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Lightning protection zones in substation using shield wires

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Abstract

Lightning protection system in substation may employ mast, shield wire or both. Calculation of lightning protection zone (LPZ) is based on striking distance to ground, object and mast or shield wires. LPZ generated by mast looks like a tent and is different from that of shield wire. Equipment in substation is safe if it is covered by LPZ. Calculation of the LPZ is complicated especially when there are more masts or parallel/convergence shield wires making it more difficult to picture LPZ. This paper proposes Zone Apportionment Algorithm (ZAA) to apportion the LPZ into two zones corresponding to mast and shield wire, and further sub-apportion in two zones corresponding to non-overlapped and overlapped zones. The maximum height of protected equipment at each point in substation is then calculated. Integrating all points, results in a visual roof representing the LPZ. Equipment with its size and height is then laid in substation. If there is an emerging part above the visual roof, it displays the part that may encounter lightning strikes. ZAA is tested on five cases: one shield wire, two to three parallel shield wires and two to three convergence shield wires. Numerical results show that ZAA can produce visual LPZ correctly in all cases and illustrate verification of protection.

Keywords: *lightning protection zone, mast, shield wire, striking distance*

บทคัดย่อ

ระบบป้องกันฟ้าผ่าในสถานีไฟฟ้าอาจใช้เสา สายชีลด์ หรือทั้งสองอย่าง โซนป้องกันฟ้าผ่าจะมีลักษณะคล้ายหลังคาบังแดดเช่นเดียวกับเต้นท์แต่มีรูปร่างแตกต่างกันระหว่างโซนป้องกันของเสากับสายชีลด์ อุปกรณ์ภายในสถานีไฟฟ้าจะปลอดภัยถ้าถูกปกคลุมด้วยหลังคาของโซนป้องกัน ซึ่งไม่สามารถเห็นได้ด้วยตาเปล่าต้องใช้การคำนวณและจินตนาการ การคำนวณโซนป้องกันจะใช้ข้อมูลระยะช่วงก้าวฟ้าผ่าลงดิน ลงวัตถุหรืออุปกรณ์ และลงเสาหรือสายชีลด์ ซึ่งค่อนข้างซับซ้อนโดยเฉพาะอย่างยิ่งเมื่อมีจำนวนเสาเพิ่มขึ้น หรือมีจำนวนสายชีลด์แบบขนานหรือแบบบรรจบมากขึ้น เป็นการยากที่จะใช้การจินตนาการเพียงอย่างเดียว บทความนี้นำเสนอวิธีแบ่งจัดโซน (Zone Apportionment Algorithm, ZAA) ทำการจัดแบ่งเป็น 2 โซน โซนที่เกิดจากเสาและที่เกิดจากสายชีลด์ และแบ่งย่อยลงไปอีก 2 โซน ตามโซนที่เกิดและไม่เกิดการทับซ้อนของโซนป้องกัน แล้วคำนวณค่าสูงสุดของอุปกรณ์ที่ได้รับการป้องกัน ณ แต่ละจุดในโซนป้องกัน นำแต่ละจุดมาเชื่อมต่อเข้าด้วยกันจะได้หลังคาของโซนป้องกัน จากนั้นก็เอาอุปกรณ์ทั้งขนาดและความสูงวางทับลงในแปลนของสถานีไฟฟ้าย่อย หากมีส่วนใดส่วนหนึ่งโผล่เหนือหลังคาของโซนป้องกัน ส่วนนั้นจะเป็นส่วนที่เสี่ยงต่อฟ้าผ่า มีการทดสอบ ZAA ทั้งหมด 5 กรณี กรณีที่มีสายชีลด์เส้นเดียว กรณีที่มีสายชีลด์ 2-3 เส้นแบบขนานกัน และกรณีที่มีสายชีลด์ 2-3 เส้นแบบบรรจบกัน ผลการทดสอบแสดงให้เห็นว่า ZAA สามารถใช้สร้างภาพของโซนป้องกันได้ถูกต้องในทุกกรณีและสามารถตรวจสอบว่าอุปกรณ์ในสถานีไฟฟ้าได้รับการป้องกันหรือไม่อย่างชัดเจน

คำสำคัญ: *โซนป้องกันฟ้าผ่า, เสา, สายชีลด์, ระยะช่วงก้าวฟ้าผ่า*

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1. Introduction

Lightning protection system (LPS) is designed to protect equipment in substation against lightning strikes. The LPS may employ mast, shield wire or both. Mast generates a lightning protection zone like a cone shaped tent, whereas shield wire generates a triangular shaped tent. Equipment in substation is safe if it is lower than the virtual tent roof. Calculation protection zone from mast is complicated. It is more difficult when more masts are used. Thus, Zone Apportionment Algorithms (ZAA) was proposed by Petcharaks (2013). Verification whether an object in substation using 1-4 mast(s) is protected or not, was proposed by Petcharaks (2012a). Determination whether equipment is protected against lightning strikes, can be carried out by identifying the critical points and calculating the corresponding critical height. If the equipment height is higher than the critical height, it will protrude above the LPZ roof and be the risk part.

LPS is designed based on the lightning distances to ground, mast and object (Hileman, 1999). The background and experience of parameters of lightning current was presented (Heidler, Zischank, Flisowski, Bouquegneau, & Mazzetti, 2008). An algorithm to design lightning protection generated by masts was proposed to minimize total length of masts (Le Viet & Petcharaks, 2010). Lightning protection can be also designed by rolling sphere method (Crispino, 2007) which requires many more parameters such as surge impedance, basic insulation level (BIL), etc.

This paper intends to calculate the LPZ generated by shield wires. However, shield wire uses masts as their poles. Thus, protection zones generated by shield wires and masts must be combined. This results in a sophisticated calculation. This paper proposes ZAA to create a three dimension visual roof generated by shield wire(s) and masts. Equipment is then laid in substation under the virtual roof. If any part emerges above the tent, it will risk being subjected to lightning strike. The correction of the generated LPZ is carried out by comparing the height of protruding part above the roof with the corresponding critical height.

2. Objectives

The objectives of this paper are to create a visual LPZ generated by shield wire(s) in a substation and to verify whether equipment in substation is protected or not. This paper employs ZAA with LPS using any number of shield wires both in parallel and convergence. Lightning magnitude is 10 kA. Young's equation is used. It is assumed that there is no shield wire sag.

3. Problem formulation

Lightning may strike to ground, mast or object depending on the height of mast, object, magnitude of lightning current, and object location. Electrogeometric striking distance models are proposed by many researchers. Young's equations are widely used (Le Viet & Petcharaks, 2010; Petcharaks, 2012a, 2012b; Petcharaks, 2013). The lightning striking distance to ground (r_g), to object (r_c), to masts (r_s) are determined by equations (1)-(3), respectively (Hileman, 1999). The parameter (γ_c) is obtained from (4) depending on the height of an object; whereas, the parameter (γ_s) is obtained from (5) depending on the height of masts and shield wires. These distances are shown in Figure 1.

$$r_g = 27I^{0.32} \tag{1}$$

$$r_c = \gamma_c r_g \tag{2}$$

$$r_s = \gamma_s r_g \tag{3}$$

$$\gamma_c = \frac{444}{462 - y} \quad \textit{for } y \geq 18 \text{, otherwise } \gamma_c = 1 \tag{4}$$

$$\gamma_s = \frac{444}{462 - h} \quad \textit{for } h \geq 18 \text{, otherwise } \gamma_s = 1 \tag{5}$$

Lightning protection zone (LPZ) looks like a tent shape. The height of any part of an object within substation must not be higher than y_{max} in Figure 1. The value of y_{max} at each location is different depending on the distance from mast or shield wires. The protection zones are divided into two zones, zone A and zone B corresponding to mast and shield wire, respectively.

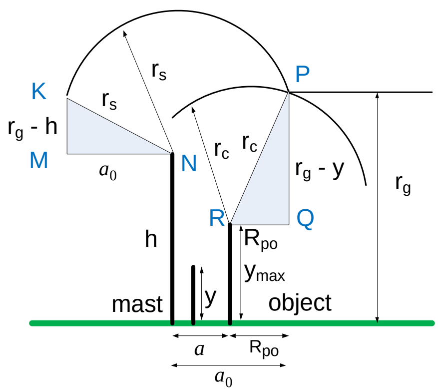

Figure 1 Lightning striking distance to ground, object and mast

3.1 Protection zone generated by mast (s)

3.1.1 One mast

The protection zone radius (a_o) is determined from triangle KMN in Figure 1 and calculated in (6). An object with height, $y_{\max}$ is located at distance, a from mast. The distance, R_{po} is determined from right triangle PQR in Figure 1 and calculated in (7) and (8). The value of y_{max} is calculated in (9).

$$a_o = \sqrt{r_s^2 - (r_g - h)^2} \tag{6}$$

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

$$R_{po} = a_o - a \tag{8}$$

$$y_{\max} = r_g - \sqrt{r_c^2 - (a_o - a)^2} \tag{9}$$

3.1.2 Two masts

LPZ generated by two masts is shown in Figure 2 (Petcharaks, 2012a), when masts are so close that the protection radius, a_0, from each mast, intersects each other. The protection zone is subdivided into two zones, zone A1 and A2. Zone A1 is protected by one mast, whereas zone A2 is an overlapped zone protected by two masts. Calculation LPZ in zone A2 is more complicated. Distance d in Figure 2 is calculated from (10), whereas distance R_{po} in zone A2 is the distance from the intersection point between two circles to object location as shown in Figure 2. More complicated geometry is used to find R_{po}. The value of y_{max} is calculated in (11).

$$d = \sqrt{a_0^2 - \frac{D_{mast}^2}{4}} \qquad (10)$$

$$y_{max} = r_g - \sqrt{r_c^2 - R_{po}^2} \qquad (11)$$

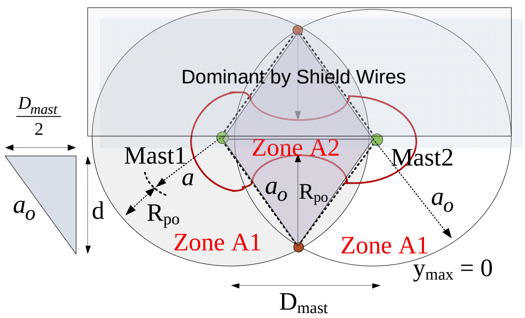

Figure 2 LPZ generated by two masts

3.2 Protection zone generated by shield wires

3.2.1 Two parallel shield wires

LPZ generated by two shield wires in case of remote distance is shown in Figure 3. An object is protected provided that it is covered by the virtual protection roof. Using Pythagoras in triangle HIJ and HPQ in Figure 4, relationships among parameters are obtained and identical to equation (6)-(8). The value of y_{max} is calculated in (12). LPZ between two wires in this case, is identical to the outside area because the distance between masts is so far that LPZ from each wire does not overlap.

$$y_{max} = r_g - \sqrt{r_c^2 - (a_0 - a)^2} \qquad (12)$$

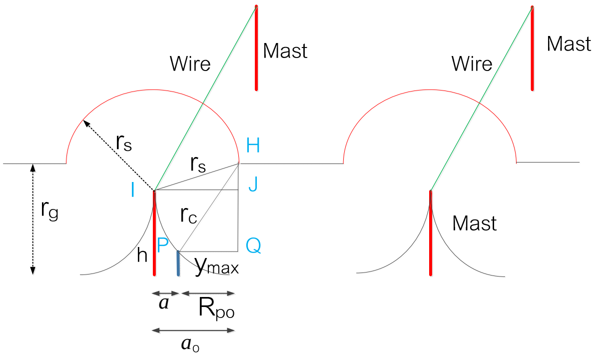

Figure 3 LPZ generated by two remote shield wires

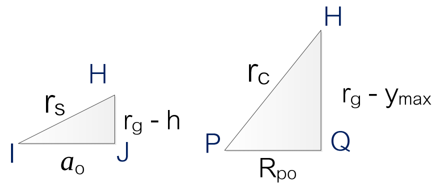

Figure 4 Geometry right triangles from Figure 3

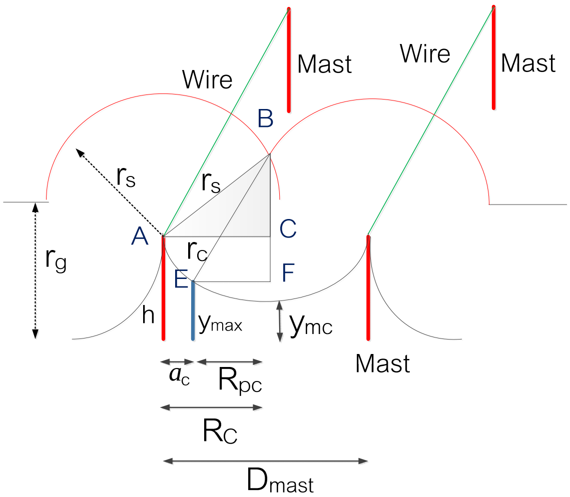

Figure 5 LPZ generated by two adjacent shield wires

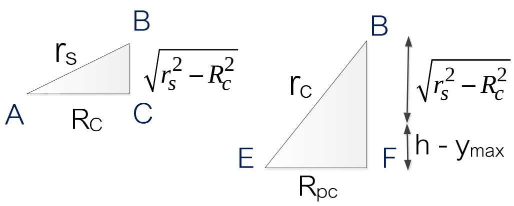

Figure 6 Geometry right triangles from Figure 5

In case of close wires, the striking distance to each mast intersects each other at point B in Figure 5. Shield wires are so close that their protection zones overlap. LPZ roof between masts are lifted up. The minimum height of an object protected in this zone (y_{mc}) is at the midpoint. The LPZ is subdivided into two zones, zone B1 and zone B2. Zone B1 is lightning protection zones outside wires on the left and right, and identical to that of one shield wire. Zone B2 is zone between wires. Using Pythagoras in triangle ABC in Figure 6, the height BC is obtained, $\sqrt{r_s^2 - R_C^2}$, where R_C is half of distance between wires. Using Pythagoras in triangle BEF, relationship among parameters is obtained from (13). Distance R_{pc}, is calculated from (14). The value of y_{max} is calculated from (15), where a_c is the shortest distance between object and shield wire.

$$R_{pc}^2 = r_c^2 - [(h - y) + \sqrt{r_s^2 - R_C^2}]^2 \qquad (13)$$

$$R_{pc} = a_0 - a_c \qquad (14)$$

$$y_{\max} = h + \sqrt{r_s^2 - R_C^2} - \sqrt{r_c^2 - R_{pc}^2} \qquad (15)$$

3.2.2 Two convergent shield wires

Shield wires need not be placed in parallel. They can be placed like a triangle as shown in Figure 7. LPZ between two masts is identical to two shield parallel wires. Then, LPZ area is reduced whereas the virtual roof is higher when the two wires get closer. The meeting point is the highest virtual roof.

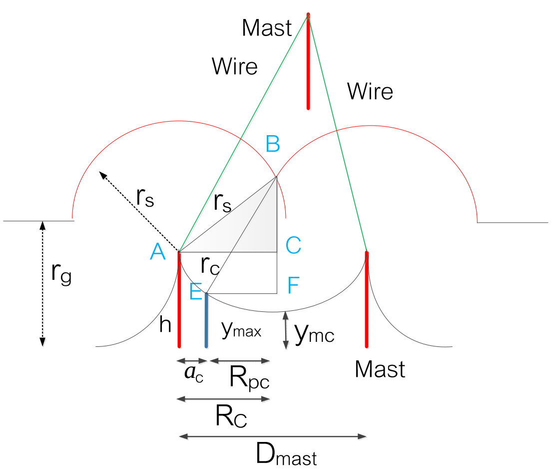

Figure 7 Two convergence shield wires

4. Methodology

First, ZAA is employed to define LPZ, A1, A2, B1, B2. Then, y_{max} at each point in each zone is calculated and drawn in a visual shape.

4.1 Two parallel shield wires

Two parallel shield wires generate the LPZ depending on the distance between the wires shown in Figure 8-10. When parallel shield wires are very close, the roof of LPZ zone B2 is quite high as shown in Figure 9. When parallel shield wires are located farther, the roof of LPZ in zone B2 is lower as shown in Figure 10. In case of far parallel shield wires, there is only LPZ zone B1 because LPZ between wires is not influenced by the overlapped LPZ.

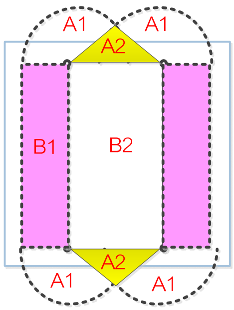

Figure 8 LPZ generated by two adjacent parallel shield wires

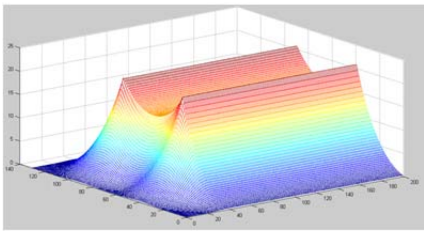

Figure 9 Virtual LPZ generated by two adjacent parallel shiel wires

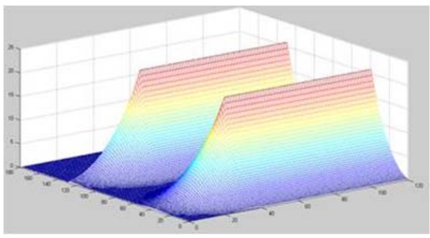

Figure 10 Virtual LPZ generated by two remote parallel shield wires

4.2 Three parallel shield wires

For a large substation, more shield wires are used. LPZ generated by the three shield wires, compose of four subzones: A1, A2, B1 and B2, shown in Figure 11. The corresponding visual LPZ is shown in Figure 12 in the case of close shield wires. If the distance between the shield wires is so far that there is no overlapping zone. The LPZ for each shield wire will look like the LPZ generated from one shield wire.

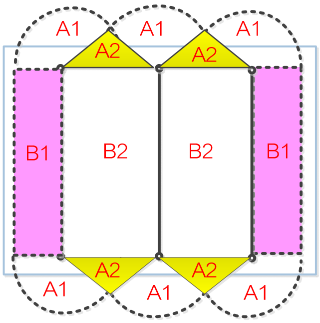

Figure 11 LPZ generated by three parallel shield wires in case of close shield wires

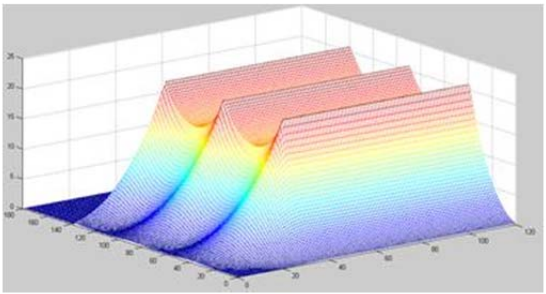

Figure 12 Virtual LPZ generated by three parallel close shield wires

4.3 Two convergence shield wires

Two convergence shield wires generate LPZ zones as shown in Figure 13. The visual LPZ is shown in Figure 14 in the case of closed shield wires. The LPZ area is reduced as the shield wires move from the starting masts to the ending mast.

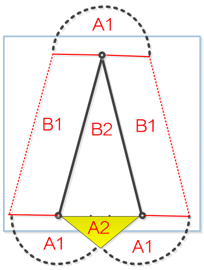

Figure 13 LPZ generated by two convergence shield wires

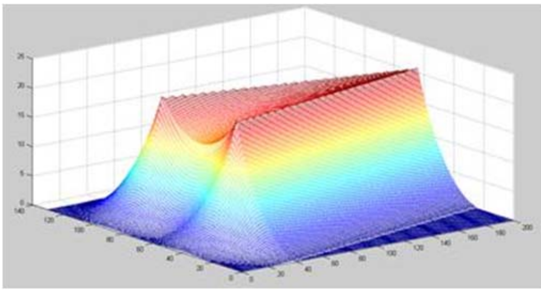

Figure 14 Virtual LPZ generated by two convergence shield wires

4.4 Three convergence shield wires

The three convergence shield wires generate LPZ zones shown in Figure 15. The visual LPZ is shown in Figure 16 in case of close shield wires at the beginning. LPZ area is reduced along the way to the end mast.

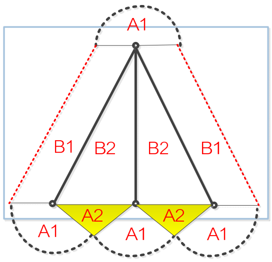

Figure 15 LPZ generated by three convergence shield wires

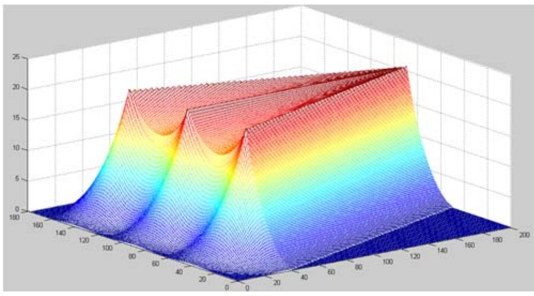

Figure 16 Virtual LPZ generated by three convergence shield wires

5. Numerical results

ZAA is tested on 5 cases, one shield wire, two and three parallel shield wires, two and three convergence shield wires. These cases are modified from (Petcharaks, 2012a). Mast height is 20.3 m. Lightning current is 10 kA. Thus, striking distance to ground (r_g) is 56.4 m. Since mast height is higher than 20 m, the parameters γ_s is calculated from (5), whereas γ_c is calculated from (4) depending on the object height. The obtained value of γ_s is 1.0052. Striking distance to mast (r_s) is 56.69 m obtained from (3). In each case, LPZ is generated, the critical height at the critical points is calculated (Petcharaks, 2012a) and compared with the protruding part in each LPZ. Thus, it is verified the correction of the generated LPZ.

Case A: One shield wire with two masts is used in a substation 80 m wide and 120 m long. Masts are located inside substation 10 m from the left and right fence, and 40 m from the top and bottom fence. Equipment with size 20 m x 20 m and 15 m high, is located under the shield wire as shown in Figure 17. Striking distance to object, (r_c) is 56.4 m obtained from (2) since object height is lower than 18 m, $\gamma_c = 1$. The part of equipment emerges above the visual roof of LPZ shown in Figure 18. Thus, LPZ cannot protect the whole equipment. The critical height of equipment at the critical points must be less than 11.18 m (Petcharaks, 2012a). To improve LPZ, more or higher shield wire is needed.

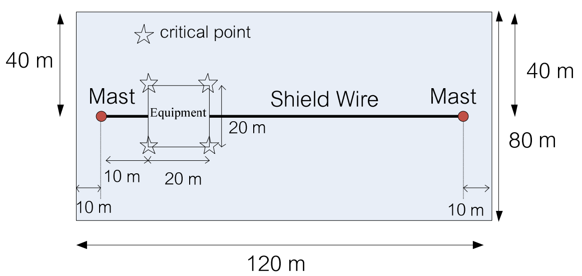

Figure 17 Case A, one shield wire

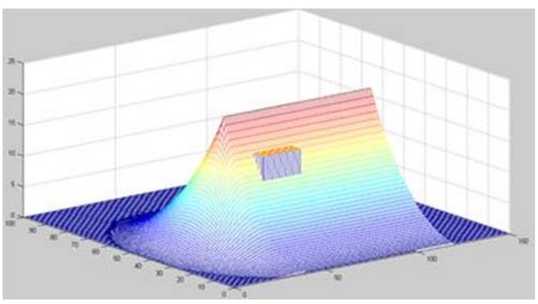

Figure 18 Case A, one shield wire, the equipment height is 15 m, the critical height is 11.8 m.

Case B: Two parallel shield wires with four masts are used in a substation 170 m wide and 200 m long. Masts are located along with the length of substation, inside substation 10 m from the left and right fence, and 40 m from the top and bottom fence. Equipment with size 50 m x 20 m and 14 m high, is located between shield wires as shown in Figure 19.

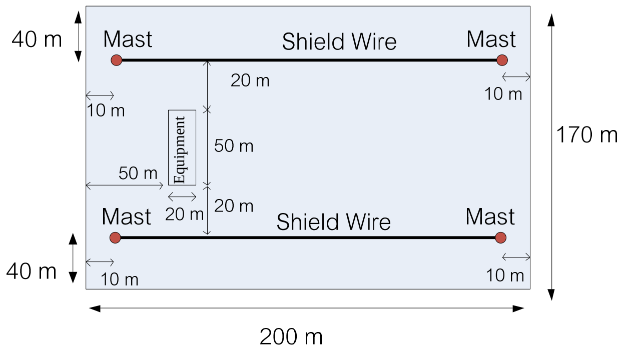

Figure 19 Case B, two parallel shield wires

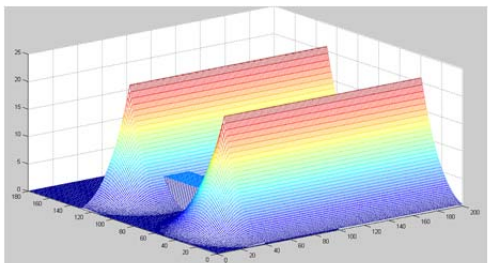

Figure 20 Case B, LPZ generated by two parallel distant shield wires, the equipment height is 14 m, the critical height is zero.

The corresponding visual LPZ is shown in Figure 20. LPZ does not cover whole equipment since distance between shield wires is so far that the LPZ roof in zone A2 and zone B2 touches earth. It means that there is no protection in this area. If shield wires are located close to each other, 50 m instead of 90 m, LPZ roof is higher and the area between wires is an overlapped zone, defined as B2. This results in a much higher roof and the whole equipment is covered and protected. Thus, no part of the equipment is above the LPZ roof. The critical point is at the center of the object. The height of protected equipment at the critical point must be less than 14.78 m (Petcharaks, 2012a). The visual LPZ looks like Figure 9. If the equipment is higher than the

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critical height i.e. 16.5 m, the protruding part appears above LPZ roof as shown in Figure 21.

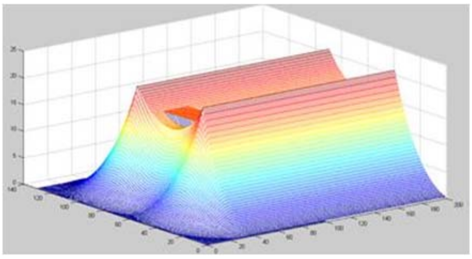

Figure 21 Case B, LPZ generated by two parallel adjacent shield wires, the equipment height is 16.5 m, the critical height is 14.78 m.

Case C: Three parallel shield wires with six masts are used in a substation 180 m wide and 200 m long. Shield wires are located along with the length of substation, whereas masts are located inside substation 10 m from the left and right fence, and 40 m from the top and bottom fence. Distance between masts is 50 m. Equipment with size 120 m x 20 m and 17 m high, is located under shield wires as shown in Figure 22. Protruding part of equipment is shown in Figure 23. Thus, equipment is not safe. In this case, there are six critical points. The critical height at C_2 is 14.78 m whereas that of C_1 is 11.18 m (Petcharaks, 2012a). Thus, equipment must not be higher than 11.18 m.

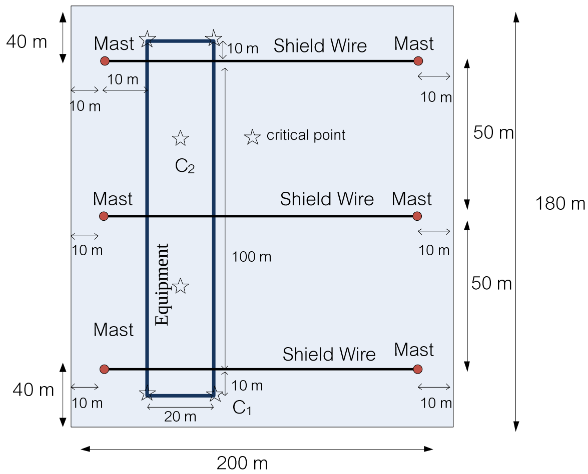

Figure 22 Case C, three parallel shield wires

Case D: Two convergence shield wires with three masts are used in a substation 130 m wide and 180 m long. Masts are located inside substation as shown in Figure 24. Distance between masts is 50 m. Equipment with size 70 m x 20 m and 10 m high, is located between shield wires as shown in Figure 24. There is a risk part of equipment emerging above the visual roof as shown in Figure 25. The critical height at the critical points is 8.04 m (Petcharaks, 2012a). Thus, equipment in this case must not be higher than 8.04 m.

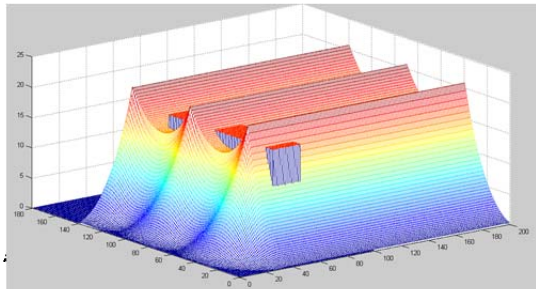

Figure 23 Case C, LPZ generated by three parallel shield wires, the equipment height is 17 m, the critical height is 11.18 m.

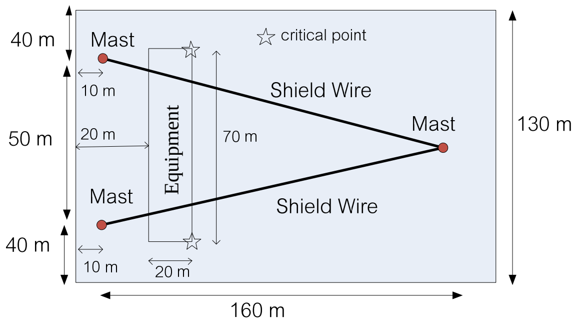

Figure 24 Case D, two convergence shield wires

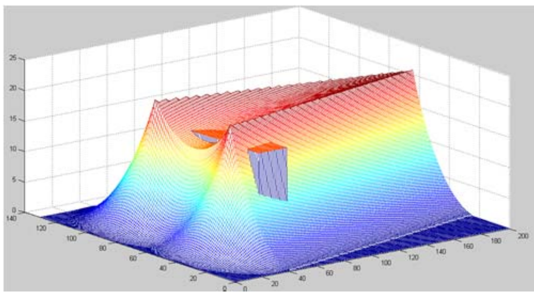

Figure 25 Case D, LPZ generated by two convergence shield wires, the equipment height is 10 m, the critical height is 8.04 m.

Case E: Three convergence shield wires with four masts are used in a substation 180 m wide and 200 m long. Masts are located inside substation as shown in Figure 26. Distance between masts is 50 m. The length of the center mast is 160 m.

Equipment with size 80 m x 50 m and 13 m high, is located under the shield wires as shown in Figure 26.

The exposed part of equipment emerges above the visual roof as shown in Figure 27. The critical height is 12.14 m (Petcharaks, 2012a). Equipment in this case must be moved forward to the left by 10 m so that the whole part will be covered. The new critical height will be 14.8 m (Petcharaks, 2012a). However, if the height of equipment in the new location is higher than 14.80 m i.e. 16 m, it will emerge above the LPZ roof as shown in Figure 28.

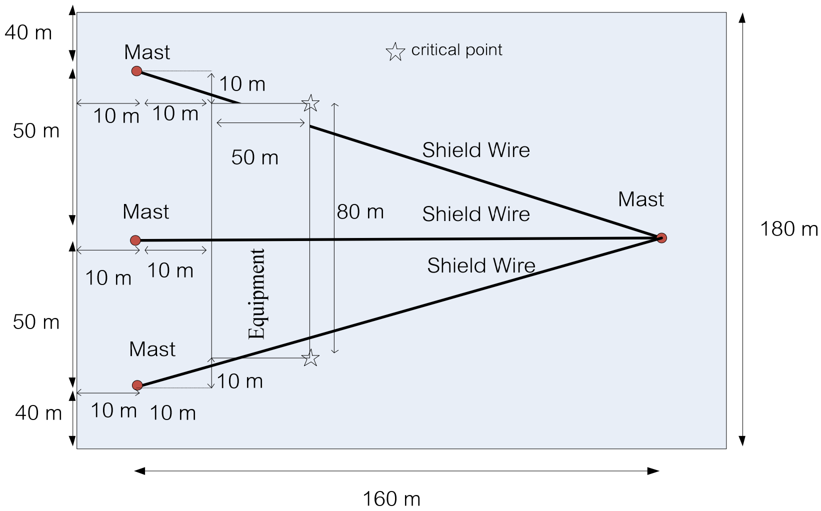

Figure 26 Case E: Three convergence shield wires

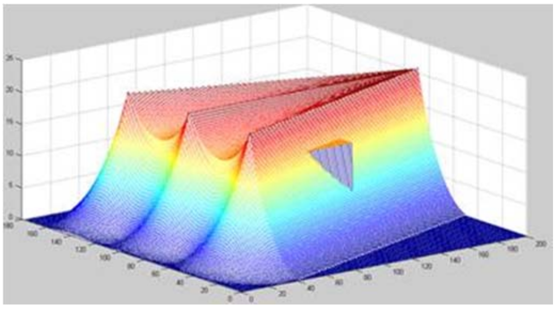

Figure 27 Case E: Three convergence shield wires, in case that the equipment height is 13 m, the critical height is 12.14 m.

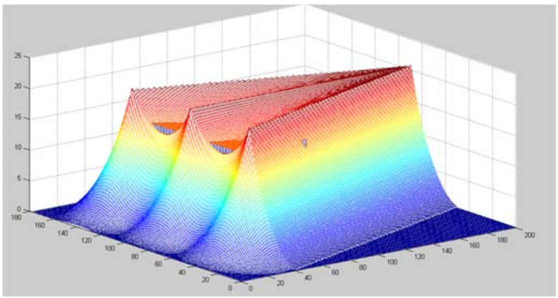

Figure 28 Case E: Three convergence shield wires, in case that equipment is moved forward by 10 m and the equipment height is 16 m, the critical height is 14.80 m.

6. Discussion

Lightning with a current magnitude of 10 kA is used in the paper. If the magnitude is higher, the striking distance will be longer. This will result in a higher visual roof which could be used to protect higher equipment. Thus, only magnitude 10 kA is applied. Equipment must not be higher than the LPZ roof. In addition, there should be some margin between shield wires and equipment. In the long term, wire sag or landslide may cause a lower virtual roof. This may result in an unprotected part of the equipment.

7. Conclusion

ZAA can be employed to build a visual roof representing LPZ in all cases properly and correctly. Verification of unprotected part in substation is shown obviously. This could help engineers to understand the complicated LPZ thoroughly and to locate equipment appropriately in case of replacing old ones.

8. References

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