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Title: **DIRECT LIGHTNING STROKE PROTECTION OF SUBSTATIONS**

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# 1. Introduction

This guideline sets out the requirements and procedure for the design and evaluation of a lightning interception system for Eskom's Generation, Transmission and Distribution 50Hz AC Substations. This standard provides some theory on lightning phenomena, an analysis of the various design methodologies, the basic design procedure and calculation of design parameters with an application of the design methodology.

Personnel safety, protection of equipment and the reliable continuous operation of a substation requires that transient surges are prevented from entering a substation. These surges can be switching surges, lightning surges from lines connected to a substation or direct strokes to the substation.

Direct strokes from lightning can damage substation equipment and poses a safety risk to personnel operating and maintaining substations. To protect personnel and equipment from direct lightning strokes to a substation, a lightning protection system is required and is designed to:

a) intercept (masts, shield wires)

b) conduct (steelwork/ earth strap)

c) and dissipate (earth mat) dangerous lightning current.

A lightning protection system design needs to consider the risk that lightning poses in a certain area based on the ground flash density, the strategic importance of the substation to customers and the surrounding network, the economic value of the equipment that is to be protected, and the cost of the lightning protection system.

# 2. Supporting clauses

## 2.1 Scope

This guideline deals with the interception of damaging direct lightning strokes to outdoor substations. The shielding system is designed to intercept all lightning strokes greater or equal to the allowable stroke current (Is) so that a flashover of the insulation does not occur. The shielding system design will allow for strokes less than the allowable stroke current to enter the protected area since the equipment can withstand voltages below its BIL [IEEE 998-2012]. This standard is applicable to new substation designs and existing substations that are due for refurbishment.

The standard does not address the following:

a) Lightning surges entering a substation via the power or communication lines connected to the HV and/or MV sides of the substation

b) Switching surges on the HV and/or MV sides of the substation

c) Conduction and dissipation of direct lightning strikes to an outdoor substation

Good engineering judgment is required in the application of the methods, particularly with respect to the importance and value of the equipment being protected [IEEE 998-2012].

### 2.1.1 Purpose

The purpose of this guideline is to set out the design criteria and procedure for the effective interception of damaging direct lightning strokes to outdoor substations thereby protecting personnel and equipment from dangerously high lightning current and voltages. This document is necessary to ensure that all business units use a standardised methodology for lightning protection of substations.

### 2.1.2 Applicability

This document shall apply throughout Eskom Holdings Limited Divisions.

## 2.2 Normative/informative references

Parties using this document shall apply the most recent edition of the documents listed in the following paragraphs.

### 2.2.1 Normative

[1] ISO 9001 Quality Management Systems.

[2] Substation Layout Design Guide.

[3] IEEE Power and Energy Society, IEEE Guide for Direct Lightning Stroke Shielding of Substations, IEEE Std 998-2012

[4] IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems IEEE Std142-2007

[5] South African National Standard SANS 62305-1:2007, Protection against lightning: Part 1- General Principles

[6] South African National Standard SANS 62305-2:2007, Protection against lightning: Part 2- Risk Management

[7] South African National Standard SANS 62305-3:2007, Protection against lightning: Part 3- Physical damage to structures and life hazard

[8] South African National Standard SANS 62305-4:2007, Protection against lightning: Part 4- Electrical and electronic systems within structures

[9] South African National Standard SANS 62561:2013, Lightning protection system components

### 2.2.2 Informative

[10] Orrell, J.T. Direct Stroke Lightning Protection. EEI Electrical System and Equipment Committee Meeting, Washington, 1988

[11] Central Station Engineers of the Westinghouse Electric Corporation, Electrical Transmission and Distribution Reference Book, Pennsylvania, 4th edition, 1964

[12] 240-127851444, Template for Direct Lightning Stroke Protection Of Substations

## 2.3 Definitions

### 2.3.1 General

| Definition | Description |
|---|---|
| **Keraunic Level** | Gives an indication of the amount of thunderstorm activity for a certain area. The average number of annual thunderstorm days or thunderstorm hours is used to determine the keraunic level. |
| **Striking distance** | The distance where the probability of the stroke tip terminating on an object S far away is greater than the probability of it striking another object S+n away. |

### 2.3.2 Disclosure classification

**Controlled disclosure:** controlled disclosure to external parties (either enforced by law, or discretionary).

## 2.4 Abbreviations

| Abbreviation | Description |
|---|---|
| **BIL** | Basic Insulation Level |
| **EGM** | Electro-Geometric Model |
| **GFD** | Ground flash density |
| **IEEE** | Institute of Electrical and Electronic Engineers |
| **OHGW** | Overhead ground wire |

## 2.5 Roles and responsibilities

Group lead engineers need to be fully briefed on the contents of this document. They will in turn be expected to instruct their direct reports in its use.

## 2.6 Process for monitoring

The document is to be updated from time to time as the technology develops.

## 2.7 Related/supporting documents

Not applicable.

# 3. Document content

## 3.1 Lightning Phenomena and Effects on a Substation

### 3.1.1 Charge formation in clouds

There are various theories as to how lightning is formed inside a cloud. One theory states that positive and negative ions in the air together with an electrical field (normal to the earth) polarize the water drops in a cloud. These polarized water drops fall towards the earth due to gravity. The electric field causes the undersides (relative to the earth surface) of these drops to acquire a positive charge, which attract negative ions in the air. Due to this effect the overall charge of the droplet becomes negative. These negatively charged drops separate the original neutral space charge in the cloud. This phenomenon in turn polarizes the cloud. The lower part of the cloud is now negatively charged due to this polarization. The upper section of the cloud is positively charged.

There is no general consensus as to how exactly the charge separation occurs. What is important is that charge separation does occur and this can lead to thunderstorms and subsequent lightning. Figure 1 illustrates the charge separation and electric field lines for a thunder cloud.

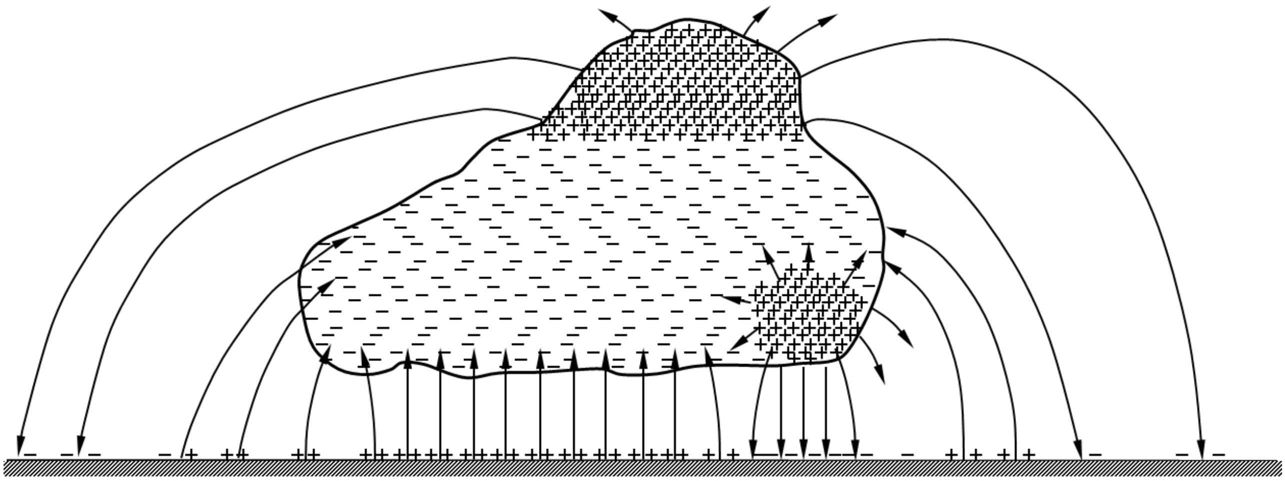


**Figure 1: Charged Cloud formation and resulting electric fields (Orrell, IEEE 998-2012)**

### 3.1.2 Stroke formation

Lightning strikes can be contained inside a cloud, between separate clouds, from clouds to structures and from clouds to ground. The discharge activities in the clouds causes air breakdown in the direction of the ground. Corona discharges start at the base of the cloud and develop into a stepped leader. The leader consists of a highly conductive ionised channel of air that is surrounded by a sheath of corona. The leader "grows" in a zig-sag like pattern towards earth. The leader is not visible to the naked eye and the current through it is small, in the order of 100A. This leader extends the charge of the cloud. As the leader grows towards earth it induces an opposite charge on the earth's surface or any conductive protrusion.

Corona then forms, extending from the earth or conductive protrusion towards the sky. When the two corona columns meet the charge neutralises itself with a flow of current from the earth to the cloud. This return stroke forms the visible part of lightning and conducts currents of the order of tens to hundreds of kilo amperes. Thunder is caused by the rapid rise in temperature of the return stroke that causes the surrounding air to explode. Figure 2 illustrates the sequential forming of a lightning strike.

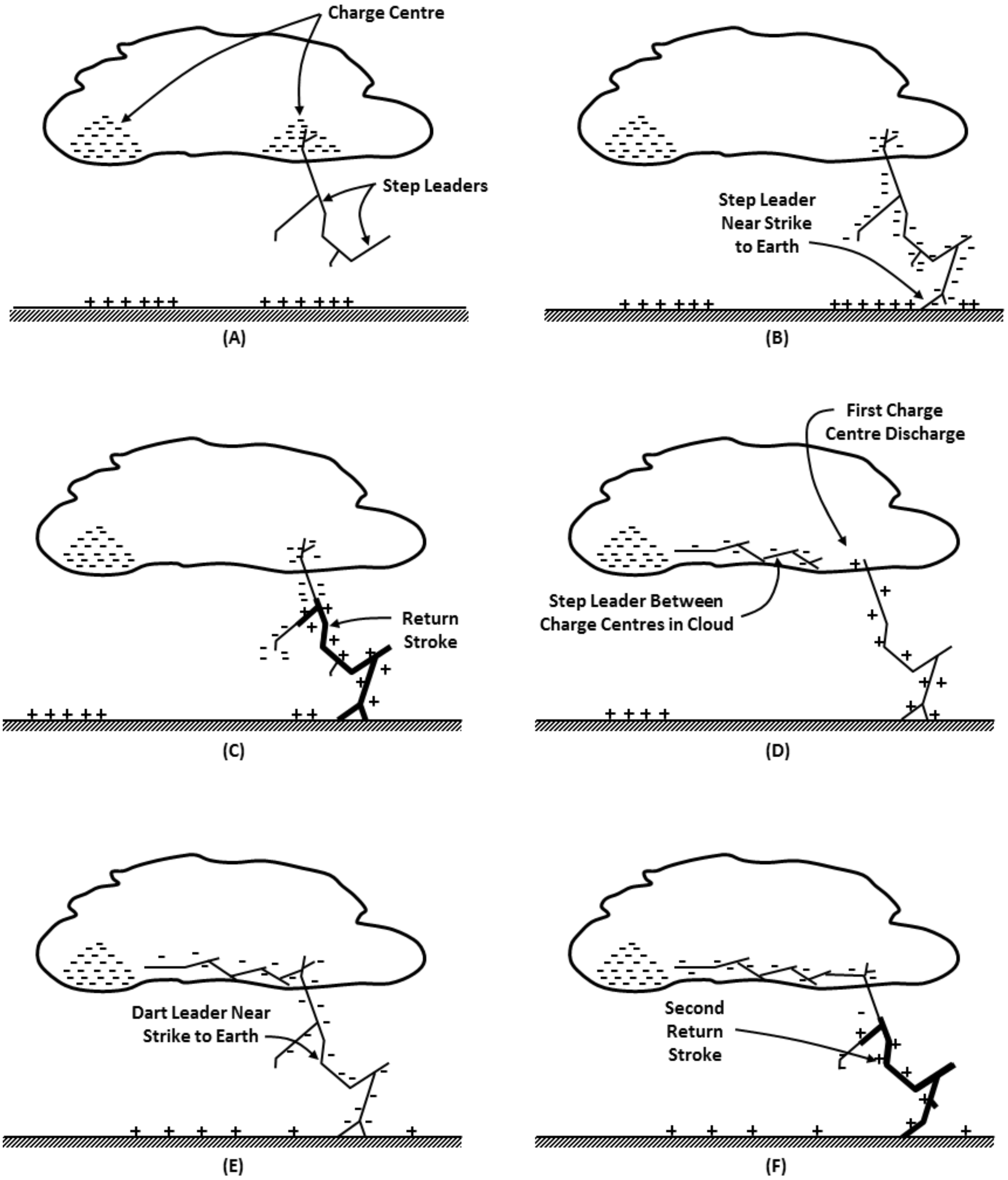



**Figure 2: Charge Distribution at various stages of lightning discharge (Central Station Engineers of the Westinghouse Electric Corporation, IEEE 998-2102)**

After the initial stroke further strokes are possible along the same ionised channel. The subsequent strokes have a lower current peak than the initial stroke but the wave shape of the current is steeper. This multiple stroke behaviour is illustrated in Figure 3.

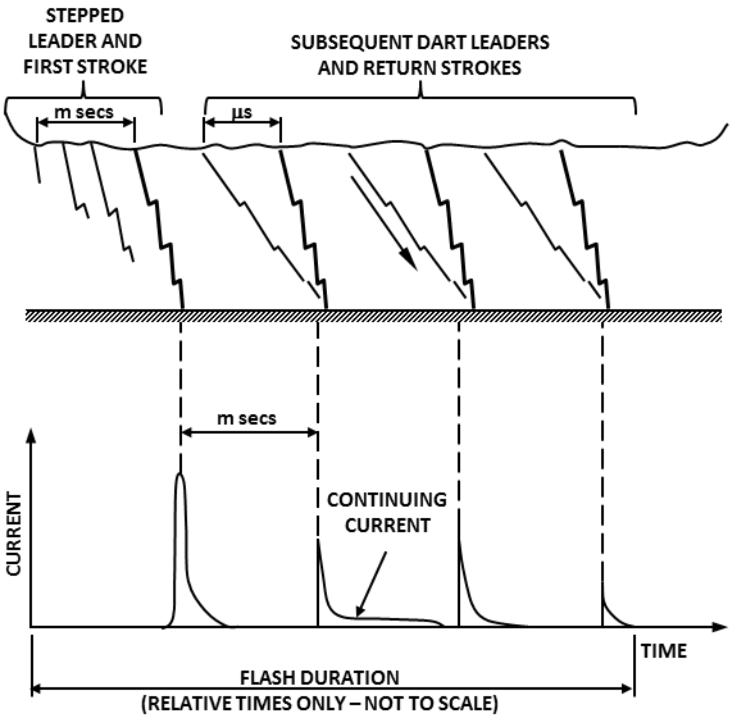



**Figure 3: Current waveforms of first and subsequent strokes**

### 3.1.3 Striking distance

The striking distance is the maximum distance between a conducting object and a stepped leader that will result in a return stroke (IEEE 998-2012). The striking distance can be visualised as a sphere with its centre at the end of the stepped leader. If any conducting object, or ground, touches this imaginary sphere a return stroke will occur. IEEE 998-2012 recommends that equation 1 be used to determine the striking distance.

$$\mathbf{S = 8 \cdot k \cdot I_S^{0.65}}$$ **Equation 1**

or

$$\mathbf{I_S = \frac{0.041 \cdot S^{1.54}}{k}}$$ **Equation 2**

where:

**S** = Striking distance (the probability of the stroke tip terminating on an object **S** far away is greater than the probability of it striking another object **S+n** away)

**I** = is the return current (kA)

**k** = 1 for strokes to shield wire

**k** = 1.2 for strokes to a lightning mast

Equations 1 and 2 show that the striking distance is a function of the return current which is in turn dependant on the size of the charge in the stepped leader. Figure 4 illustrates the relationship between the stroke current and the strike distance.

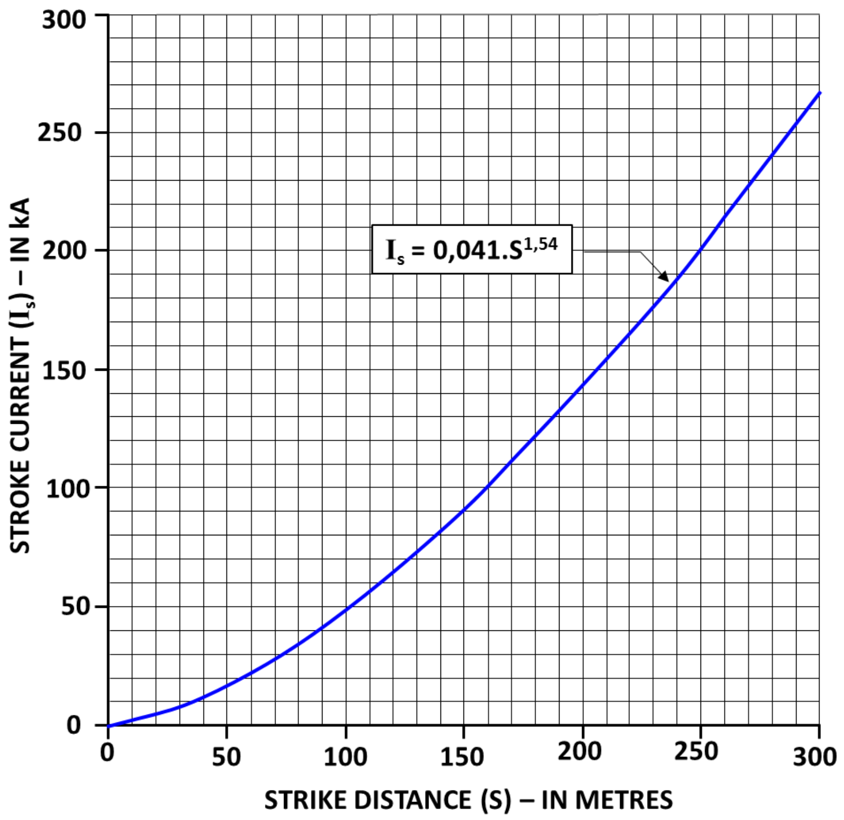



**Figure 4: Stroke current vs striking distance**

### 3.1.4 Stroke Current Magnitude

Due to the interrelation of the stroke current and the striking distance it is worthwhile to be aware of how the current magnitude probability distribution is calculated. From IEEE 998 the median current value of strokes to OHGW, conductors, structures and masts is taken to be 31kA. The probability distribution for these situations is given as:

$$\mathbf{P(I)} = \frac{\mathbf{1}}{\mathbf{1} + \left(\frac{\mathbf{I}}{\mathbf{31}}\right)^{\mathbf{2.6}}} \qquad \textbf{Equation 3}$$

where:

**P(I)** = probability that the stroke current will exceed I

**I** = crest current in kA

For situations where the lightning strikes to flat ground, the median current is taken as 24kA. The probability distribution for this situation is given by the following equation:

$$\mathbf{P(I)} = \frac{\mathbf{1}}{\mathbf{1} + \left(\frac{\mathbf{I}}{\mathbf{24}}\right)^{\mathbf{2.6}}} \qquad \textbf{Equation 4}$$

The probability distribution for lightning strikes to ground is plotted in Figure 5.

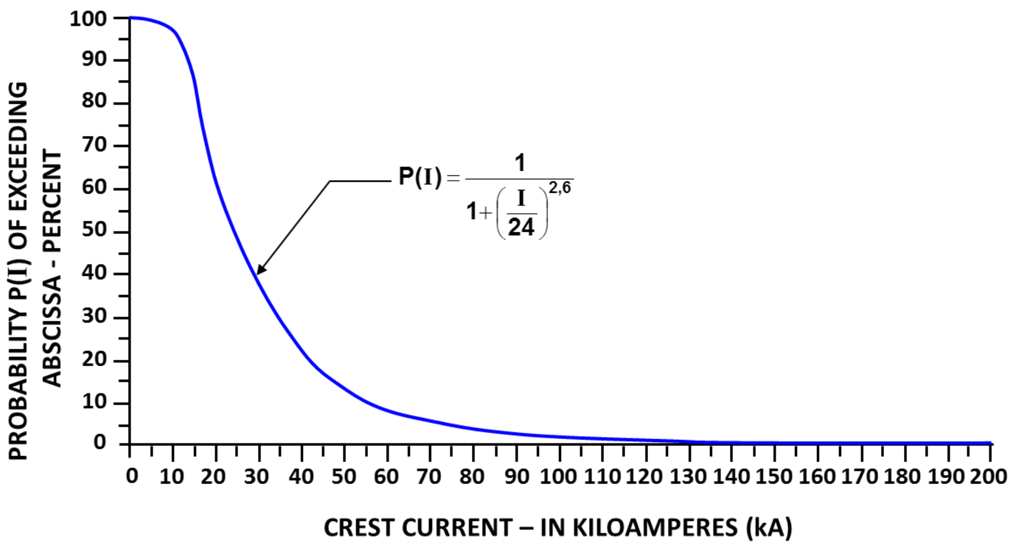



**Figure 5: Probability distribution for lightning strikes to ground**

$$\mathbf{S = 8 \cdot k \cdot I_S^{0.65}}$$ (from Eq.1)

and $$\mathbf{I_S = \frac{0.041 \cdot S^{1.54}}{k}}$$ (from Eq.2)

were found to produce the best correlation with available data and observations.

### 3.1.5 Keraunic Level

The keraunic level gives an indication of the amount of thunderstorm activity for a certain area. The average number of annual thunderstorm days or thunderstorm hours is used to determine the keraunic level. A thunderstorm day is defined as a day in which thunder was heard one or more times during a 24 hour period. The daily keraunic level is defined as the annual average of these thunderstorm-days. Similarly a thunderstorm-hour is defined as a 60min period during which thunder was heard one or more times. The average amount of thunderstorm-hours in a year is called the hourly keraunic level. The keraunic data can be compiled onto a map with isokeraunic lines that join areas of the same keraunic level.

### 3.1.6 Ground Flash Density

Ground flash density (GFD) is described as the average number of lightning strikes in a specified area for a specified period of time. The assumption is usually made that the GFD of an area is proportional to the keraunic level of that area. IEEE 998 provides the following formulas regarding the calculation of GFD:

$$\mathbf{N_k = 0.12 \cdot T_d}$$ **Equation 5**

or

$$\mathbf{N_k = 0.054 \cdot T_h^{1.1}}$$ **Equation 6**

where:

$\mathbf{N_k}$ = number of flashes to earth per square kilometre per year

$\mathbf{T_d}$ = keraunic level in thunderstorm days

**$T_h$** = keraunic level in thunderstorm hours

### 3.1.7 Lightning Detection Networks

The South African weather service installed a lightning detection network throughout South Africa in 2006. The system consists of 19 sensors placed around the country that allow 95% of all lightning strikes to be detected with 500m accuracy. This system is also able to detect the polarity of the strike. Before the current system the South African GFD map was created by the CSIR using flash detectors. Figure 6 indicates the placement of the detection sites throughout South Africa as well as the GFD measurements made since 1994.

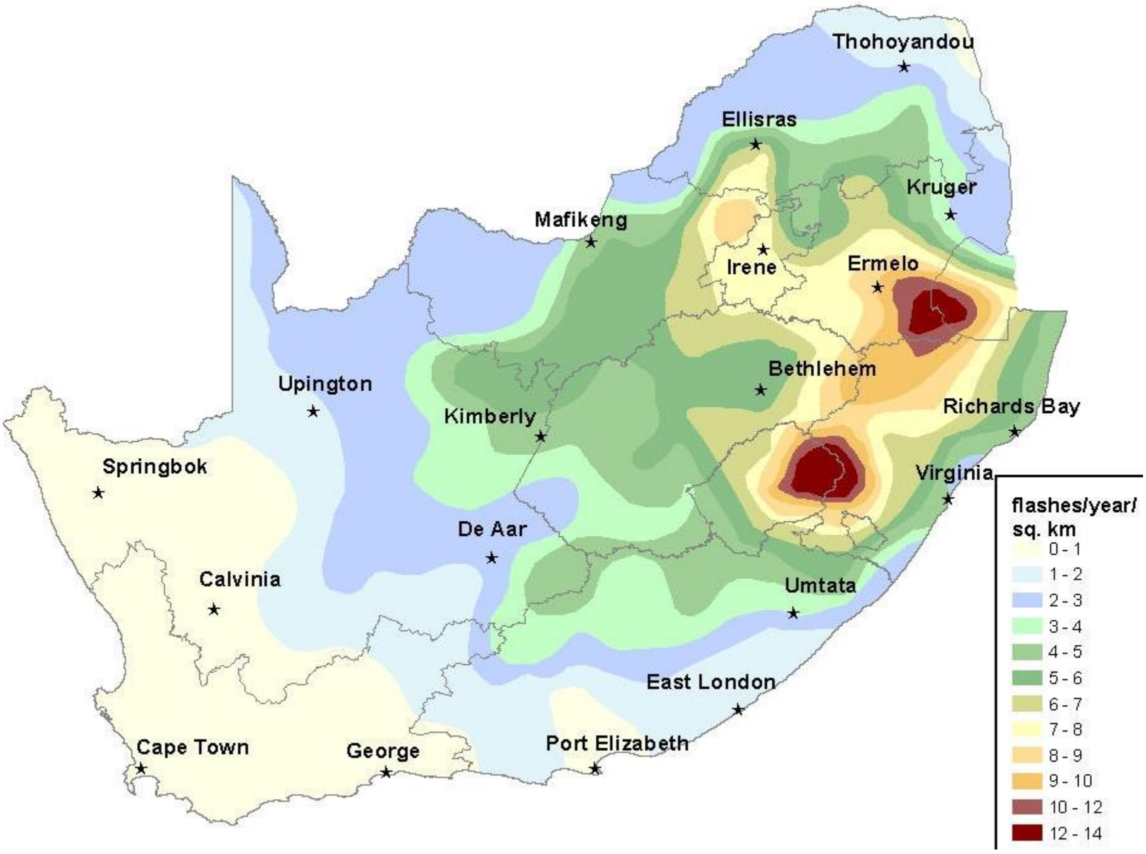



**Figure 6: Ground flash density for South Africa**

## 3.2 Purpose of a Lightning protection System for a Substation

Damage caused by lightning strikes cannot be completely prevented either technically or economically, however, the probability of direct lightning strikes can be greatly reduced on the basis of model experiments, measurements and years of observation with various methods that have been employed. The purpose of a substation lightning protection system is therefore to ensure the safest conditions for equipment, personnel and buildings from lightning strikes based on techno-economic considerations.

## 3.3 The Design Problem

The IEEE Standard 998-2012 identifies the following factors that make a lightning protection system for a substation difficult to design:

a) The unpredictable, probabilistic nature of lightning.

b) The lack of data due to the infrequency of lightning strokes in substations.

c) The complexity and economics involved in analysing a system in detail.

There is no known method of providing 100% shielding or protection of a substation from lightning, other than enclosing the equipment in a solid metallic enclosure. Due to the uncertainty, complexity, and cost of performing a detailed analysis of a shielding system, IEEE 998-2012 recommends the following approach in the design of a protection system:

a) Evaluate the importance and value of the substation being protected.

b) Investigate the severity and frequency of thunderstorms in the area of the substation facility and the exposure of the substation.

c) Select an appropriate design method consistent with the above evaluation and then lay out an appropriate system of protection.

d) Evaluate the effectiveness and cost of the resulting design.

## 3.4 Design Methods: Electro-Geometric Model

### 3.4.1 Striking Distance

$$\mathbf{S = 8 \cdot k \cdot I_S^{0.65}} \qquad \text{(from Eq.1)}$$

**k** = 1.0 for strokes to shield wire

**k** = 1.2 for strokes to mast

**k** = 1.0 for strokes to combination of shield wire and mast

### 3.4.2 Shielding Failure

The EGM theory states that the protective area of a shield wire or mast depends on the amplitude of the stroke current $\mathbf{I_s}$. If a lightning protection system protects equipment for a stroke current Is, it may not shield for a stroke current less than an Is that has a shorter striking distance.

Since strokes less than the critical current or stroke current can penetrate the shielding system and terminate on the protected equipment, the insulation system must be able to withstand the resulting voltages without flashover.

### 3.4.3 Allowable stoke current

$$\mathbf{I_S = \frac{1.1 \cdot BIL}{\left(\frac{Z_S}{2}\right)}}$$

$$\mathbf{I_S = \frac{2.2 \cdot BIL}{Z_S}}$$

**Equation 7**

a) 110% of the BIL

b) Impedance is divided by 2 since two different current paths for the lightning strike to flow

c) Strikes at the end of a busbar:

Entire stroke current produces a surge voltage across equipment. The allowable stroke current can only flow in one direction, so the allowable stroke current must be halved or

$$\mathbf{I_S = \frac{1.1 \cdot BIL}{Z_S}}$$

**Equation 8**

d) Strikes at transformer, open isolators or open breakers:

At opens isolators, open breakers and transformers where surge impedance changes to a large value along the conductor, the voltage wave will reverse its direction of flow and return along the conductor since it has a lower impedance. The voltage stress at these points will double the incoming value and is referred to as **voltage doubling**. Surge arrestors are required at these points. If there are no surge arrestors, the allowable stroke current must be halved or again:

$$\mathbf{I_S = \frac{1.1 \cdot BIL}{Z_S}} \qquad \text{(from Eq.8)}$$

### 3.4.4 Application of the EGM by the Rolling Sphere Method

a) For stroke current Is:

$$\mathbf{R_c \cdot \ln\left(\frac{2 \cdot h}{R_c}\right) - \frac{V_c}{E_0} = 0} \qquad \textbf{Equation 9}$$

where:

$\mathbf{R_c}$ = corona radius for a single conductor (m)

**h** = average height of conductor (m)

$\mathbf{V_c}$ = BIL for post insulators

$\mathbf{E_0}$ = limiting corona gradient = 1500kV/m

The surge impedance of conductors under corona in ohms is given by Brown [B24]:

$$\mathbf{Z_S = 60 \cdot \sqrt{\ln\left(\frac{2 \cdot h}{R_c}\right) \cdot \ln\left(\frac{2 \cdot h}{r_e}\right)}} \qquad \textbf{Equation 10}$$

where:

$\mathbf{r_e}$ = the metallic radius of the conductor or equivalent radius of the bundle

In the case of bundled conductors, the radius of the bundle under corona $\mathbf{R_c'}$ is taken as follows:

$$\mathbf{R'_c = R_c + R_0} \qquad \textbf{Equation 11}$$

where:

$\mathbf{R_0}$ = equivalent radius of the bundle conductor (m)

Equivalent radius ($\mathbf{R_0}$) for bundled conductors

Two conductor bundle

$$\mathbf{R_0 = \sqrt{r \cdot l}} \qquad \textbf{Equation 12}$$

where:

**r** = radius of sub-conductor (m)

***l*** = spacing between sub-conductors (m)

Three conductor bundle

$$\mathbf{R_0 = \sqrt[3]{r \cdot \mathit{l}^2}} \qquad \textbf{Equation 13}$$

Four conductor bundle

$$\mathbf{R_0} = \sqrt[4]{\sqrt{2} \cdot \mathbf{r} \cdot l^3} \qquad \textbf{Equation 14}$$

More than four conductor bundle

$$\mathbf{R_0} = 0.5 \cdot l' \cdot \sqrt[n]{\mathbf{n} \cdot \frac{2 \cdot \mathbf{r}}{l'}} \qquad \textbf{Equation 15}$$

where:

***l'*** = diameter of the circle on which the sub-conductors lie (m)

**n** = number of sub-conductors

$$\mathbf{I_S} = \frac{2.2 \cdot \mathbf{BIL}}{\mathbf{Z_S}} \qquad \text{(from Eq.7)}$$

$$\mathbf{S} = 8 \cdot \mathbf{k} \cdot \mathbf{I_S^{0.65}} \qquad \text{(from Eq.1)}$$

Assuming that **S** is the same striking distance to ground, mast or shield wire.

Use of the rolling sphere method involves an imaginary sphere of radius **S** over the surface of the 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 7.

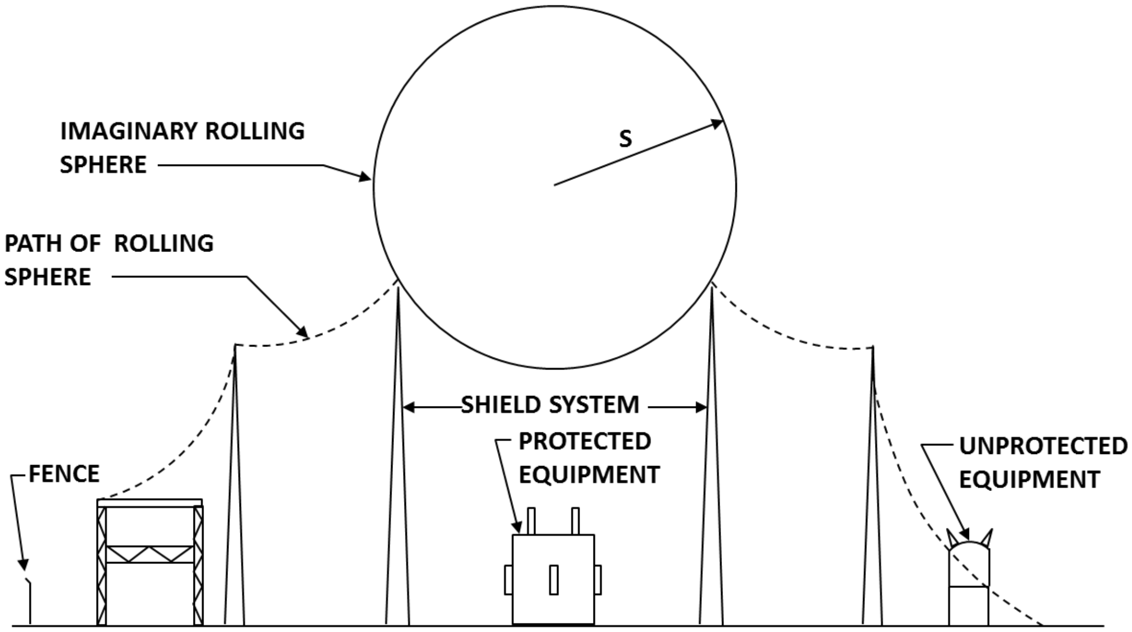



**Figure 7: Principle of rolling sphere with multiple shielding electrodes**

### 3.4.5 Protection against Stroke Current $I_s$

Continuing the discussion of protection against stroke current $I_s$, 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 8. An arc of radius **S** that touches the shield mast and the ground plane is shown in Figure 8. All points below this arc are protected against the stroke current $I_s$. This is the protected zone.

The arc is constructed as follows (see Figure 8). A dashed line is drawn parallel to the ground at a distance **S** (the striking distance as obtained from Eq. 1) above the ground plane. An arc of radius **S**, with its centre located on the dashed line is drawn so the radius of the arc just touches the mast. Stepped leaders that result in stroke current $I_s$ 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 $I_s$ 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.

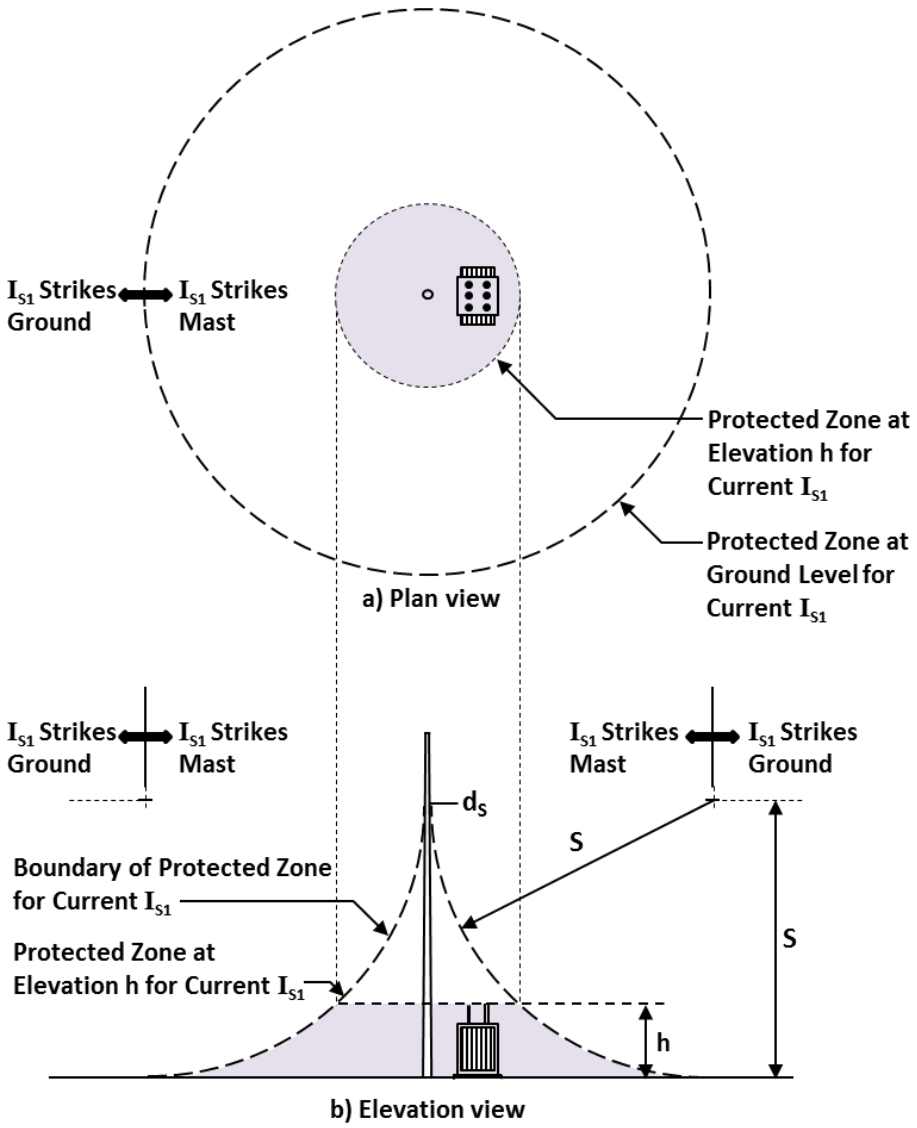



**Figure 8: Shield mast protection for stroke current $I_s$**

### 3.4.6 Protection against Stroke Currents Greater than $I_s$

Paragraph 3.4.5 demonstrated the protection provided for a stroke current $I_s$. 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 $I_{s1}$ with magnitude greater than $I_s$. Strike distance, determined from Eq. 1, is $S_1$. The geometrical model for this condition is shown in Figure 9. Arcs of protection for stroke current $I_{s1}$ and for the previously discussed $I_s$ are both shown. The figure shows that the zone of protection provided by the mast for stroke current $I_{s1}$ is greater than the zone of protection provided by the mast for stroke current $I_s$.

Stepped leaders that result in stroke current $I_{s1}$ 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 $I_{s1}$ 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 $S_1$ protected zone. Again, the protective zone can be visualized as the surface of a sphere touching the mast. In this case, the sphere has a radius $S_1$.

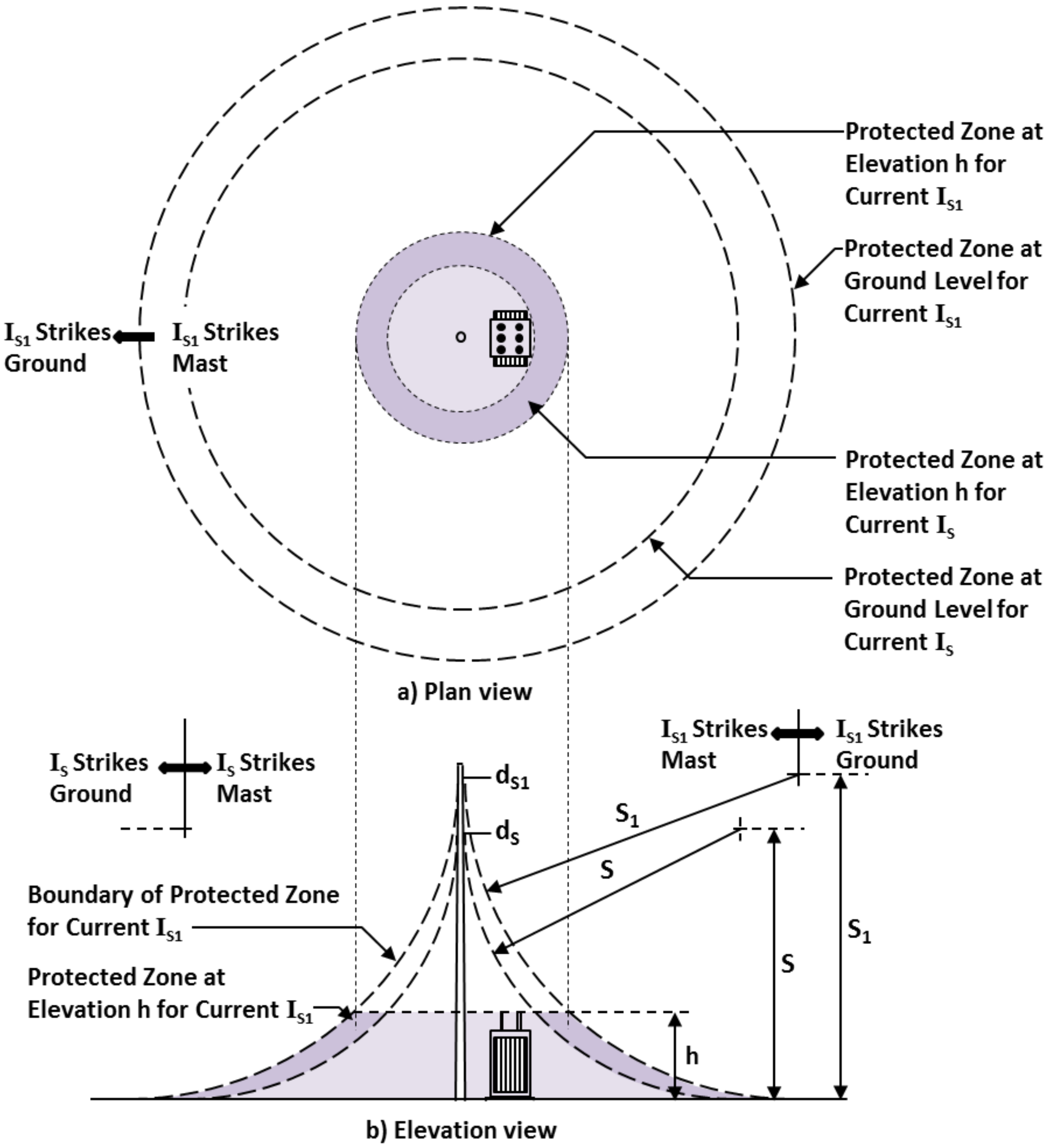



**Figure 9: Shield mast protection for stroke current $I_{s1}$**

### 3.4.7 Protection against Stroke Currents Less than $I_s$

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

Consider a stroke current $I_{s0}$ with magnitude less than $I_s$. The striking distance, determined from Eq. 1, is $S_0$. The geometrical model for this condition is shown in Figure 10. Arcs of protection for stroke current $I_{s0}$ and $I_s$ are both shown. The figure shows that the zone of protection provided by the mast for stroke current $I_{s0}$ is less than the zone of protection provided by the mast for stroke current $I_s$. It is noted that a portion of the equipment protrudes above the dashed arc or zone of protection for stroke current $I_{s0}$. Stepped leaders that result in stroke current $I_{s0}$ 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 $I_{s0}$ 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 10. Stepped leaders for stroke current $I_{s0}$ that descend inside the inner protective zone will strike the mast and protect equipment that is **h** in height. Stepped leaders for stroke current $I_{s0}$ that descend in the shaded unprotected zone will strike equipment of height **h** in the area. If, however, the value of $I_s$ was selected based on the withstand insulation level of equipment used in the substation, stroke current $I_{s0}$ should cause no damage to equipment.

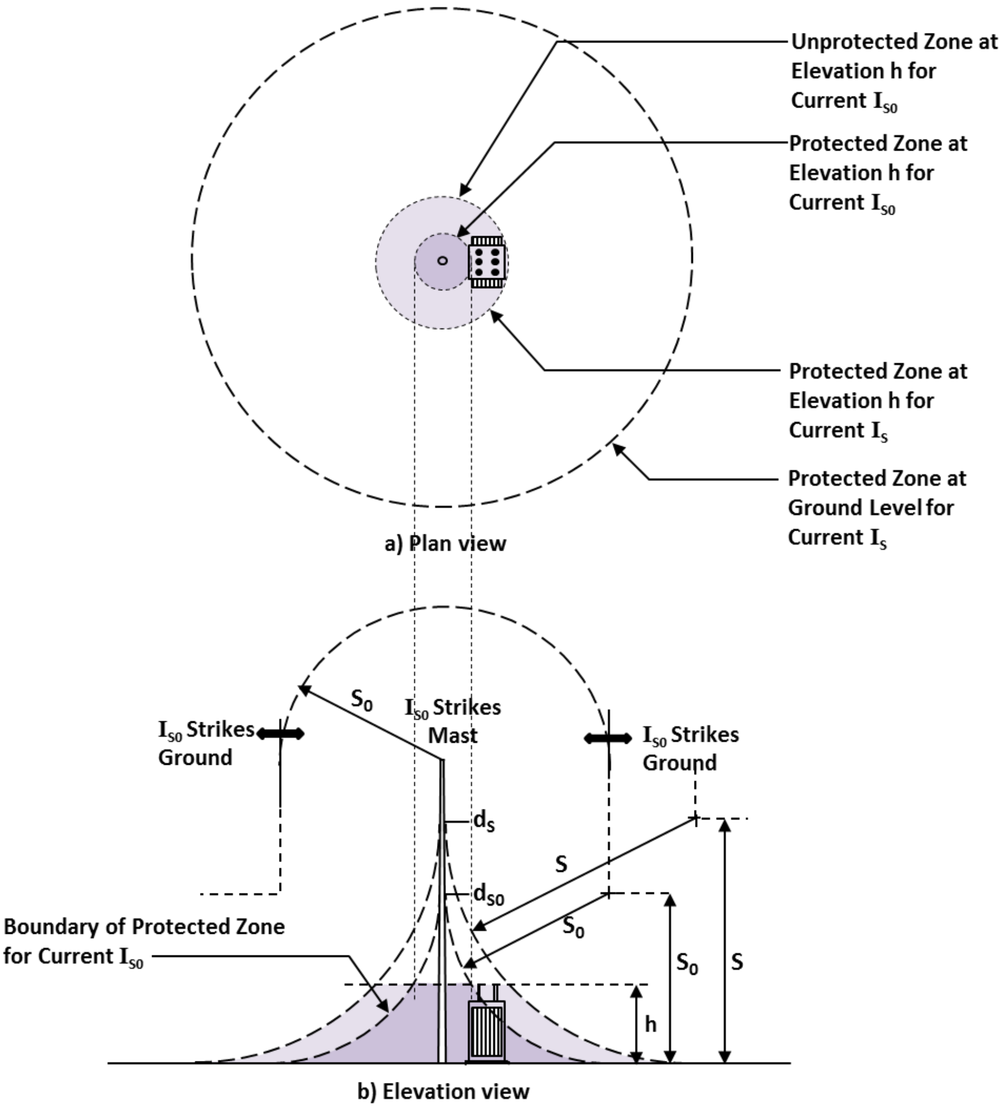



**Figure 10: Shield mast protection for stroke current $I_{s0}$**

### 3.4.8 Multiple shielding electrodes

The electro-geometric modelling 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 11 shows this application considering four shield masts in a multiple shield mast arrangement. The arc of protection for stroke current $I_s$ is shown for each set of masts. The dashed arcs represent those points at which a descending stepped leader for stroke current $I_s$ 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 centre at the intersection of the two dashed arcs.

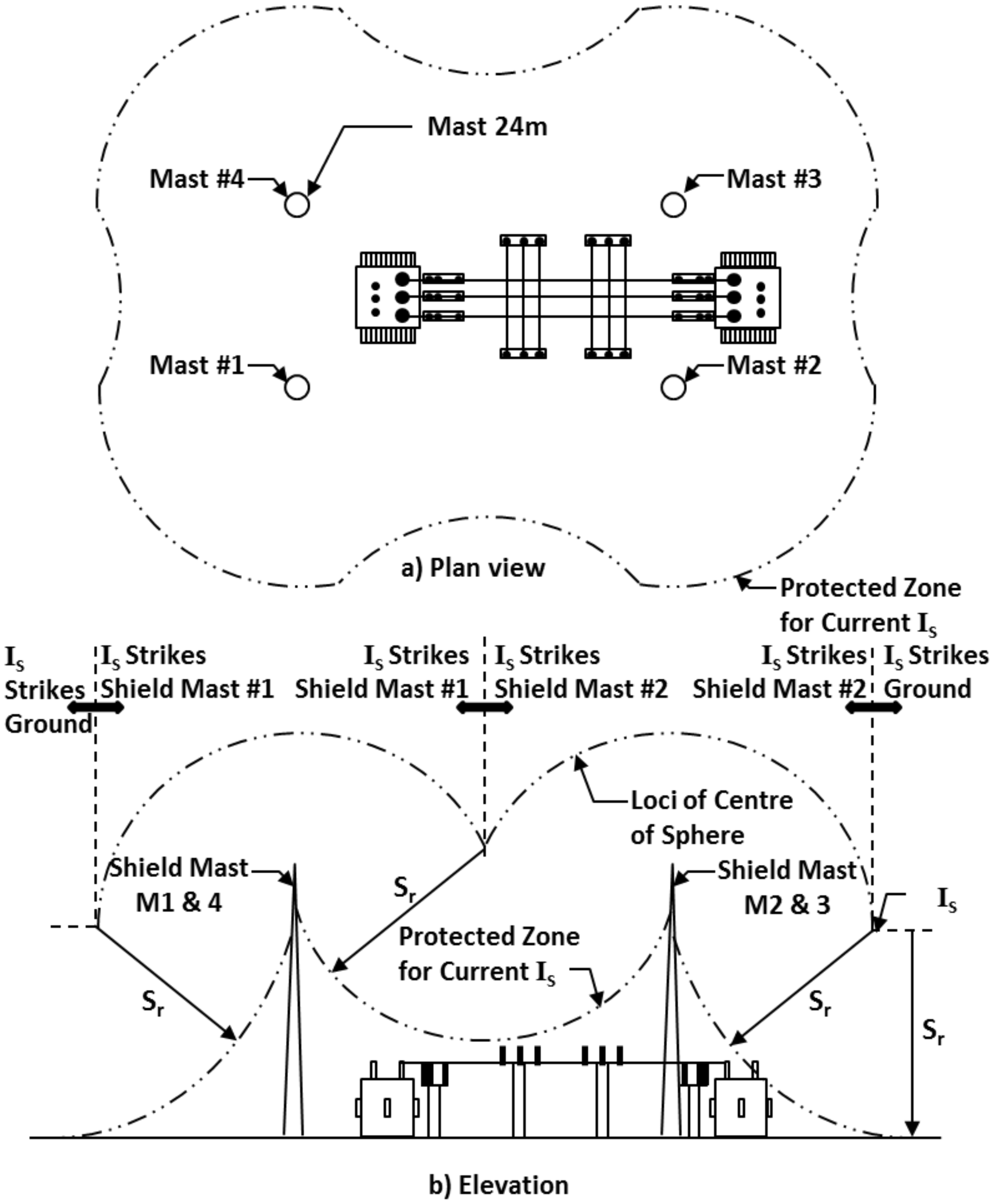



**Figure 11: Multiple shield mast protection for stroke current $I_s$**

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 centre 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 12 shows an application to a combination of masts and shield wires.

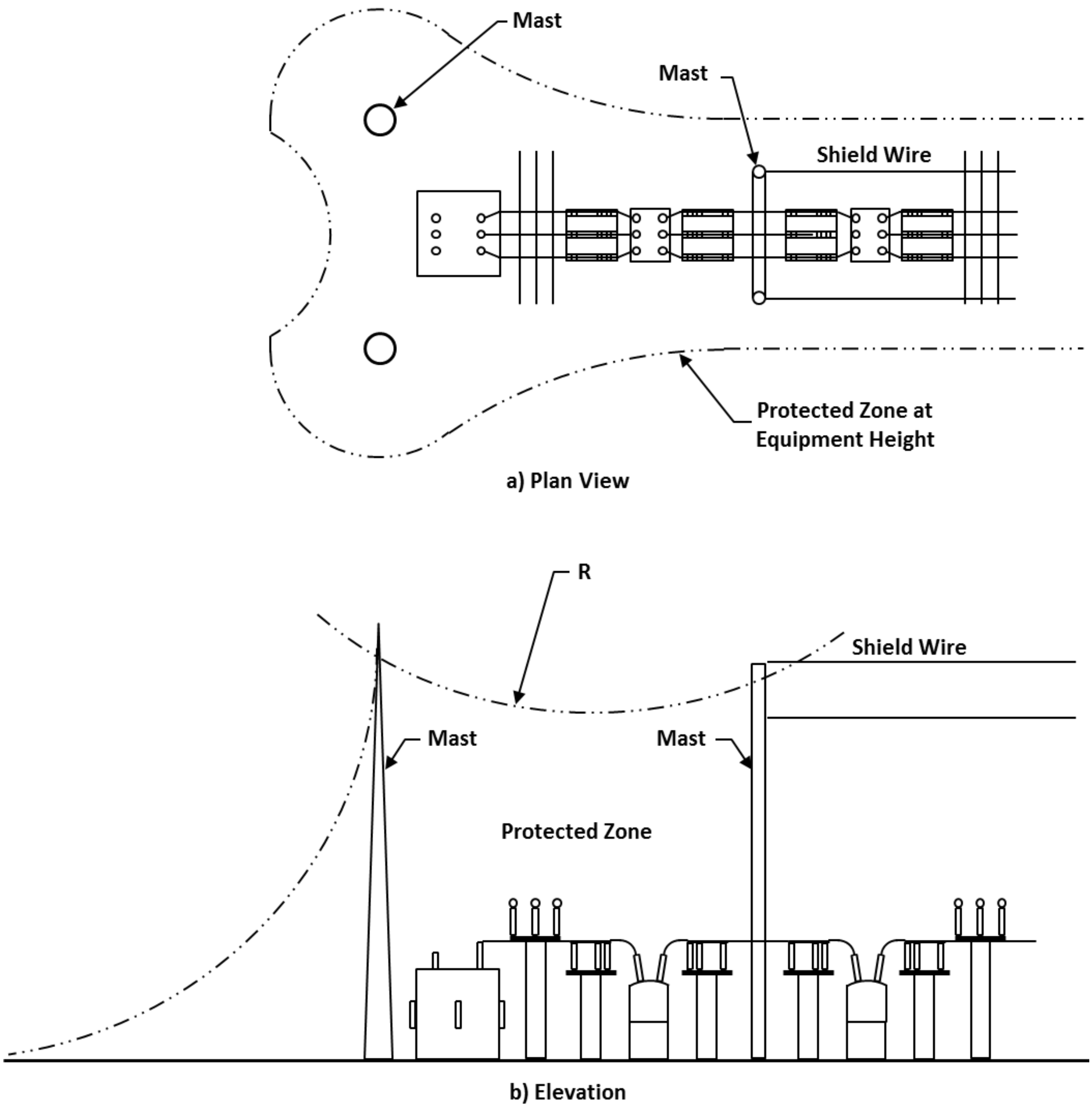


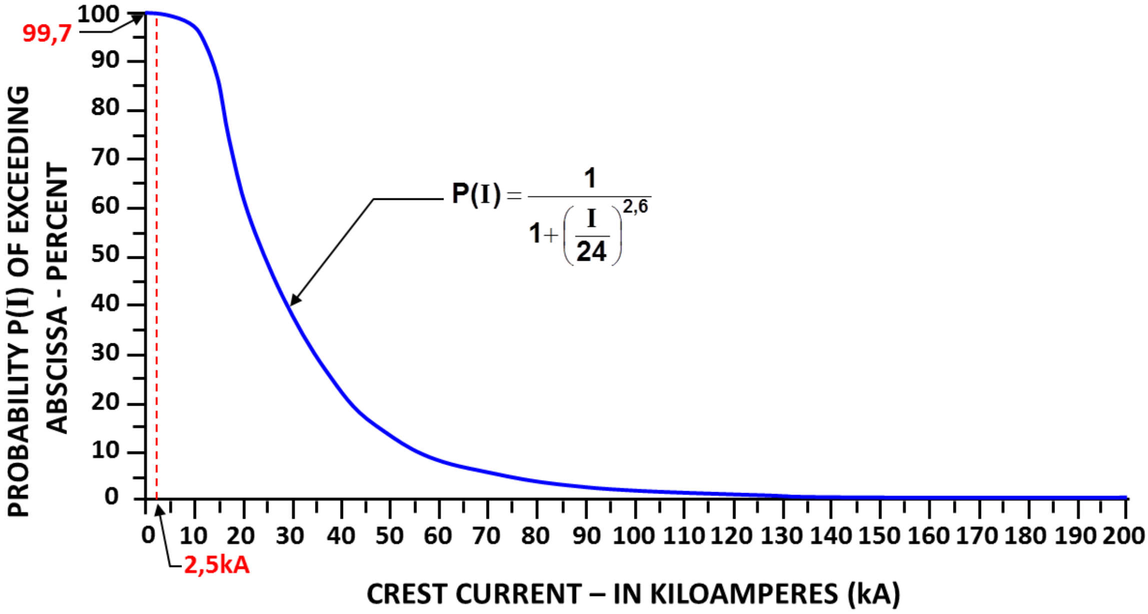

**Figure 12: Protection by shield wire and masts**

### 3.4.9 Changes in voltage level

Protection has been illustrated with the assumption of a single voltage level. Substations, however, have two or more voltage levels. 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. Example calculations for a substation with two voltage levels are given under paragraphs 3.6.1 and 3.6.2 for 220kV and 500kV respectively.

### 3.4.10 Minimum stroke current

The designer will find that shield spacing becomes quite close at voltages of 66 kV and below. It may be appropriate to select some minimum stroke current, perhaps 2,5 kA for shielding stations below 110 kV. Such an approach is justified by an examination of Figure 5, repeated below for clarity. It will be found that 99.7% of all strokes will exceed 2,5 kA.




By calculation:

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

$$\mathrm{P(I)} = \frac{1}{1 + \left(\frac{2.5}{24}\right)^{2.6}} \qquad \text{(from Eq.4)}$$

$$\mathrm{P(I)} = 99.7\%$$

Therefore, this limit will result in very little exposure, but will make the shielding system more economical.

## 3.5 Dealing with a Single Voltage Substation (66kV)

This example is based on a 66kV switchyard in an H-formation comprising a single sectionalised busbar with two feeders and two transformers as illustrated in the plan view (Figure 13) and elevations (Figures 14 and 15). All of the relevant dimension are given in these figures and associated figures throughout the example.

The symbols used in the various figures are defined as they are used.

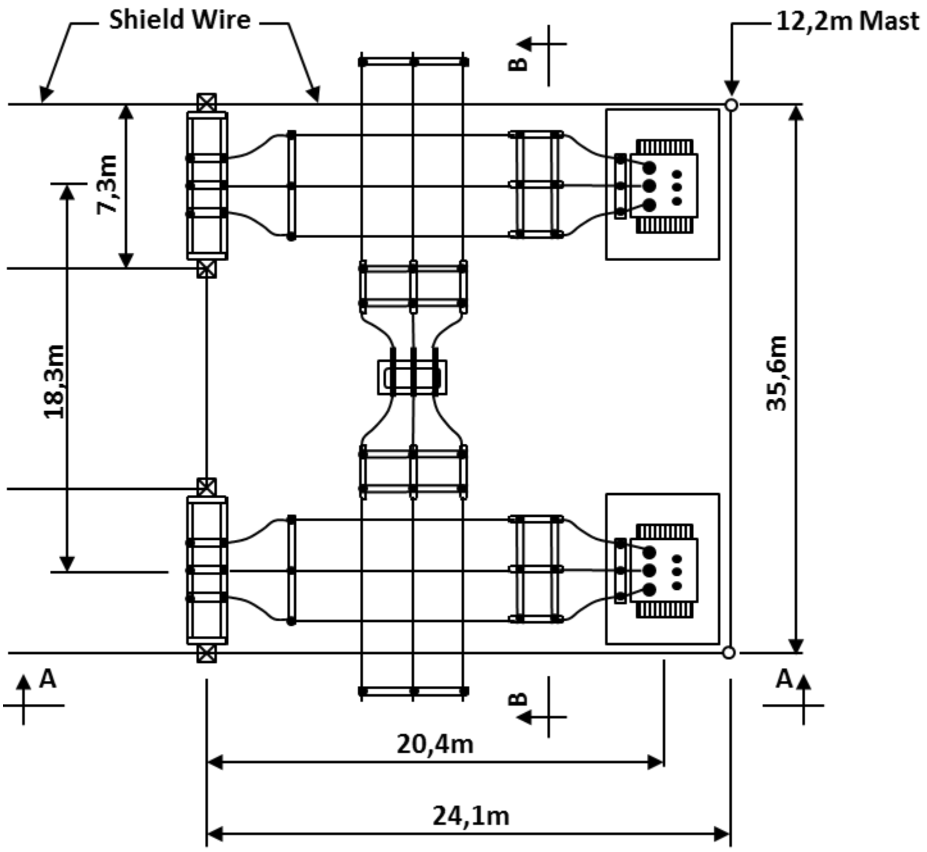



**Figure 13: Proposed protection by shield wire and masts for 66kV switchyard**

**Table 1: Data for 66kV Switchyard**

| Electrical data | Busbar data | Height (A) [m] | Number of Conductors | Diameter [mm] |
|---|---|---|---|---|
| Nominal voltage: 66kV | Busbar 1 | 4.267 | 1 | 120 |
| Bus **BIL**: 350kV | Busbar 2 | 5.790 | 1 | 120 |
| Equipment **BIL**: 350kV | Busbar 3 | 10.060 | 1 | 26.5 |

A design using lightning masts for protection will be considered first. The procedure for masts is as follows:

a) Calculate the surge impedance, $\mathbf{Z}_s$ from Eq.10.

b) Calculate the critical stroke current, $\mathbf{I}_s$ from Eq.7.

c) Calculate the striking distance, **S** (which will become the sphere radius) from Eq.1.

d) Calculate T as shown by the calculations that follow. **T** is the maximum horizontal distance from the mast that an object at a height, **A**, is protected from a direct stroke. A circle with radius, **T**, is the area of protection afforded by a single mast for an object at height, **A**.

e) Calculate **X**, the maximum separation of two masts to prevent a side stroke. (It may help to visualize a sphere resting on the ground that is then rolled over to just touch the two masts. The bus is arranged so that it also just touches the surface of the sphere. By studying the various views of the figure, it can be seen that this determines the maximum separation to prevent side strokes.)

f) Calculate **P**, the maximum separation of masts to prevent a vertical stroke.

g) Calculate **Q**, the maximum separation of three masts to prevent a vertical stroke.

h) With this information masts can be spotted in the substation; arcs can be drawn around them and adjustments can be made for an optimal layout.

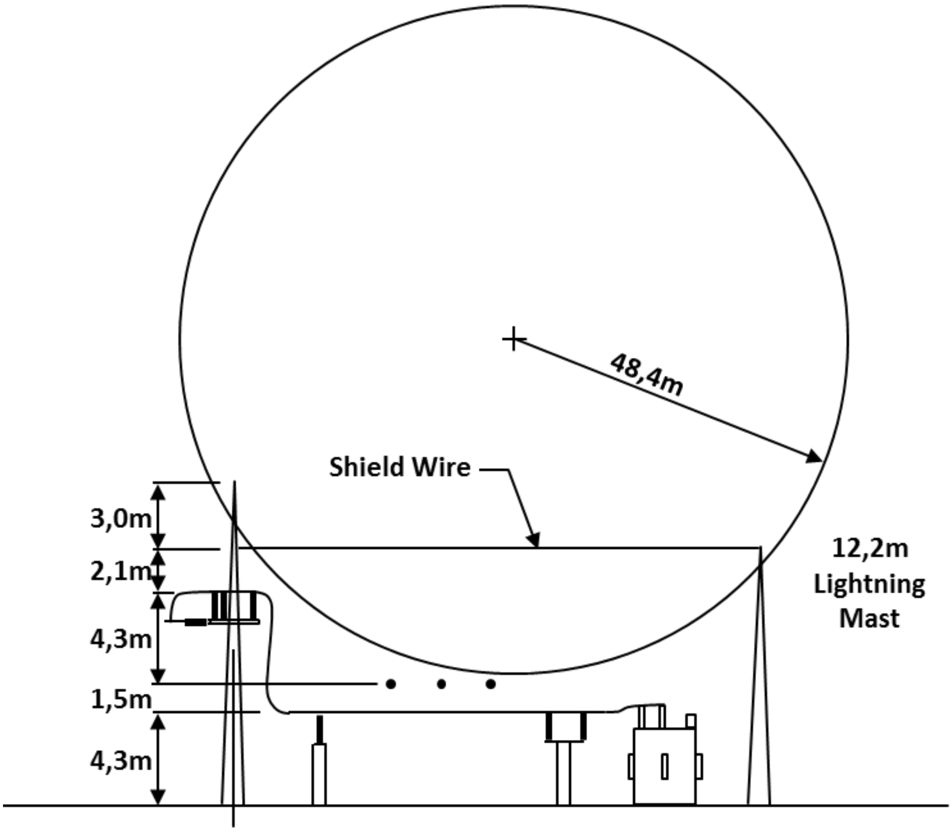



**Figure 14: Proposed protection by shield wire and masts for 66kV switchyard - Section on A-A**

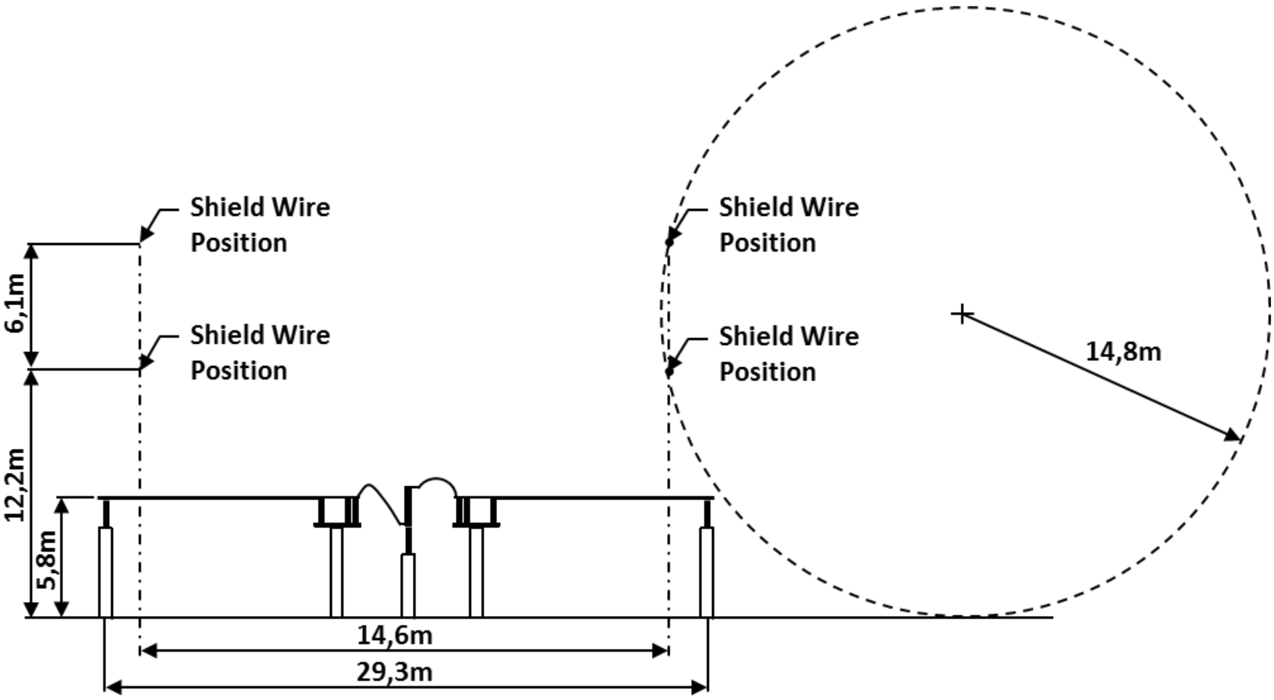



**Figure 15: Proposed protection by shield wire and masts for 66kV switchyard - Section on B-B**

A design using lightning masts for protection will be considered first followed by the procedure for overhead earth-wires.

### 3.5.1 The procedure for one mast by first calculating the effective surge impedance

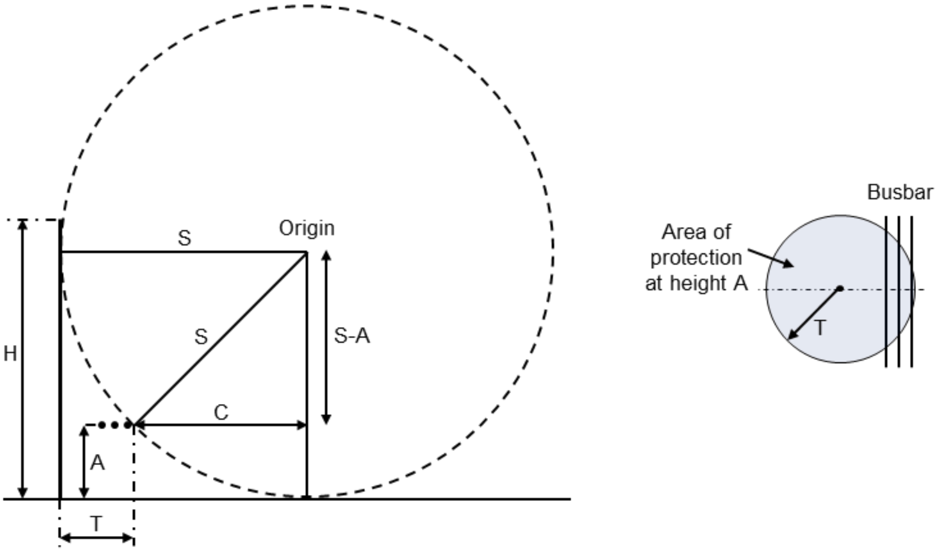



**Figure 16: Calculations for One Mast Protection of a 66kV Substation**

**S** = Sphere radius

**A** = Bus height

H = Mast height

**T** = Maximum separation from mast to bus for protection

C = Horizontal distance from Sphere Origin to the busbar

#### 3.5.1.1 Calculate the effective surge impedance ($Z_S$)

$$Z_S = 60 \cdot \sqrt{\ln\left(\frac{2 \cdot A}{R_c}\right) \cdot \ln\left(\frac{2 \cdot A}{r_e}\right)}$$ (from Eq.10)

and

$$R_c \cdot \ln\left(\frac{2 \cdot A}{R_c}\right) - \frac{V_c}{E_0} = 0$$ (from Eq.9)

where:

$R_c$ = Corona radius in m

$r_e$ = Metallic radius of the conductor, or equivalent radius in the case of bundled conductors in m

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

$E_0$ = Limiting corona gradient, this is taken equal to 1500 kV/m

In the case of bundle conductors, the radius of the bundle under corona $R_c'$ is taken as follows:

$$R'_c = R_c + R_0$$ (from Eq.11)

where:

$R_c$ = value for a single conductor as given by Eq.9

$R_0$ = equivalent radius of the bundle

| A (m) | 4.267m | 5.790m | 10.060m |
|---|---|---|---|

$$\mathbf{R_c \cdot \ln\left(\frac{2 \cdot A}{R_c}\right) - \frac{V_c}{E_0} = 0}$$ (from Eq.9)

| | | | |
|---|---|---|---|
| $R_c$ (m) | $R_c \cdot \ln\left(\frac{2 \cdot 4.267}{R_c}\right) - \frac{350}{1500} = 0$ Using Interval Halving: $R_c$ = 0.04432m | $R_c \cdot \ln\left(\frac{2 \cdot 5.790}{R_c}\right) - \frac{350}{1500} = 0$ Using Interval Halving: $R_c$ = 0.04142m | $R_c \cdot \ln\left(\frac{2 \cdot 10.060}{R_c}\right) - \frac{350}{1500} = 0$ Using Interval Halving: $R_c$ = 0.03704m |

$$\mathbf{r_e = \frac{d}{2}}$$ (from Eq.10)

| | | | |
|---|---|---|---|
| $r_e$ (m) | $r_e = \frac{120}{2}$ $r_e$ = 0.060m | $r_e = \frac{120}{2}$ $r_e$ = 0.060m | $r_e = \frac{0.265}{2}$ $r_e$ = 0.01325m |

$$\mathbf{Z_S = 60 \cdot \sqrt{\ln\left(\frac{2 \cdot A}{R_c}\right) \cdot \ln\left(\frac{2 \cdot A}{r_e}\right)}}$$ (from Eq.10)

| | | | |
|---|---|---|---|
| $Z_S$ ($\Omega$) | $= 60 \cdot \sqrt{\ln\left(\frac{2 \cdot 4.267}{0.04436}\right) \cdot \ln\left(\frac{2 \cdot 4.267}{0.060}\right)}$ $Z_S$ = 306.402Ω | $= 60 \cdot \sqrt{\ln\left(\frac{2 \cdot 5.790}{0.04142}\right) \cdot \ln\left(\frac{2 \cdot 5.790}{0.060}\right)}$ $Z_S$ = 326.692Ω | $= 60 \cdot \sqrt{\ln\left(\frac{2 \cdot 10.06}{0.03705}\right) . \ln\left(\frac{2 \cdot 10.06}{0.0133}\right)}$ $Z_S$ = 407.527Ω |

#### 3.5.1.2 Calculate the critical stroke current, $I_s$

$$\mathbf{I_S = \frac{2.2 \cdot BIL}{Z_S}}$$ (from Eq.7)

| | | | |
|---|---|---|---|
| $I_s$ (kA) | $I_S = \frac{2.2 \cdot 350}{306.402}$ $I_S$ = 2.513kA | $I_S = \frac{2.2 \cdot 350}{326.692}$ $I_S$ = 2.357kA | $I_S = \frac{2.2 \cdot 350}{407.527}$ $I_S$ = 1.889kA $I_S$ ≈ 2.000kA |

#### 3.5.1.3 Calculate the striking distance, S (which will become the sphere radius)

$$\mathbf{S = 8 \cdot k \cdot I_S^{0.65}}$$ (from Eq.1)

For conductors, **k** = 1; for masts, **k** = 1.2

| | | | |
|---|---|---|---|
| S (m) | $S = 8 \cdot 1.2 \cdot 2.513^{0.65}$ S = 17.474m | $S = 8 \cdot 1.2 \cdot 2.357^{0.65}$ S = 16.761m | $S = 8 \cdot 1.2 \cdot 2.000^{0.65}$ S = 15.064m |

#### 3.5.1.4 Calculate T (Maximum separation from mast to bus for protection)

This is shown in Figure 16 and by the calculations that follow. T is the maximum horizontal distance from the mast that an object at a height, A (bus height), is protected from a direct stroke. A circle with radius, T, is the area of protection afforded by a single mast for an object at height, A.

$$\mathbf{C} = \sqrt{\mathbf{S}^2 - (\mathbf{S} - \mathbf{A})^2}$$ **Equation 16**

| | | | |
|---|---|---|---|
| **C** (m) | $C = \sqrt{17.474^2 - (17.474 - 4.267)^2}$ C = 11.442m | $C = \sqrt{16.761^2 - (16.761 - 5.790)^2}$ C = 12.762m | $C = \sqrt{15.064^2 - (15.064 - 10.060)^2}$ C = 14.209m |

$$\mathbf{T} = \mathbf{S} - \mathbf{C}$$ **Equation 17**

| | | | |
|---|---|---|---|
| **T** (m) | $T = 17.474 - 11.442$ T = 6.032m | $T = 16.761 - 12.762$ T = 4.089m | $T = 15.064 - 14.209$ T = 0.855m |

These are the maximum separation distances between the mast and the protected busbar for the three bus heights.

### 3.5.2 The procedure for one mast given the effective surge impedance

$\mathbf{Z_S} = 300\Omega$ ; BIL = 350KV

#### 3.5.2.1 Calculate the critical stroke current ($\mathbf{I_S}$)

$$I_S = \frac{2.2 \cdot 350}{300}$$ (from Eq.7)

$I_S$ = 2.567kA

#### 3.5.2.2 Calculate the striking distance, S (which will become the sphere radius)

$$S = 8 \cdot 1.2 \cdot 2.567^{0.65}$$ (from Eq.1)

S = 17.716m

#### 3.5.2.3 Calculate T (Maximum separation from mast to bus for protection)

This is shown in Figure 16 and by the calculations that follow. T is the maximum horizontal distance from the mast that an object at a height, A (bus height), is protected from a direct stroke. A circle with radius, T, is the area of protection afforded by a single mast for an object at height, A.

**H** = 18,288m

| **A** (m) | 4.267m | 5.790m |
|---|---|---|

$$\mathbf{C} = \sqrt{\mathbf{S}^2 - (\mathbf{S} - \mathbf{A})^2}$$ (from Eq.16)

| | | |
|---|---|---|
| C (m) | $C = \sqrt{17.716^2 - (17.716 - 4.267)^2}$ C = 11.532m | $C = \sqrt{17.716^2 - (17.716 - 5.790)^2}$ C = 13.101m |

$$\mathbf{T} = \mathbf{S} - \mathbf{C}$$ (from Eq.17)

| **T** (m) | T = 17.716 – 11.532<br>T = 6.184m | T = 17.716 – 13.101<br>T = 4.615m |
|---|---|---|

These are the maximum separation distances between the mast and the protected busbar for the three bus heights.

### 3.5.3 The procedure for two masts given the surge impedance

One must calculate **X**, the maximum separation of two masts to prevent a side stroke. (It may help to visualize a sphere resting on the ground that is then rolled over to just the touch two masts. The bus is arranged so that it also just touches the surface of the sphere. By studying the various views, one obtains Figure 18 and it can be seen that this determines the maximum separation to prevent side strokes.)

Previously calculated values:

$Z_S$ = 300Ω; $I_S$ = 2.567kA; S = 17.716m

**H** = Mast height (calculations use an assumed height; designer should pick a mast height suitable for the design)

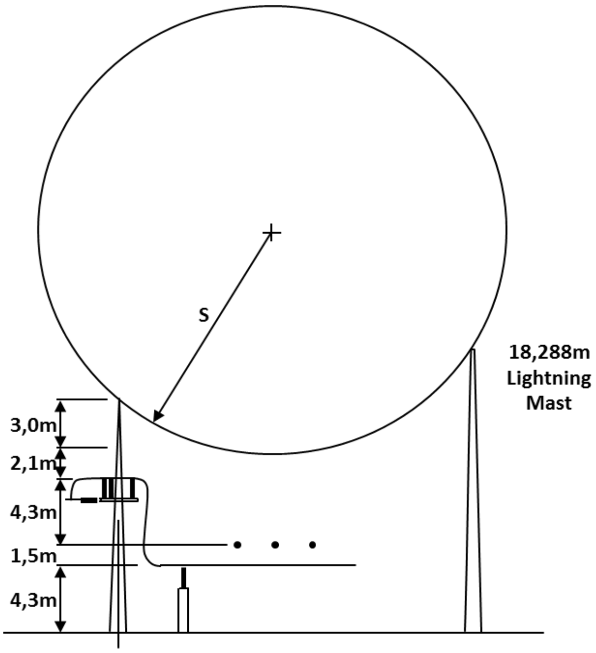



**Figure 17: Two Mast Protection of a 66kV Substation**

Suppose a second mast is introduced which is of height (**H**) located a distance **X** from the first.

**H** = 18.288m

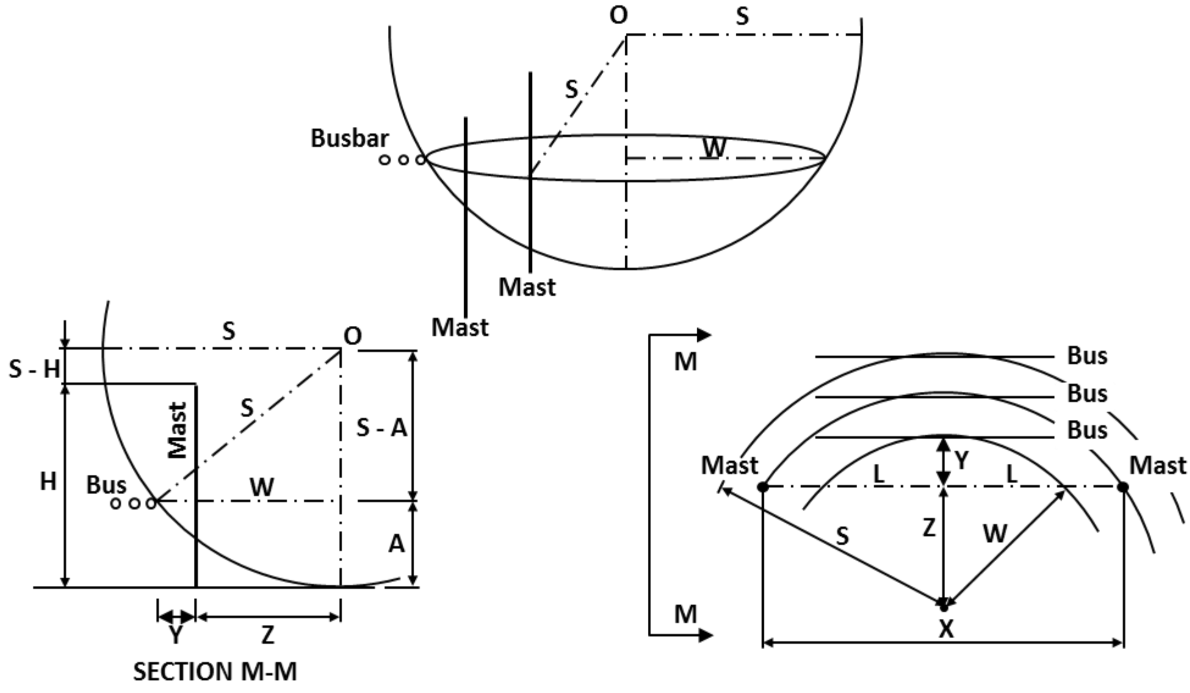



**Figure 18: Two Mast Protection of a 66kV Substation**

**L** = Half the separation between two masts

**X** = Maximum separation between two masts

**W** = Horizontal distance from origin of sphere (OOS) to busbar of the second mast

**Z** = Horizontal distance between OOS and line drawn between two masts

**Y** = Minimum phase to steel clearance (= 0.770m phase-to-earth clearance for 66kV)

| | | |
|---|---|---|
| **A** (m) | 4.267 | 5.790 |

$$\mathbf{W} = \sqrt{\mathbf{S}^2 - (\mathbf{S} - \mathbf{A})^2}$$ **Equation 18**

| | | |
|---|---|---|
| **W** (m) | $W = \sqrt{17.716^2 - (17.716 - 4.267)^2}$<br>W = 11.532m | $C = \sqrt{17.716^2 - (17.716 - 5.790)^2}$<br>C = 13.101m |

$$\mathbf{Z} = \mathbf{W} - \mathbf{Y}$$ **Equation 19**

| | | |
|---|---|---|
| **Z** (m) | Z = 11.532 – 0.770<br>Z = 10.762m | Z = 13.101 – 0.770<br>Z = 12.331m |

$$\mathbf{L} = \sqrt{\mathbf{S}^2 - \mathbf{Z}^2}$$ **Equation 20**

| | | |
|---|---|---|
| **L** (m) | $L = \sqrt{17.716^2 - 10.762^2}$<br>L = 14.073m | $L = \sqrt{17.716^2 - 12.331^2}$<br>L = 12.720m |

$\mathbf{X = 2 \cdot L}$ **Equation 21**

| | | |
|---|---|---|
| **X** (m) | $X = 2 \cdot 14.073$<br>X = 28.146m | $X = 2 \cdot 12.720$<br>X = 25.440m |

These are the maximum separations of the two masts for protection of buses 1 and 2 at the two different heights **A**.

### 3.5.4 The procedure for four masts given the surge impedance

Calculate **P** (Distance between masts when four masts support the sphere), the maximum separation of masts to prevent a vertical stroke.

**D** = Elevation difference between mast and bus

**E** = Elevation difference between mast and OOS

**J** = Horizontal distance between OOS and mast

**K** = Diagonal distance between masts when four masts support the sphere

**D** must be less than or equal to **H – A** for protection at height **A**.

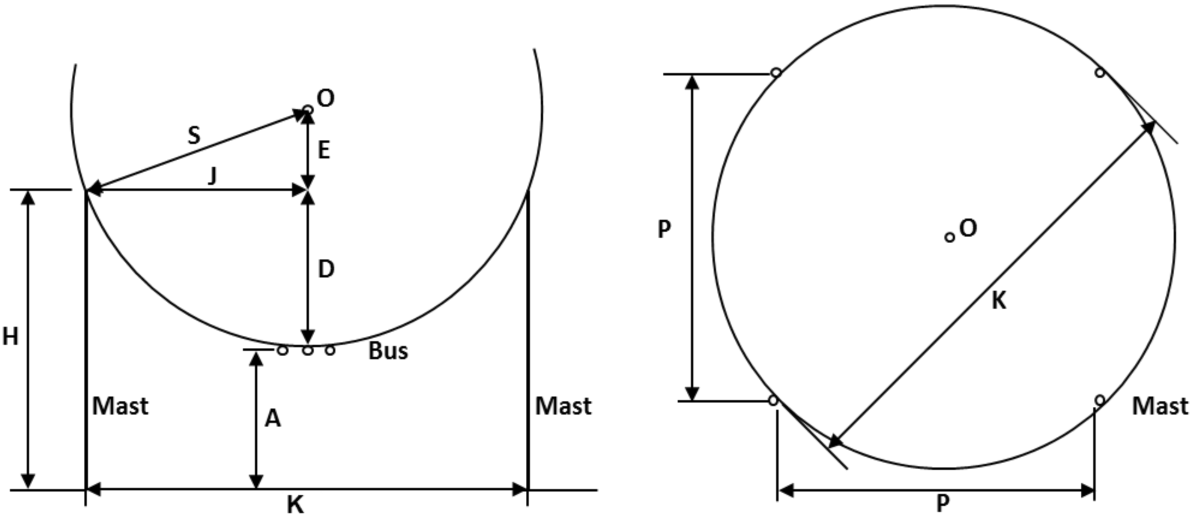



**Figure 19: Four Mast Protection System of a 66kV Substation**

**D = H – A** **Equation 22**

| | | |
|---|---|---|
| **D** (m) | D = 18.288 – 4.267<br>D = 14.021m | D = 18.288 – 5.790<br>D = 12.498m |

**E = S – D** **Equation 23**

| | | |
|---|---|---|
| **E** (m) | E = 17.716 – 14.021<br>E = 3.695m | E = 17.716 – 12.498<br>E = 5.218m |

$$\mathbf{J} = \sqrt{\mathbf{S}^2 - \mathbf{E}^2}$$ **Equation 24**

| | | |
|---|---|---|
| **J** (m) | $J = \sqrt{17.716^2 - 3.695^2}$<br>J = 17.326m | $J = \sqrt{17.716^2 - 5.218^2}$<br>J = 16.930m |

$$\mathbf{K} = \mathbf{2} \cdot \mathbf{J}$$ **Equation 25**

| | | |
|---|---|---|
| **K** (m) | $K = 2 \cdot 17.326$<br>K = 34.652m | $K = 2 \cdot 16.930$<br>K = 33.860m |

$$\mathbf{P} = \frac{\mathbf{K}}{\sqrt{\mathbf{2}}}$$ **Equation 26**

| | | |
|---|---|---|
| **P** (m) | $P = \frac{34.652}{\sqrt{2}}$<br>P = 24.503m | $P = \frac{33.860}{\sqrt{2}}$<br>P = 23.943m |

These are the maximum spacing of the four masts for protection of buses at the heights **A**.

### 3.5.5 The procedure for three masts given the surge impedance

Calculate **Q** (Distance between masts when three masts support the sphere), the maximum separation of three masts to prevent a vertical stroke.

$$\mathbf{Q} = \mathbf{2} \cdot \mathbf{cos}\left(\boldsymbol{\pi} \cdot \frac{\mathbf{30}}{\mathbf{180}}\right) \cdot \mathbf{J}$$ **Equation 27**

| | | |
|---|---|---|
| **Q** (m) | $Q = 2 \cdot \cos\left(\pi \cdot \frac{30}{180}\right) \cdot 17.326$<br>Q = 30.010m | $Q = 2 \cdot \cos\left(\pi \cdot \frac{30}{180}\right) \cdot 16.930$<br>Q = 29.324m |

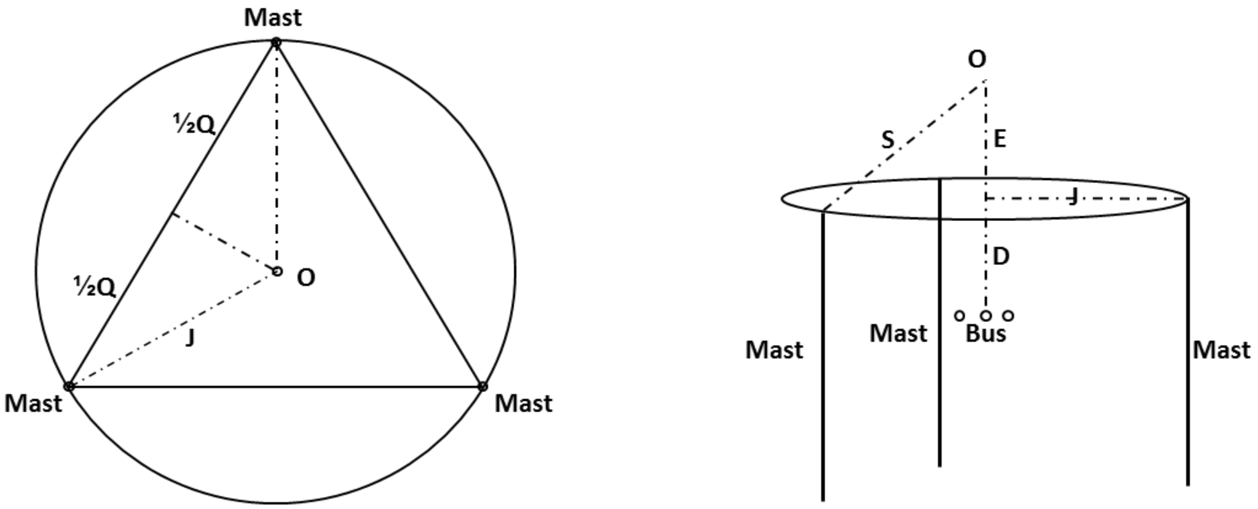



**Figure 20: Calculations for a Three Mast Protection System of a 66kV Substation**

### 3.5.6 Combining the one, two, three and four mast information

With this information masts can be spotted in the substation; arcs can be drawn around them and adjustments can be made for an optimal layout.

The resulting layout is found in Figure 21.

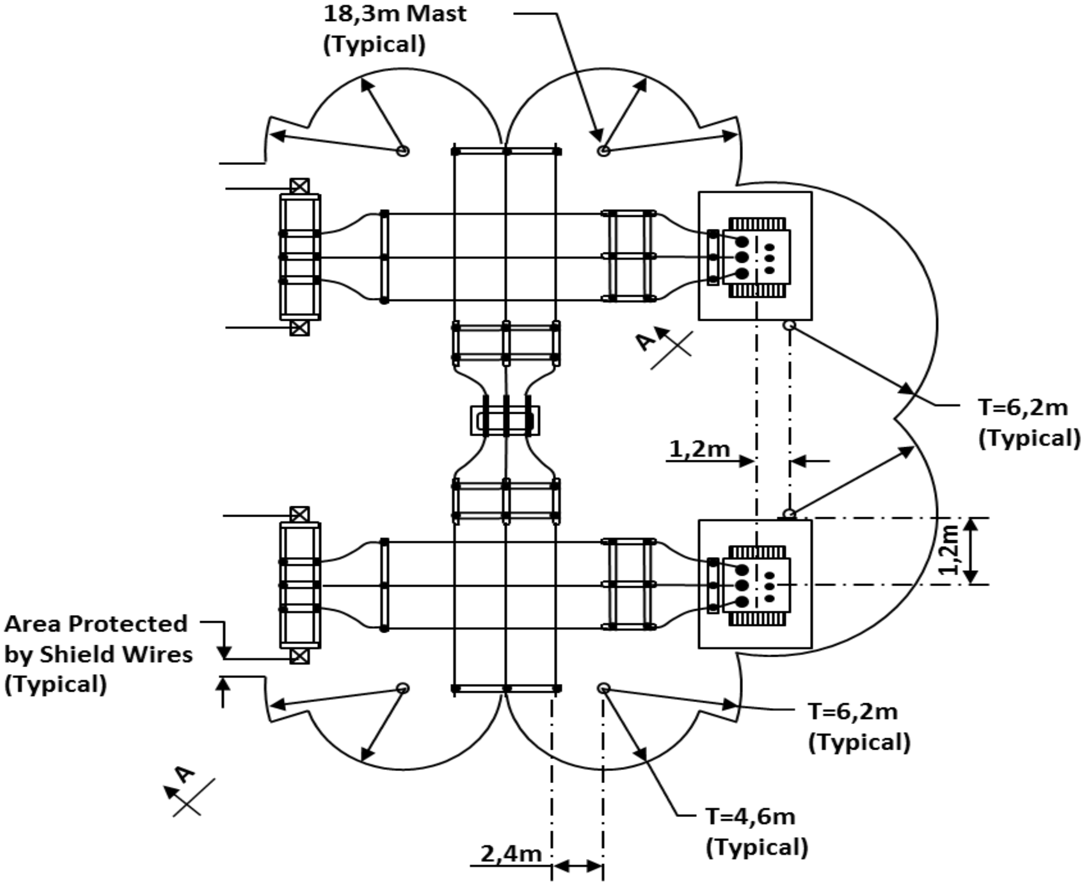



**Figure 21: Shield mast protection for stroke current $I_s$**

### 3.5.7 Protection using shield wires

The procedure for designing a shield wire system follows a similar routine as for the masts. For parallel wires, only two calculations are required; the horizontal distance **C**, to prevent side strokes and the distance **X** the maximum separation to prevent vertical strokes.

The calculation results are shown below in 3.5.7.1 to 3.5.7.4. The 4.267m bus (or the transformer that is at the same height) may extend 3.962m beyond the shield wire and still be protected from a side stroke. Since the transformer does not extend beyond the shield wire, it is protected. The high bus may extend 2.743m beyond the shield wire and be protected. Since it extends only 1.829m beyond, it is protected.

Calculations are also included for an 18.288m shield wire height. Notice that the values for **C** are slightly less than for a 12.192m wire height. This illustrates that a 18,288m wire height would give less protection from a side stroke. A study of Section B-B of Figure 24 will show why this is true.

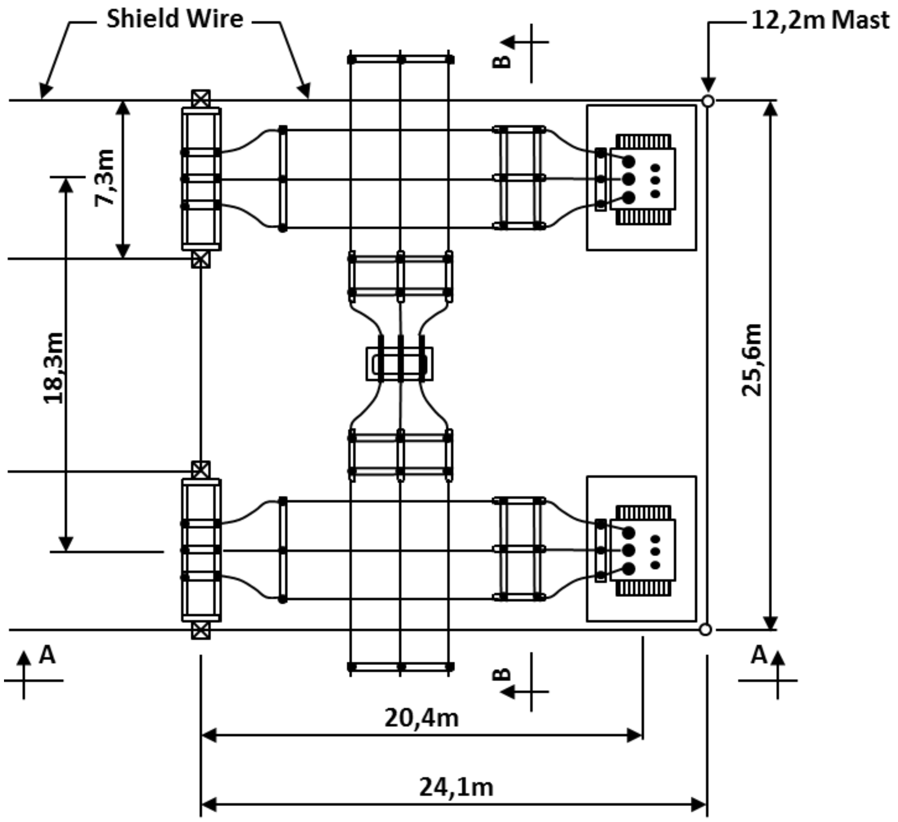



**Figure 22: Plan View of the Lightning Protection System**

The calculations for maximum shield wire separation for the 4,267m bus yield a value of 26,213m. Since the actual separation is 25,603m, the bus is protected. A maximum separation of 24,384m is permitted for the 5,791m bus and it is protected since the separation is 24,079m. This set of shield wires actually protects the low bus as well and the other set is needed only for side stroke protection. The incoming line conductors are fully shielded by the existing shield wires. This completes the protection of the substation.

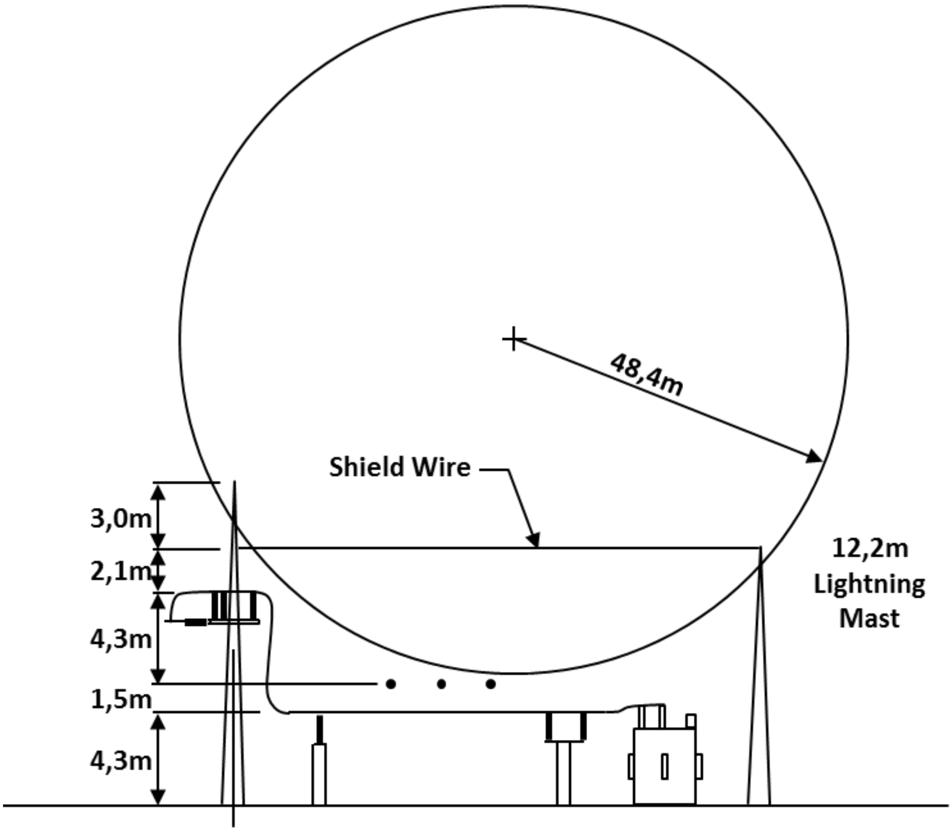



**Figure 23: Lightning Protection System on Section A-A**

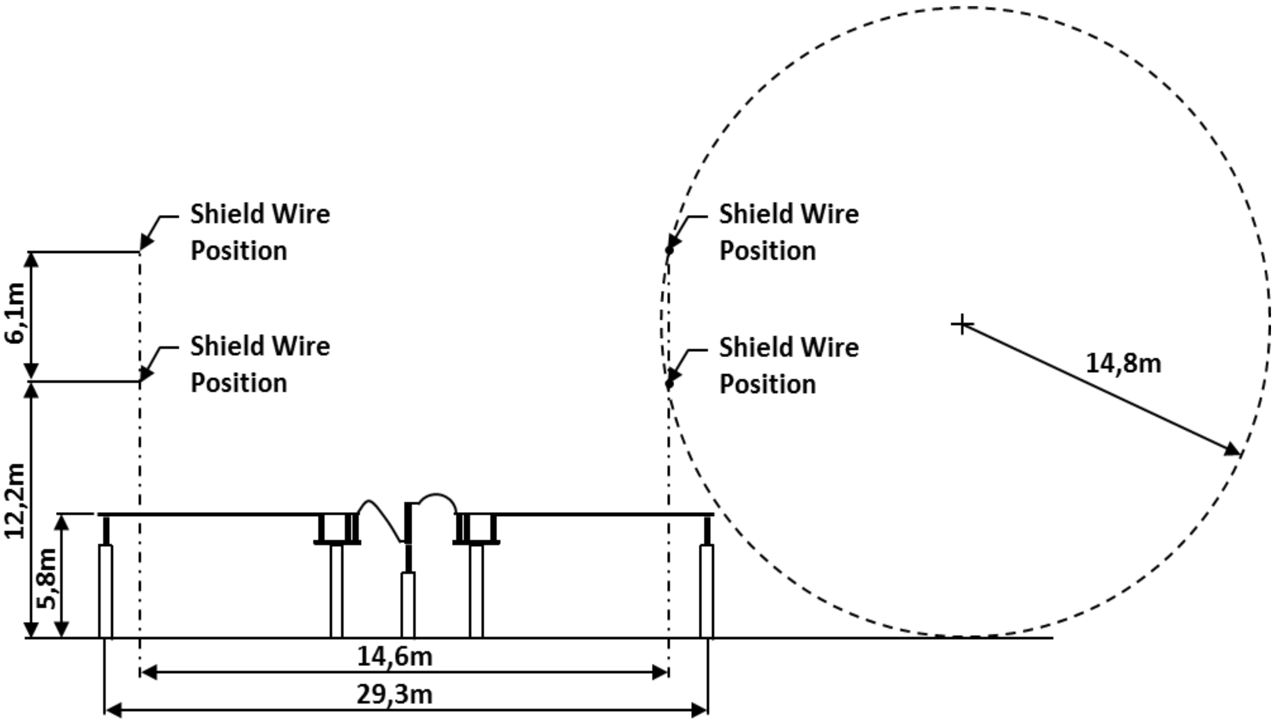



**Figure 24: Lightning Protection System on Section B-B**

The resulting layout is found in Figures 22 to 24.

### 3.5.7.1 Protection by shield wires at 18,288m for a side stroke

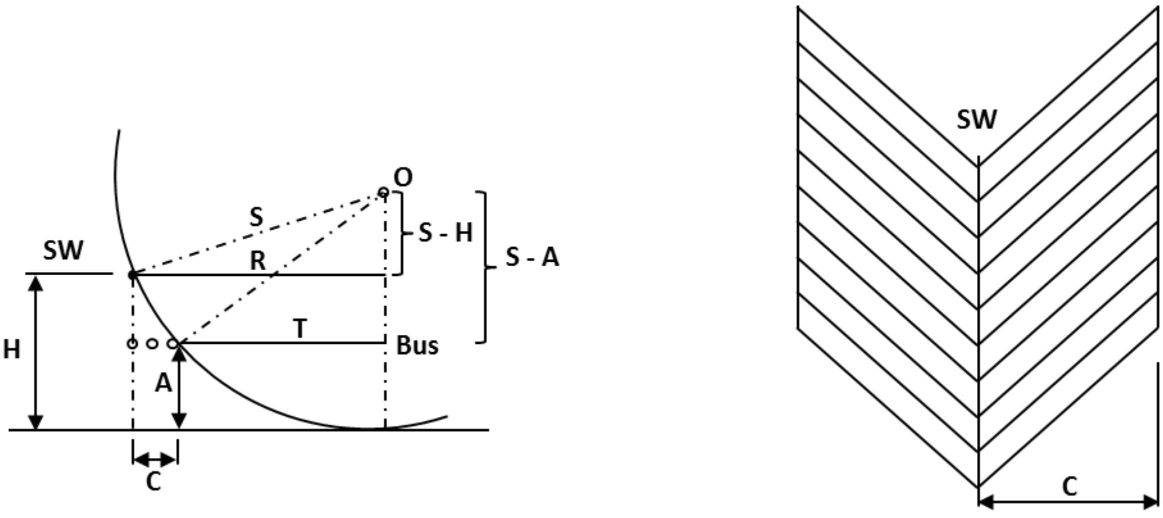



**Figure 25: Side Stroke Protection by One Shield Wire of a 66kV Substation**

**S** = Sphere radius

**H** =Wire height (calculations use assumed heights; designer should pick mast height suitable for his/her design)

**A** = Bus height

**L** = Half the separation between two wires

**X** = Maximum separation between two wires

**D** = Elevation difference between wire and bus

**E** = Elevation difference between wire and OOS

**R** = Horizontal distance between OOS and wire

**T** = Horizontal distance between OOS and bus

**C** = Horizontal distance between shield wire and bus

**Y** = Minimum phase to steel clearance

**Z** = Horizontal distance between OOS and line drawn between two masts

**W** & **C** = Horizontal distance from origin of sphere (OOS) to bus

$Z_S = 300\Omega$; $I_S = 2.567kA$

**k** = 1.0 for wires

$$S = 8 \cdot 1.0 \cdot 2.567^{0.65}$$ (from Eq.1)

S = 14.763m

Suppose a wire is introduced which is of height **H** = 18.288m

$$\mathbf{R} = \sqrt{\mathbf{S}^2 - (\mathbf{S} - \mathbf{H})^2}$$ **Equation 28**

$$R = \sqrt{14.736^2 - (14.736 - 18.288)^2}$$

R = 14.336m

$$\mathbf{T} = \sqrt{\mathbf{S}^2 - (\mathbf{S} - \mathbf{A})^2}$$ **Equation 29**

| | | |
|---|---|---|
| **T** (m) | $\mathrm{T} = \sqrt{14.736^2 - (14.736 - 4.267)^2}$<br>T = 10.382m | $\mathrm{T} = \sqrt{14.736^2 - (14.736 - 5.790)^2}$<br>T = 11.723m |

**C = R – T** **Equation 30**

| | | |
|---|---|---|
| **C** (m) | C = 14.336 – 10.382<br>C = 3.954m | C = 14.336 – 11.723<br>C = 2.613m |

These are the maximum horizontal separation distances of the shield wire and bus for protection at bus height **A**.

### 3.5.7.2 The maximum distance between two wires at 18,288m for a vertical stroke (D must be less than or equal to H-A for protection at height A)

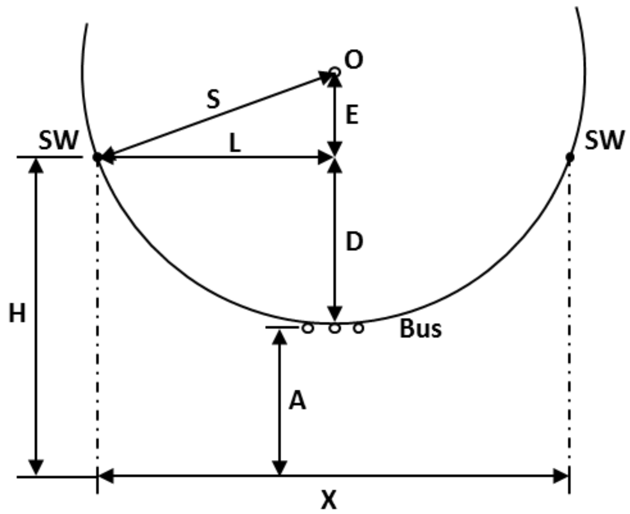



**Figure 26: Vertical Stroke Protection by Two Shield Wire at 18,288m of 66kV Substation**

**D = H – A** (from Eq.22)

| | | |
|---|---|---|
| **D** (m) | D = 18.288 – 4.267<br>D = 14.021m | D = 18.288 – 5.790<br>D = 12.498m |

**E = S – D** **(from Eq.23)**

| | | |
|---|---|---|
| **E** (m) | E = 14.763 – 14.021<br>E = 0.742m | E = 14.763 – 12.498<br>E = 2.265m |

$$\mathbf{L} = \sqrt{\mathbf{S}^2 - \mathbf{E}^2}$$ **Equation 31**

| | | |
|---|---|---|
| **L** (m) | $\mathrm{L} = \sqrt{14.763^2 - 0.742^2}$<br>L = 14.745m | $\mathrm{L} = \sqrt{14.763^2 - 2.265^2}$<br>L = 14.588m |

$\mathbf{X = 2 \cdot L}$ (from Eq.21)

| **X** (m) | X = 2 · 14.745<br>X = 29.490m | X = 2 · 14.588<br>X = 29.176m |
|---|---|---|

These values are the maximum horizontal separation of the shield wire and bus for protection at bus height **A.**

### 3.5.7.3 Protection by shield wires at 12.192m for a side stroke

$\mathbf{Z_S} = 300\Omega$

$$I_S = \frac{2.2 \cdot 350}{300}$$ (from Eq.7)

$I_S$ = 2.567kA Previously calculated value

**k** = 1.0 for wires

$$\mathbf{S = 8 \cdot k \cdot I_S^{0.65}}$$ (from Eq.1)

$$S = 8 \cdot 1.0 \cdot 2.567^{0.65}$$

S = 14.763m

Suppose a wire is introduced which is of height **H** = 12.192m

$$\mathbf{R = \sqrt{S^2 - (S - H)^2}}$$ (from Eq.28)

$$R = \sqrt{14.763^2 - (14.763 - 12.192)^2}$$

R = 14.537m

$$\mathbf{T = \sqrt{S^2 - (S - A)^2}}$$ (from Eq.29)

| **T** (m) | $T = \sqrt{14.763^2 - (14.763 - 4.267)^2}$<br>T = 10.382m | $T = \sqrt{14.736^2 - (14.736 - 5.790)^2}$<br>T = 11.723m |
|---|---|---|

**C = R – T** **(**from Eq.30)

| **C** (m) | C = 14.537 – 10.382<br>C = 4.156m | C = 14.537 – 11.723<br>C = 2.814m |
|---|---|---|

These are the maximum horizontal separation of the shield wire and bus for protection at bus height **A.**

**3.5.7.4 The maximum distance between two wires at <u>12,192m</u> for a vertical stroke (D must be less than or equal to H-A for protection at height A)**

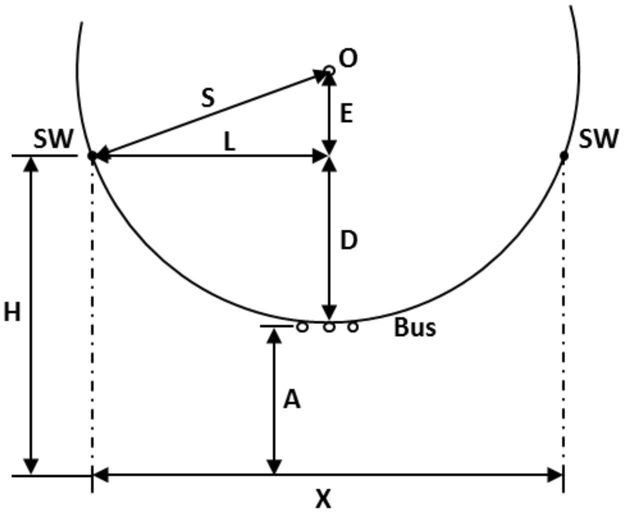



**Figure 27: Vertical Stroke Protection by Two Shield Wire at 12,192m of 66kV Substation**

**D = H – A** (from Eq.22)

| | | |
|---|---|---|
| **D** (m) | D = 12.192 – 4.267<br>D = 7.925m | D = 12.192 – 5.790<br>D = 6.402m |

**E = S – D** (from Eq.23)

| | | |
|---|---|---|
| **E** (m) | E = 14.763 – 7.925<br>E = 6.838m | E = 14.763 – 6.402<br>E = 8.361m |

$\mathbf{L = \sqrt{S^2 - E^2}}$ (from Eq.31)

| | | |
|---|---|---|
| **L** (m) | $L = \sqrt{14.763^2 - 6.838^2}$<br>L = 13.084m | $L = \sqrt{14.763^2 - 8.361^2}$<br>L = 12.167m |

**X = 2 · L** (from Eq.21)

| | | |
|---|---|---|
| **X** (m) | X = 2 · 13.084<br>X = 26.168m | X = 2 · 12.167<br>X = 24.334m |

These values are the maximum horizontal separation distance of the shield wire and bus for protection at bus height **A**.

## 3.6 Dealing with a Multiple Voltage Substation

The procedure of applying the rolling sphere method when there are multiple voltages in a substation is quite simple. 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.

If low voltage buses are present, it may be appropriate to use a minimum stoke current of 2 kA for the design calculations in these areas.

Consider a 500/220kV Substation with a layout as shown in Figure 28. The procedure for the 500 kV portion of the switchyard and for the 220 kV portion taken separately follow the same routine as has been previously discussed for the example of the 69 kV substation yard. Calculations for mast placement in the 220 kV portion of the station are found under paragraph 3.6.1 and calculations for the 500 kV portion are found below under paragraph 3.6.2. The resulting shielding layout is shown in Figure 39. The calculations for shield wires are found under the same paragraphs as mentioned above and the resulting layout is shown in Figure 42.

**Table 2: Data for 220kV and 500kV Switchyards**

| Electrical data | Busbar data | Height (A) [m] | Number of Conductors | Diameter (mm) |
|---|---|---|---|---|
| Nominal voltage: 220kV | Busbar 1 | 6.096 | 1 | 120 |
| Bus BIL: 900kV | Busbar 2 | 8.534 | 1 | 120 |
| Equipment BIL: 900kV | Busbar 3 | 11.887 | 1 | 26.5 |
| Nominal voltage: 500kV | Busbar 1 | 9.144 | 1 | 250 |
| Bus BIL: 1800kV | Busbar 2 | 16.764 | 1 | 250 |
| Equipment BIL: 1800kV | | | | |

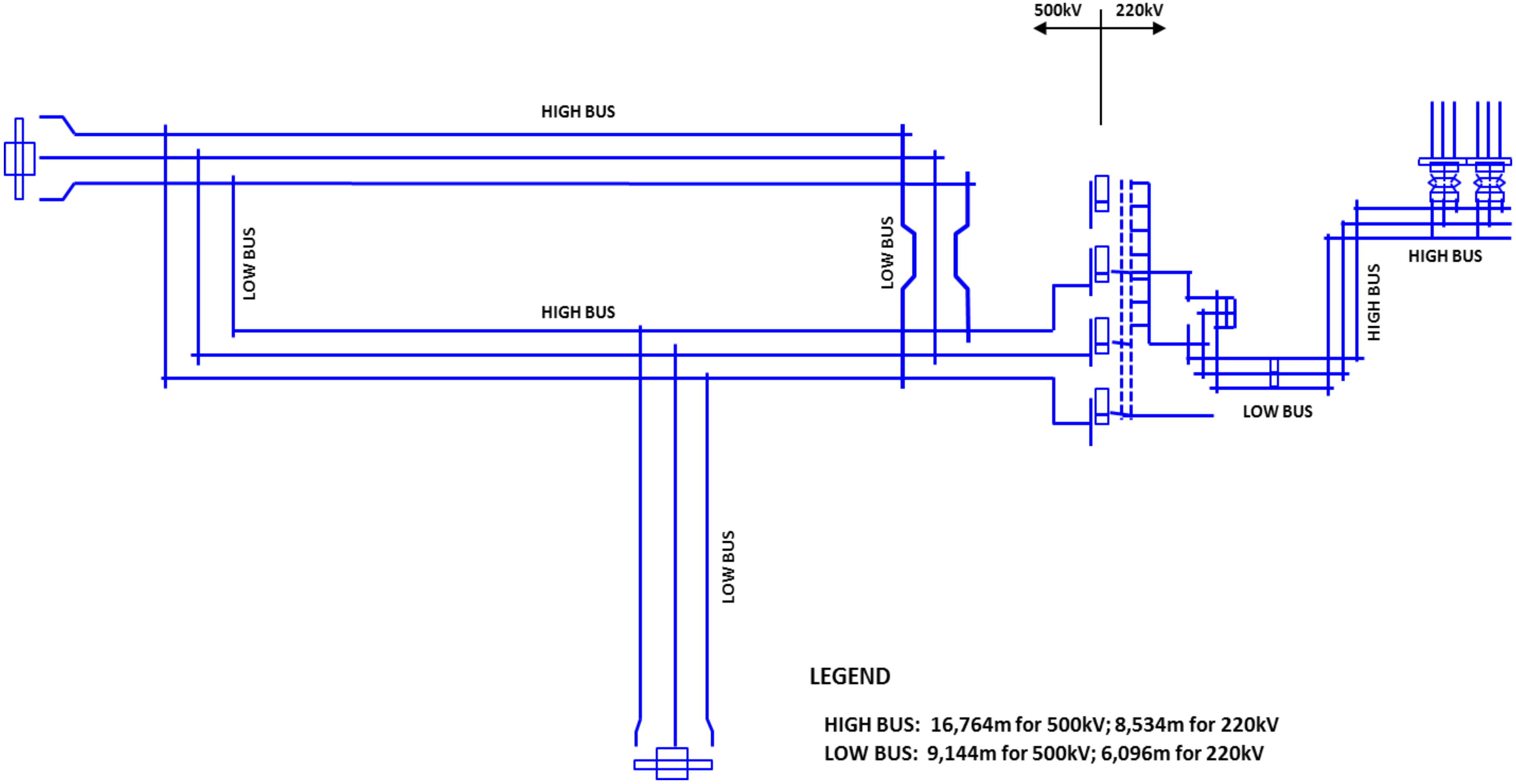



**Figure 28: Layout of a 500/220kV Substation**

### 3.6.1 The 220kV Portion

#### 3.6.1.1 The procedure for one mast (220kV)

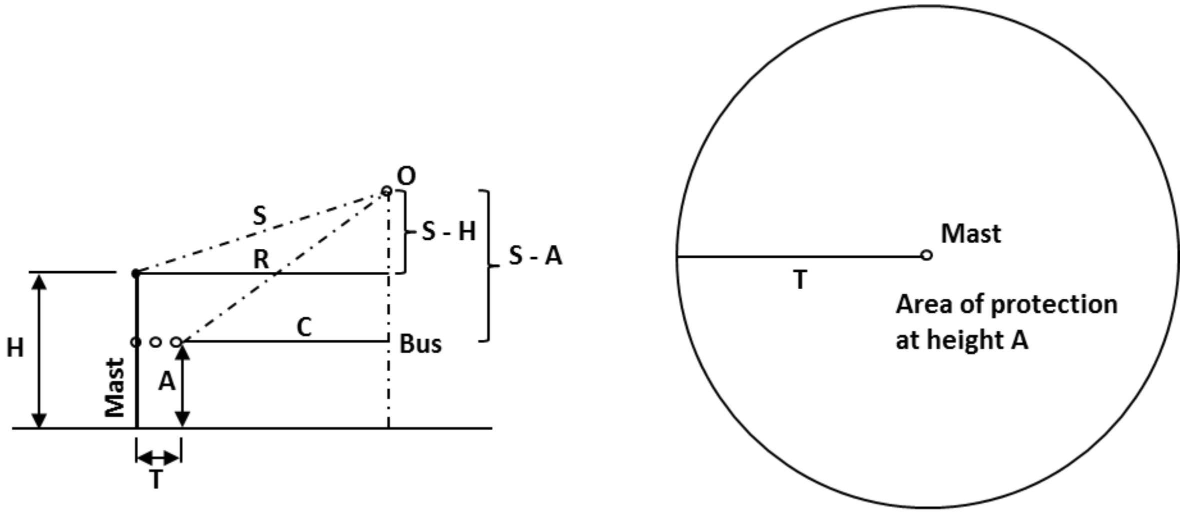



**Figure 29: Single Mast Protection System for the 220kV Yard**

Given:

$Z_S$ = 336 Ω, BIL = 900kV

a) Calculate the critical stroke current, $\mathbf{I_S}$

$$\mathbf{I_S = \frac{2.2 \cdot BIL}{Z_S}} \qquad \text{(from Eq.7)}$$

$$I_S = \frac{2.2 \cdot 900}{336}$$

$I_S$ = 5.893kA

b) Calculate the striking distance, S (which will become the sphere radius)

$$\mathbf{S = 8 \cdot k \cdot I_S^{0.65}} \qquad \text{(from Eq.1)}$$

For conductors, **k** = 1; for masts, **k** = 1,2

$$S = 8 \cdot 1.2 \cdot 5.893^{0.65}$$

S = 30.408m

c) Calculate **T** (Maximum separation from mast to bus for protection) as shown in Figure 29 and by the calculations that follow. **T** is the maximum horizontal distance from the mast that an object at a height, **A** (bus height), is protected from a direct stroke. A circle with radius, **T**, is the area of protection afforded by a single mast for an object at height, **A**.

Given:

| | | | |
|---|---|---|---|
| **A** (m) | 6.096 | 8.534 | 11.887 |
| **H** (m) | 30.480 | | |

$\mathbf{C} = \sqrt{\mathbf{S}^2 - (\mathbf{S} - \mathbf{A})^2}$ (from Eq.16)

| | | | |
|---|---|---|---|
| **C** (m) | $C = \sqrt{30.408^2 - (30.408 - 6.096)^2}$ C = 18.264m | $C = \sqrt{30.408^2 - (30.408 - 8.534)^2}$ C = 21.123m | $C = \sqrt{30.408^2 - (30.408 - 11.887)^2}$ C = 24.117m |

$\mathbf{R} = \sqrt{\mathbf{S}^2 - (\mathbf{S} - \mathbf{H})^2}$ (from Eq.28)

| | |
|---|---|
| **R** (m) | $C = \sqrt{30{,}408^2 - (30{,}408 - 30{,}480)^2}$ R = 30.408m |

$\mathbf{T} = \mathbf{R} - \mathbf{C}$ **Equation 32**

| | | | |
|---|---|---|---|
| **T** (m) | $T = 30.408 - 18.264$ T = 12.144m | $T = 30.408 - 21.123$ T = 9.285m | $T = 30.408 - 24.117$ T = 6.291m |

These are the maximum separation distances between the mast and the protected busbar for the three busbar heights.

### 3.6.1.2 The procedure for two masts (220kV)

One must calculate **X**, the maximum separation of two masts to prevent a side stroke. (It may help to visualize a sphere resting on the ground that is then rolled over to just the touch two masts. The bus is arranged so that it also just touches the surface of the sphere. By studying the various views, one obtains Figure 18 and it can be seen that this determines the maximum separation to prevent side strokes.)

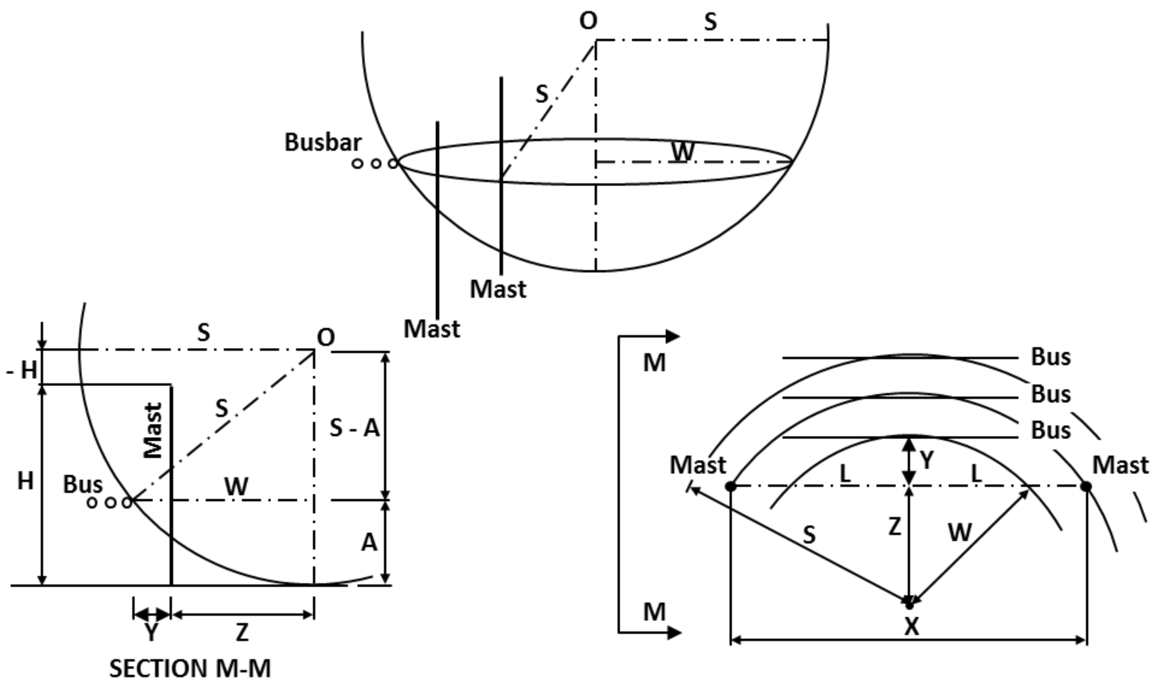



**Figure 30: Two Mast Protection System for the 220kV Yard**

For calculations when using a second mast:

**Y** = Minimum phase to steel clearance (= 1.850m phase-to-earth clearance for 220kV)

**S** = 30.408m

Given:

| | | | |
|---|---|---|---|
| **A** (m) | 6.096 | 8.534 | 11.887 |

$\mathbf{W} = \sqrt{\mathbf{S}^2 - (\mathbf{S} - \mathbf{A})^2}$ (from Eq.18)

| | | | |
|---|---|---|---|
| **W** (m) | $= \sqrt{30.408^2 - (30.408 - 6.096)^2}$<br>W = 18.264m | $= \sqrt{30.408^2 - (30.408 - 8.534)^2}$<br>W = 21.123m | $= \sqrt{30.408^2 - (30.408 - 11.887)^2}$<br>W = 24.117m |

$\mathbf{Z} = \mathbf{W} - \mathbf{Y}$ (from Eq.19)

| | | | |
|---|---|---|---|
| **Y** (m) | 1.850m | | |
| **Z** (m) | Z = 18.264 – 1.850<br>Z = 16.414 | Z = 21.123 – 1.850<br>Z = 19.273 | Z = 24.117 – 1.850<br>Z = 22.267 |

$\mathbf{L} = \sqrt{\mathbf{R}^2 - \boldsymbol{Z}^2}$ **Equation 33**

| | | | |
|---|---|---|---|
| **L** (m) | $L = \sqrt{30.408^2 - 16.414^2}$ L = 25.597m | $L = \sqrt{30.408^2 - 19.273^2}$ L = 23.520m | $L = \sqrt{30.408^2 - 22.267^2}$ L = 20.708m |

$\mathbf{X} = \mathbf{2} \cdot \mathbf{L}$ (from Eq.21)

| | | | |
|---|---|---|---|
| **X** (m) | X = 2 · 25.597 X = 51.194m | X = 2 · 23.520 X = 47.040m | X = 2 · 20.708 X = 41.416m |

These are the maximum separations of the two masts for protection of buses 1 and 2 at the two different heights **A.**

### 3.6.1.3 The procedure for four masts (220kV)

Calculate **P** (Distance between masts when four masts support the sphere), the maximum separation of masts to prevent a vertical stroke.

**D** must be less than or equal to **H – A** for protection at height **A**.

**H** = 30,480m

**D** = Elevation difference between mast and bus

**E** = Elevation difference between mast and OOS

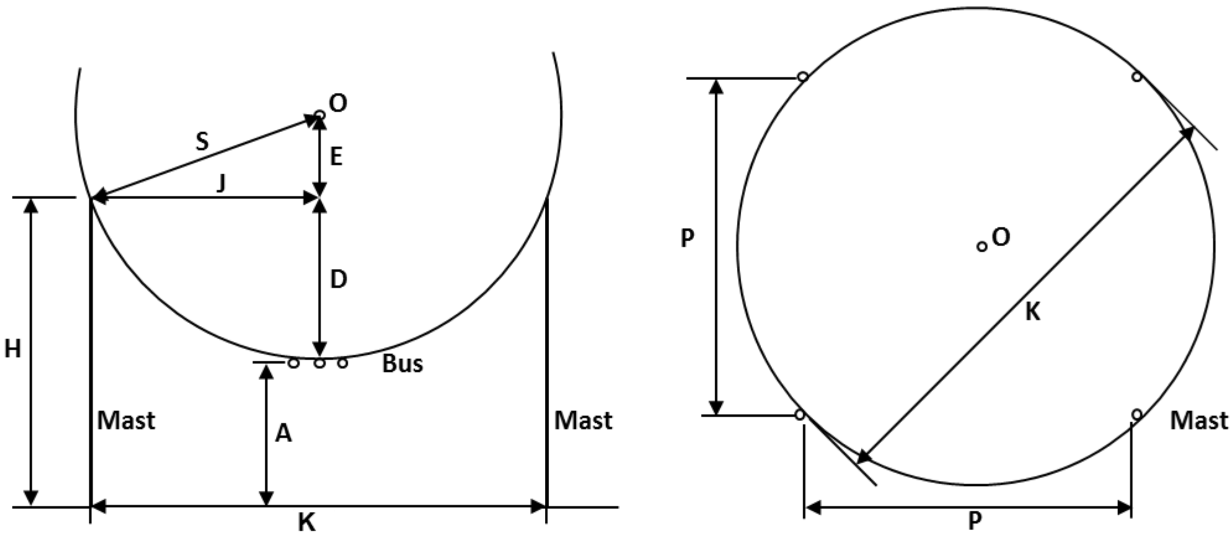



**Figure 31: Four Mast Protection System of the 220kV Yard**

Given:

| | | | |
|---|---|---|---|
| **A** (m) | 6.096m | 8.534m | 11.887m |

**D = H – A** (from Eq.22)

| | | | |
|---|---|---|---|
| **D** (m) | D = 30.480 – 6.096 D = 24.384m | D = 30.480 – 8.534 D = 21.946m | D = 30.480 –11.887 D = 18.593m |

**E = S – D** (from Eq.23)

| | | | |
|---|---|---|---|
| **E** (m) | E = 30.408 – 24.384<br>E = 6.024m | E = 30.408 – 21.946<br>E = 8.462m | E = 30.408 – 18.593<br>E = 11.815m |

$\mathbf{J = \sqrt{S^2 - E^2}}$ (from Eq.24)

| | | | |
|---|---|---|---|
| **J** (m) | $J = \sqrt{30.408^2 - 6.024^2}$<br>J = 29.805m | $J = \sqrt{30.408^2 - 8.462^2}$<br>J = 29.207m | $J = \sqrt{30.408^2 - 11.815^2}$<br>J = 28.019m |

$\mathbf{K = 2 \cdot J}$ (from Eq.25)

| | | | |
|---|---|---|---|
| **K** (m) | K = 2 · 29.805<br>K = 59.610m | K = 2 · 29.207<br>K =58.414m | K = 2 · 28.019<br>K = 56.038 |

$\mathbf{P = \frac{K}{\sqrt{2}}}$ (from Eq.26)

| | | | |
|---|---|---|---|
| **P** (m) | $P = \frac{59.610}{\sqrt{2}}$<br>P = 42.151m | $P = \frac{58.414}{\sqrt{2}}$<br>P = 41.304m | $P = \frac{56.038}{\sqrt{2}}$<br>P = 39.624m |

These are the maximum spacing of the four masts for protection of buses at the heights **A**.

#### 3.6.1.4 Maximum distance between two masts for vertical stroke sphere supported by three masts (220kV)

Calculate **Q** (Distance between masts when three masts support the sphere), the maximum separation of three masts to prevent a vertical stroke.

$\mathbf{Q = 2 \cdot \cos\left(\pi \cdot \frac{30}{180}\right) \cdot J}$ (from Eq.27)

| | | | |
|---|---|---|---|
| **Q** (m) | $Q = 2 \cdot \cos\left(\pi \cdot \frac{30}{180}\right) \cdot 29.805$<br>Q = 51.624m | $Q = 2 \cdot \cos\left(\pi \cdot \frac{30}{180}\right) \cdot 29.207$<br>Q = 50.587m | $Q = 2 \cdot \cos\left(\pi \cdot \frac{30}{180}\right) \cdot 28.019$<br>Q = 48.530m |

**Q** should not be greater than **X**.

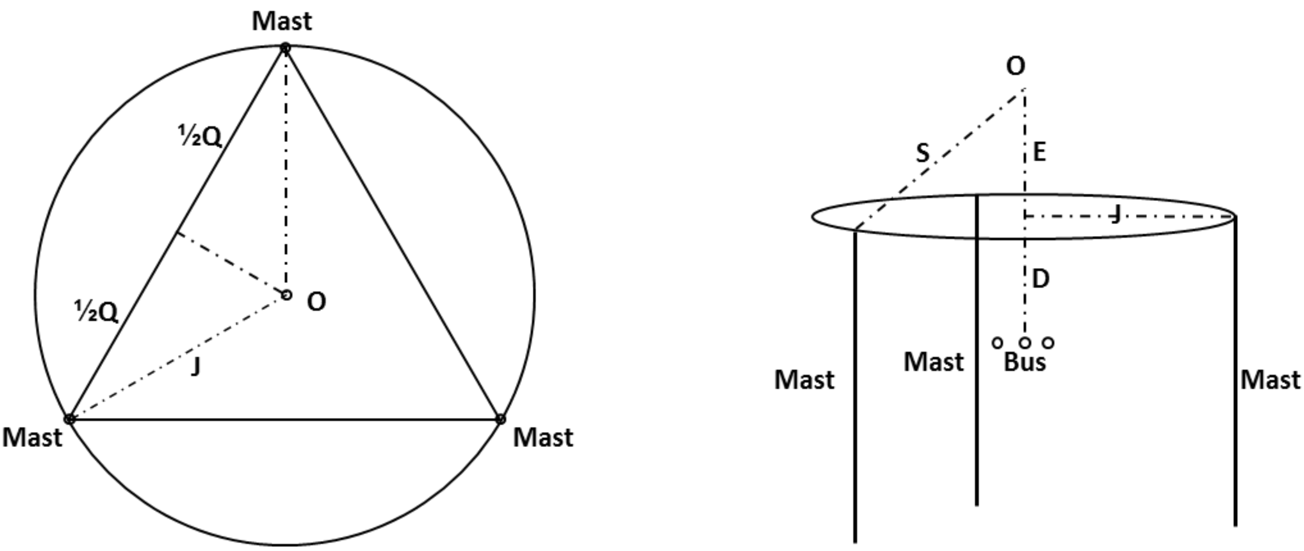



**Figure 32: Three Mast Protection System of the 220kV Yard**

### 3.6.1.5 Protection by shield wires (220kV)

Given:

$Z_S$ = 336 Ω, BIL = 900kV

a) Calculate the critical stroke current, $\mathbf{I_s}$

$$\mathbf{I_S = \frac{2.2 \cdot BIL}{Z_S}} \qquad \text{(from Eq.7)}$$

$$I_S = \frac{2.2 \cdot 900}{336}$$

$I_S$ = 5.893kA

b) Calculate the striking distance, **S** (which will become the sphere radius)

$$\mathbf{S = 8 \cdot k \cdot I_S^{0.65}} \qquad \text{(from Eq.1)}$$

For conductors, **k** = 1; for masts, **k** = 1,2

$$S = 8 \cdot 1.0 \cdot 5.893^{0.65}$$

S = 25.340m

| | | | |
|---|---|---|---|
| **A** (m) | 6.096m | 8.534m | 11.887m |
| **H** (m) | 30.480m | | |

$\mathbf{R} = \sqrt{\mathbf{S}^2 - (\mathbf{S} - \mathbf{H})^2}$ (from Eq.28)

| | |
|---|---|
| **R** (m) | $R = \sqrt{25.340^2 - (25.340 - 30.480)^2}$<br>R = 24.813m |

$\mathbf{T} = \sqrt{\mathbf{S}^2 - (\mathbf{S} - \mathbf{A})^2}$ (from Eq.29)

| | | | |
|---|---|---|---|
| **T** (m) | $T = \sqrt{25.340^2 - (25.340 - 6.096)^2}$<br>T = 16.486m | $T = \sqrt{25.340^2 - (25.340 - 8.534)^2}$<br>T = 18.965m | $T = \sqrt{25.340^2 - (25.340 - 11.887)^2}$<br>T = 21.474 |

**C = R – T** (from Eq.30)

| | | | |
|---|---|---|---|
| **C** (m) | C = 24.813 – 16.486<br>C = 8.327m | C = 24.813 – 18.965<br>C = 5.848m | C = 24.813 – 21.474<br>C = 3.339m |

These values are the maximum separation between the mast and protected bus for two bus heights **A**.

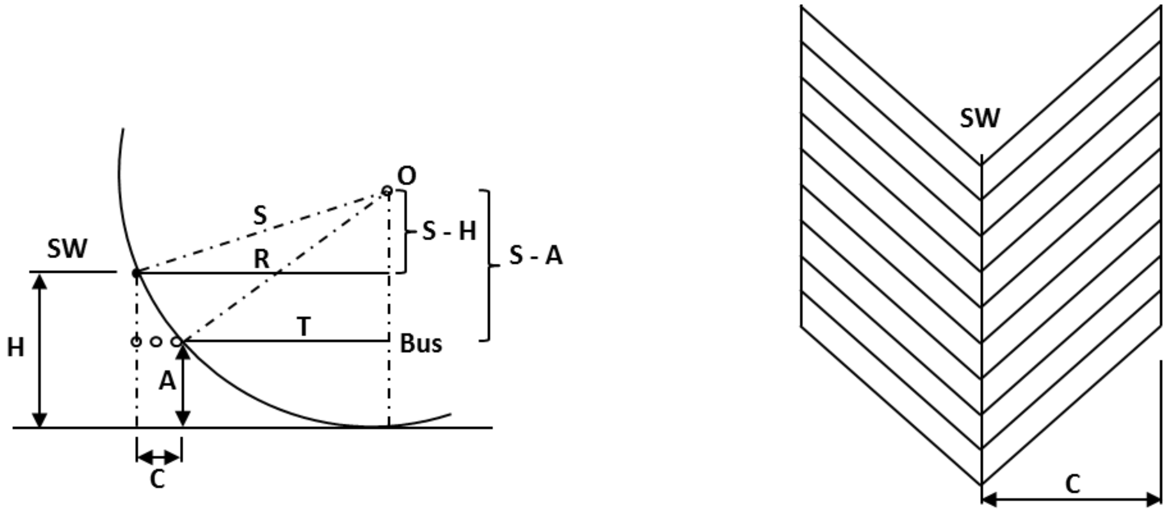



**Figure 33: Single Shield Wire Protection System for the 220kV Yard**

### 3.6.1.6 Maximum distance between two wires for vertical stroke (220kV)

**D** must be less than or equal to **H – A** for protection at height A.

**D = H – A** (from Eq.22)

| | | | |
|---|---|---|---|
| **A** (m) | 6.096m | 8.534m | 11.887m |
| **D** (m) | D = 30.480 – 6.096<br>D = 24.384m | D = 30.480 – 8.534<br>D = 21.946m | D = 30.480 – 11.887<br>D = 18.593m |

**E = S – D** (from Eq.23)

| | | | |
|---|---|---|---|
| **E** (m) | E = 25.340 – 24.384<br>E = 0.956m | E = 25.340 – 21.946<br>E = 3.394m | E = 25.340 – 18.593<br>E = 6.747m |

$\mathbf{L = \sqrt{S^2 - E^2}}$ (from Eq.31)

| | | | |
|---|---|---|---|
| **L** (m) | $L = \sqrt{25.340^2 - 0.956^2}$<br>L = 25.322m | $L = \sqrt{25.340^2 - 3.394^2}$<br>L = 25.111m | $L = \sqrt{25.340^2 - 6.747^2}$<br>L = 24.425m |

$\mathbf{X = 2 \cdot L}$ (from Eq.21)

| | | | |
|---|---|---|---|
| **X** (m) | X = 2 · 25.322<br>X = 50.644m | X = 2 · 25.111<br>X = 50.222m | X = 2 · 24.425<br>X = 48.850m |

These values are the maximum separation of shield wires for protection at bus heights A

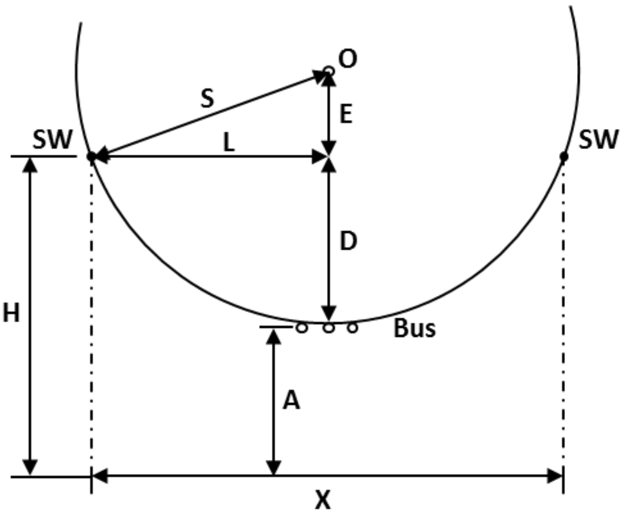



**Figure 34: Two Shield Wire Protection System for the 220kV Yard**

### 3.6.2 The 500kV portion

#### 3.6.2.1 Procedure for single mast

Given:

$Z_S$ = 336 Ω, BIL = 1800kV (LIWL)

a) Calculate the critical stroke current, $\mathbf{I_S}$

$$\mathbf{I_S = \frac{2.2 \cdot BIL}{Z_S}}$$ (from Eq.7)

$$I_S = \frac{2.2 \cdot 1800}{336}$$

$I_S$ = 11.786kA

#### 3.6.2.2 Calculate the striking distance, S (which will become the sphere radius)

$$\mathbf{S = 8 \cdot k \cdot I_S^{0.65}}$$ (from Eq.1)

For conductors, **k** = 1; for masts, **k** = 1,2

$$S = 8 \cdot 1.2 \cdot 11.786^{0.65}$$

S = 47.715m

$$\mathbf{R = \sqrt{S^2 - (S - H)^2}}$$ (from Eq.28)

| | |
|---|---|
| **H** (m) | 30.480m |
| **R** (m) | $R = \sqrt{47.715^2 - (47.715 - 30.480)^2}$<br>R = 44.493m |

| | | |
|---|---|---|
| **A** (m) | 9.144m | 16.764m |

$$\mathbf{C = \sqrt{S^2 - (S - A)^2}}$$ (from Eq.16)

| | | |
|---|---|---|
| **C** (m) | $C = \sqrt{47,715^2 - (47,715 - 9,144)^2}$<br>C = 28,089m | $C = \sqrt{47,715^2 - (47,715 - 16.764)^2}$<br>C = 36.315m |

$$\mathbf{T = R - C}$$ (from Eq.32)

| | | |
|---|---|---|
| **T** (m) | T = 44.493 – 28.089<br>T = 16.404m | T = 44.493 – 36.315<br>T = 8.176m |

These values are the maximum separation between the mast and protected bus for two bus heights **A**.

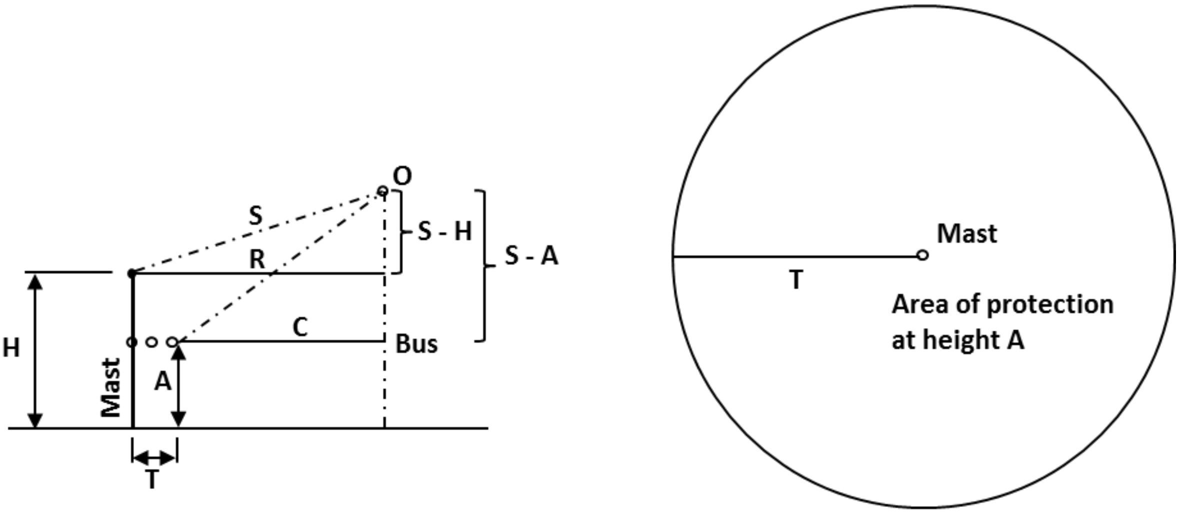



**Figure 35: Single Mast Protection for the 500kV Yard**

#### 3.6.2.3 Maximum distance between two masts for side strokes (500kV)

$\mathbf{W} = \sqrt{\mathbf{S}^2 - (\mathbf{S} - \mathbf{A})^2}$ (from Eq.18)

| | | |
|---|---|---|
| **W** (m) | $W = \sqrt{47.715^2 - (47.715 - 9.144)^2}$<br>W = 28.089m | $W = \sqrt{47.715^2 - (47.715 - 16.764)^2}$<br>W = 36.315m |

$\mathbf{Z} = \mathbf{W} - \mathbf{Y}$ (from Eq.19)

| | | |
|---|---|---|
| **Y** (m) | 6.000 | |
| **Z** (m) | Z = 28.089 – 6.000<br>Z = 22.089m | Z = 36.315 – 6.000<br>Z = 30.315m |

$\mathbf{L} = \sqrt{\mathbf{R}^2 - \boldsymbol{Z}^2}$ (from Eq.33)

| | | |
|---|---|---|
| **L** (m) | $L = \sqrt{44.493^2 - 22.089^2}$<br>L = 38.623m | $L = \sqrt{44.493^2 - 30.315^2}$<br>L = 32.568m |

$\mathbf{X} = \mathbf{2} \cdot \mathbf{L}$ (from Eq.21)

| | | |
|---|---|---|
| **X** (m) | X = 2 · 38.623<br>X = 77.246m | X = 2 · 32.568<br>X = 65.136m |

These values are the maximum separation of two masts for protection of buses at the two bus heights **A**.

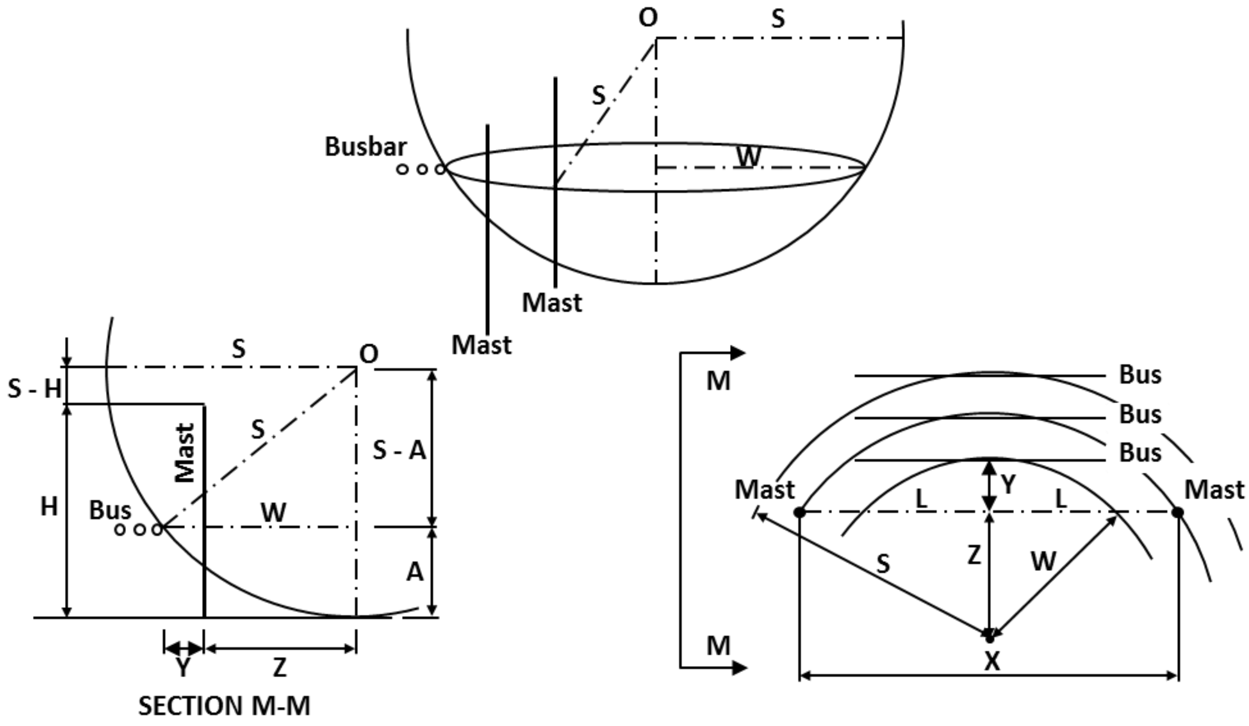



**Figure 36: Two Mast Protection System for the 500kV Yard**

#### 3.6.2.4 Maximum distance between two masts for vertical stroke sphere supported by four masts

**D** must be less than or equal to **H – A** for protection at height A.

**D = H – A** (from Eq.22)

| | | |
|---|---|---|
| **D** (m) | D = 30.480 – 9.144<br>D = 21.336m | D = 30.480 – 16.764<br>D = 13.716m |

**E = S – D** (from Eq.23)

| | | |
|---|---|---|
| **E** (m) | E = 47.715 – 21.336<br>E = 26.379m | E = 47.715 – 13.716<br>E = 33.999m |

$\mathbf{J} = \sqrt{\mathbf{S}^2 - \mathbf{E}^2}$ (from Eq.24)

| | | |
|---|---|---|
| **J** (m) | $J = \sqrt{47.715^2 - 26.379^2}$<br>J = 39.760m | $J = \sqrt{47.715^2 - 33.999^2}$<br>J = 33.478m |

$\mathbf{K} = \mathbf{2} \cdot \mathbf{J}$ (from Eq.25)

| | | |
|---|---|---|
| **K** (m) | K = 2 · 39.760<br>K = 79.520m | K = 2 · 33.478<br>K = 66.956m |

$$\mathbf{P} = \frac{\mathbf{K}}{\sqrt{\mathbf{2}}}$$ (from Eq.26)

| | | |
|---|---|---|
| **P** (m) | $P = \frac{79.520}{\sqrt{2}}$<br>P = 56.229m | $P = \frac{66.956}{\sqrt{2}}$<br>P = 47.345m |

These values are the maximum spacing of four masts for protection of buses at the two bus heights **A.**

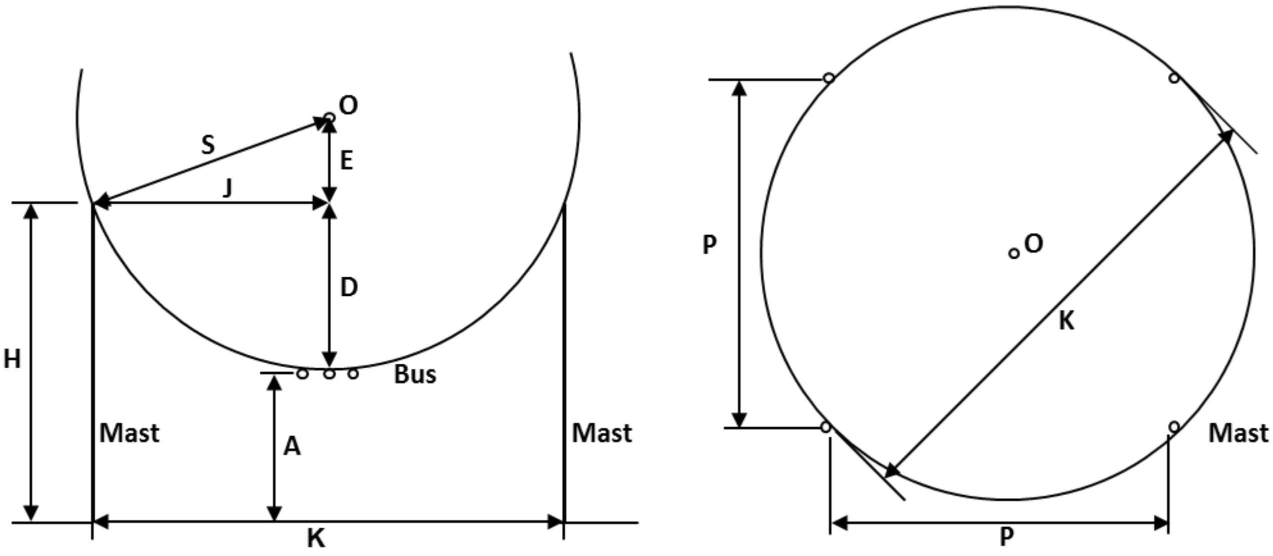



**Figure 37: Four Mast Protection System for the 500kV Yard**

### 3.6.2.5 Maximum distance between two masts for vertical stroke sphere supported by three masts

Calculate **Q** (Distance between masts when three masts support the sphere), the maximum separation of three masts to prevent a vertical stroke.

$$\mathbf{Q} = \mathbf{2} \cdot \mathbf{cos}\left(\boldsymbol{\pi} \cdot \frac{\mathbf{30}}{\mathbf{180}}\right) \cdot \mathbf{J}$$ (from Eq.27)

| | | |
|---|---|---|
| **Q** (m) | $Q = 2 \cdot \cos\left(\pi \cdot \frac{30}{180}\right) \cdot 39.760$<br>Q = 68.866m | $Q = 2 \cdot \cos\left(\pi \cdot \frac{30}{180}\right) \cdot 33.478$<br>Q = 57.986m |

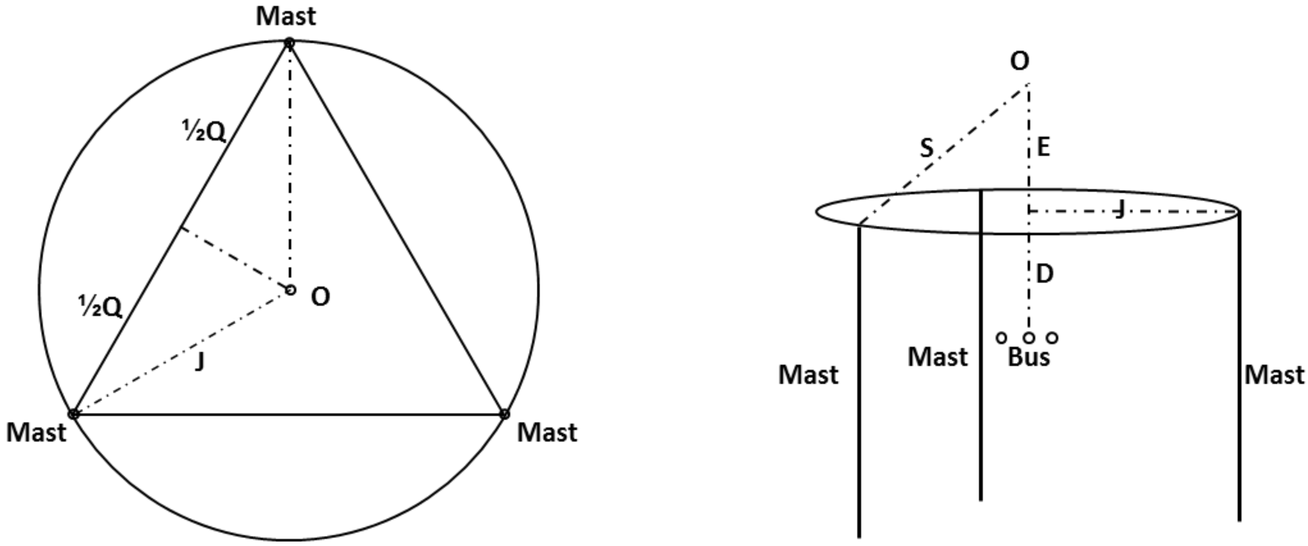
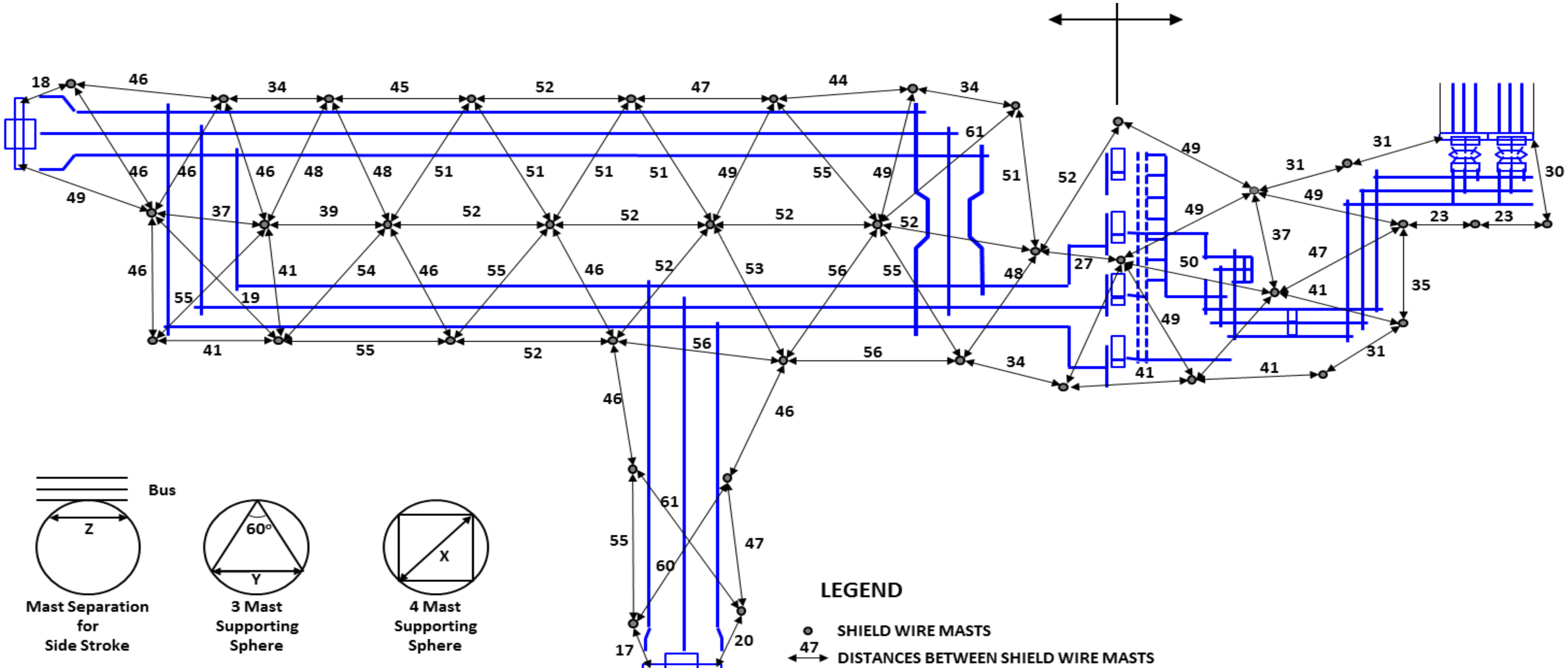



**Figure 38: Three Mast Protection System for the 500kV Yard**




MAX. MAST SEPARATION

| DISTANCE | BUS | | | | |
|---|---|---|---|---|---|
| | 500 HIGH | 500 LOW | 220 HIGH | 220 LOW | 220 COLLECT |
| X (m) | 67 | 80 | 59 | 60 | 56 |
| Y (m) | 58 | 69 | 51 | 52 | 49 |
| Z (m) | 56 | 72 | 47 | 51 | 42 |

**Figure 39: Shielding of a 500/220kV Substation with Masts Using the Rolling Sphere Method**

### 3.6.2.6 Protection by shield wires

Given:

$Z_S$ = 336 Ω, BIL = 1800kV (LIWL)

Calculate the critical stroke current, $\mathbf{I_s}$ from Eq. 5-2A.

$$\mathbf{I_S} = \frac{\mathbf{2.2 \cdot BIL}}{\mathbf{Z_S}} \qquad \text{(from Eq.7)}$$

$$I_S = \frac{2.2 \cdot 1800}{336}$$

$I_S$ = 11.786kA

Calculate the striking distance, **S** (which will become the sphere radius) from Eq. 5-1B.

$$\mathbf{S = 8 \cdot k \cdot I_S^{0.65}} \qquad \text{(from Eq.1)}$$

For conductors, **k** = 1; for masts, **k** = 1,2

$$S = 8 \cdot 1.0 \cdot 11.786^{0.65}$$

S = 39.762m

| | | |
|---|---|---|
| **A** (m) | 9.144m | 16.764m |

$$\mathbf{R} = \sqrt{\mathbf{S^2 - (S - H)^2}} \qquad \text{(from Eq.28)}$$

| | |
|---|---|
| **H** (m) | 30.480m |
| **R (m)** | $R = \sqrt{39.762^2 - (39.762 - 30.480)^2}$<br>R = 38.664m |

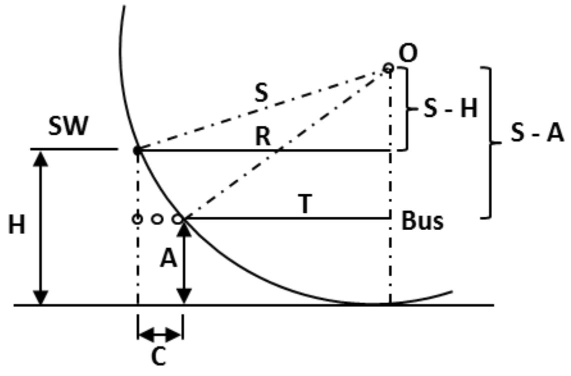
$$\mathbf{T} = \sqrt{\mathbf{S^2 - (S - A)^2}} \qquad \text{(from Eq.29)}$$

| | | |
|---|---|---|
| **T** (m) | $T = \sqrt{39.762^2 - (39.762 - 9.144)^2}$<br>T = 25.368m | $T = \sqrt{39.762^2 - (39.762 - 16.764)^2}$<br>T = 32.436m |

**C = R – T** (from Eq.30)

| | | |
|---|---|---|
| **C** (m) | C = 38.664 – 25.368<br>C = 13.295m | C = 38.664 – 32.436<br>C = 6.227m |

These values are the maximum separation between the mast and protected bus for two bus heights **A**.



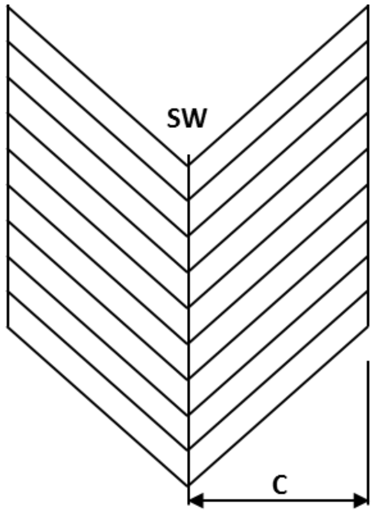




**Figure 40: Single Shield Wire Protection System for the 500kV Yard**

### 3.6.2.7 Maximum distance between two shield wires for vertical stroke

**D** must be less than or equal to **H – A** for protection at height **A**.

**D = H – A** (from Eq.22)

| | | |
|---|---|---|
| **D** (m) | D = 30.480 – 9.114<br>D = 21.336m | D = 30.480 – 16.764<br>D = 13.716m |

**E = S – D** (from Eq.23)

| | | |
|---|---|---|
| **E** (m) | E = 39,763 - 21,336<br>E = 18,426m | E = 39,763 – 13,716<br>E = 26,046m |

$\mathbf{L} = \sqrt{\mathbf{S}^2 - \mathbf{E}^2}$ (from Eq.31)

| | | |
|---|---|---|
| **L** (m) | $L = \sqrt{39{,}763^2 - 18{,}426^2}$<br>L = 35,235m | $L = \sqrt{39{,}763^2 - 26{,}046^2}$<br>L = 30,044m |

$\mathbf{X} = \mathbf{2} \cdot \mathbf{L}$ (from Eq.21)

| | | |
|---|---|---|
| **X** (m) | X = 2 · 35.235<br>X = 70,470m | X = 2 · 30.044<br>X = 60,088m |

These values are the maximum separation of shield wires for protection at bus heights **A**.

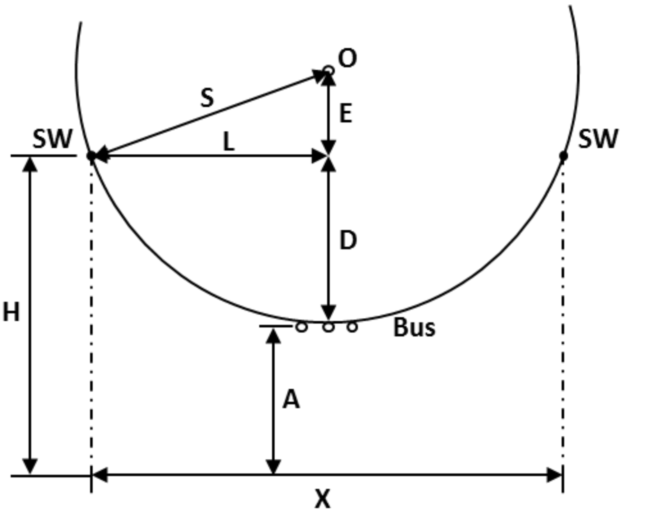
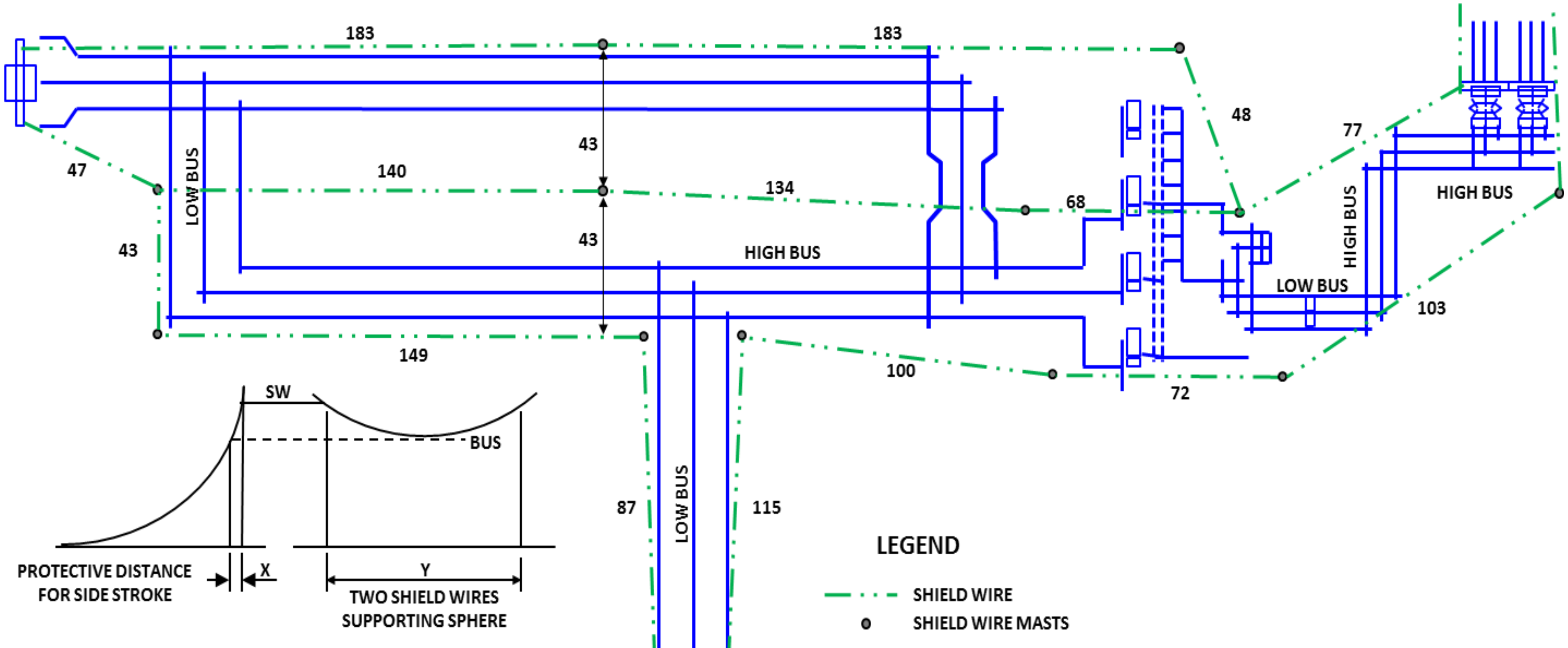



**Figure 41: Two Shield Wire Protection System for the 500kV Yard**




| DISTANCE | BUS | | | | |
|---|---|---|---|---|---|
| | 500 HIGH | 500 LOW | 220 HIGH | 220 LOW | 220 COLLECT |
| X (m) | 6,1 | 13,1 | 5,8 | 8,2 | 3,6 |
| Y (m) | 58 | 69 | 51 | 52 | 49 |

**Figure 42: Shielding of a 500/220kV Substation with Shield Wires by Using the Rolling Sphere Method**

## 4. Authorization

This document has been seen and accepted by:

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|---|---|
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## 5. Revisions

| Date | Rev | Compiler | Remarks |
|---|---|---|---|
| Feb 2021 | 3 | Theunus Marais | Table 2 title corrected<br>Updated values for: $R_c$, $Z_s$ on page 26<br>C, T on page 27<br>Z on page 30<br>Q on page 31<br>D on page 36<br>L, X on page 37<br>X on page 38<br>R, T on page 42<br>Y on page 43<br>J on page 45<br>X on page 48<br>C on page 49<br>L, X on page 50 |

| Date | Rev | Compiler | Remarks |
|---|---|---|---|
| | | | E, L, X on page 56<br>ANNEX A, B, C, D, E, F updated |
| Dec 2016 | 2 | AJS Groenewald | Update section 3.4.10 from 2kA to 2.5kA as was the original intent. |
| July 2016 | 1 | AJS Groenewald | First Issue. |

## 6. Development team

The following people were involved in the development of this document:

- Braam Groenewald Technology Group Johannesburg
- Jayant Raghubir Kwa-Zulu Natal Op Unit New Germany
- Theunus Marais Technology Group Johannesburg

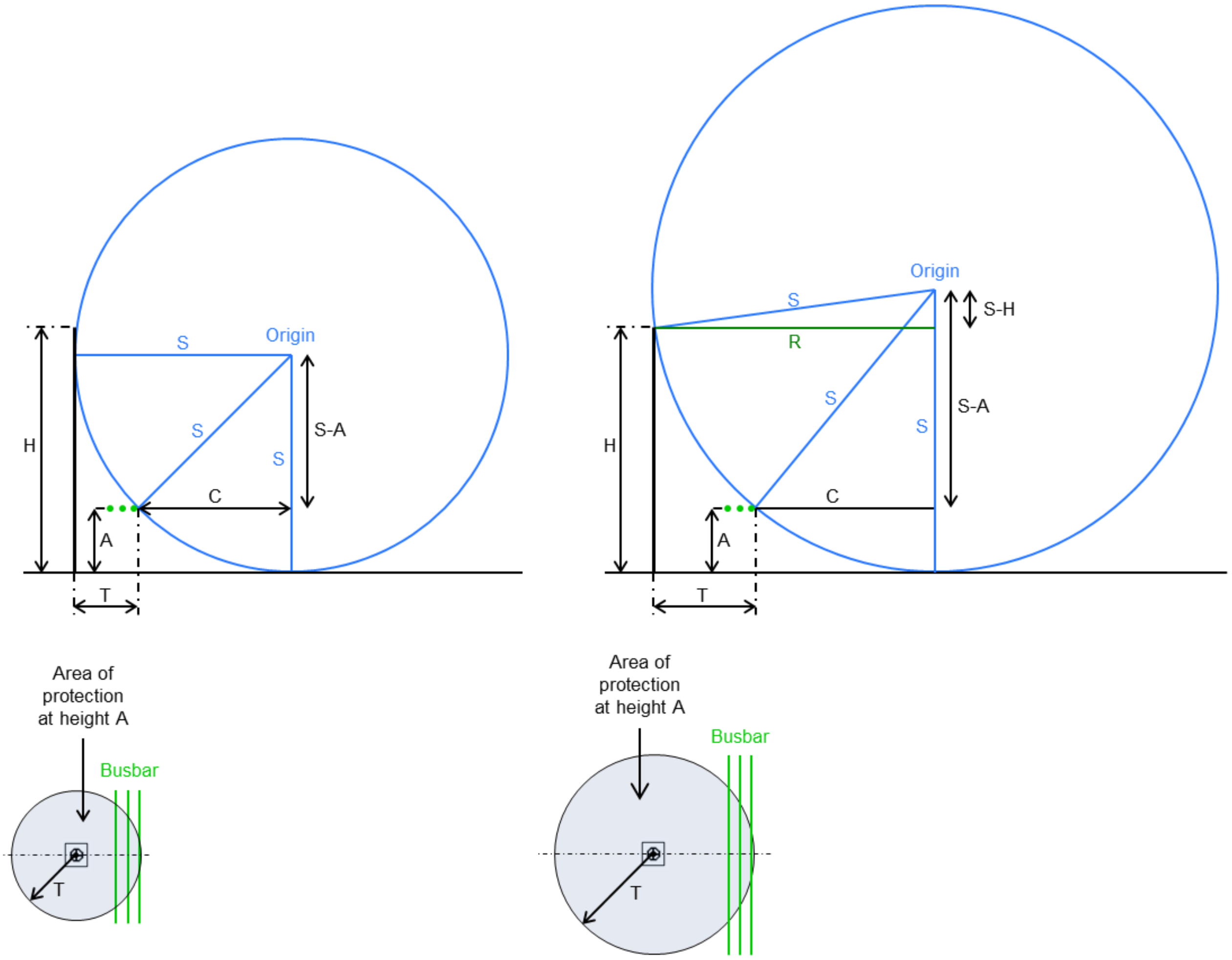
## 7. Acknowledgements

The Lightning Protection Work Group is acknowledged for their work that contributed materially to this document.

Theunus Marais, Enderani Naicker, Jayant Raghubir, Lenah Mabusela, Dr Henri Geldenhuys, Chris van der Merwe

# Annex A – One Mast Example (Based on Template 240-127851444)

| | UoM | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | |
|---|---|---|---|---|---|---|
| **INPUTS** | | | | | | |
| System voltage | kV | 132 | | 220 | | GIVEN |
| Mast height: H | m | 22.2 | | | | GIVEN |
| Busbar/Conductor/Equipment height: A | m | 6.100 | 8.5 | 8.5 | 11.900 | GIVEN |
| Conductor | | Centipede (26,46mm diameter) | | | | GIVEN |
| Bundle configuration | | Single conductor | | Twin conductor | | GIVEN |
| Conductor separation/spacing | mm | - | | 150 | | GIVEN |
| **PARAMETERS** | | | | | | |
| BIL | kV | 550 | | 825 | | CHOSEN |
| Phase to earth clearance | m | 1.200 | | 1.850 | | CHOSEN |
| Factor "k" | | 1.2 | | | | CHOSEN |
| Limiting corona gradient | kV/m | 1500 | | | | FIXED |
| **CALCULATED RESULTS** | | | | | | |
| Conductor corona radius: $R_c$ | m | 0.071 | 0.066 | 0.109 | 0.101 | Eq. 9 |
| Bundle corona radius: $R_c'$ | m | 0.071 | 0.066 | 0.153 | 0.145 | Eq. 11 |
| Surge Impedance of the conductor: $Z_s$ | ohm | 355.5 | 378.2 | 317.4 | 339.6 | Eq. 10 |
| Allowable stroke current: $I_s$ | kA | 3.404 | 3.199 | 5.718 | 5.345 | Eq. 7 |
| Strike distance to mast: $S_m$ | m | 21.284 | 20.443 | 29.818 | 28.538 | Eq. 1 |
| C | m | 14.915 | 16.592 | 20.848 | 23.186 | Eq. 16 |
| R | m | H > S | H > S | 28.828 | 27.826 | Eq. 28 |
| Protective distance of one mast at specified equipment height: T | m | 6.369 | 3.852 | 7.980 | 4.639 | Eq. 17/32 |

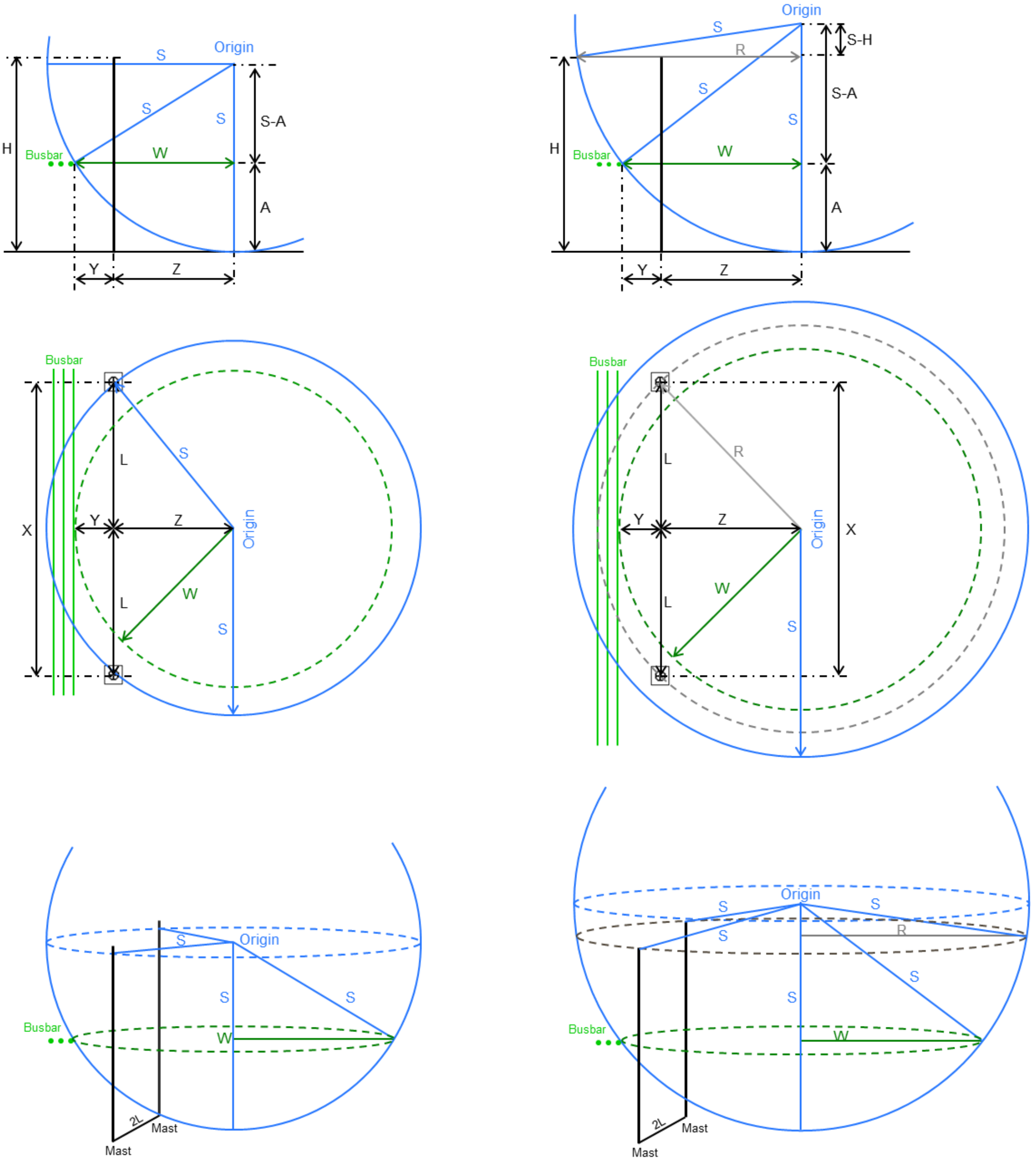



**(a) Mast height ≥ striking distance (H ≥ S)** **(b) Mast height < striking distance (H < S)**

**Figure A.1: Single mast protection area**

# Annex B – Two Masts Example (Based on Template 240-127851444)

| | **UoM** | **Scenario 1** | **Scenario 2** | **Scenario 3** | **Scenario 4** | |
|---|---|---|---|---|---|---|
| **INPUTS** | | | | | | |
| System voltage | kV | 132 | | 220 | | GIVEN |
| Mast height: H | m | 22.2 | | | | GIVEN |
| Busbar/Conductor/Equipment height: A | m | 6.100 | 8.5 | 8.5 | 11.900 | GIVEN |
| Conductor | | Centipede (26,46mm diameter) | | | | GIVEN |
| Bundle configuration | | Single conductor | | Twin conductor | | GIVEN |
| Conductor separation/spacing | mm | - | | 150 | | GIVEN |
| **PARAMETERS** | | | | | | |
| BIL | kV | 550 | | 825 | | CHOSEN |
| Phase to earth clearance | m | 1.200 | | 1.850 | | CHOSEN |
| Factor “k” | | 1.2 | | | | CHOSEN |
| Limiting corona gradient | kV/m | 1500 | | | | FIXED |
| **CALCULATED RESULTS** | | | | | | |
| Conductor corona radius: $R_c$ | m | 0.071 | 0.066 | 0.109 | 0.101 | Eq. 9 |
| Bundle corona radius: $R_c'$ | m | 0.071 | 0.066 | 0.153 | 0.145 | Eq. 11 |
| Surge Impedance of the conductor: $Z_s$ | ohm | 355.5 | 378.2 | 317.4 | 339.6 | Eq. 10 |
| Allowable stroke current: $I_s$ | kA | 3.404 | 3.199 | 5.718 | 5.345 | Eq. 7 |
| Strike distance to mast: $S_m$ | m | 21.284 | 20.443 | 29.818 | 28.538 | Eq. 1 |
| W | m | 14.915 | 16.592 | 20.848 | 23.186 | Eq. 18 |
| Z | m | 13.715 | 15.392 | 18.998 | 21.336 | Eq. 19 |
| R | m | H > S | H > S | 28.828 | 27.826 | Eq. 28 |
| L | m | 16.276 | 13.454 | 21.683 | 17.861 | Eq. 20/33 |
| Maximum separation between two masts to prevent a side stroke at specified equipment height: X | m | 32.552 | 26.909 | 43.365 | 35.723 | Eq. 21 |




**(a) Mast height ≥ striking distance (H ≥ S)** **(b) Mast height < striking distance (H < S)**

**Figure B.1: Two masts protective area**

# Annex C – Four Masts (Based on Template 240-127851444)

| | UoM | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | |
|---|---|---|---|---|---|---|
| **INPUTS** | | | | | | |
| System voltage | kV | 132 | | 220 | | GIVEN |
| Mast height: H | m | 22.2 | | | | GIVEN |
| Busbar/Conductor/Equipment height: A | m | 6.100 | 8.5 | 8.5 | 11.900 | GIVEN |
| Conductor | | Centipede (26,46mm diameter) | | | | GIVEN |
| Bundle configuration | | Single conductor | | Twin conductor | | GIVEN |
| Conductor separation/spacing | mm | - | | 150 | | GIVEN |
| **PARAMETERS** | | | | | | |
| BIL | kV | 550 | | 825 | | CHOSEN |
| Phase to earth clearance | m | 1.200 | | 1.850 | | CHOSEN |
| Factor “k” | | 1.2 | | | | CHOSEN |
| Limiting corona gradient | kV/m | 1500 | | | | FIXED |
| **CALCULATED RESULTS** | | | | | | |
| Conductor corona radius: $R_c$ | m | 0.071 | 0.066 | 0.109 | 0.101 | Eq. 9 |
| Bundle corona radius: $R_c'$ | m | 0.071 | 0.066 | 0.153 | 0.145 | Eq. 11 |
| Surge Impedance of the conductor: $Z_s$ | ohm | 355.5 | 378.2 | 317.4 | 339.6 | Eq. 10 |
| Allowable stroke current: $I_s$ | kA | 3.404 | 3.199 | 5.718 | 5.345 | Eq. 7 |
| Strike distance to mast: $S_m$ | m | 21.284 | 20.443 | 29.818 | 28.538 | Eq. 1 |
| D | m | 16.100 | 13.700 | 13.700 | 10.300 | Eq. 22 |
| E | m | 5.184 | 6.743 | 16.118 | 18.238 | Eq. 23 |
| J | m | 20.643 | 19.299 | 25.086 | 21.950 | Eq. 24 |
| K | m | 41.286 | 38.598 | 50.173 | 43.900 | Eq. 25 |
| Maximum separation between four masts to prevent a vertical stroke at specified equipment height: P | m | 29.194 | 27.293 | 35.477 | 31.042 | Eq. 26 |

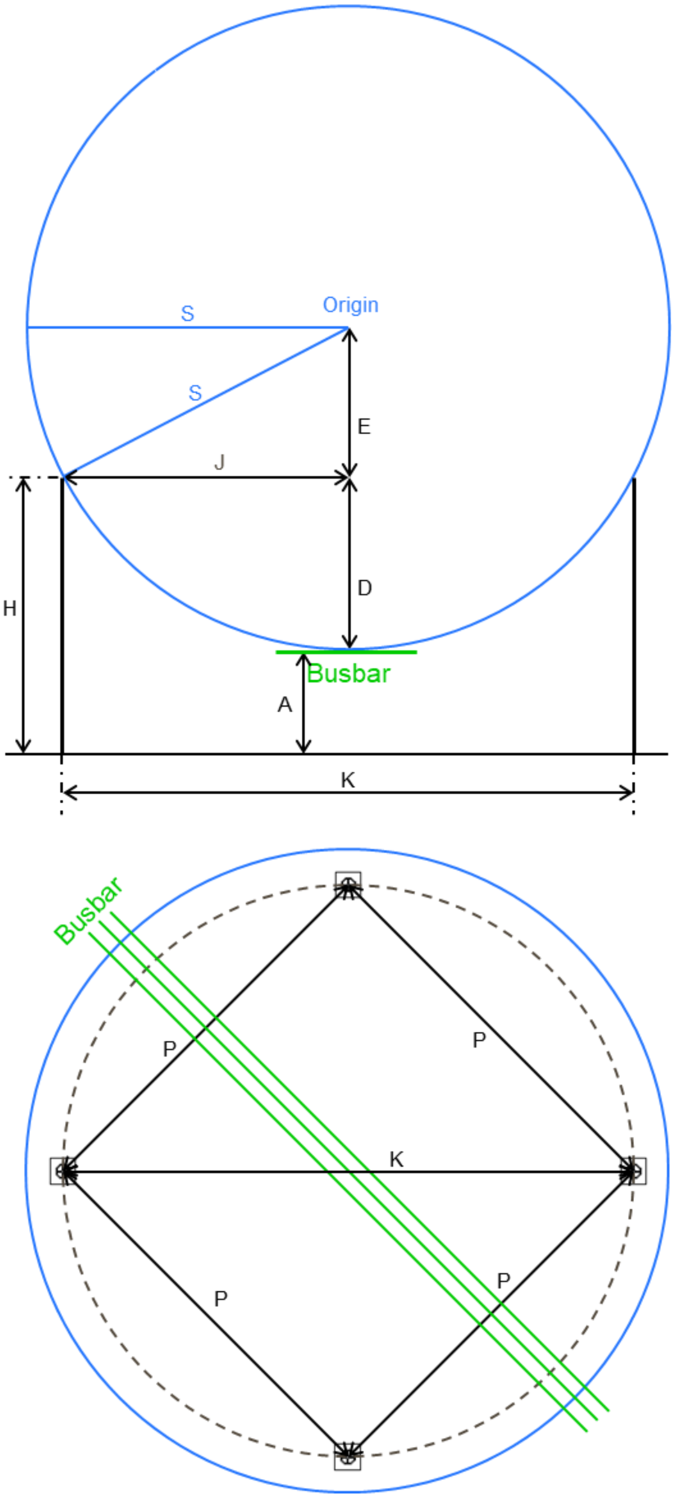



**Figure C.1: Four masts protective area**

# Annex D – Three Masts (Based on Template 240-127851444)

| | UoM | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | |
|---|---|---|---|---|---|---|
| **INPUTS** | | | | | | |
| System voltage | kV | 132 | | 220 | | GIVEN |
| Mast height: H | m | 22.2 | | | | GIVEN |
| Busbar/Conductor/Equipment height: A | m | 6.100 | 8.5 | 8.5 | 11.900 | GIVEN |
| Conductor | | Centipede (26,46mm diameter) | | | | GIVEN |
| Bundle configuration | | Single conductor | | Twin conductor | | GIVEN |
| Conductor separation/spacing | mm | - | | 150 | | GIVEN |
| **PARAMETERS** | | | | | | |
| BIL | kV | 550 | | 825 | | CHOSEN |
| Phase to earth clearance | m | 1.200 | | 1.850 | | CHOSEN |
| Factor “k” | | 1.2 | | | | CHOSEN |
| Limiting corona gradient | kV/m | 1500 | | | | FIXED |
| **CALCULATED RESULTS** | | | | | | |
| Conductor corona radius: $R_c$ | m | 0.071 | 0.066 | 0.109 | 0.101 | Eq. 9 |
| Bundle corona radius: $R_c'$ | m | 0.071 | 0.066 | 0.153 | 0.145 | Eq. 11 |
| Surge Impedance of the conductor: $Z_s$ | ohm | 355.5 | 378.2 | 317.4 | 339.6 | Eq. 10 |
| Allowable stroke current: $I_s$ | kA | 3.404 | 3.199 | 5.718 | 5.345 | Eq. 7 |
| Strike distance to mast: $S_m$ | m | 21.284 | 20.443 | 29.818 | 28.538 | Eq. 1 |
| D | m | 16.100 | 13.700 | 13.700 | 10.300 | Eq. 22 |
| E | m | 5.184 | 6.743 | 16.118 | 18.238 | Eq. 23 |
| J | m | 20.643 | 19.299 | 25.086 | 21.950 | Eq. 24 |
| Maximum separation between three masts to prevent a vertical stroke at specified equipment height: Q | m | 35.755 | 33.427 | 43.451 | 38.018 | Eq. 27 |

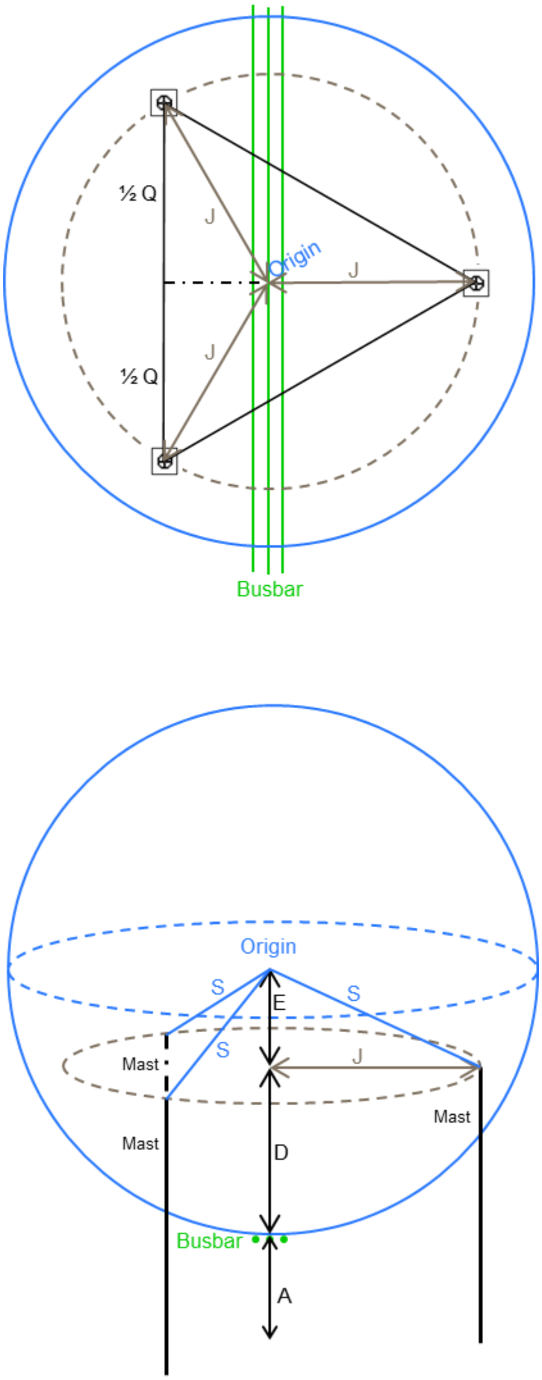



**Figure D.1: Three masts protective area**

# Annex E – One Shield Wire (Based on Template 240-127851444)

| | UoM | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | |
|---|---|---|---|---|---|---|
| **INPUTS** | | | | | | |
| System voltage | kV | 132 | | 220 | | GIVEN |
| Shield wire height: H | m | 14.45 | | 22.2 | | GIVEN |
| Busbar/Conductor/Equipment height: A | m | 6.1 | 8.5 | 8.5 | 11.9 | GIVEN |
| Conductor | | Centipede (26,46mm diameter) | | | | GIVEN |
| Bundle configuration | | Single conductor | | Twin conductor | | GIVEN |
| Conductor separation/spacing | mm | - | | 150 | | GIVEN |
| **PARAMETERS** | | | | | | |
| BIL | kV | 550 | | 825 | | CHOSEN |
| Phase to earth clearance | m | 1.200 | | 1.850 | | CHOSEN |
| Factor “k” | | 1.0 | | | | CHOSEN |
| Limiting corona gradient | kV/m | 1500 | | | | FIXED |
| **CALCULATED RESULTS** | | | | | | |
| Conductor corona radius: $R_c$ | m | 0.071 | 0.066 | 0.109 | 0.101 | Eq. 9 |
| Bundle corona radius: $R_c'$ | m | 0.071 | 0.066 | 0.153 | 0.145 | Eq. 11 |
| Surge Impedance of the conductor: $Z_s$ | ohm | 355.5 | 378.2 | 317.4 | 339.6 | Eq. 10 |
| Allowable stroke current: $I_s$ | kA | 3.404 | 3.199 | 5.718 | 5.345 | Eq. 7 |
| Strike distance to mast: $S_w$ | m | 17.737 | 17.036 | 24.848 | 23.782 | Eq. 1 |
| T | m | 17.430 | 16.839 | 24.707 | 23.729 | Eq. 29 |
| R | m | 13.386 | 14.743 | 18.713 | 20.601 | Eq. 28 |
| Protective distance of one shield wire at specified equipment height: C | m | 4.044 | 2.095 | 5.994 | 3.128 | Eq. 30 |

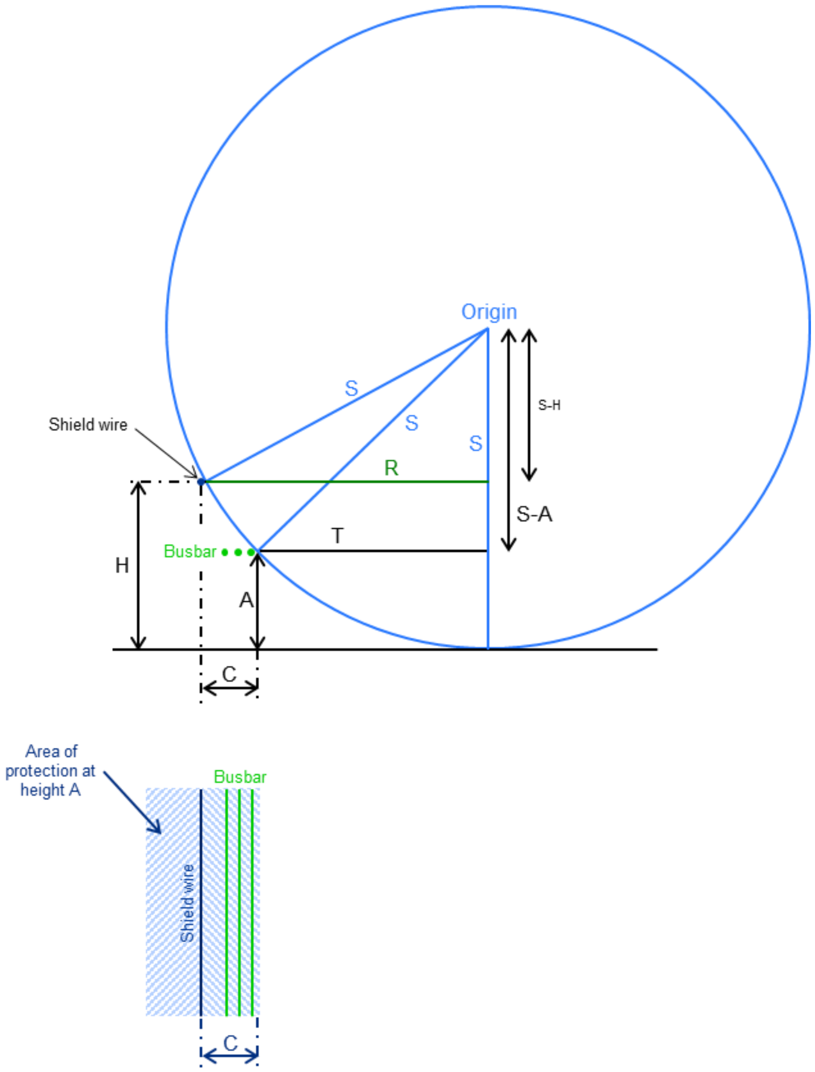



**Figure E.1: One shield wire protective area**

## Annex F – Two Shield Wires (Based on Template 240-127851444)

| | UoM | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | |
|---|---|---|---|---|---|---|
| **INPUTS** | | | | | | |
| System voltage | kV | 132 | | 220 | | GIVEN |
| Shield wire height: H | m | 14.45 | | 22.2 | | GIVEN |
| Busbar/Conductor/Equipment height: A | m | 6.1 | 8.5 | 8.5 | 11.9 | GIVEN |
| Conductor | | Centipede (26,46mm diameter) | | | | GIVEN |
| Bundle configuration | | Single conductor | | Twin conductor | | GIVEN |
| Conductor separation/spacing | mm | - | | 150 | | GIVEN |
| **PARAMETERS** | | | | | | |
| BIL | kV | 550 | | 825 | | CHOSEN |
| Phase to earth clearance | m | 1.200 | | 1.850 | | CHOSEN |
| Factor "k" | | 1.0 | | | | CHOSEN |
| Limiting corona gradient | kV/m | 1500 | | | | FIXED |
| **CALCULATED RESULTS** | | | | | | |
| Conductor corona radius: $R_c$ | m | 0.071 | 0.066 | 0.109 | 0.101 | Eq. 9 |
| Bundle corona radius: $R_c'$ | m | 0.071 | 0.066 | 0.153 | 0.145 | Eq. 11 |
| Surge Impedance of the conductor: $Z_s$ | ohm | 355.5 | 378.2 | 317.4 | 339.6 | Eq. 10 |
| Allowable stroke current: $I_s$ | kA | 3.404 | 3.199 | 5.718 | 5.345 | Eq. 7 |
| Strike distance to mast: $S_w$ | m | 17.737 | 17.036 | 24.848 | 23.782 | Eq. 1 |
| D | m | 8.350 | 5.950 | 13.700 | 10.300 | Eq. 22 |
| E | | 9.387 | 11.086 | 11.148 | 13.482 | Eq. 23 |
| L | m | 15.049 | 12.935 | 22.207 | 19.591 | Eq. 31 |
| Protective distance of two shield wires at specified equipment height: X | m | 30.099 | 25.871 | 44.414 | 39.183 | Eq. 21 |

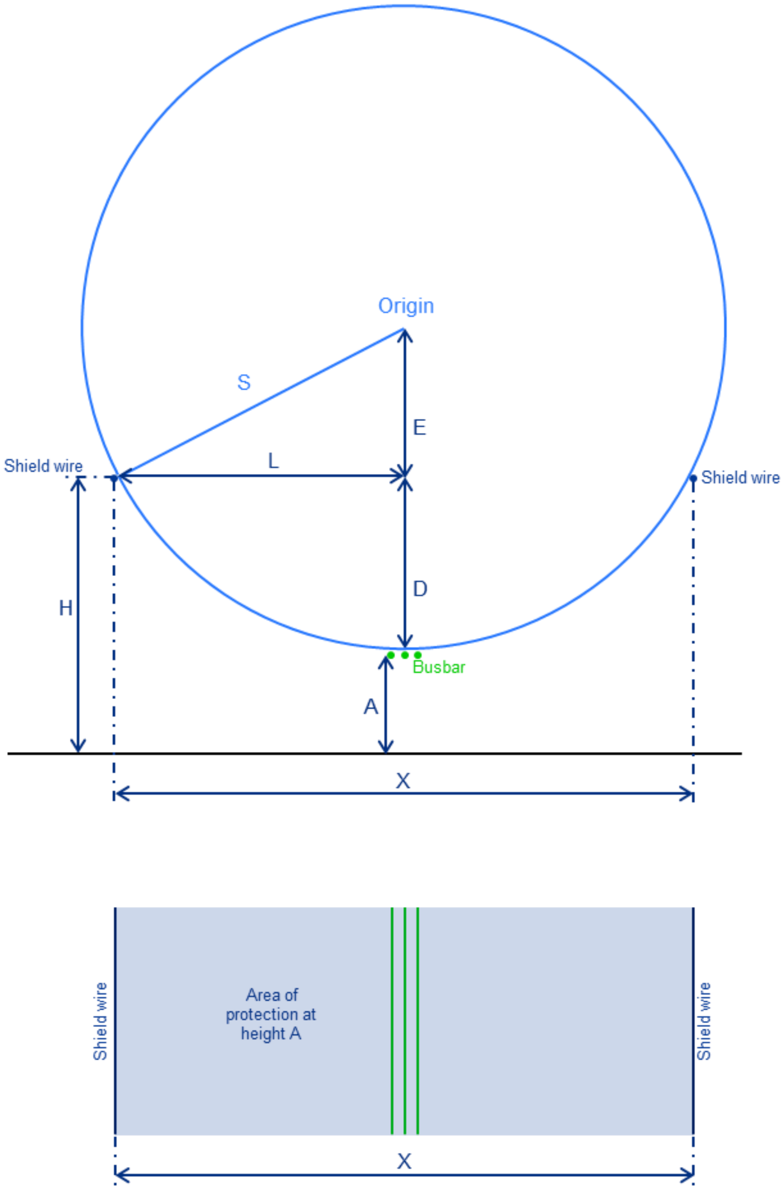



**Figure F.1: Two shield wires protective area**