at distance $\sqrt{5} \cdot H$ from the footing point of the lightning rod.

The area between two lightning rods whose distance from each other is $\sqrt{3} \cdot H$ forms another protected zone, which in the sectional plane shown in Fig. 5-15 b) is bounded by an arc with radius R and midpoint M1 at $3 \cdot H$, beginning at the tips of the lightning rods.

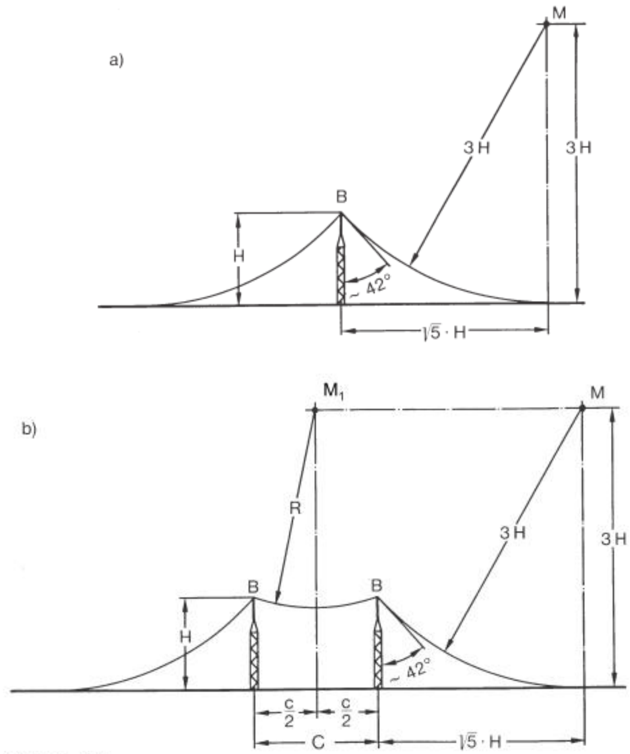


Fig. 5-15

Fig. 5 – 15 Sectional plane of the zone protected by lightning rods: a) sectional plane of the protected zone with one lightning rod, b) sectional plane of the protected zone with two lightning rods.

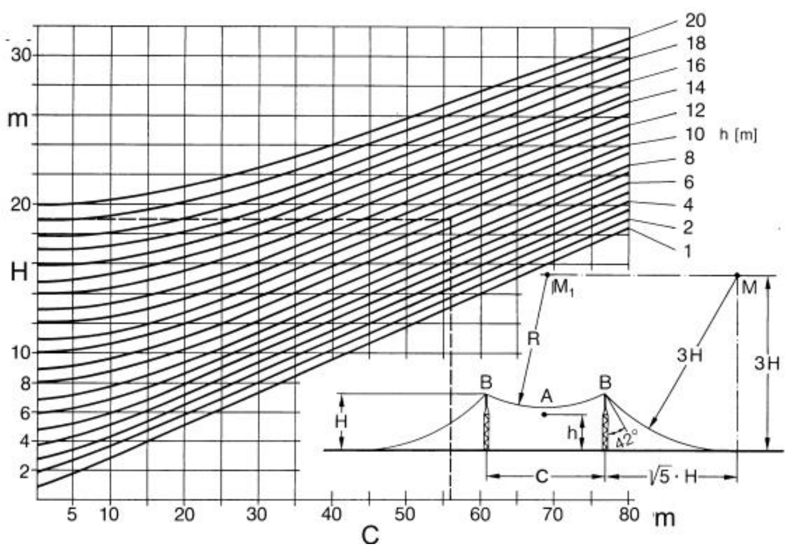


Fig. 5-16 Sectional plane of the protected zone for two lightning rods

The height H of the lightning rod can be calculated from Fig. 5-16. The curves show the protected zone for two lightning rods.

Example: equipment is centrally placed between two lightning rods, which are at distance C = 560 m from each other; the live part is at height h = 10.0 m above ground level: the lightning rods must be at a height of H = 19.0 m (Fig. 5-16).

The width of the protected zone Lx – at a specific height h – in the middle between two lightning rods can be roughly determined from Figs. 5-17 a) and 5-17 b) and from the curves in Fig. 5-17 c). Example: equipment is centrally placed between two lightning rods at distance Lx = 6.0m from the axis of the lightning rods; the live part is at height h = 8.0 m above ground level: When the lightning rods are at a distance of C = 40.0 m the height of the lightning rods must be H = 18.5 m (Fig. 5-17).

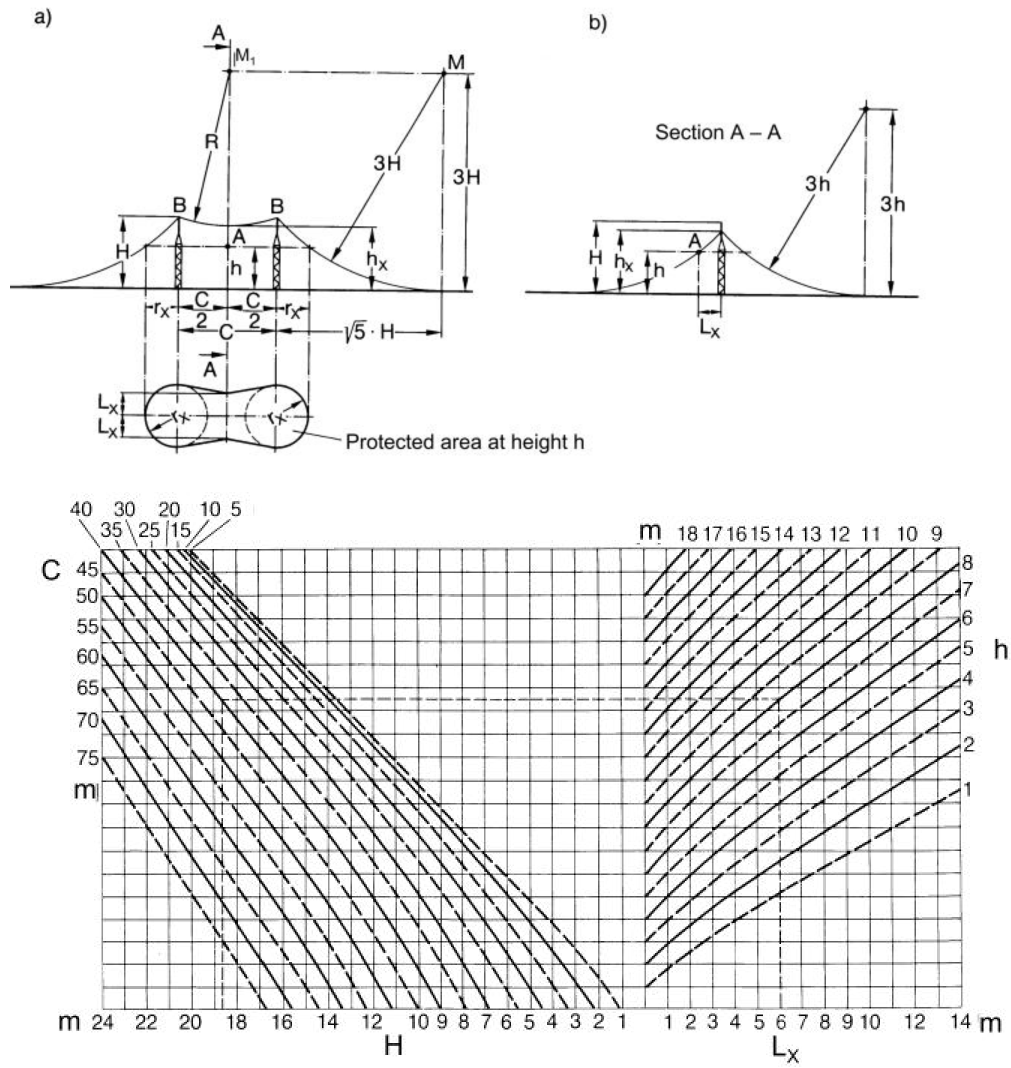


Fig. 5-17 Protected zone outside the axis of 2 lightning rods

<u>Application to 132/11 kV Mobile Substation</u> : using Rods & Shield Wires :
132 / 11 KV , 40 KA
HV Trailer dimensions : 12.5m x 3m x 4.5 m
MV & LV Trailer dimensions : 9.5m x 2.5m x 3.7m
Shield Wire Height : 10.55 m

Introduction :

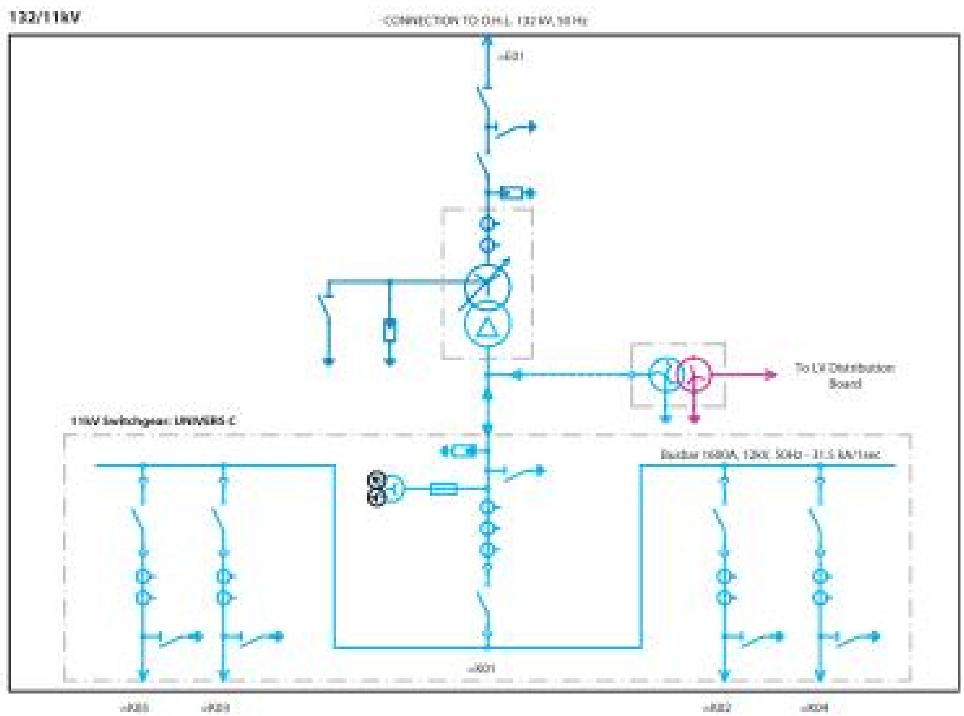
- **What are mobile substations?**

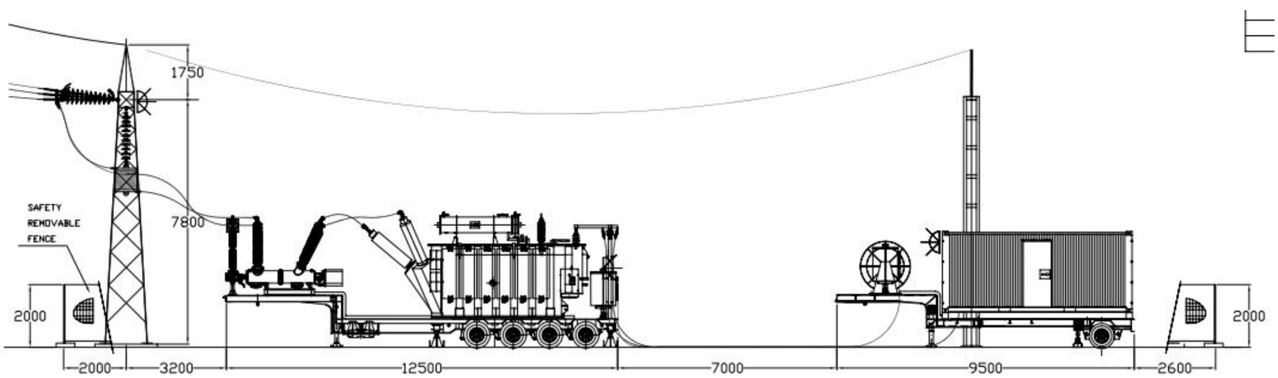
Mobile substations are fully equipped electrical substations mounted on semi-trailers. The most important advantages of these units are their rapid integration into the network and the ability to reuse them in different places. They are a tool for increasing operational flexibility and reliability.

- **Why use mobile substations?**

The main applications for mobile substations are: As emergency units:

- In the event of equipment failure, for substations without spare transformer capacity
- In the event of maintenance or repair activities in existing substations
- In the event of natural disasters, for the supply of vital energy
- Owing to its short delivery time (10 to 12 months), a mobile substation can be used while a permanent installation is being built
- As stand-by units for peak-load periods
- As a substitute for conventional substations: in areas where the demand for electricity rapidly expands beyond the scheduled increase in main system capacity
- As sources of power in isolated areas.
- Optimization of mobility and maneuverability





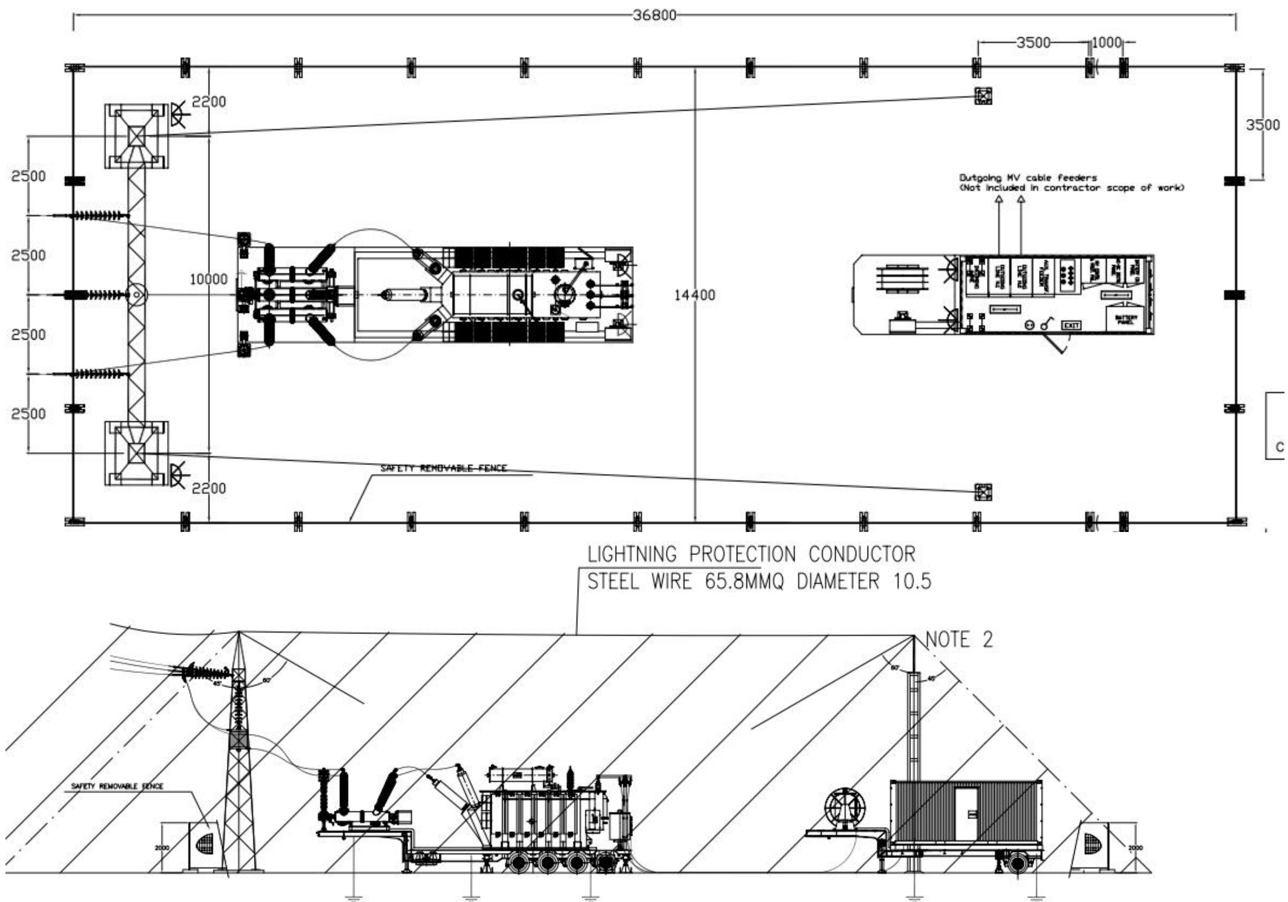
Since the mobile substations are normally connected to an existing OHL , the OHL shield wire height may be or mostly more than the new mast height , the shield wire height on the new mast is to be considered in the lightning protection design and calculations . This will give a better design and more safe system .

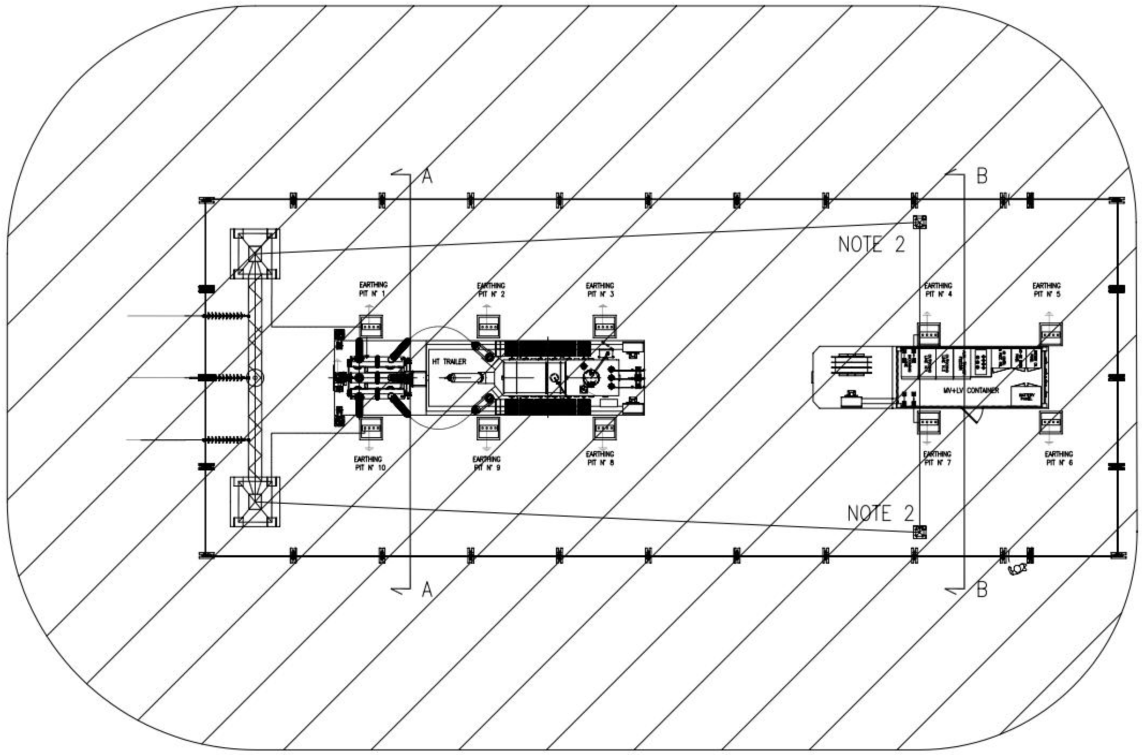
Several aspects should be considered in applying mobile transformers or substations:

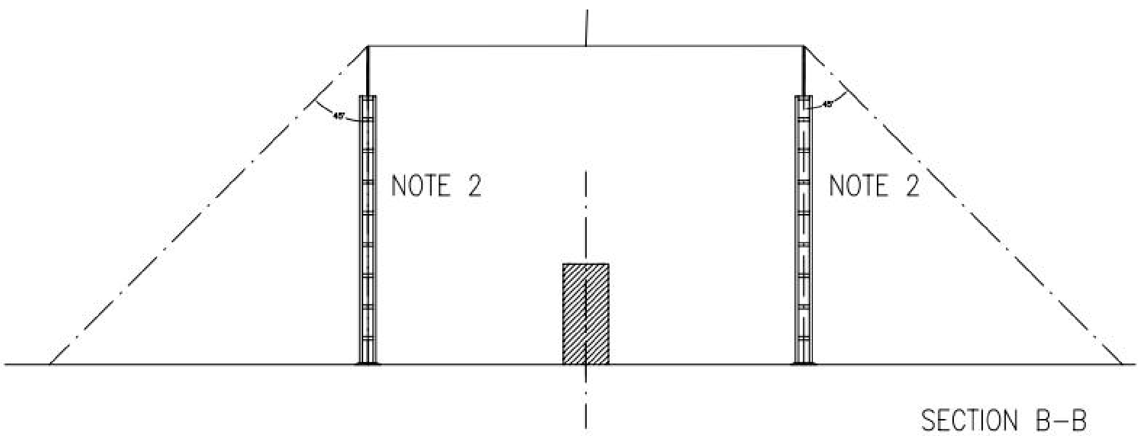
1. Size and maneuverability of the equipment
2. Installation location and provisions

3. Electrical clearances
4. Primary and secondary connections
5. Grounding
6. Auxiliary system requirements
7. Safety

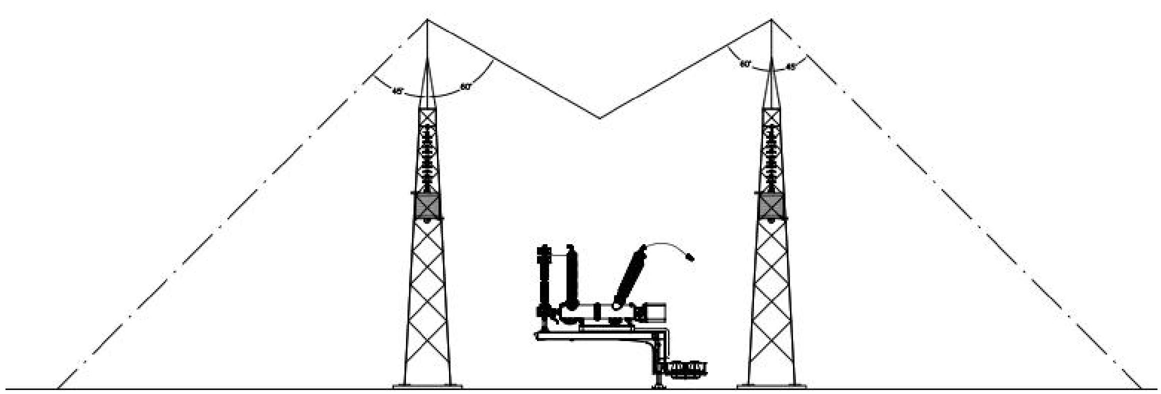
Grounding
Adequate grounding of mobile transformers and substations is extremely important for safe operation. At least two independent connections should be made between the trailer and the ground system. The mobile equipment should be connected to the substation ground grid whenever it is close to the substation. In situations where the mobile is located a long distance from the substation and connection to the substation ground grid is impractical, a separate ground system has to be provided.





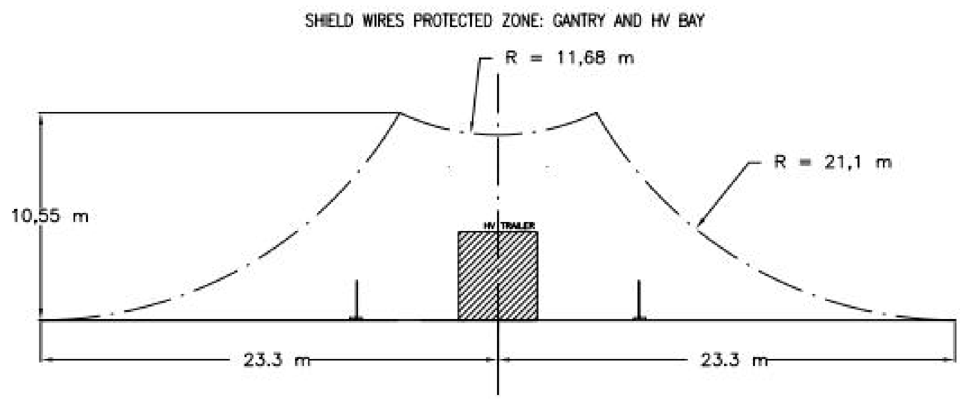


SECTION B–B



SECTION A–A

إعداد وتحضير م\محمد صبحي حسن عبد الحليم



Designers using the fixed angle method may want to reduce the shielding angles as the height of the structures increases in order to maintain a low failure rate. Using the EGM, calculated shielding failures as a function of the height of the conductor above ground and the protective angle for transmission lines. As can be seen from table 4-1, the protective angle must be decreased as the conductor is raised in order to maintain a uniform failure rate.
A protective angle of 40° - 45° for heights up to 15 m (49 ft), 30° for heights between 15-25 m (49-82 ft) and less than 20° for heights on up to 50 m (164 ft). A failure rate of 0.1- 0.2 shielding failures/100 km/year was assumed in these recommendations. This approach could also be used for selecting shielding angles for ground wires in substations.
A similar approach could be used for applying lightning masts in substations. Using the rolling sphere method was suggested to compile a table of shielding angles vs. conductor heights.

Table 4-1 calculated frequency of shielding failures as a function of the height and the protective angle

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	0.0 982	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

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b) The electro-geometric model (EGM)

Description of the revised EGM

The concept that the final striking distance is related to the magnitude of the stroke current was introduced and Eq. 2-1D was selected as the best approximation of this relationship.

A coefficient k accounts for the different striking distances to a mast, a shield wire, and to the ground. Eq. 2-1D is repeated here with this modification:

$$S_m = 8 \cdot k \cdot I^{0.65} \qquad (5\text{-}1A)$$

where

S_m is the strike distance in meters

I is the return stroke current in KA

k is a coefficient to account for different striking distances to a mast, a shield wire, or the ground plane.

Value of k = 1 for strokes to wires or the ground plane and a value of k = 1.2 for strokes to a lightning mast.

Allowable stroke current

Some additional relationships need to be introduced before showing how the EGM is used to design a zone of protection for substation equipment. Bus insulators are usually selected to withstand a basic lightning impulse level (BIL). Insulators may also be chosen according to other electrical characteristics including negative polarity impulse critical flashover (C.F.O.) voltage. Flashover occurs if the voltage produced by the lightning stroke current flowing through the surge impedance of the station bus exceeds the withstand value.

$$I_s = \frac{BIL \times 1.1}{(\frac{Z_S}{2})} = 2.2 \times \frac{BIL}{Z_S} \qquad (5\text{-}2A)$$

or ,

$$I_s = \frac{0.94 \times C.F.O \times 1.1}{(\frac{Z_S}{2})} = 2.068 \times \frac{C.F.O}{Z_S} \qquad (5\text{-}2B)$$

Where,

I_S is the allowable stroke current in KA

BIL is the basic lightning impulse level in kilovolts

C.F.O is the negative polarity critical flashover voltage of the insulation being considered in kilovolts

Z_S is the surge impedance of the conductor through which the surge is passing in Ω

1.1 is the factor to account for the reduction of stroke current terminating on a conductor as compared to zero impedance earth

In Equation 5-2B, the C.F.O. has been reduced by 6% to produce a withstand level roughly equivalent to the BIL rating for post insulators.

Adjustment for end of bus situation

Equations 5-2A and 5-2B address the typical situation in which a direct lightning stroke to a conductor would have at least two directions to flow. The equations assume the surge impedances are the same in both directions, and therefore the total surge impedance is the parallel combination of the two, or 1/2 Z_S. Occasionally a designer may be concerned with a situation in which the entire direct stroke current produces a surge voltage across the equipment. An example would be a direct stroke to the end of a radial bus. The surge can only flow in one direction, and the surge voltage impressed across the insulators of the bus would be the product of the total direct stroke current multiplied by the bus surge impedance. For such situations, the allowable: stroke current I_S can be determined by dividing the results of calculations using equations 5-2A and 5-2B by 2.

Adjustment for transformer, open switch or open breaker :

Another situation where a designer may have concern is at open points in the conductor (such as open switches and open breakers), or points along, the conductor where the surge impedance changes to a large value such as at transformer windings. At such locations, the voltage wave will reverse its direction of flow and return along the conductor. The voltage stress at these points will be up to two times the incoming value. This is referred to as the voltage doubling effect. If the design has incorporated surge arresters at the point of high surge impedance change, such as at the bushings of transformers, the concern for voltage doubling is minimized. The arresters should operate and maintain the voltage at the discharge voltage level of the arresters. However, if arresters have not been applied at such points, the designer may wish to determine the allowable stroke currents for these locations considering voltage doubling. The allowable stroke current I_S can again be determined by dividing the results of calculations using Equations 5-2A and 5-2B by 2.

The designer should keep in mind that reduced BIL equipment is not protected by a design based on stroke current Is. Such equipment should be protected by surge arresters in accordance with IEEE Std C62.22-1991 [B45].

Application of the EGM by the rolling sphere method :

The previous explanation introduced the concept of the electro-geometric model and gave the tools necessary to calculate the unknown parameters. The concept will now be further developed and applied to substation situations.

It was previously stated that it is only necessary to provide shielding for the equipment from all lightning strokes greater than Is that would result in a flashover of the buswork. Strokes less than Is are permitted to enter the protected zone since the equipment can withstand voltages below its BIL design level.

Lightning strokes have a wide distribution of current magnitudes, as shown in figure 2-4. The EGM theory shows that the protective area of a shield wire or mast depends on the amplitude of the stroke current. If a shield wire protects a conductor for a stroke current I_s, it may not shield the conductor for a stroke current less than Is that has a shorter striking distance. Conversely, the same shielding arrangement will provide greater protection against stroke. Currents greater than I_s that have greater striking distances. Since strokes less than some critical value Is can penetrate the shield system and terminate on the protected conductor, the insulation system must be able to withstand the resulting voltages without flashover. Stated another way, the shield system should intercept all strokes of magnitude Is and greater so that flashover of the insulation will not occur.

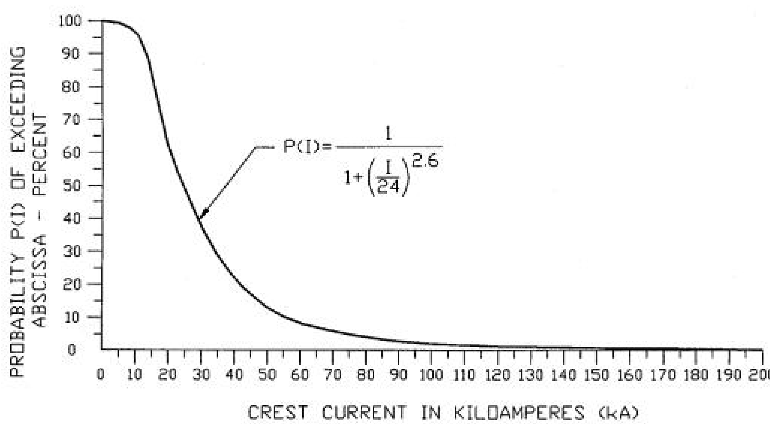


Figure 2-4 —Probability of stroke current exceeding abscissa for strokes to flat ground

This will be illustrated by considering three levels of stroke current; Is, stoke currents greater than Is, and stroke current less than Is. First, let us consider the stroke current Is.

1. **Protection against stroke current Is**

Is is calculated from Eq. 5-2 as the current producing a voltage the insulation will just withstand. Substituting this result in Eq. 5-1 gives the striking distance S for this stroke current. Use of the rolling sphere method involves rolling 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 by virtue of the sphere being elevated by shield wires or other devices. Equipment that touches the sphere or penetrates its surface is not protected. The basic concept is illustrated in figure 5-3 . The radius of the sphere is determined by calculating the strike distance. The strike distance is the length of the final jump of the stepped leader as its potential exceeds the breakdown resistance of the last gap of air to ground. A stepped leader is the static discharge that propagates from a cloud into the air.
The allowable stroke current that may be received by a substation bus without exceeding the withstand value, or BIL, of the substation is defined by Equation (5 – 2A).
These equations provide a very basic evaluation of the lightning protection provided by the rolling sphere method. The many nuances and criteria on which the procedure is based are found in the engineer designing the shielding system needs to also take into account the isokeraunic level of the area where the substation will be built. The isokeraunic level is the average annual number of thunderstorm days for a given locality.

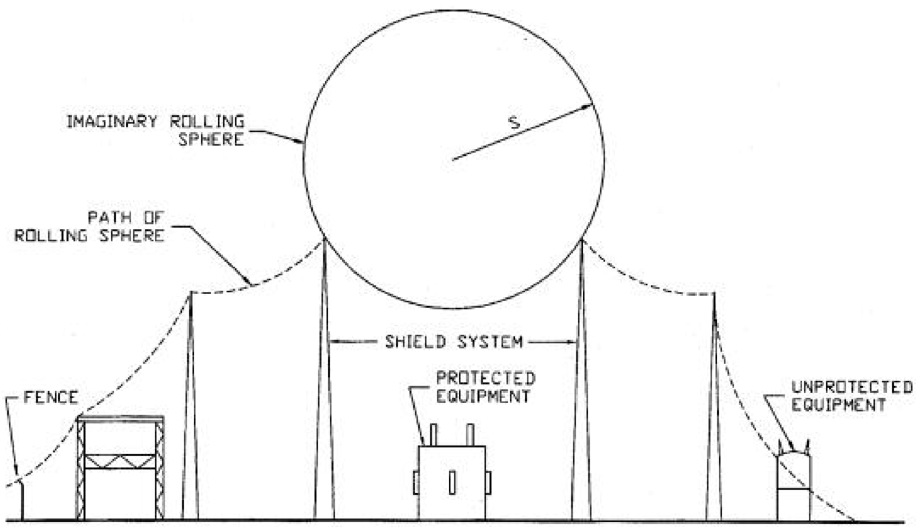
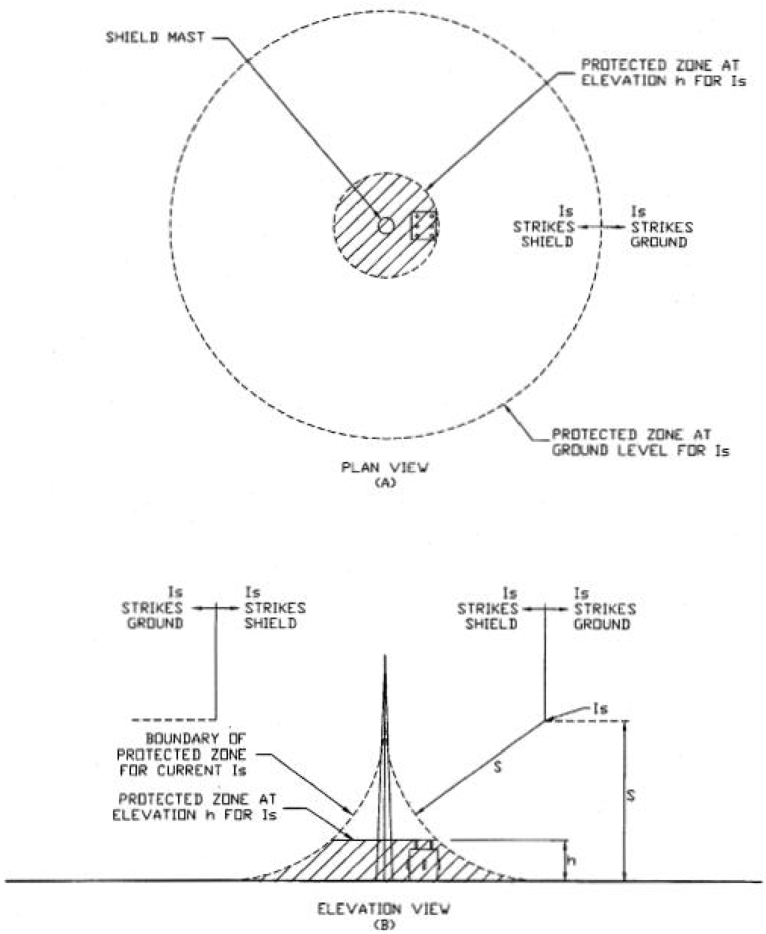


Figure 5-3 —Principle of rolling sphere

Continuing the discussion of protection against stroke current Is, consider first a single mast. The geometrical model of a single substation shield mast, the ground plane, the striking distance, and the zone of protection are shown in figure 5-4. An arc of radius S that touches the shield mast and the ground plane is shown in figure 5-4. All points below
this arc are protected against the stroke current Is. This is the protected zone.
The arc is constructed as follows (see figure 5-4). A dashed line is drawn parallel to the ground at a distance S (the striking distance as obtained from Eq. 5-1) above the ground plane. An arc of radius S, with its center located on the dashed line, is drawn so the radius of the arc just touches the mast. Stepped leaders that result in stroke current Is and that descend outside of the point where the arc is tangent to the ground will strike the ground. Stepped leaders that result in stroke current Is and that descend inside the point where the arc is tangent to the ground will strike the shield mast, provided all other objects are within the protected zone. The height of the shield mast that will provide the maximum zone of protection for stroke currents equal to Is is S. If the

mast height is less than S, the zone of protection will be reduced. Increasing the shield mast height greater than S will provide additional protection in the case of a single mast. This is not necessarily true in the case of multiple masts and shield wires.
The protection zone can be visualized as the surface of a sphere with radius S that is rolled toward the mast until touching the mast. As the sphere is rolled around the mast, a three-dimensional surface of protection is defined. It is this concept that has led to the name rolling sphere for simplified applications of the electro-geometric model.



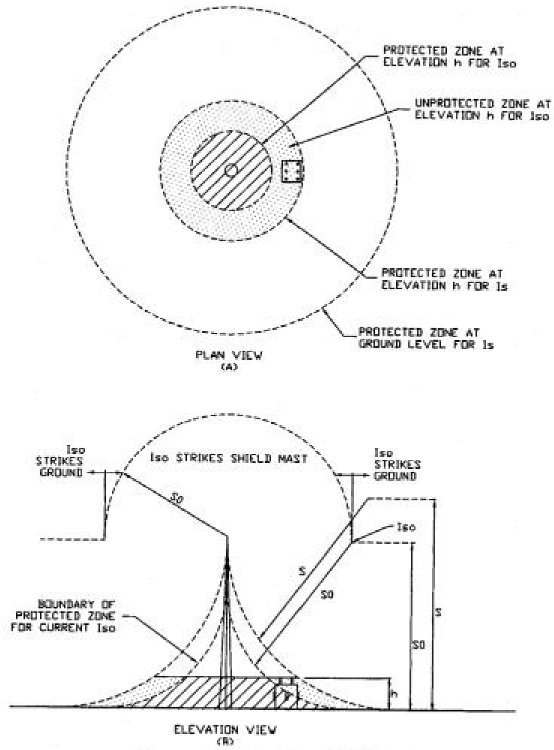
Source: Adapted from [B74]

Figure 5-4 —Shield mast protection for stroke current I_s

2. Protection against stroke currents greater than Is

Item 1 demonstrated the protection provided for a stroke current Is. A lightning stroke current has an infinite number of possible magnitudes, however, and the substation designer will want to know if the system provides protection at other levels of stroke current magnitude.
Consider a stroke current I_{so} with magnitude less than Is. The striking distance, determined from Eq. 5-1, is So. The geometrical model for this condition is shown in figure 5-6. Arcs of protection for stroke current I_{so} and Is are both shown. The figure shows that the zone of protection provided by the mast for stroke current I_{so} is less than the zone of protection provided by the mast for stroke current Is. It is noted that a portion of the equipment protrudes above the dashed arc or zone of protection for stroke current I_{so}. Stepped leaders that result in stroke current I_{so} and that descend outside of the point where the arc is tangent to the ground will strike the ground.

However, some stepped leaders that result in stroke current Iso and that descend inside the point where the arc is tangent to the ground could strike the equipment. This is best shown by observing the plan view of protective zones shown in figure 5-6. Stepped leaders for stroke current I_{so} that descend inside the inner protective zone will strike the mast and protect equipment that is h in height. Stepped leaders for stroke current I_{so} that descend in the shaded unprotected zone will strike equipment of height h in the area. If, however, the value of Is was selected based on the withstand insulation level of equipment used in the substation, stroke current I_{so} should cause no damage to equipment.



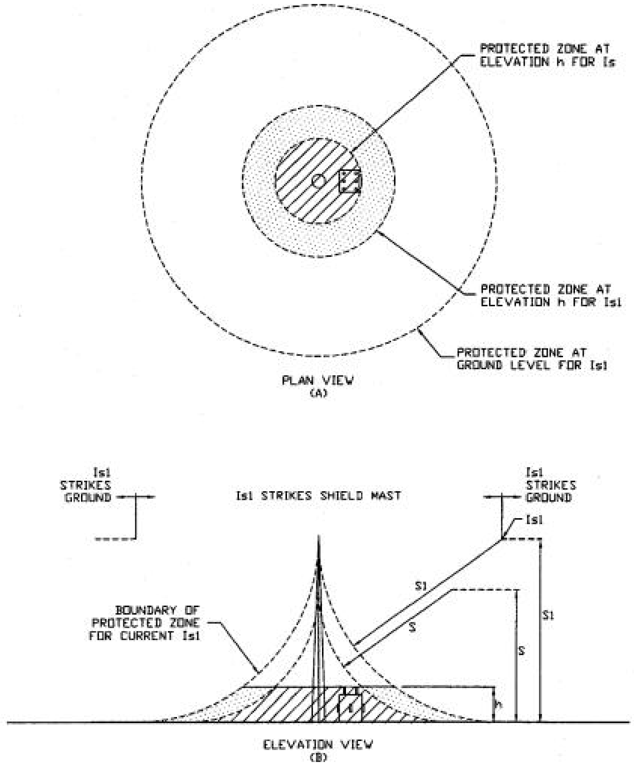
Source: Adapted from [B74]

Figure 5-6 —Shield mast protection for stroke current I_{so}

3. Protection against stroke currents less than Is

It has been shown that a shielding system that provides protection at the stroke current level Is provides even better protection for larger stroke currents. The remaining scenario to examine is the protection afforded when stroke currents are less than Is.

Consider a stroke current I_{so} with magnitude less than Is. The striking distance, determined from Eq. 5-1, is So. The geometrical model for this condition is shown in figure 5-6. Arcs of protection for stroke current I_{so} and Is are both shown. The figure shows that the zone of protection provided by the mast for stroke current I_{so} is less than the zone of protection provided by the mast for stroke current Is. It is noted that a portion of the equipment protrudes above the dashed arc or zone of protection for stroke current I_{so}. Stepped leaders that result in stroke current I_{so} and that descend outside of the point where the arc is tangent to the ground will strike the ground. However, some stepped leaders that result in stroke current Iso and that descend inside the point where the arc is tangent to the ground could strike the equipment. This is best shown by observing the plan view of protective zones shown in figure 5-6. Stepped leaders for stroke current Iso that descend inside the inner protective zone will strike the mast and protect equipment that is h in height. Stepped leaders for stroke current Iso that descend in the shaded unprotected zone will strike equipment of height h in the area. If, however, the value of Is was selected based on the withstand insulation level of equipment used in the substation, stroke current Iso should cause no damage to equipment.



Source: Adapted from [B74]

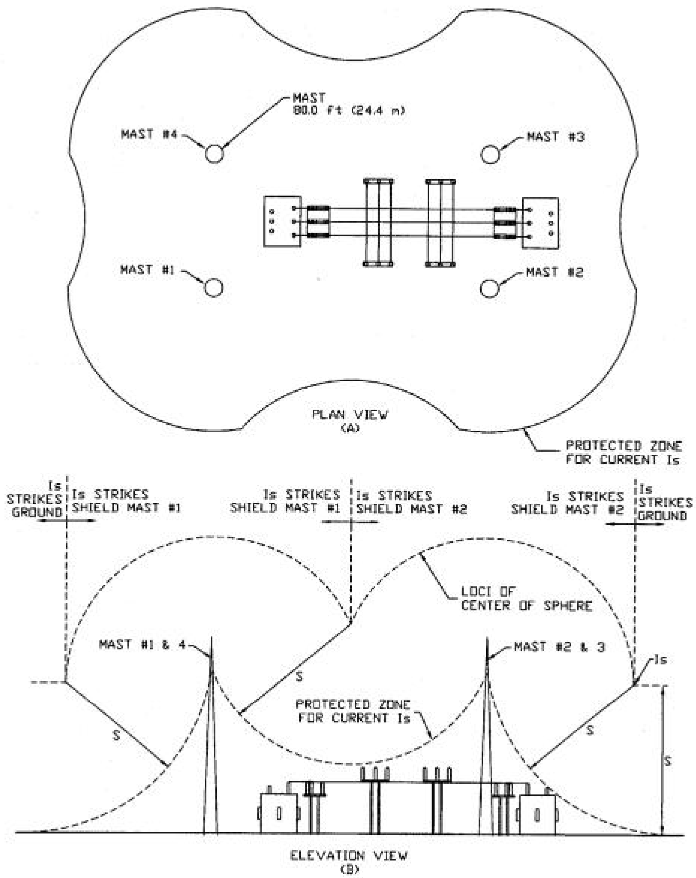
Figure 5-5 —Shield mast protection for stroke current I_{s1}

Multiple shielding electrodes

The electro-geometric modeling concept of direct stroke protection has been demonstrated for a single shield mast. A typical substation, however, is much more complex. It may contain several voltage levels and may utilize a combination of shield wires and lightning masts in a three-dimensional arrangement.

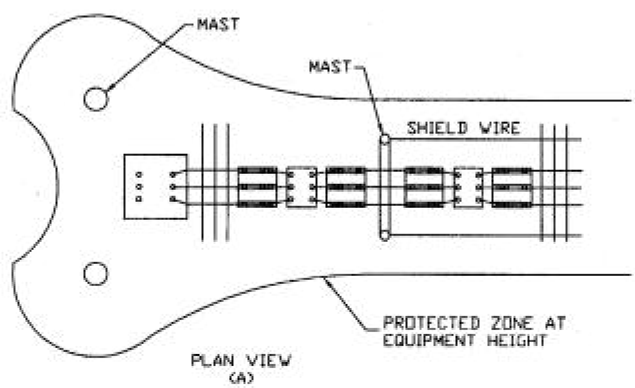
The above concept can be applied to multiple shielding masts, horizontal shield wires, or a combination of the two. Figure 5-7 shows this application considering four shield masts in a multiple shield mast arrangement. The arc of protection for stroke current Is is shown for each set of masts. The dashed arcs represent those points at which a descending stepped leader for stroke current Is will be attracted to one of the four masts. The protected zone between the masts is defined by an arc of radius S with the center at the intersection of the two dashed arcs. The protective zone can again be visualized as the surface of a sphere with radius S, which is rolled toward a mast until touching the mast,

then rolled up and over the mast such that it would be supported by the masts. The dashed lines would be the locus of the center of the sphere as it is rolled across the substation surface. Using the concept of rolling sphere of the proper radius, the protected area of an entire substation can. be determined. This can be applied to any group of different height shield masts, shield wires, or a combination of the two. Figure 5-8 shows an application to a combination of masts and shield wires.



Source: Adapted from [B74]

Figure 5-7 —Multiple shield mast protection for stroke current I_s



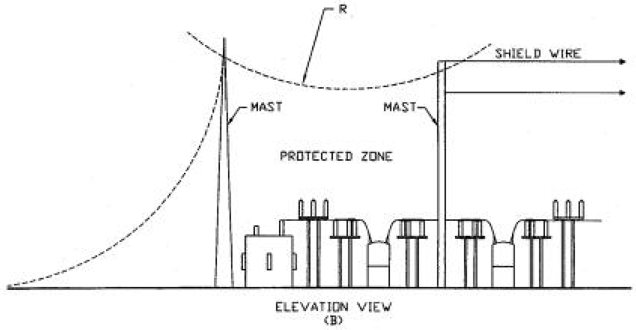


Figure 5-8 —Protection by shield wires and masts

Changes in voltage level

Protection has been illustrated with the assumption of a single voltage level. Substations, however, substations having Outdoor switchgears with two or more voltage levels in the same yard . The rolling sphere method is applied in the same manner in such cases, except that the sphere radius would increase or decrease appropriate to the change in voltage at a transformer. The designer simply makes a separate calculation for each voltage level in the station using the appropriate BIL and surge impedance. At the voltage interface (usually the transformer) the designer should ensure that the lower voltage equipment is protected by using the appropriate lower striking distance. This will not be discussed in this guide. (Refer to IEEE 998 – 1996 annex B, Example calculations for a substation with two voltage levels are given).

Calculation of failure probability :

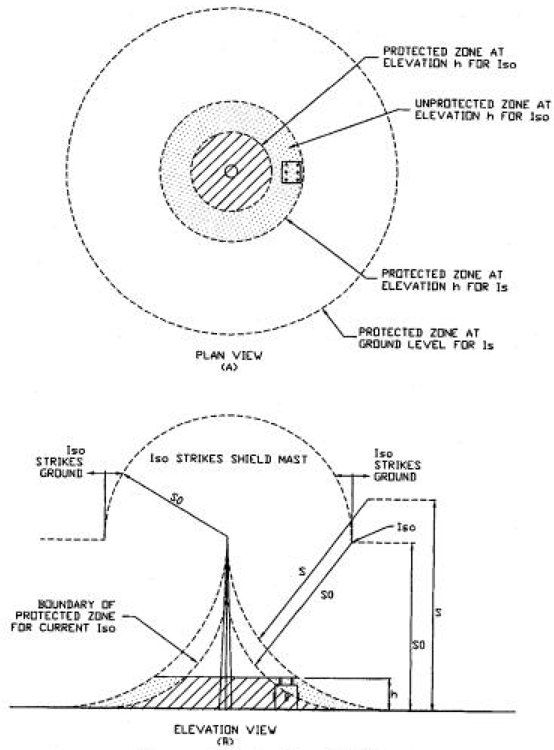
1. **Failure probability**

For the three conditions described in Items1 through Item 3 of this guide, if Is is chosen according to Eq. 5-2, there should theoretically be no equipment failures due to direct strokes. This is because only those strokes that could produce a surge voltage wave less than the BIL of the equipment were able to penetrate the shielding system, and these strokes should, therefore, cause no problem. Unfortunately, substation shielding that will provide such ideal protection is not always economical. This is especially true when one is working with substation equipment BIL levels below 550 kV.

The designer is then faced with the problem of first determining the level of failure risk he or she is willing to base the design on, then developing a design that will meet this criteria. The following clauses discuss a method of determining the unprotected area of a design and show how to calculate expected failure rates.

2. **Unprotected area**

To visualize an unprotected area, refer again to figure 5-6. Assume that equipment is sized and located as shown and further assume that, based on equipment BIL levels, equipment can withstand stroke currents less than Iso. The associated strike distance is S_o. Based on the layout, the shield mast will provide protection for all stroke currents greater than Is. However, those stroke current magnitudes between Iso and Is could reach equipment and would be expected to cause damage. The unprotected area for this condition would be the shaded area shown in figure 5-6.



Source: Adapted from [B74]

Figure 5-6 —Shield mast protection for stroke current I_{so}

3. **Probability of strokes causing equipment damage :**

Equation 2-2B or figure 2-4 can be used to determine the probability that any stroke will be greater than Is, which is the level above which the shield masts will intercept the stroke. This probability is P(Is). The same equation or figure can be used to determine the probability that the stroke will be greater than I_{so}, where Iso is the level of stroke current that can be handled by the equipment based on its BIL. This probability is $P(I_{so})$. The probability that a stroke is less than Is is 1.0 minus P(Is) or P(<Is). The probability that a stroke is less than I_{so} is 1.0 minus $P(I_{so})$or $P(<I_{so})$. For all lightning strokes that descend upon the shaded area of figure 5-6, the probability that equipment damage will occur is

$P(<Is) - P(<I_{so})$ or $P(I_{so}) - P(Is)$.

Example 1 :

These probabilities can best be demonstrated by the following example:

a) Assume that the stroke current for the striking distance So is 4.03 kA. Strokes of this magnitude may strike within the protected area.
b) Assume the strike distance S, above which protection is provided, is 40 m. From Eq. 2-1D, the stroke current above which protection is provided is 11.89 kA.
c) The probability that a stroke will exceed 4.03 kA, using Eq 2-2B or figure 2-4, is 0.990.
d) The probability that a stroke will exceed 11.89 kA, using Eq 2-2B or figure 2-4, is 0.861.
e) Therefore, the probability that a stroke which descends upon the unprotected area will be of a magnitude that can cause equipment damage and failure is 0.990 - 0.861 = 0.129 or 12.9%.

4. **Failure rate**

The substation designer is basically concerned with the rate of failure of the shielding design or the number of years expected between failures. In Item 3 , the methodology was presented for the designer to determine the probability that a stroke in the unprotected area would cause failure. By knowing the number of strokes expected to descend upon the area, the failure rate can be determined.

The number of strokes per unit area expected in the vicinity of the substation is the ground flash density (GFD). GFD is calculated using Eq. 2-3 or 2-4. The number of strokes expected to descend upon the area is the GFD multiplied by the unprotected area. The annual failure rate is the product of the number of strokes to the area times the probability that the stroke in the area will cause failure.

Example 2 :

The calculation of failure rate will be demonstrated by continuing the example begun in Example 1 .

a) Assume the outside radius of the unprotected area is 35 m and the inside radius of the unprotected area is 22 m. The unprotected area is p [(35)^2 - (22)^2] = 2328 m^2 or 2328×10^{-3} Km^2.

b) Assume the isokeraunic level is 50 thunderstorm-days per year. (T values across the USA can be read from figure 2-6). The GFD, from Eq. 2-3A, is 6.0 strokes per square kilometer per year.

c) The annual number of strokes expected to descend into the unprotected area is 6.0 x 2328×10^{-3} = 0.01397 strokes/year.

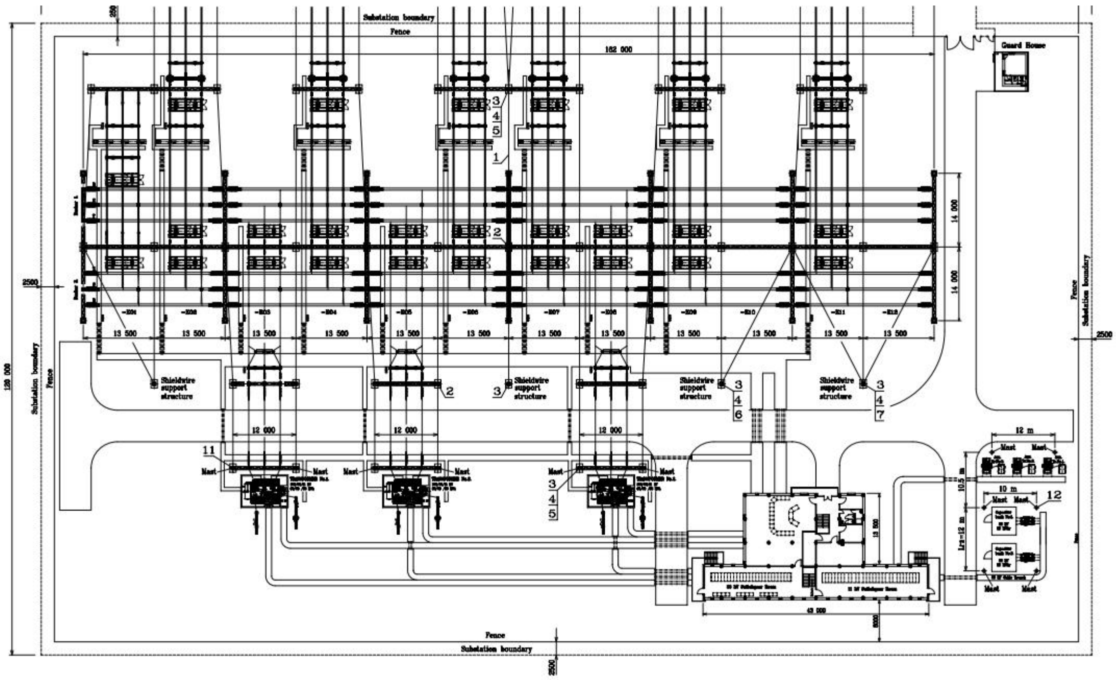
d) The annual expected number of equipment failures due to direct lightning strokes, using the 0.129 probability developed in Example 1, is 0.01397 x 0.129 = 0.00180 failures/year or 556 years between failures.

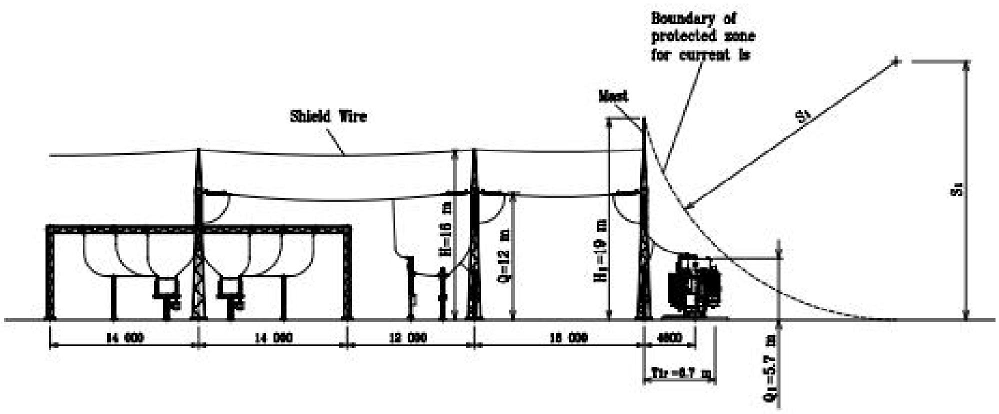
The above calculated failure rate would be for the simplified single mast substation described in the example. If a utility had 20 such substations of identical design scattered throughout its system, the total system substation failure rate due to direct strokes would be 556 divided by 20 = 28 years between failures.

<u>EXAMPLE</u>:

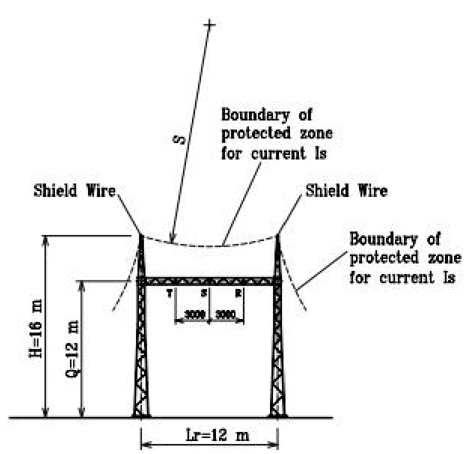
Lightning Protection Design Calculations for 132 / 11 KV Outdoor Substation with 132 KV AIS (Air Insulated Switchgear) , 40 KA with the following data and Layout :

Nominal System Voltage	Un= 132 kV
Basic Lightning Impulse Level	BIL=650 kV
Isokeraunic Level	Th= 25 thunder-days per year
Ground Flash Density (GFD)	GFD=3.84 strokes per km2 per year
Shielding Failure Risk	SP_{max}=1 failure per 100 years
Substation area	A= 120x200 = 24 000 m2
Height of the shield wires	H = 16 m
Height of the mast	H1 = 19 m
Height of the protected object (bus)	Q = 12 m
Height of the protected object (equipment)	Q1 = 5.7 m
Distance of two shield wires	Lr = 13.5 m (or 12 m)
Distance of two masts	Lr1= 12 m





Transformer Bay was chosen because it was not considered earlier and it was covered by the failure rate which was rejected and new masts were added in the design to cover the transformers area and the capacitor banks area .



Application of the Electrogeometric Model (EGM) :

Calculation of corona radius and surge impedance (According to IEEE Std 998-1996, Annex C)

1. **Calculation of corona radius and surge impedance under corona**

In case of a single conductor, the corona radius Rc is given by :

$$R_c \times \ln\left(\frac{2 \times h}{R_c}\right) - \frac{V_c}{E_0} = 0 \qquad \text{(C.1)}$$

where

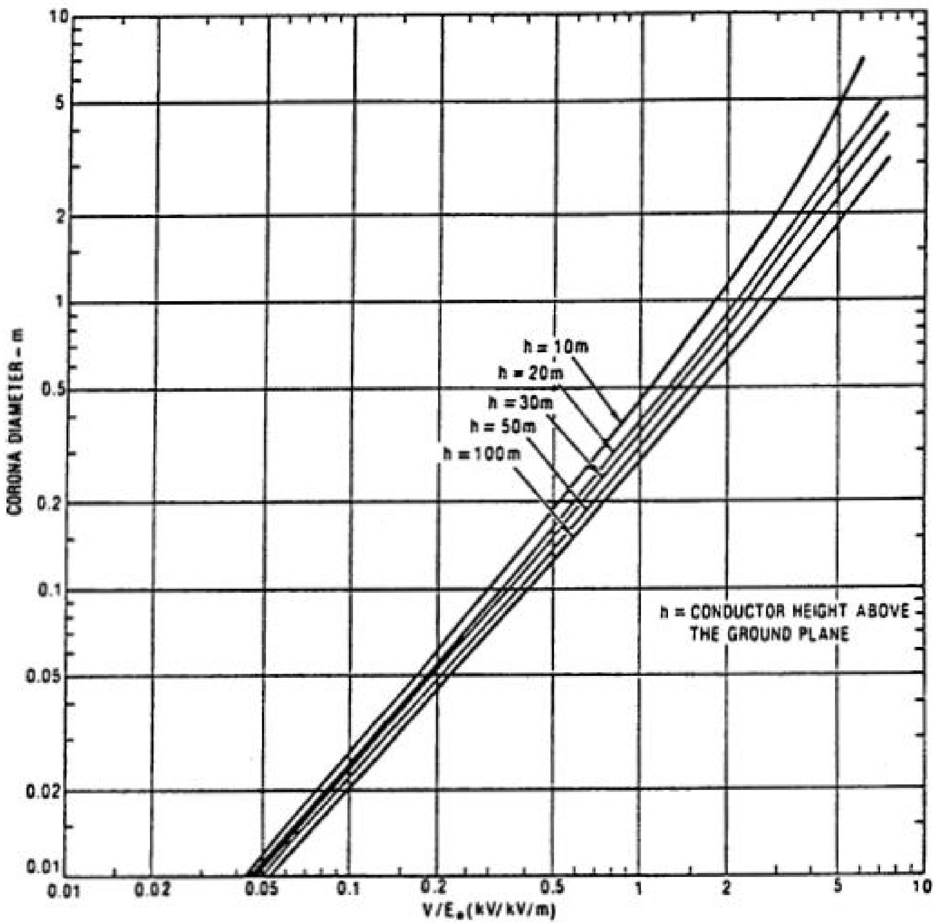
Rc is the corona radius in meters

h is the average height of the conductor in meters

V_c is the allowable insulator voltage for a negative polarity surge having a 6 ms front in kilovolts (Vc = the BIL for post insulators)

E_0 is the limiting corona gradient, this is taken equal to 1500 kV/m

Eq. C.1 can be solved by trial and error using a programmable calculator (an approximate solution is given in figure C.1).



Reprinted with permission from *Transmission Line Reference Book 345 kV an dAbove*, Second Edition, Revised© 1982, Electric Power Research Institute, Palo Alto, CA.

Figure C.1—Approximate diameter of corona sheath around a single conductor under impulse conditions

Corona radius:

Rc = 0.071 m

where

Rc is the corona radius in meters
h is the average height of the conductor in meters

2. **Surge impedance under corona**

The surge impedance of conductors under corona in ohms is given by:

$$Z_s = 60 \times \sqrt{\ln\left(\frac{2 \times h}{R_c}\right) \times \ln\left(\frac{2 \times h}{r}\right)} \qquad (C.7)$$

where

h is the average height of the conductor
Rc is the corona radius (use Eq. C.1 for a single conductor or refer to IEEE Std. 998 – 1996 Annex – C as appropriate)
r is the metallic radius of the conductor, or equivalent radius in the case of bundled conductors

Z_s = 365 ohm

3. **The allowable stroke current:**

There are Two methods for calculating the I_s :

1. Either using the Surge Arrester Current Rating which is normally 10 KA .
2. Calculate the I_s from the following equation :

$$I_s = \frac{BIL \times 1.1}{(\frac{Z_S}{2})} = 2.2 \times \frac{BIL}{Z_S} \qquad (5-2A)$$

$$I_s = 2.2 \times \frac{650}{365} = 3.917 KA$$

a) **Protection by shield wires**

The coefficient to account for different striking distances to shield wires:
k = 1.0
Sphere radius:

$$S_m = 8 \cdot k \cdot I^{0.65} \qquad (Eq. 5-1A)$$

$$S_m = 8 \times 1.0 \times 3.917^{0.65}$$

= 19.45 m

OR, if 10 KA is used .

$$S_m = 8 \times 1.0 \times 10^{0.65}$$

= 35.73 m

Elevation difference between wire and bus:
D = H - Q =16 -12 = 4 m
Elevation difference between wire and OOS:
E = S – D =19.45 – 4 = 15.45 m
Half the separation between two wires:
$L = (S^2 - E^2)^{½} = [(19.45)^2 - (15.45)^2]^{½} = 13.02$ m
Maximum separation between two wires:
X = 2L=26.04 m
(This value is the maximum separation of shield wires for protection of bus at height Q)
Distance of two shield wires Lr =13.5 m (or 12 m) < X=26.04 m

b) **Protection by masts**

The coefficient to account for different striking distances to mast:
k_1 = 1.2
Sphere radius:

$$S_m = 8 \cdot k_1 \cdot I^{0.65} = 8 \times 1.2 \times 3.917^{0.65}$$

= 23.34 m

Horizontal distance from OOS to equipment:

$$C_1 = (S_1^2 - (S_1 - Q_1)^2)^{1/2} = (23.34^2 - (23.34 - 5.7)^2)^{1/2} = 15.2 \text{ m}$$

Maximum separation from mast to equipment for protection:

$T_1 = S_1 - C_1 = 23.34 - 15.2 = 8.14$ m

(This value is the maximum separation between the mast and protected equipment at height Q_1)

Separation between the mast and protected equipment at height 5.7 m:

$T_1r = 6.7 \text{ m} < T_1 = 8.14 \text{ m}$

Lightning Protection Calculation for Capacitor banks and Aux. transformers

Nominal System Voltage	Un= 33 kV
Basic Lightning Impulse Level	BIL=170 kV
Height of the mast	H2 = 11 m
Height of the protected object (equipment)	Q2 = 3.8 m
Spacing of four masts	Lr2= 12 m

Application of the Electrogeometric Model (EGM) :

Calculation of corona radius and surge impedance (According to IEEE Std 998-1996, Annex C) :

Corona radius:

In case of a single conductor, the corona radius Rc is given by :

$$R_c \times \ln\left(\frac{2 \times h}{R_c}\right) - \frac{V_c}{E_0} = 0 \qquad \text{(C.1)}$$

$R_c = 0.02$ m

The surge impedance of conductor under corona:

The surge impedance of conductors under corona in ohms is given by:

$$Z_s = 60 \times \sqrt{\ln\left(\frac{2 \times h}{R_c}\right) \times \ln\left(\frac{2 \times h}{r}\right)} \qquad \text{(C.7)}$$

$Z_s = 300$ ohm

The allowable stroke current:

$$I_s = \frac{BIL \times 1.1}{(\frac{Z_S}{2})} = 2.2 \times \frac{BIL}{Z_S}$$

$$I_s = 2.2 \times \frac{170}{300} = 1.25 KA$$

Protection by masts

The coefficient to account for different striking distances to mast:

k1 = 1.2

Sphere radius:

$$S_m = 8 \cdot k_1 \cdot I^{0.65} = 8 \times 1.2 \times 1.25^{0.65}$$

= 11.1 m

Elevation difference between mast and equipment:

D2 = H2 – Q2 = 11 – 3.8 = 7.2 m

Elevation difference between mast and OOS:

E2 = S2 – D2 = 11.1 – 7.2 = 3.9 m

Horizontal distance between OOS and mast:

$$J_2 = (S_2^2 - E_2^2)^{1/2} = (11.1^2 - 3.9^2)^{1/2} = 10.4 \text{ m}$$

Diagonal distance between masts when four masts support the sphere:

K2 = 2J2=20.8 m

Distance between masts when four masts support the sphere:

$$P_2 = K_2/2^{1/2} = 20.8/2^{1/2} = 14.2 \text{ m}$$

(This value is the maximum spacing of four masts for protection of equipments at the height Q2)

Spacing of four masts Lr2 =12 m < P2 =14.2 m

<u>Calculation of failure probability</u>:

<u>Note</u> : (In my opinion ,this should not be considered for any Area within the substation where equipment is installed and personnel attendance cannot be waived and can be considered only for Empty Areas to save costs).

Because I_s is chosen according to Eq. 5-2A there should be no equipment failures due to direct strokes on the protected area. (under the curves with radius S).
The curve with radius S (S=19.45 m) do not cover the whole Tr., but the curve with radius S1 (S1=22 m) cover the whole Tr.,

a) Assume that the stroke current for the striking distance S is Is=3.92 kA. Strokes of this magnitude may strike within the protected area.
b) Assume the stroke distance S1, above which protection is provided, is 22 m. From
$S_1 = 8 \cdot I_{s1}^{0.65}$ Equation, (ref. Eq. 2-1D)
the stroke current above which protection is provided is:

$$I_{S1} = \left(\frac{S_1}{8}\right)^{\frac{1}{0.65}} = \left(\frac{22}{8}\right)^{\frac{1}{0.65}} = 4.75 \text{ kA}$$

c) The probability that a stroke will exceed Is = 3.92 kA:

$$P(I_s) = \frac{1}{1+(\frac{I}{24})^{2.6}} = \frac{1}{1+(\frac{3.92}{24})^{2.6}} = 0.991 \quad \text{(ref. Eq. 2-2B)}$$

d) The probability that a stroke will exceed Is_1= 4.75 kA:

$$P_{(I_{S1})} = \frac{1}{1+(\frac{I}{24})^{2.6}} = \frac{1}{1+(\frac{4.75}{24})^{2.6}} = 0.985 \quad \text{(ref. Eq. 2-2B)}$$

e) Therefore, the probability that a stroke which descends upon the unprotected area will be of a magnitude that can cause equipment damage and failure is:
$P = P_{(I_{S)}} - P_{(I_{S1})} = 0.991 – 0.985 = 0.006 = 0.6$ %

Calculation of failure rate:

To evaluate the expected shielding performance of a substation site, proceed as follows:

a) Determine the ground flash density using Eq. 2-3 or Eq. 2-4.

$$N_K = 0.12 \cdot T_d$$

b) Calculate the number of flashes to the substation area, Ns.
Ns = GFD x A / $(1000)^2$

Where,
GFD is the ground flash density in strokes per square kilometer per year
A is the substation area in square meters

c) Calculate number of strokes per year penetrating the shield, SP.
SP = Ns x Exposure rate

1. The unprotected area 1 (at the Tr.-s) is:

Au_1= 3 x 1.8 x 12 = 64.8 m² = 64.8 x 10^{-6} km²

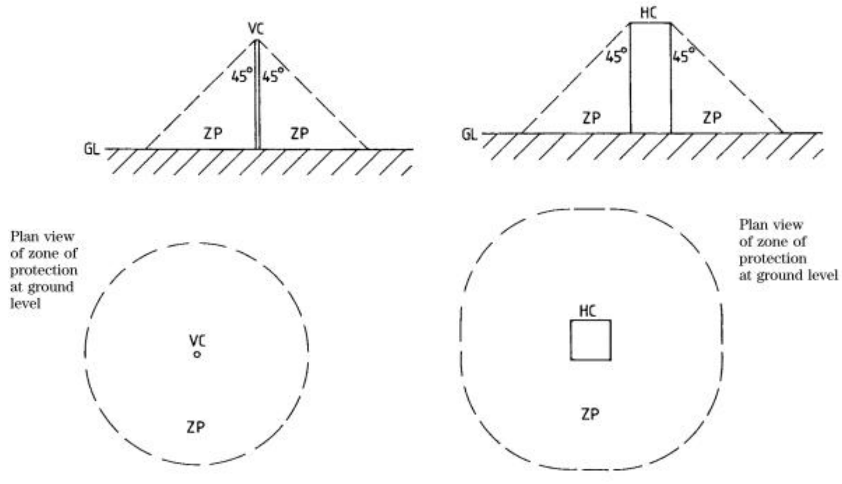
a) The GFD=3.84 strokes per km² per year
b) The annual number of strokes expected to descend into the unprotected area 1 is:
Ns = GFD x Au_1= 3.84 x 64.8 x 10^{-6} = 250 x 10^{-6} strokes per year
c) The annual expected number of equipment failures due to direct lightning strokes:
SP1= N1 x P=250 x 10-6 x 0.006 =1.5 x 10^{-6} failures per year
SP1= 0.00015 failures per 100 years

2. The unprotected area 2 (outside of the area which is covered by the 132 kV AIS) is:
   a) $Au2= 670\ m2 = 0.67 \times 10^{-3}\ km^2$
   b) The GFD=3.84 strokes per km² per year
   c) The annual number of strokes expected to descend into the unprotected area 2 is:
      $N2=GFD \times Au_2= 3.84 \times 0.67 \times 10^{-3}$ 10-3 = 2.573×10^{-3} strokes per year
   d) The annual expected number of equipment failures due to direct lightning strokes:
      SP2= 0.002573 failures per year
      SP2= 0.2573 failures per 100 years
      SP= SP1 + SP2 = 0.00015 + 0.2573 = 0.25745 failures per 100 years (or 390 years between failures)
      SP = 0.25745 failures per 100 years < SP_{max}=1 failure per 100 years

Conclusions:
The shielding failure risk is not greater than one failure per 100 years as specified.
But, note that if a utility had 20 such substations of identical design scattered throughout its system, the total system substation failure rate due to direct strokes would be 390 divided by 20 = 19.5 years between failures.

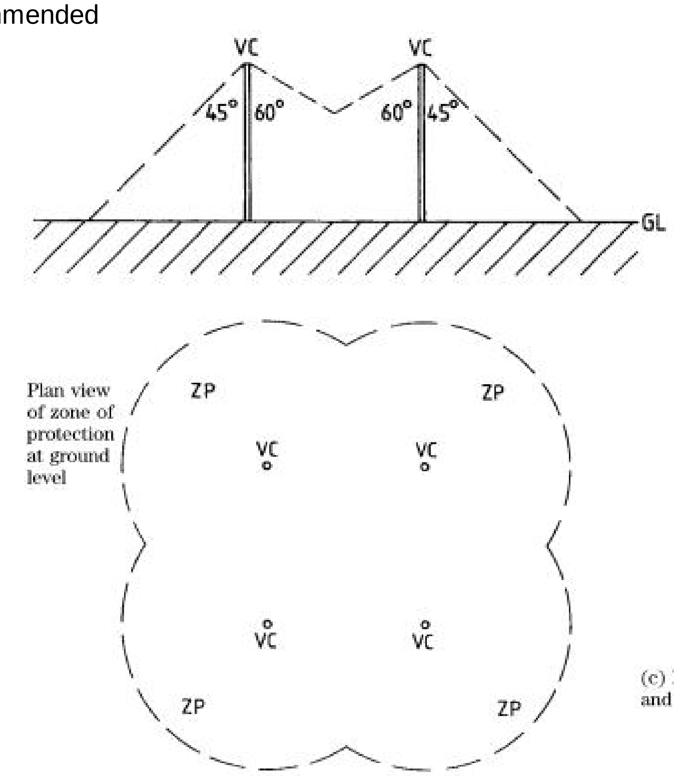
Indoor GIS Substation and Control Building Lightning Protection :
Lightning protection shall be provided on all buildings.
BS.6651 is widely used for the design, installation and materials for the lightning protection systems . The lightning protection system may be inter-connected with the earthing system provided the conductors form the most direct path for lightning currents from the air terminals to the earth electrodes. Additional conductors and earth electrodes shall be installed as necessary to ensure a direct path.
The adequacy of lightning protection shall be attained by installing air terminals and over the buildings. The down leads shall be brought in such a manner that they pose minimum risk to the personnel. As far as possible, the conductor shall be taken to the earth rod without any bends or twist in the route.
Only brief description of the relevant BS 6651 clauses is given in this guidance . For more details , please refer to BS 6651 .

Protective angle
For structures not exceeding 20 m in height, the angle between the side of the cone and the vertical at the apex of the cone is known as the protective angle, as shown in Figure 6. The magnitude of the protective angle cannot be precisely stated because it depends upon the severity of the stroke and the presence within the protective zone of conductive objects providing independent paths to earth. All that can be stated is that the protection afforded by a lightning conductor increases as the assumed protective angle decreases. For structures exceeding 20 m in height, the protective angle of any conductors up to the height of 20 m would be similar to that for lower structures. However, for structures above 20 m, where there is a possibility of such buildings being struck on the side, it is recommended that the protected volume is determined using the rolling sphere method.
For the practical purpose of providing an acceptable degree of protection for an ordinary structure up to 20 m high and up to a height of 20 m for a higher structure, the protective angle of any single component part of an air termination network, namely either one vertical or one horizontal conductor, is considered to be 45º [see Figures 6a) and b)].
A protection angle of 30° from the vertical plane is also widely used



(a) One vertical conductor (b) Horizontal air termination

Between two or more vertical conductors, spaced at a distance not exceeding twice their height, the equivalent protective angle may, as an exception, be taken as 60º to the vertical; an example is shown in Figure 6c). For a flat roof, the area between parallel horizontal conductors is deemed to be effectively protected if the air termination network is arranged as recommended in 15.2 and 15.3. For structures requiring a higher degree of protection, other protective angles are recommended



(c) Four vertical conductors showing protective angles and associated zones of protection

Figure 6 — Protective angles and zones of protection for various forms of air termination

Air terminations

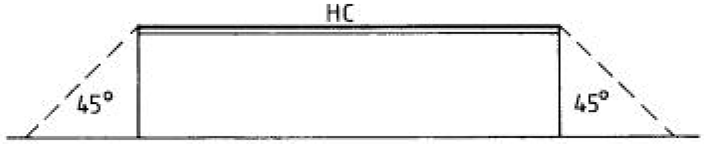
15.1 General

Basic guidelines on the design of air terminations are given in 15.2 and explanatory notes on the various forms that are commonly used follow in 15.3.

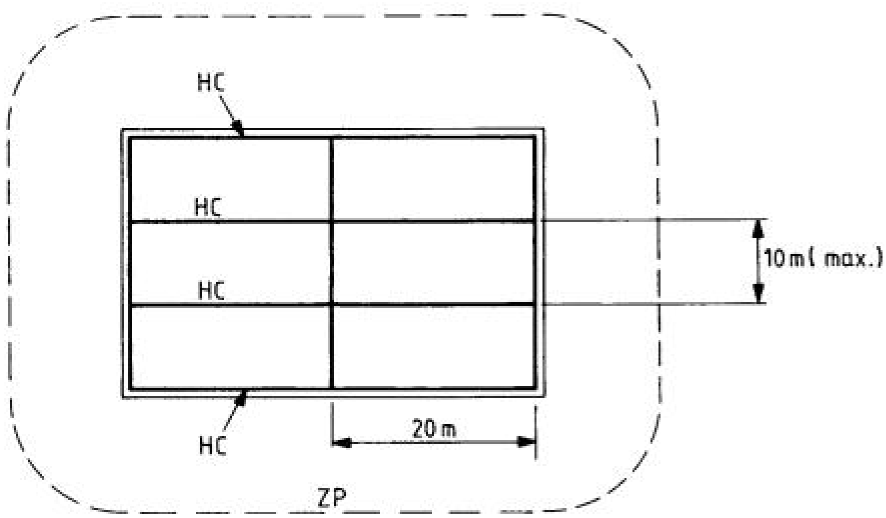
15.2 Basic rules

Air termination networks may consist of vertical or horizontal conductors or combinations of both (see, for example, Figures 10 to 15). No part of the roof should be more than 5 m from the nearest horizontal conductor and a 20 m x 10 m mesh should be maintained. For large flat roofs, this is achieved typically by use of an air termination network mesh of approximately 10 m x 20 m. to ensure that the lightning current at the point of strike is quickly dispersed throughout the air terminations to all down conductors thus reducing mechanical and thermal stress and minimizing the risk of side-flashing.

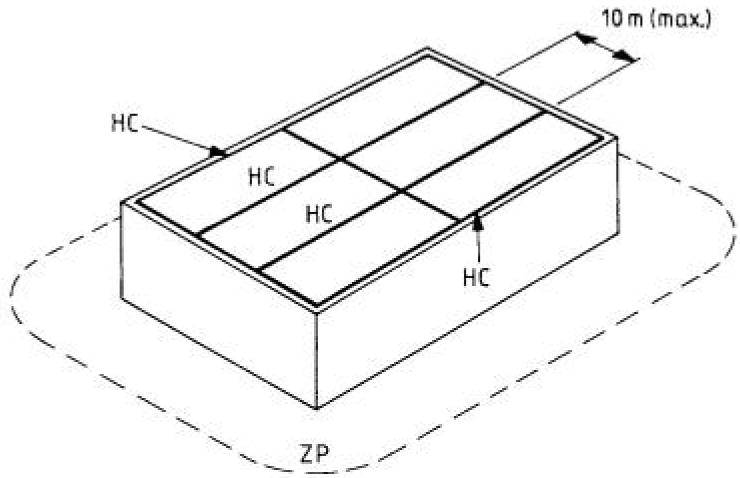
On multiple ridge roofs, additional conductors are necessary if the separation, S (in meters), of the ridges is greater than 10 + 2H, where H is the height of the ridge (in meters). See Figure 12.
On a reinforced concrete structure, the air termination should be connected to the reinforcing bars in the number of positions needed for down conductors.
All metallic projections on or above the main surface of the roof which are connected, intentionally or fortuitously, to the general mass of the earth should be bonded to, and form part of, the air termination network (see, for example, Figure 5 and Figure 7 Metallic coping, roof coverings, handrails, window washing equipment and metallic screens around play areas should be considered for inclusion as part of the air termination network (see Figure 5, Figure 7).
If portions of a structure vary considerably in height, any necessary air terminations or air termination networks for the lower portions should be joined to the down conductors of the taller portions in addition to being joined to their own down conductors.



(a) Elevation showing protective angle

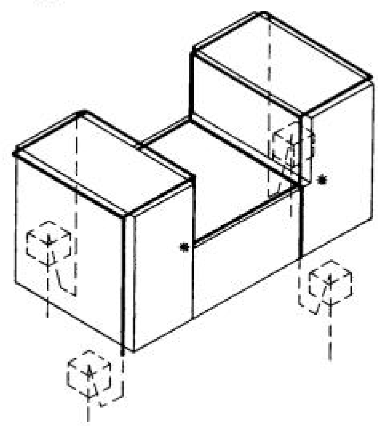


(b) Plan showing zone of protection at ground level

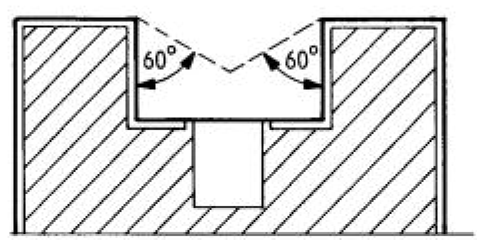


(c) General arrangement

Figure 10 — Air terminations for a flat roof



* Join down conductors and horizontal conductors on lower parapet.



Section A-A

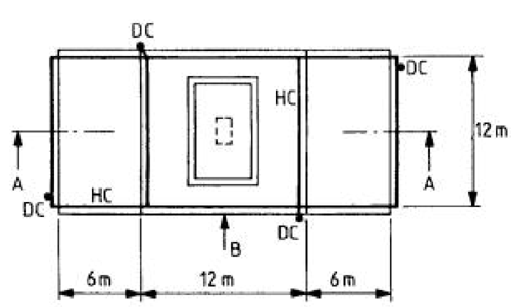
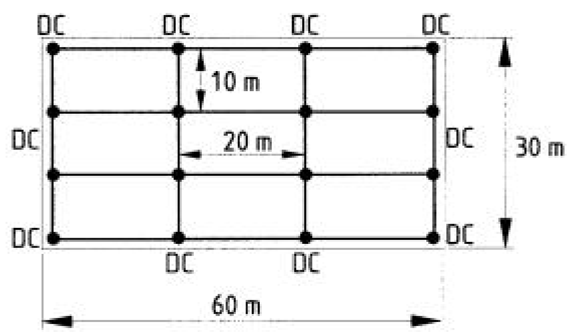


Figure 11 –Air terminations for flat roofs at different levels
Perimeter = 24 + 24 + 12 + 12 = 72
Number of down conductors required
= 72/20 = 4.

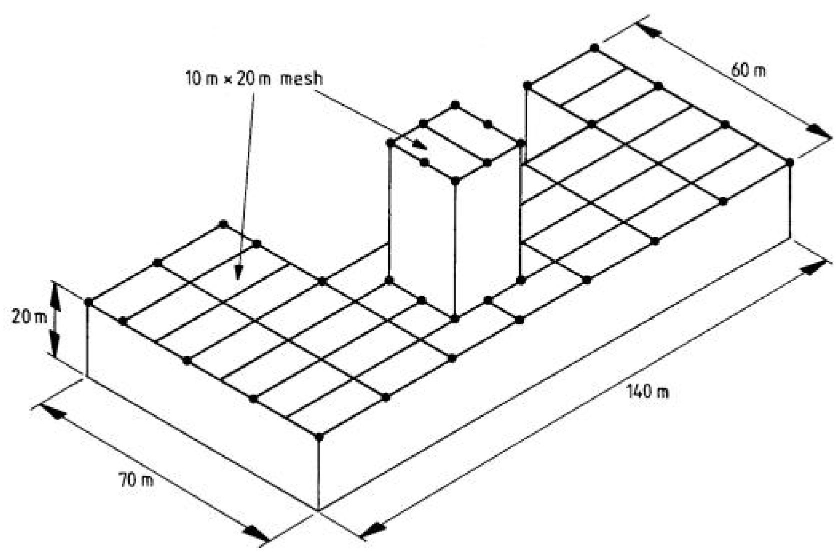
NOTE 1 An air termination along the outer perimeter of the roof is required and no part should be more than 5 m from the nearest horizontal conductor, except that an additional 1 m may be allowed for each meter by which the part to be protected is below the nearest conductor.

NOTE 2 Horizontal conductors are not necessary on the parapets of the light well; a zone of protection of 608 is provided by the two adjacent horizontal conductors for structures less than 20 m high. This principle does not apply to taller structures.



NOTE Horizontal air termination conductors should be jointed at the interconnections in accordance with **16.10.4**.

Figure 14 — Air terminations and down conductors for flat roof buildings



NOTE The air termination network for a tall reinforced concrete or steel structure should be as follows:

a) horizontal conductors on roofs from a 10 m × 20 m network;

b) bonds to steelwork at corners, at 20 m intervals around the periphery and on the tower 0.5 m above the lower roof level;

c) key bonding to the building steelwork ●.

Figure 15 — Air terminations for tall conducting structures

15.3 Forms of air termination

15.3.1 General

In practice, very few of the many forms of structure can be protected by any reasonable arrangement of single conductors. Recommendations for various forms of air termination are given in Figures 10 to 15. Guidance on their application is given in 15.3.2 to 15.3.6. Although, for the sake of clarity, down conductors and earth terminations have been omitted from the figures, these should be provided as recommended elsewhere in this code of practice, taking account as necessary of the architectural and structural features of the structure and of the site conditions.

15.3.2 Simple vertical conductor(s)

Figure 6a) shows a simple vertical conductor and the zone of protection in plan and elevation. Figure 6c) shows four vertical conductors with the increased angle of protection available between them. The zones of protection for this arrangement are shown in the plan view. However, although in suitable cases advantage may be taken of the increased protection zone, there can be no certainty about the precise shape of the envelope since this is only a statistical concept.

The position and spacing of down conductors on large structures is often governed by architectural convenience. However, there should be one down conductor for each 20 m or part thereof of the perimeter at roof level or ground level, whichever is the greater. Structures over 20 m high should have one per 10 m or part thereof.

15.3.3 Horizontal conductor(s) for flat roofs

Figure 6b) shows a simple horizontal air termination consisting of a roof conductor around the periphery of a rectangular building. The resulting zone of protection is shown in plan and elevation.

Figure 10 shows a typical arrangement for a structure with a large area of flat roof where the use of a system of horizontal roof conductors is strongly recommended. The network of the air termination on a flat roof is recommended to be in the form of a grid to reduce the effect of flashover caused by large induction loops.

16 Down conductors

16.1 General

The function of a down conductor is to provide a low impedance path from the air termination to the earth electrode so that the lightning current can be safely conducted to earth. This code of practice covers the use of down conductors of various types including the use of strip, rod, reinforcing bars and structural steel stanchions, etc. Any good conductor which forms part of the building structure can be included, appropriately jointed to the air and earth terminations. In general, the greater the number of down conductors used, the lower the risk of side-flashing and other undesirable phenomena. Likewise, large conductors reduce the risk of side-flashing, especially if insulated.

In brief, the down conductor system should, where practicable, be directly routed from the air termination to the earth termination network and be symmetrically placed around the outside walls of the structure starting from the corners. In all cases, consideration should be given to side-flashing.

16.3 Recommended number

The position and spacing of down conductors on large structures is often governed by architectural convenience. However, there should be one down conductor for each 20 m or part thereof of the perimeter at roof level or ground level, whichever is the greater. Structures over 20 m high should have one per 10 m or part thereof.

16.11 Test points

Each down conductor should be provided with a test joint in such a position that, whilst not inviting unauthorized interference, it is convenient for tests.

Plates indicating the position, number and type of earth electrodes should be fitted above each test point

17.2 Importance of reducing resistance to earth

An earth electrode should be connected to each down conductor. Each of these earths should have a resistance (in ohms) not exceeding the product given by 10 times the number of earth electrodes to be provided (see 16.3). The whole of the earth termination network should have a combined resistance to earth not exceeding 10 V without taking account of any bonding to other services.

If the value obtained for the whole of the lightning protection system exceeds 10 V, a reduction can be achieved by extending or adding to the electrodes or by interconnecting the individual earth electrodes of the down conductors by a conductor installed at least 0.6 m below the ground, sometimes referred to as a ring earth electrode (see Figure 23). Ring earth electrodes should preferably pass below incoming services.

Buried ring earth electrodes laid in such a manner are considered to be an integral part of the earth termination network and should be taken into account when assessing the overall value of resistance to earth of the installation.

A reduction in the resistance to earth to a value below 10 V has the advantage of reducing the potential gradient around the earth electrodes when discharging lightning current. It may also reduce the risk of side-flashing to metal in or on a structure

17.4 Isolation of earth electrode systems for testing

Isolation of earth electrode systems for testing Earth electrodes should be capable of being isolated and a reference earth electrode (see 3.1.12) should be provided for testing purposes. Where the steel structure of a building is used as the down conductors, sufficient points of test should be provided to enable the low resistance continuity of the steel structure to be checked. This is especially important for those parts of the structure that are not visible. A reference earth electrode will be necessary for these tests.

Annex A :

Surge Arrester Protection : Lightning over-voltages

- **General remarks**

The over-voltages in substations depend on amplitude and shape of the overvoltage impinging on the substation from the overhead line conductor as well as on the travelling wave behavior of the substation itself. The frequency with which such impinging over-voltages occur is given by the lightning performance of the overhead line connected to the substation. For substations or parts of a substation to which no surge arrester is connected, the most important parameter is the amplitude of the impinging overvoltage; for substations protected by surge arresters, it is its steepness and the separation distance between surge arrester and the equipment under consideration.

The steepness of an impinging overvoltage surge is reduced mainly by corona damping effects on the overhead line . This means that the steepness of the impinging surge can be only sufficient to cause a certain overvoltage amplitude if the lightning stroke hits the overhead line within a certain distance from the substation . For further strokes the steepness will be too low, irrespective of the amplitude of the surge.The knowledge of this limit distance is of primary importance.

Determination of the limit distance (Xp)

- **Protection with arresters in the substation**

This sub-clause contains more detailed information on surge arrester protection , more than one overhead line is connected to the substation, the original steepness (S) of the impinging surge can be divided by the number of lines (n). However, it is emphasized that the number of lines should correspond to the minimum number which reasonably remains in service taking into account possible outages during lightning storms.

Allowing for the fact that the steepness of the impinging surge reduces inversely with the travel distance on the overhead line, the steepness S of the impinging surge to be used in equation (1) is approximately equal to:

$S = 1/(n\, K_{co}\, X)$ (Eq. - 1)

Where ,

n is the number of overhead lines connected to the substation; if multi-circuit towers are involved and double-system back flashovers have to be taken into account, it is recommended to divide the number by two;

K_{co} is the corona damping constant according to Table F.1 [µs/(kV.m)];

X is the distance between struck point of lightning and substation (m).

The use of this steepness value in equation (1) does not yield sufficiently accurate results for the calculation of overvoltage at the equipment. However, it is sufficient (and conservative) to estimate the limit distance Xp by:

$X_p = 2\, T/[nK_{co}\, (U - U_{pl})]$ (Eq. - 2)

Where,

U is the lowest considered overvoltage amplitude;

T is the longest travel time between any point in the substation to be protected and the closest arrester (µs);

U_{pl} is the lightning impulse protective level of the arrester.

For distances larger than X_p the steepness will be reduced such that the overvoltage at the equipment will in general be smaller than the assumed value U.

Table F.1 — Corona damping constant K_{co}

Conductor configuration	K_{co} [µs/(kV.m)]
Single conductor	$1{,}5 \times 10^{-6}$
Double conductor bundle	$1{,}0 \times 10^{-6}$
Three or four conductor bundle	$0{,}6 \times 10^{-6}$
Six or eight conductor bundle	$0{,}4 \times 10^{-6}$

Reference Documents :

1. IEEE Std. 998 –1996 .
2. BS 6651 .
3. Design Guide for Rural Substations - United States Department of Agriculture - June 2001.
4. Example is from Contractor Submittal for Lightning Protection Design for 132 KV AIS S/S.