International Journal of Engineering, Mathematical and Physical Sciences
ISSN: 2517-9934
Vol:4, No:5, 2010

Lightning Protection Systems Design for Substations by Using Masts and Matlab

Le Viet Dung and K. Petcharaks,
Department of Electrical Engineering, Chulalongkorn University,
254 Phayathai Road, Pathumwan, Bangkok, Thailand, 10330

Abstract—The economical criterion is accounted as the objective function to develop a computer program for designing lightning protection systems for substations by using masts and Matlab in this work. Masts are needed to be placed at desired locations; the program will then show mast heights whose sum is the smallest, i.e. satisfies the economical criterion. The program is helpful for engineers to quickly design a lightning protection system for a substation. To realize this work, methodology and limited conditions of the program, as well as an example of the program result, were described in this paper.

Keywords—lightning, protection, substation, computer.

I. Introduction

Lightning, a unpredictable, probabilistic phenomenon [1], can be the cause of severe failures in substations such as insulation flashover and damage of substation devices [2], as in [3], [4], [5]. Consequently, the power supply is interrupted; and economic losses are considerable [2]. Lightning protection systems for substations are therefore needed to minimize direct lightning strokes to equipment and buses within substations [1].

To protect a substation from lightning, there are three methods: using masts, using shielding wires, or using both of masts and shielding wires [1]. However, breakage of shielding wires (due to lightning current or poor maintenance) can cause catastrophic faults in substations. On the other hand, one more disadvantage of using shielding wires is high cost in comparison with the using of masts [6]. In addition, if the tip of mast is sufficiently small then the mast attracts lightning flashes more easily than the shielding wire [7]. Masts are thus preferred to shielding wires for lightning protection for substations.

In addition, the model, which should be applied for lightning protection, is electrogeometric model [1], [8], [9], with varied equations, such as Young's equations, IEEE-1992 equations, IEEE-1995 equations, CIGRE equations and Love's equations [6]. However, Love's equations were applied for this work because no modification is necessary in comparison with Young's equations, IEEE-1992 equations, and CIGRE equations [6]. Moreover, Love's equations and IEEE-1995 equations look like the same, but the value of the striking distances, i.e. the maximum mast height, is higher with Love's equations [6]; thus the using Love's equations is more favorable in the calculation.

However, an issue is considered: how to design a lightning protection system using masts within a short time. To solve this concern, this paper describes a computer program to design lightning protection systems using masts for substations. Matlab was applied to write the program.

On the other hand, a lightning protection system designed should has the cost as minimum as possible, as an objective [1]. Thus, this paper describes a manner to determine this objective via the sum of the mast heights calculated by the program. Also, some limited conditions, which are still existing in this program, are referred. By the way, an example is analyzed to realize how to use the program.

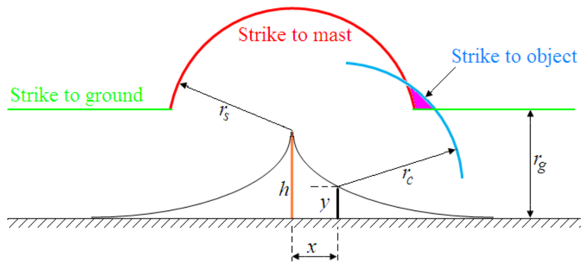

Fig. 1. Striking distances

II. Methodology

To protect a substation from lightning, we consider firstly three striking distances, as shown in Fig. 1: the striking distance to the shielding mast r_s, the striking distance to the object to be protected r_c, and the striking distance to ground r_g. This is, the lightning flash will strike to the mast, the object or ground due to the striking area, which is the area "strike to mast", the area "strike to object", or the area "strike to ground". [6], [10]

As was stated above, the electrogeometric model was applied and it provides some equations to determine the striking distances as the following

$$r_s = \gamma_s r_g \qquad r_c = \gamma_c r_g \tag{1}$$

where γ_s and γ_c are coefficients. [1], [6], [10]

Here, Love's equations were used

$$r_g = 10 \cdot I^{0.65} \tag{2}$$

$$\gamma_s = \gamma_c = 1 \tag{3}$$

where I is the design current in kA, r_s, r_c, and r_g are distances in meters. In a case of nominal system voltage < 230 kV, the

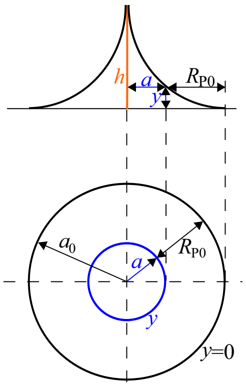

Fig. 2. Protective zone of a single mast

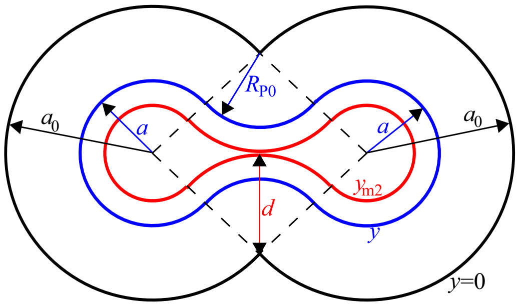

Fig. 3. Protective zone of two masts

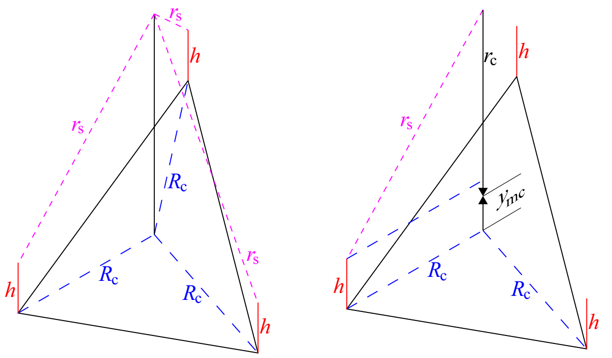

Fig. 4. Determinations of R_c and y_{mc}

design current is 5 kA. If nominal system voltage $\geq$ 230 kV, the design current is 10 kA. [1], [6], [10], [11]

In a substation, a height of a device can range between a height of a mast and zero. As the goal of the substation protection, the heights of the masts, as well as the locations of the masts, should be determined to protect properly for all devices within this range. This is, the protected zone of the masts should cover the devices as much as possible. To realize more about this concept, we consider the simplest case, one mast. Here, the protected zone of one mast is based on: the mast height of h and the object protected, which has a height of y and is located at a distance of x from the foot of the mast. From Fig. 1, the top of the object is not protected by the mast when lightning strike to the pink area. Thus, the object must be moved more closely to the mast in order to being protected by the mast. Assume that the distance now from the object to the mast is x_1. As a result, the protective zone at the distance x_1 is determined by set of the top of the object to be protected.

However, the protective zone depends on a number of masts in use. The mast heights is also based on the mast number and is determined to protect appropriately as following. [1], [6], [9], [10]

A. One Mast

The protected zone of one mast is shown as in Fig. 2. Assume that there is a object of a height of y, and the object is intended to be protected by one mast. If the location of the mast is given, i.e. the distance a from the mast to the object is known, then the height h of the mast, which can protect properly the object, is determined as the following equations

$$R_{P0} = \sqrt{r_c^2 - (r_g - y)^2} \quad (4)$$
$$a_0 = a + R_{P0} \quad (5)$$
$$h = r_g - \sqrt{r_s^2 - a_0^2} \quad (6)$$

where, a_0 is treated as the distance from the mast to the object of the height of zero $y = 0$ to be protected (Fig. 2)

B. Two Masts

If the number of the masts, which protect the object of the height y, is two, then the protective zone looks like as in Fig. 3. The closer the masts is, the higher the height of the object is protected. The height h of the masts are determined via equations, which are the same as in case of one mast (see (4), (5), and (6)). It's evident that the protective zone in case of two mast is better than in case of one mast, since the area is formed by four dashed lines and the red curve (see Fig. 3). Here, a value, which should be considered, is the minimum protected height y_{m2} to be protected by both masts as in (7). The area, which is outside the dashed-line area or is inside the red area, is protected by only one mast.

$$y_{m2} = r_g - \sqrt{r_c^2 - d^2} \quad (7)$$

C. Three Masts

Assuming three masts with the equal height h form a triangle as in Fig. 4. Three spheres, which have the centers at the tops of the masts and the equal radius r_s, intersect at the middle of the triangle so that the horizontal distance to each mast is R_c. This point is called A. Consequently, R_c is the radius of the circumscribed circle of the triangle. Here, if the lengths of three sides of the triangle are a_1, a_2, and a_3, and the altitude of the triangle to the side a_1 is h_1, then R_c is determined as the following equation

$$R_c = \frac{a_2 a_3}{2h_1} \quad (8)$$

If the locations of three masts are given, i.e. the point A is known, then the horizontal distance from the point A to the

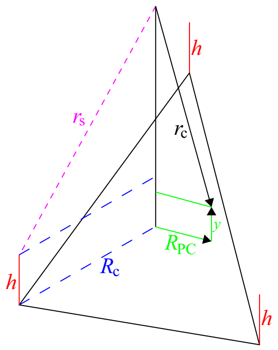

Fig. 5. The object of height y is protected by three masts

object R_{PC} is known (Fig. 5). As a result, the height of the masts is determined as the following equation

$$h = y + \sqrt{r_c^2 - R_{PC}^2} - \sqrt{r_s^2 - R_c^2} \quad (9)$$

where, y is the height of the object to be protected.

Since the protective zone of three masts is a part of the sphere with the center A and the radius of r_s, the minimum height of the protected zone of three masts y_{mc} should be considered (Fig. 4)

$$y_{mc} = h - r_c + \sqrt{r_s^2 - R_c^2} \quad (10)$$

However, there are two conditions for the three-mast case to be existed:

- R_c must be less than a_0.
- The center of the masts must be within the triangle.

In addition, one proper three-mast group should be satisfied following condition:

- There isn't any mast inside the triangle, which is formed by the three-mast group (those four masts have the same voltage level). It's result of the mast inside the triangle has no meaning in lightning protection.

D. More than Three Masts

The masts are grouped into three-mast configuration. This is, the heights of the masts will be calculated by the determining height of three-mast cases; so a mast height will be the maximum value which satisfies all three-mast groups containing this mast.

E. The Economical Criterion

As in [1], the economical criterion is always the goal of the designing, if the technical goal is achieved. This is, the total of the material used should be as less as possible. Here, to attain the economical criterion, the sum of the heights calculated should be as small as possible. However, a mast height is a complicated function of the striking distances, the height of the object to be protected, locations of masts (6,9). Moreover, the mast height also bases on a number of masts used as was stated above. Therefore, a computer program is developed to obtain quickly the economical criterion, the sum of the mast heights being the smallest.

III. Simulation and Results

By using Matlab, a program was developed in order to locate and determine the height of masts to protect equipment in substation from lightning strike.

A. Limited Conditions

In case of more than two masts, for a certain nominal system voltage, three conditions are considered as the follows

- Each mast of this voltage level is contained by at least one three-mast group.
- For outside masts, two consecutive outside masts are two ends of a side of a three-mast group. They are neighbor masts.
- Each outside mast has only two neighbor masts.

According to the limited conditions, masts will be placed the user. After that, the program will show the mast heights, which can protect properly all devices in the substation. This result satisfies the economical criterion, of course.

B. Usage and Graphic Interface of the Program

To realize how to use the program and its application, we consider a substation with the following information

1) the dimension of the substation is $30 \times 40\ \text{m}^2$.
2) there are three devices: a 230 kV device A with a height of 15 m, a 500 kV device B with a height of 15 m, and a 230 kV device C with a height of 5 m.

In this program, there are two steps to input information: the substation edge, the location of equipment within the substation and the desired location of masts. The last step is the result. Namely

Step 1: Inputting substation edge as shown in Fig. 6. Two opposite apices of the substation edge are entered by two buttons 'Apex 1' and 'Apex 2'.

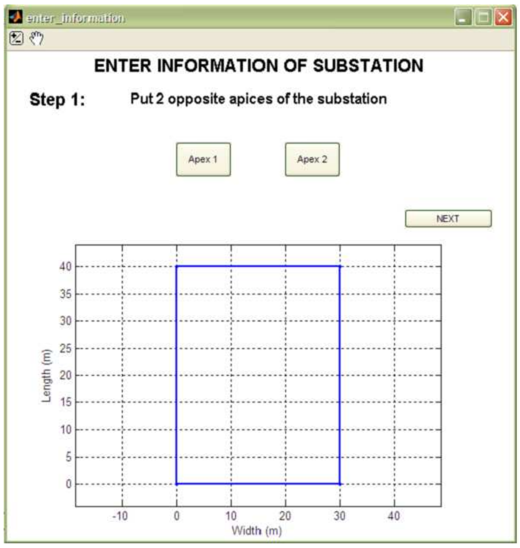

Fig. 6. Input the substation layout

International Journal of Engineering, Mathematical and Physical Sciences
ISSN: 2517-9934
Vol:4, No:5, 2010

Step 2: Inputting equipment and masts information as shown in Fig. 7. For equipment, needful information is apex locations, voltage level, and height. For masts, needful information is location, protective and voltage.

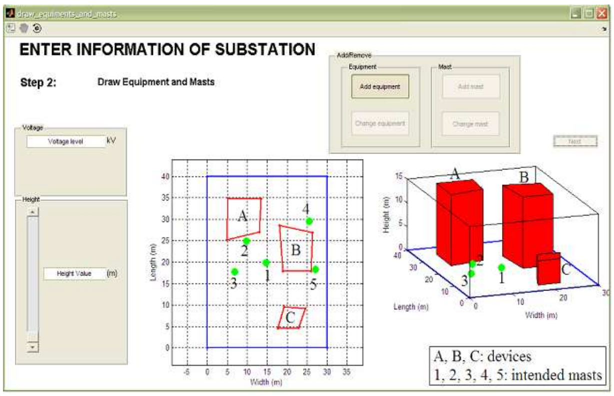

Fig. 7. Input equipment dimensions and the location of masts

Step 3: The results are shown in Fig. 8. Protected zone for a certain voltage and a certain height is shown in this figure. The calculated mast heights are shown in the panel 'Information of Masts'.

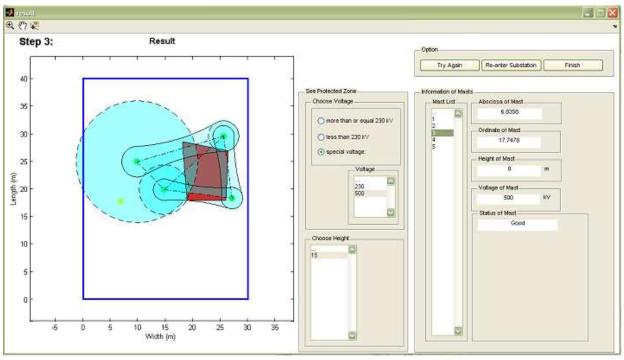

Fig. 8. Protective zone for 500 kV equipment and the mast heights

Here, we assigned five masts:

- The masts #1 and #2 are used to protect the 230 kV and 500 kV equipment.
- The masts #3, #4, and #5 are used to protect the 500 kV equipment. The locations of the devices and the masts are shown in Fig. 7.

Since Fig. 8, the calculated mast heights are 21 m, 40 m, 0 m, 28 m, and 17 m, for the masts #1, #2, #3, #4, and #5 respectively.

When the user chooses one mast from the panel 'Information of Masts', the color of the mast will be changed from green to yellow; and the user can see some information of this mast such as height, location,...

Furthermore, because a protective zone bases on voltage level, the user can choose voltage from the panel 'Choose Voltage' to see protective zones of this voltage level. There are three manners to see protective zones: according to voltages more than 230 kV, according to voltages less than or equal 230 kV, or according to a certain voltage level. As a result, we can see whether the equipment is protected or not. The green areas are protective zones. A solid line green area is a protective zone by two masts; a dashed line green curve is a protective zone by a mast; and a dash-dot line triangle is a protective zone by three masts. If the equipment is inside the protective zone, the equipment is protected.

In the step 3, there are three options for user. Two buttons 'Try Again' and 'Re-enter Substation' will be chosen if the user want to change or add some device, or adjust the substation edge. Otherwise, the user can choose the button 'Finish' to complete designing lightning protection system.

According to the program, the plan views of the protected zones for the devices of different voltage levels and for varying heights are shown in Fig. 9, Fig. 10, Fig. 11

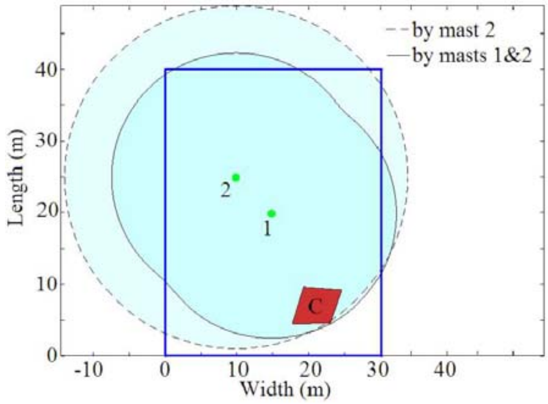

Fig. 9. Plan view of the protected zone for a 230 kV device with a height of 5 m.

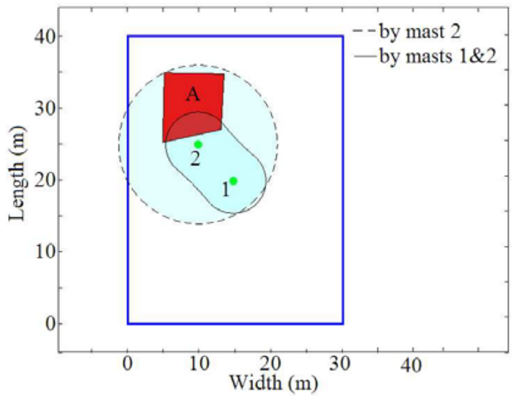

Fig. 10. Plan view of the protected zone for a 230 kV device with a height of 15 m.

C. Result discussion

From Fig. 9, Fig. 10, Fig. 11 it's evidence that all devices are inside the protected zones. Thus, the calculated heights of the masts are satisfactory.

Obviously, if the mast heights were decrease, the protective zones would be narrowed. However, since the those figures, if

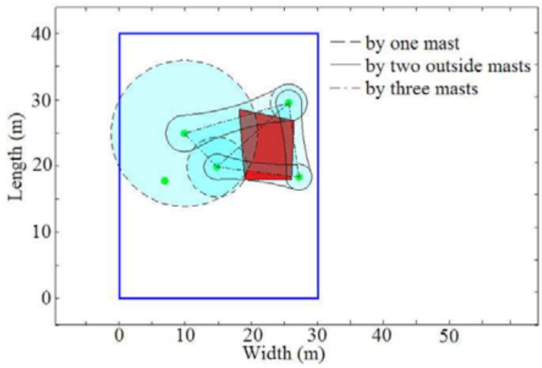

Fig. 11. Plan view of the protected zone for a 500 kV device with a height of 15 m.

the protective zones were narrowed, they couldn't cover whole devices. Therefore, the economical criterion is satisfied.

On the other hand, the program was developed by applying Love's equations. In comparison with the previous works [12], [1], the program is intended to apply other equations (such as Young, CIGRE, IEEE...). As a result, some differences between applying different equations can be obtained, as well as being compared with the real substation data.

There are still some limited conditions; and they are expected to be eliminated in our developing work.

IV. Conclusion

The developed program provides a convenient method to use masts for the designing of lightning protection system of a substation with the result satisfies the economical criteria, i.e. the sum of the mast heights calculated is the smallest.

In addition, if there are some masts with certain heights and the user wants to use those masts for lightning protection, the user can use this program to calculate the required mast heights. The heights of existing masts are then compared with the calculated mast heights. The user will know that which installed masts can be salvaged and which masts must be freshly installed.

According to the describing of the simulation, we see that the program can be applied for any area, not limited to substations.

References

[1] *IEEE Guide for Direct Lightning Stroke Shielding of Substations*. IEEE Std 998–1996, 20 Dec 1996.
[2] P. K. Sen, "Understanding direct lightning stroke shielding of substations," PSERC Seminar, Golden, Colorado, 6 Nov 2001.
[3] Chris Redmond, "Flash about the power failure," tech. rep., Information and Public Affairs, University of Waterloo, 1996.
[4] Nils Olvesen, "'96 Power Outage," tech. rep., HAL-PC Internet Services, 1996.
[5] P. McGeehan, "It was lightning, con ed says, that caused the lights to go out," tech. rep., New York Times, 29 June 2007.
[6] Andrew R. Hileman, *Insulation Coordination for Power Systems*. New York: Marcel Dekker, 1999.
[7] X. W. Xingjia Tang and Q. Peng, "Experiment and research of a new lightning protection measure," in *International Conference on High Voltage Engineering and Application*, (Chongqing, China), pp. 176–179, 2008.
[8] Golde, R.H., "The validity of lightning tests and scale models," *Journal IEE*, vol. 88, part II, no. 2, pp. 67–68, 1941.
[9] Golde, R.H., *Lightning Protection*. London U.K, 1977.
[10] John D. McDonald, *Electric Power Substations Engineering*. CRC, 2007.
[11] E. R. Love, "Improvements on the lightning stroke modeling and application to design of EHV and UHV transmission lines," Master's thesis, University of Colorado, Colorado, 1973.
[12] A. M. Mousa, "A computer program for designing the lightning shielding systems of substation," *IEEE Transactions on Powet Delivery*, vol. 6, January 1991.