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Lightning protection zone in substation using mast

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Abstract

This paper proposes zone apportionment algorithms (ZAA) to apportion lightning protection zonegenerated by mast. Mast may be used to protect equipment within substation against lightning. Lightning distance equations are used to determine striking distance to ground, object and mast. The calculation of corresponding protection zone is sophisticated especially when more masts are used. ZAA is proposedto apportion the lightning protection zone generated by 1–4 mast(s), calculate the critical protection height at each point, and create a three dimension protection volume to be visualized. Each point of equipment is laid out in substation with its height. Then, the equipment height at each point is compared with the corresponding critical protection height to determine whether equipmentareprotected or not.The risk part of unprotected equipment will emerge above the comparable protection roof and be visualized clearly. This will help engineers to understand the protection zone thoroughly and ensure that equipment are protected. ZAA algorithms are tested on a 30 m x 30 m substation protected by 1–4 mast(s)located outside substation with height of 32 m, 17 m, 14 m and 13 m, respectively. Equipment are located at the center of substation. Calculation from ZAA indicated that equipment with size 10 m x 10 m should not be higher than 10.14 m, 10.28 m, 10.26 m and 10.97 m in case of 1–4 mast(s), respectively. For larger equipment, with size 12 m x 12 m, they should not be higher than 9.31 m, 9.59 m, 10.26 m and 10.97 m in case of 1–4 mast(s), respectively. Numerical results indicated that the proposed algorithms, ZAA could identify the unprotected part of equipment correctly and produce a three dimension protection volume with emerging of the unprotected part of equipment. ZAA could verify the lightning protection correctly in all cases.

Keywords :Lightning protection zone, Substation, Lightning distance equation, Mast, Zone apportion

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1. Introduction

Equipment in a substation would be exposed to lightning strike. Lightning striking to electrical equipment could cause great damage. Thus, equipment must be protected against lightning. Lightning protection system (LPS) could employ mast or shield wire or both. However, the broken shield wire may cause great damage to equipment underneath. Thus, in a small substation,mast(s) may be used to protect equipment against lightning strike.

The distance equations are used to determine the lightning strikingdistance to ground, object and mast [1] The lightning striking distance depends on the magnitude of the lightning current. The parameters of lightning current were studied and proposed in [2] Lightning peak current may exceed 100 kA with fast rising in front time and slowly decaying in tail time [2], [3] Design the protection system using mast was proposed in [4] to minimize the sum of the height of masts used. This may lead to minimize total cost of material. Petcharaks [5] proposed the lightning protection program to verify whether object in a substation was protected or not. However, only critical points were determined in [5].

Lightning protection zone by a mast is alike tent with cone shape. An object is safe if it is within the cone area and its height is lower than the roof of the comparable tent [1].

This paper proposes zone apportionment algorithms (ZAA) to apportion lightning protection zone depending on the influence of each mast. Then, each point of object is laid out with its height. The critical height at each point is calculated. Finally, every point of object is determined whether it is protected or not, and a three dimension protection volume is created.

2. Problem formulation

Lightning may strike to ground or object or mast as shown in Figure 1. Many electrogeometric models (EM) of the last step of lightning strike are developed and proposed by many researchers. The corresponding lightning distance equations (1) - (3) which represent the striking distance to ground (r_g), object (r_c) and mast (r_s), respectively [1] They depend on lightning current, I in kA [1] It is recommended to use 5 kA when system voltage is less than 230 kV or 10 kA, otherwise [1] The value of parameters A, b, γ_c and γ_s are different in various models as shown in Table 1. The value of and in some EM models depends on the height of object, y and mast, h respectively.

$$r_g = A \cdot I^b \quad (1)$$

$$r_c = \gamma_c \cdot r_g \quad (2)$$

$$r_s = \gamma_s \cdot r_g \quad (3)$$

Table 1 The value of parameters in (1) – (3)

EM model	Parameter A	b	γ_c	γ_s
Young	27	0.32	$\frac{444}{462-y}$ for y>18; 1 for y≤18	$\frac{444}{462-h}$ for h>18; or 1 for h≤18
Brown-White head	6.4	0.75	$1+\frac{y-18}{108}$ for y>18; or 1 for y≤18	$1+\frac{h-18}{108}$ for h>18; or 1 for h≤18
Love	10	0.65	1	1
IEEE - 1995	8	0.65	1	1

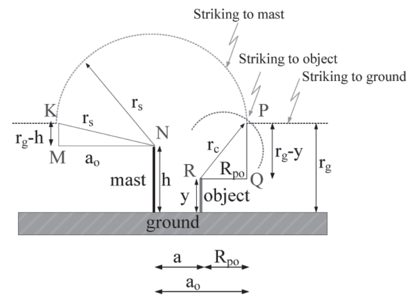


Figure 1 Lightning striking distance to ground, object and mast.

2.1 Protection zone generated by one mast

A mast generates a protection volume in a cone shape shown in Figure 2. A protected object must be covered beneath the cone.

Geometric model in Figure 1 creates the relationship of the mast height, object height, and object location. Variables are obtained by employing Pythagoras.From the right triangle, KMNon the left side in Figure 1, the radius of the protection zone, a_o can be calculated from (4).The distance R_{po} is obtained from (5). From the right triangle, PQR on the right side in Figure 1, the relationship of parameters is calculated from (6). An object in the protection zone is protected against lightning if it is lower than $y_{critical}$ in (7) rearranged from (6).

$$a_o = \sqrt{r_s^2 - (r_g - h)^2} \tag{4}$$

$$R_{po} = a_o - a \tag{5}$$

$$R_{po} = \sqrt{r_c^2 - (r_g - y)^2} \tag{6}$$

$$y_{critical} = r_g - \sqrt{r_c^2 - R_{po}^2} \tag{7}$$

$y_{critical}$: the maximum height of protected object (m)

a: the distance between mast and object (m)

a_o: the distance between mast and the boundary of the protection zone (m)

R_{po}: the distance between object and the boundary of the protection zone (m)

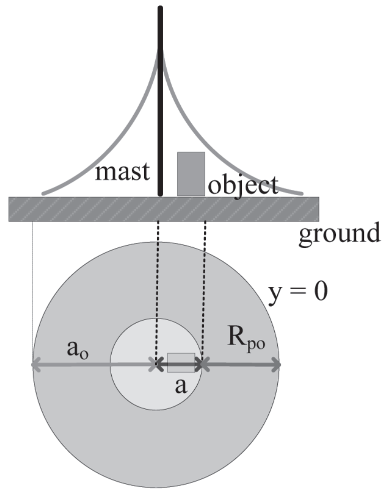


Figure 2 Protection zone generated by LPS using 1 mast.

2.2 Protection zone generated by two masts

The protection zone generated by each mast will intersect each other. The intersection points between r_g and lightning distance, r_s to mast 1, to mast 2 relocates the crucial point, P in Figure 1 to point A_1 in Figure 3.

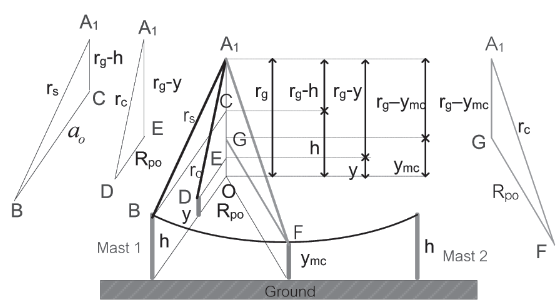


Figure 3 New intersection point in LPS using 2 masts.

This generates two right triangles A_1BC and A_1DE in Figure 3. From the relationship among sides of the triangle A_1BC, the distance a_o could be obtained from (4). Whereas, the relationship of parameterscould be obtained from (6) using the triangle A_1DE. The protection zone generated by two masts from top view is shown in Figure 4 R_{po} in the intersection zone $A_1C_1A_2C_2$ is the distance between an object and point A_1 or A_2, whichever is the shorter. This results in a longer

R_{po} than that of (5) Therefore, a protected object in the intersection zone $A_1C_1A_2C_2$ (zone A) could be higher than an object at the same distance from the mast in zone B, protection zone generated by one mast, within two circles but outside zone A shown in Figure 4.The intersection zone (zone A) depends on the distance between masts. The distance *d* could be computed from (8). A protected object at the middle point between masts is the highest one, y_{mc}, computed from (9) This occurs when R_{po} reaches $R_{po,\max}$ equaling to *d*. Consequently, longer R_{po} causes higher $y_{critical}$ in (7)

$$d = \sqrt{a_o^2 - \frac{D_{mast}^2}{4}} \quad (8)$$

$$y_{mc} = r_g - \sqrt{r_c^2 - d^2} \quad (9)$$

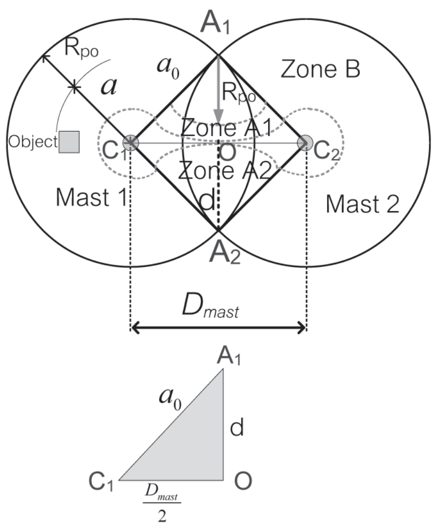


Figure 4 Protection zone generated by LPS using 2 masts.

2.3 Protection zone generated by three masts

The protection zone generated by three masts is shown in Figure 5-8. The intersection point of the lightning distance, r_s, to mast 1, 2 and 3 is located at point K shown in Figure 5. Whereas point O is the center point of the triangle which makes the distance between point O and any mast equivalent, R_c.This model generates two right triangles KLM and KPR. Pythagoras is applied to triangle KLM to obtain the distance KM, $\sqrt{r_s^2 - R_c^2}$. Then, the relationship among R_{po} and other parameters is produced in (11) employing Pythagoras to triangle KPR.

$$R_{po} = \sqrt{r_c^2 - [\sqrt{r_s^2 - R_c^2} + (h - y)]^2} \quad (10)$$

The protection zone is divided into three zones, zone A, zone B and zone C protected by three masts, two masts and one mast, respectively as shown in Figure 6. To apportion the areas protected by zone A and zone B in Figure 7, the relationship between

$$R_{pc} \left(= \sqrt{R_c^2 - \frac{D_{mast}^2}{4}}\right) \text{ and } R_{po} \left(= \sqrt{a_o^2 - \frac{D_{mast}^2}{4}}\right) \quad (11)$$

is formulated in (12) [6]. Then, iteration method is used to find $y_{criteria}$ in (13) developing from (12)

$$\sqrt{r_c^2 - ((h - y_{criteria}) + \sqrt{r_s^2 - R_c^2})^2} + \sqrt{r_c^2 - (r_g - y_{criteria})^2}$$

$$= \sqrt{R_c^2 - \frac{D_{mast}^2}{4}} + \sqrt{a_o^2 - \frac{D_{mast}^2}{4}}$$

$$y_{criteria}^{(k+1)} = h + \sqrt{r_s^2 - R_c^2} \quad (12)$$

$$-\sqrt{r_c^2 - [XX - \sqrt{r_c^2 - (r_g - y_{criteria}^{(k)})^2}]^2} \quad (13)$$

where $y_{criteria}^{(k)}$ is $y_{criteria}$ at iteration k^{th} ,

$$XX = \sqrt{R_c^2 - \frac{D_{mast}^2}{4}} + \sqrt{a_o^2 - \frac{D_{mast}^2}{4}} \quad (14)$$

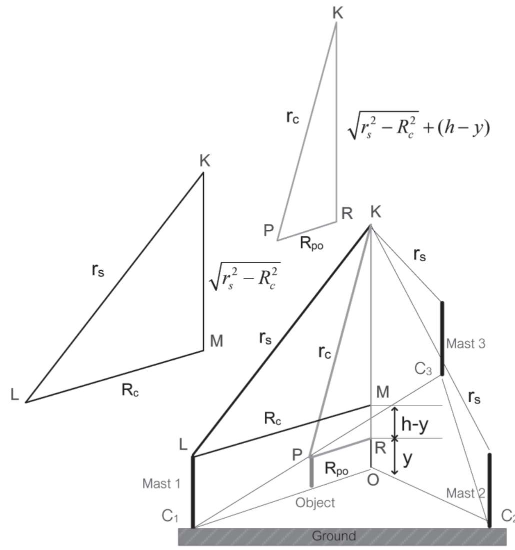


Figure 5 Intersection point, K existing in LPS using 3 masts.

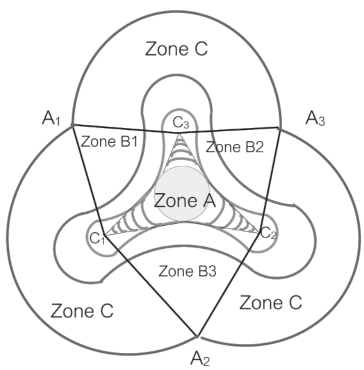


Figure 6 Protection zone generated by LPS using three masts.

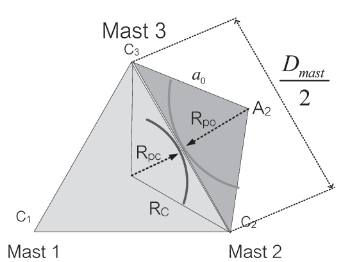


Figure 7 Apportioningzone A and zone B by LPS using three masts.

After $y_{criteria}^{(k)}$ converging to a final value, $y_{criteria}$ it will be used in (15) to find $R_{pc,\max}$ which is the maximum radius of the circle in the center of Figure 6 and 8. For an object in zone A, the distance from center point, O is defined as R_{pc}. Then, the maximum height of a protected object at each point in zone A, $y_{critical}$ is calculated from (16). The corresponding shape of protection zone islikewisevalley basin shown in Figure 8. y_{mc} is the lowest height of the object at the center where y_n, y_p and y_q are the height of an object at the outer uphill circle inascending order. y_{mc} could be calculated from (16) by replacing $R_{pc} = 0$. For an object in zone B_i in Figure 6, the distance from an object to point A_i where i = 1 or 2 or 3, is defined as R_{po}. For an object in zone C, R_{po} represents the distance between object and the boundary of protection zone C. in zone B and zone C could be calculated from (7).

$$R_{pc,\max} = \sqrt{r_c^2 - ((h - y_{criteria}) + \sqrt{r_s^2 - R_c^2})^2} \quad (15)$$

$$y_{critical} = h - (\sqrt{r_c^2 - R_{pc}^2} - \sqrt{r_s^2 - R_c^2}) \quad (16)$$

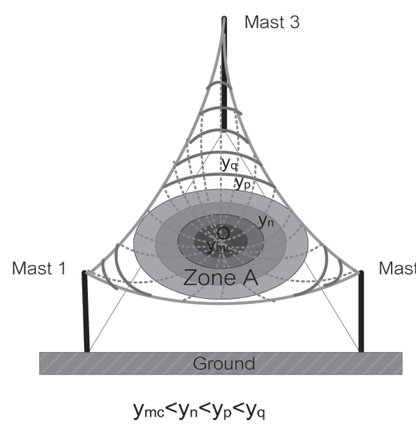


Figure 8 A likewise valley basin shape of protection zone A in LPS using 3 masts.

2.4 Protection zone generated by four masts

The protection zone generated by four masts is shown in Figure 9-11. The intersection point of the lightning distance, r_s, to mast 1, 2, 3 and 4 is located at point K shown in Figure 9. The protection zone is divided into three zones, zone A, zone B and zone C protected by four masts, two masts and one mast, respectively, as shown in Figure 10. The calculation of zone apportionment algorithms is similar to that of three masts. Iteration process is first carried out to find , $y_{criteria}$ then it will be used in (15) to find $R_{pc,\max}$. The shape of protection zone, zone A is likewise valley basin shown in Figure 11.

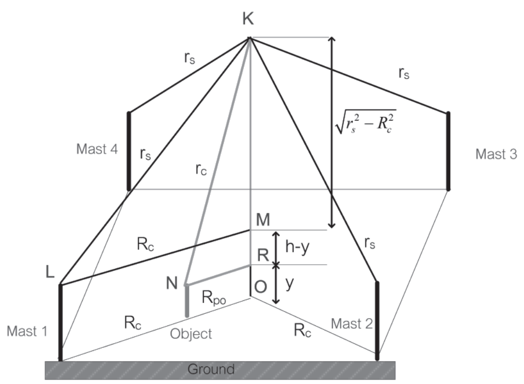


Figure 9 Intersection pointK existing in LPS using 4 masts.

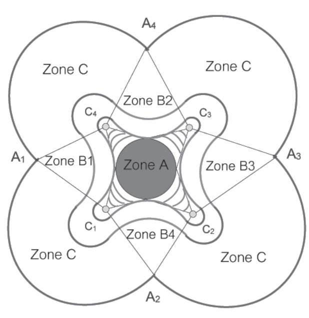


Figure 10 Protection zone generated by four masts

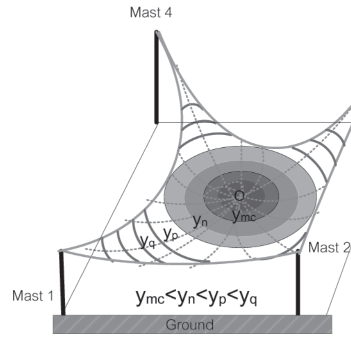


Figure 11 Valley shape protection zone by four masts.

3. Zone apportionment algorithms

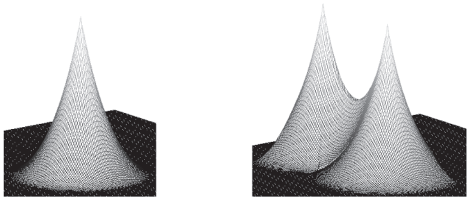
The zone apportionment algorithms (ZAA) specifies the lightning protection zone corresponding the influence of mast(s). The critical height, $y_{critical}$ at each point in each protection zone is calculated. ZAA is applied to LPS using one mast or two masts or three masts or four masts.

3.1 ZAA for LPS using one mast

The protection zone generated by LPS using one mast is a cone shape shown in Figure 12 (a). First, a_o is calculated from (4). Knowing a_o and the location of each point of equipment, a, the value of R_{po} is obtained from (5) Equipment are safe if the height of equipment at each point,*y*,is lower than $y_{critical}$ calculated from (7).

3.2 ZAA for LPS using two masts

The protection zone generated by two masts depends on the distance between masts shown in Figure 12 (b). The intersection of two protection cones generated by each mast results in moving intersection points between r_g and r_s to points A_1 and A_2 in Figure 4.Thus, the maximum height of a protected object in zone A is higher than that of zone B. The corresponding shape is shown in Figure 12 (b), the roof of the protection zone linking two cones is higher than the roof of a likewise tent of each cone.



(a) (b)

Figure 12 Protection zone generated by LPS using 1-2 mast(s).

ZAA for LPS using two masts in Figure 4, is described in the following steps.

Step 1 Obtain substation size and mast location, C_1, and C_2 in Figure 4.

Step 2 Calculate a_o from (4) and *d* from (8).

Step 3 Lay out substation border and locate A_1, A_2, C_1, and C_2 in Figure 4.

Step 4 Apportion zone A and zone B in Figure 4.

Step 5 Calculate the protection height at each point. In zone A1 or A2, R_{po} is the distance from the considered point to point A_1 or A_2, whichever is the shorter. Otherwise, is obtained from (5).

Step 6 Lay out each point of equipment and its height in the substation.

Step 7 Compare the height of equipment, *y* with the corresponding $y_{critical}$. Equipment are safe if equipment height, *y*, at every point is lower than $y_{critical}$ calculated from (7).

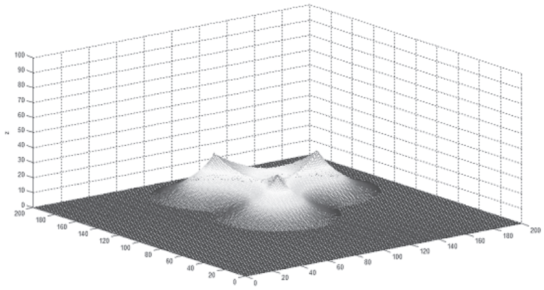


Figure 13 Protection zone generated by LPS using 3 masts.

3.3 ZAA for LPS using three masts

The protection zone generated by LPS using three mast is shown in Figure 6 and 13. Protection zone in Figure 6, zone A in the center is a likewise valley basin shape with three hilltops. Linking protection zones between two cones are zone B. Whereas the outer individual cone generated by each mast are zone C.

ZAA for LPS using three masts in Figure 6 and 13, is described in the following steps.

Step 1 Obtain substation size and mast location, C_1, C_2, and C_3 in Figure 6.

Step 2 Calculate a_o from (4). Compute R_c and locate point O in Figure 5. Calculate $y_{criteria}$ from (13) and $R_{pc,\max}$ from (15).

Step 3 Lay out substation border and locate point A_1, A_2, A_3, C_1, C_2, and C_3.

Step 4 Apportion zone A, B_1, B_2 B_3 and C.

Step 5 Calculate the protection height at each point. In zone A, the distance from point O to the considered point, R_{pc} is used to calculate $y_{critical}$ in (16).

Step 6 In zone B_1 or B_2 or B_3. R_{po} is the distance from the considered point to point A_1 or A_2 or A_3. In zone C, R_{po} is obtained from (5). If R_{po} is larger than a_o, $y_{critical} = 0$, otherwise $y_{critical}$ is calculated from (7).

Step 7 Lay out each point of equipment and its height in the substation.

Step 8 Compare the height of equipment, y with the corresponding $y_{critical}$. Equipment are safe if equipment height, *y*, at every point is lower than $y_{critical}$.

3.4 ZAA for LPS using four masts

The protection zone generated by four mastsis shown in Figure 14. Protection zones are similar to those of three masts, zone A existing in the center is a likewise valley basin shape with fourhilltops. ZAA for LPS using four masts in Figure 10 and 14, is similar to that of LPS using three mast, but some changes are needed: mast location C_i, point A_i location and zone B_i, i = 1,..,4.

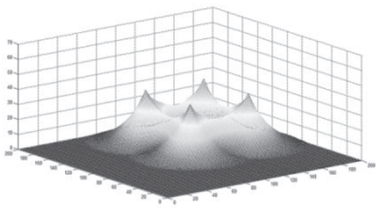


Figure 14 Protection zone generated by LPS using four masts.

4. Numerical results

The algorithms are tested on a 30 m x 30 m substation with location (0,0), (30,0), (30,30) and (0,30). Equipment are protected by mast(s) located outside the border of the substation shown in Table 2 and Figure 15. There are3 cases in Table 3, group of equipment located in the center of the substation. It is modified from[1], [5]. The lightning current is 10 kA. Young's equation is used to determined striking distances,

$$r_g = 27 \cdot 10^{0.32} = 56.41 \text{ m}, r_g = 56.41 \text{ m}.$$

Numerical results for all cases are shown in Table 4.In case A, all points of equipment are protected. In case B, Equipment are protected only in case of using 3 and 4 masts. In case C, equipment are not protected in all cases.

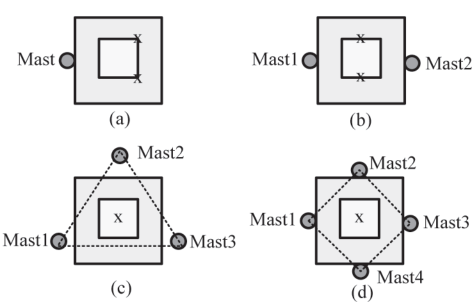


Figure 15 LPS using 1 – 4 mast(s).

Table 2 Lightning protection system using mast

Number of mast(s)	Mast Height (m)	MastLocation	D_{mast} (m)
1	32	(0, 15)	-
2	17	(0,15), (30,15)	30.00
3	14	(-2.5,4.89),(32.5,4.89) (15, 35.21)	35.00
4	13	(0,15),(15,0), (30,15), (15,30)	21.21

For LPS using one mast with 32 m height, the corresponding variables are following: r_s = 58.25 m, a_o = 52.89 m, R_{po} = 32.27 m.The part of equipment closer to mastoccupies higher $y_{critical}$. Thus, the farthest corner of equipment, point x in Figure 15 (a), occupies the lowest $y_{critical}$. Equipment with size 10 m x 10 m must be lower than 10.14 m whereas equipment with size 12 m x 12 m must be lower than 9.31 m. If equipment are 12 m high, their size must not be larger than 5 m x 5 m. Thus, equipment in case B and case C are not protected if using one mast as shown in Figure 16,the risk part emerges above the cone.

For LPS using two masts with 17 m height each, the corresponding variables are following: r_s = 56.41 m, a_o = 40.36 m, d = 37.37 m and R_{po} = 32.47 m. Equipment in all cases are in zone A of Figure 4. The part closer to the center of substation occupies higher $y_{critical}$. Thus, the middle points of the edge of equipment, point x in Figure 15 (b), occupy the lowest $y_{critical}$. Equipment with size 10 m x 10 m must be lower than 10.28 m whereas equipment with size 12 m x 12 m must be lower than 9.59 m. Thus, equipment in case B and case C are not protected in case of using two masts. If equipment are 12 m high, their size must not be larger than 5.3 m x 5.3 m.

Table 3 Cases used in numerical results

	Size of group of equipment(m x m)	Equipment Height(m)
Case A	10 x 10	10
Case B	12 x 12	10
Case C	10 x 10	12

Table 4 Numerical results of case A, B and C

$y_{critical}$ at point x in Fig. 15		Number of Mast(s)			
		1	2	3	4
Case A	$y_{critical}$ (m)	10.14	10.28	10.26	10.97
	Equipment	Safe	Safe	Safe	Safe
Case B	$y_{critical}$ (m)	9.31	9.59	10.26	10.97
	Equipment	Unsafe	Unsafe	Safe	Safe
Case C	$y_{critical}$ (m)	10.14	10.28	10.26	10.97
	Equipment	Unsafe	Unsafe	Unsafe	Unsafe

For LPS using three masts with 14 m height each, the corresponding variables are following: r_s = 56.41 m and a_o = 37.20 m. Equipment in all cases are in zone A in Figure 6.The center of masts (point O in Figure 5) is located at the center of substation resulting in R_c = 20.21 m, $R_{pc,\max}$ = 9.13 m. The part of equipment at the center of substation is the critical point with lowest $y_{critical}$ of 10.26 m. Whereas, the corner parts located further from the center occupy the highest $y_{critical}$ i.e. 10.70 m for case A and case C, and 10.90 m for case B. Thus, equipment in case C are not protected.

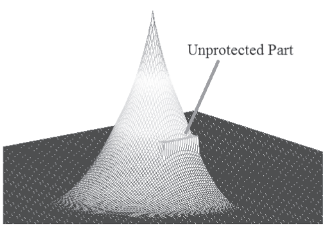


Figure 16 Unprotected part of equipment emerging above a likewise protection roof generated by 1 mast

For LPS using four masts with 13 m height each, the corresponding variables are following: r_s = 56.41 m, and a_o = 36.02 m. Equipment in all cases are in zone A in Figure 10. The center of masts (point O in Figure 9) is located at the center of substation resulting in R_c = 15 m, $R_{pc,\max}$ = 10.53 m. The part of equipment at the center of substation is the critical point with lowest $y_{critical}$ of 10.97 m. Whereas, the corner parts located further from the center occupy the highest $y_{critical}$ i.e. 11.41 m for case A and case C, and 11.61 m for case B. Thus, All parts of equipment in case C are not protected and emerge above the likewise protection roof shown in Figure 17.

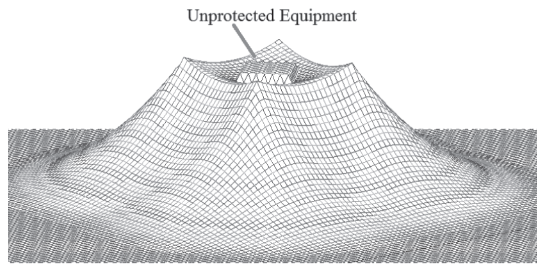


Figure 17 Unprotected object emerging above a likewise protection roof generated by 4 masts.

5. Conclusion

The proposed algorithms, ZAA can be used to apportion the protection zone in three dimensions and verify whether the object is protected or not. This could help engineers to ensure that equipment are protected against lightning. The unprotected part will emerge above the likewise protection roof and be visualized clearly. Numerical results indicate that ZAA could be used correctly and effectively.

6. References

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