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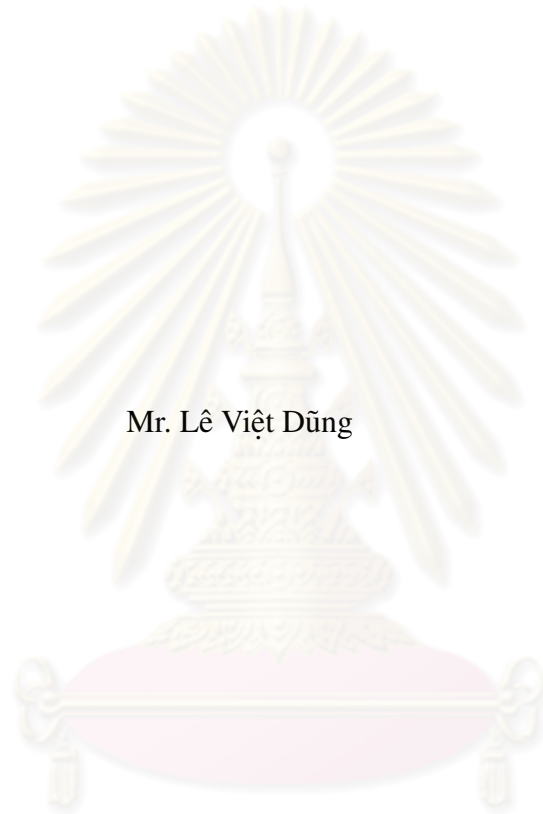
Mr. Lê Việt Dũng

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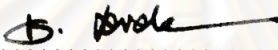Faculty of Engineering
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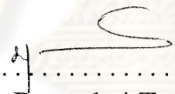Copyright of Chulalongkorn University
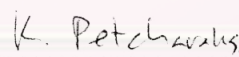
Thesis Title   LIGHTNING PROTECTION FOR SUBSTATIONS BY MASTS

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Field of Study   Electrical Engineering

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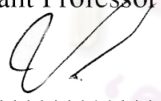
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      ฟ้าผ่าเป็นปรากฏการณ์ทางธรรมชาติที่เกิดขึ้นทั่วไปโดยเฉพาะอย่างยิ่งในเขตภูมิอากาศร้อนชื้น เช่น เวียตนามและไทย สถานีไฟฟ้าที่อยู่กลางแจ้งซึ่งมีความสำคัญเป็นอย่างยิ่งในระบบส่งพลังงานไฟฟ้า จึงมีโอกาสถูกฟ้าผ่าโดยตรงจนอาจเกิดความเสียหายต่อทั้ง อุปกรณ์ไฟฟ้าในสถานี ระบบเศรษฐกิจ และ บางครั้งอาจรวมไปถึงชีวิตมนุษย์ด้วย

      อย่างไรก็ตาม ความเสียหายนี้อาจป้องกันได้ด้วยการออกแบบระบบป้องกันฟ้าผ่าสถานีไฟฟ้าที่ เหมาะสม ซึ่งยุ่งยากมากในการคำนวณด้วยมือหากต้องการป้องกันสถานีไฟฟ้าขนาดใหญ่ด้วยเสาหลาย ต้น

      วิทยานิพนธ์นี้เสนอโปรแกรมช่วยออกแบบระบบป้องกันฟ้าผ่าสำหรับสถานีไฟฟ้า ด้วยวิธีโมเดล แบบ electrogeometric ที่นิยมใช้ในปัจจุบัน โปรแกรมสามารถเลือกวิธีการหาระยะฟ้าผ่าตามสมการของ Love Young CIGRE หรือ IEEE พร้อมทั้งเสนอเกณฑ์วิธีที่เหมาะสมในการเลือกสมการของระยะฟ้าผ่าที่ เหมาะสม ในการออกแบบระบบป้องกันฟ้าผ่าของสถานีไฟฟ้า

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สาขาวิชา	วิศวกรรมไฟฟ้า	ลายมือชื่อ อ.ที่ปรึกษาวิทยานิพนธ์หลัก
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Lightning is one of the most destructive natural phenomena that we know. It occurs frequently in tropical countries, such as Vietnam and Thailand. Thus, the air insulated substations, which is an important asset in the electric power transmission, are prone to be struck by lightning. The consequences are: physical, economic, and sometimes life damages.

However, the damages may be reduced by using a suitable lightning protection system, LPS. But, the design of an LPS of large substation by using masts is very difficult, especially if we use hand-calculation.

This thesis proposes a software tool to design an LPS for a substation by using mast. The model in use is the most currently acceptable one, i.e. electrogeometric model. Users can select various striking distances in the design, e.g. from Love, Young, CIGRE, or IEEE equations. The criteria for the selection of an appropriate kind of striking distance equations in the design of an LPS of a substation are also discussed.

Department: ...Electrical Engineering... Student's Signature: ....

Field of Study: ...Electrical Engineering... Advisor's Signature: ....

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จุฬาลงกรณ์มหาวิทยาลัย

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Symbols

r_g Striking Distance to Ground
r_c Striking Distance to Object to Be Protected
r_s Striking Distance to Mast
I_d Design Current

Acronyms

3-D Three Dimensions
LPS Lightning Protection System
EGM Electrogeometric Model
IEEE The Institute of Electrical and Electronic Engineers
IEC The International Electrotechnical Commission
CIGRE The Conseil International des Grands Réseaux Électriques
(The International Council on Large Electric Systems)

CHAPTER I

Introduction

1.1 Introduction

Lightning, an unpredictable, probabilistic phenomenon [1], may cause severe failures in substations such as insulation flashover and damage of substation devices [2–5]. On the other hand, a substation is a very important section of an electrical power system. Consequently, the power supply may be interrupted by lightning; and economic losses are considerable [2]. LPSs for substations are therefore needed to minimize direct lightning strokes to equipment and buses within substations [1].

This chapter presents a general introduction for substation protection against lightning by using masts. Causes and results that may occur when a lightning strikes a substation are discussed. Objectives and scope of the research, and the outline of this thesis are also presented.

1.2 Problem Statement

Lightning risks, which influence electrical power systems in general and substations in particular, including device damage and people hazard, may be caused by direct strokes and indirect strokes [6]. A lightning stroke is called direct stroke if it terminated on a tower, a shielding wire, a conductor, etc. An indirect stroke is caused by a nearby stroke which strikes the ground. The effect is a high value of an induce voltage on the transmission line which places a high stress on an insulation string and equipment within substation. Both types of strokes may cause damage to electrical devices, or flashover of external insulation.

As a consequence, outages together with economic losses may happen. But, they can be prevented by using some protective devices such as surge arrester and LPS, or coordinating insulations. However, the application of LPS is a complicated issue as it covers the entire system, i.e. from generating station, transmission line, substation, distribution line and customer. Here, we concern only on the direct stroke and its effect on substations.

To protect a substation against direct strokes, either masts, shielding wires, or both of them can be used. However, breakages of shielding wires (due to lightning current or poor maintenance) can cause catastrophic faults in substations. One more disadvantage of using shielding wires is high cost in comparison with the use of masts [7]. In addition, if the tip

of a mast is too small then the mast attracts lightning flashes more easily than a shielding wire [8]. Masts are thus preferred to shielding wires for lightning protection for substations.

For direct lightning protection using masts, there are two methods investigated [1]: the classical empirical method and the EGM. According to [1], the model which should be applied is the EGM. Here, the striking distances are very important factors in the design of LPS of substations as well as the evaluation whether the LPS protects appropriately or not. The striking distances depend on the equations that are applied in the design of LPS, such as Young's equations, IEEE-1992 equations, Love's equations [7].

On the other hand, an LPS designed should has as small cost as possible, as an objective function [1]. Here, the total of the material quantity used should be the smallest.

Therefore, an issue is considered: a hand-calculation to design LPS for substation takes a long time and is complicated when the objective function is considered; so how to design a lightning protection system using masts within a shorter time and more easily. To solve this concern, this thesis describes a computational tool to design LPSs for substations by using masts. MATLAB® [9] was applied to develop the tool.

Also, two limited conditions, which are still existing in this program, are referred.

Moreover, based on the tool, the author investigated effect of various striking distance equations, Young's equations, IEEE-1992 equations, IEEE-1995 equations, CIGRE equations, and Love's equations on LPSs designed. Some suggestions about how and which circumstance each kind of equations should be used are given.

1.3   Objectives

The objectives of the thesis has twofold

1. To develop a computational tool to design substation protection systems using masts against direct lightning strokes which has as small cost as possible.

2. To investigate the effect of various striking distance equations on the designed LPSs and give some suggestions about applications of the equations.

1.4   Scope of Thesis

The scope of thesis covers research on direct lightning strokes and a protection method by using masts.

1.5 Outline of Thesis

The summary of this thesis is as follows

Chapter 2

Methodology of LPS for substation is contained in this chapter. A general introduce about LPS will be presented; and then, the EGM will be shown as a principal part of this chapter. At last, an economical criterion, i.e. the objective function, will be mentioned.

Chapter 3

This chapter will describe the computational tool with some examples; and then, the method which was used to achieve the economical criterion will be explained.

Chapter 4

The effect of the various striking distance formulae on LPSs will be presented in this chapter. It was done as an application of the computational tool. Suggestions about usage of the formulae will be given.

Chapter 5

The chapter 5 will show an application of the computational tool on a real substation, an area 220 kV of a substation Ha Dong in Vietnam. This chapter proves the applicability of the tool in practical design.

Chapter 6

This chapter presents conclusions and suggests for further work.

CHAPTER II

Methodology

2.1 Introduction

Lightning risk is one of concerns of human being, especially in engineering. Lightning investigations have been performed for a long time. One of the first reports for lightning risks which was published in Munich in 1784 is *A Proof that the Ringing of Bells during Thunderstorms May Be More Dangerous than Useful* [7, 10]. Subsequently, there are a lot of researches carried out to propose lightning protection methods. For some reasons that will be explained later, one of those methods, i.e. EGM was used in this work to design LPSs. The goal of the method is to achieve a good technical index. Once the technical goal is satisfied, the economical index must be considered. That is, the investment of an LPS must be lower than the cost of damage without an LPS.

This chapter presents a general overview of the lightning study, the method to protect substations against lightning by using masts, and the economical criterion.

2.2 Lightning Protection Investigations

The beginning of lightning protection investigations was marked by Benjamin Franklin's experiments, which were described through letters to his friend Peter Collinson during the years from 1747 to 1750. Subsequently, the lightning rod - a significant invention - was mentioned in his 1749 letter and was published in May 1750. [7, 11]

From that time until now, there are two methods investigated to be widely used [1] as the following

- The classical empirical methods.

- The electrogeometric model, EGM.

The classical empirical methods, or geometrical methods, can be divided based on two classical design methods: fixed angles [12, 13] and empirical curves [13–15]. Actually, they still have been used in some lightning protection designs, e.g. transmission line protection by using overhead ground wire.

The first research about EGM was given in 1945 by Golde [16]; but it had been abandoned for quite a long time. Fortunately, since a high outage rate from lightning of the

first North American 345 kV transmission lines in the mid-1950s, the EGM research was restarted again and has been developed up to now [1]. Many investigations of EGM were published by J. G. Anderson [17], Young et al. [18], E. R. Whitehead [19], Love [20], and Gilman and Whitehead [21]. In 1976, the application of the EGM for substations was stated by Mousa [22]. The last version of EGM was developed by applying the rolling sphere method [23–25] and Mousa and Srivastava's method [26,27]. Currently, this model has been accepted by most investigators for lightning protection design [1].

From [28, 29] and a survey in [30], the investigators claimed that there are some mistakes in the classical empirical methods and *"designers are not achieving the protection they expect from the Geometrical methods"*. In addition, investigations showed that *"The EGM attempts to provide 100% flashover protection, whereas the other two methods permit a small failure rate"* [1], where "the other two methods" are the fixed angles and the empirical curves. As a result, the preferred method which should be used is the EGM [31]. Therefore, the EGM was applied in this work.

2.3 The Electrogeometric Model

In this method, three striking distances are very important in the design of an LPS for a substation. They are the striking distance to the mast r_s, the striking distance to the object to be protected r_c, and the striking distance to ground r_g [7] as shown in Fig. 2.1.
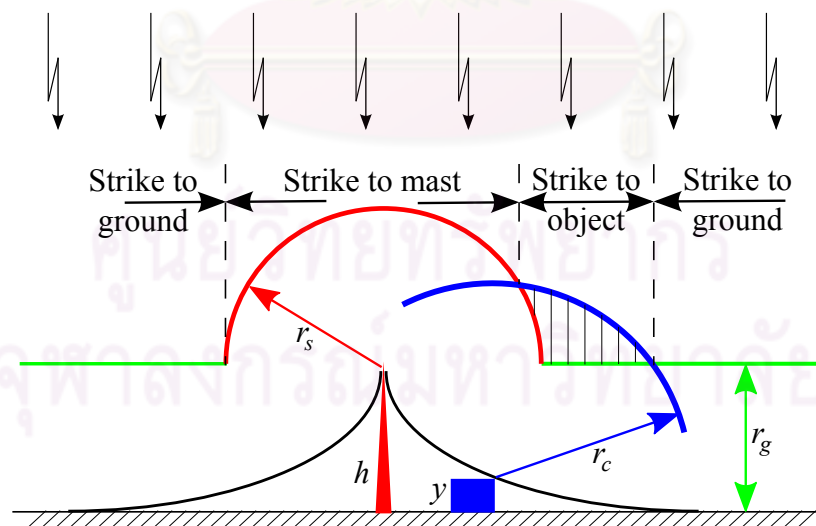
Figure 2.1: Striking distances

Why should the striking distances be considered? That is because they relate directly to the determination of a protected zone, which represents a protection ability of a mast or a group of masts. Indeed, 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 properly protect all devices within this range. That is, the protected zone of the masts should cover the devices as much as possible. To explain this concept, we will consider the simplest case of one mast, as shown in Fig. 2.1. Here, the protected zone of one mast is based on: the mast height h, the object to be protected which has a height y, and the distance from the foot of the mast to the object. When a lightning flash reaches the shaded area, the object will be struck by this flash. As a result, the object should be moved closer to the mast until the shaded area disappears. Doing like this with every location around the mast, the protected zone would be determined by the set of the height of objects to be protected. In addition, it is important that a mast height must be less than or equal to the striking distance to ground, r_g, to protect objects properly [7].

Consequently, if the objects' height, and the locations of the objects and the masts are given, the required mast heights can be calculated. The three striking distances may be determined by the following equations

$$r_g = A \cdot I_d^a \qquad r_s = \gamma_s r_g \qquad r_c = \gamma_c r_g$$

where I_d is the design current in kA; r_g, r_s, and r_c are in meters. If nominal system voltage < 230 kV, I_d is 5 kA. If the voltage ≥ 230 kV, I_d is 10 kA. Coefficients A, a, γ_s, γ_c are proposed by various investigators, such as (here, h is the mast height and y is the height of the object to be protected in meter)

1. Young's Equations [7]
$$r_g = 27 I_d^{0.32} \tag{2.1}$$

$$\gamma_s = \frac{444}{462-h} \text{ for } h \geq 18 \text{ m} \qquad \text{otherwise } \gamma_s = 1$$
$$\gamma_c = \frac{444}{462-y} \text{ for } y \geq 18 \text{ m} \qquad \text{otherwise } \gamma_c = 1$$

2. Love's Equations [1, 7]
$$r_g = 10 I_d^{0.65} \qquad \gamma_s = \gamma_c = 1 \tag{2.2}$$

3. Brown-Whitehead - CIGRE Equations [7]
$$r_g = 6.4 I_d^{0.75} \tag{2.3}$$

$$\gamma_s = 1 + \frac{h-18}{108} \text{ for } h \geq 18 \text{ m} \qquad \text{otherwise } \gamma_s = 1$$
$$\gamma_c = 1 + \frac{y-18}{108} \text{ for } y \geq 18 \text{ m} \qquad \text{otherwise } \gamma_c = 1$$

4. IEEE-1992 - IEEE T & D Committee Equations [7]

$$r_g = 9I_d^{0.65} \tag{2.4}$$

$$
\begin{aligned}
\gamma_s &= \frac{1}{0.36 + 0.17\ln(43-h)} \qquad \text{If } h \geq 30 \text{ m, set } h = 30 \\
\gamma_c &= \frac{1}{0.36 + 0.17\ln(43-y)} \qquad \text{If } y \geq 30 \text{ m, set } y = 30
\end{aligned}
$$

5. IEEE-1995 - IEEE Substations Committee Equations [1,7]

$$r_g = 8I_d^{0.65} \qquad\qquad \gamma_s = \gamma_c = 1 \tag{2.5}$$

The necessary heights of masts can be determined from these striking distances. However, the protected zone, as well as the mast heights, also base on the number of the masts in use. Determination of mast heights is as follows

1. **One Mast**

   Figure 2.2 depicts the protected zone of one mast.
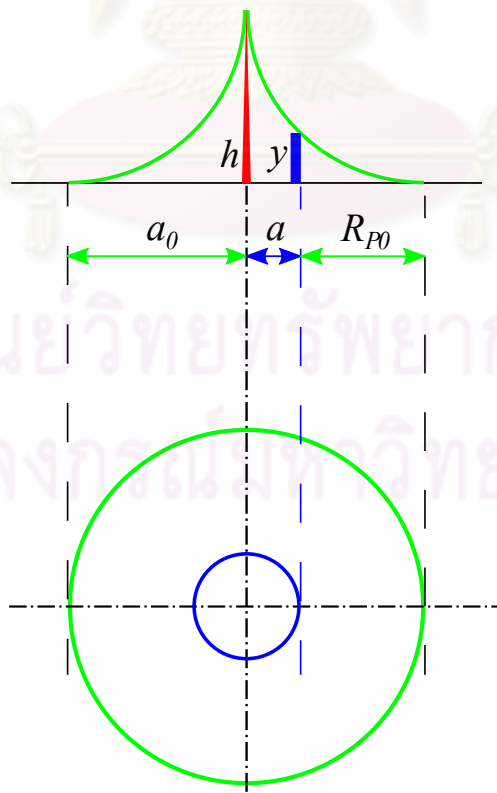
Figure 2.2: Protected zone of a single mast

Assume that there is an 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 the object, can be determined from the following equations

$$R_{P0} = \sqrt{r_c^2 - (r_g - y)^2} \tag{2.6}$$

$$a_0 = a + R_{P0} \tag{2.7}$$

$$h = r_g - \sqrt{r_s^2 - a_0^2} \tag{2.8}$$

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

2. **Two Masts**

If the number of the masts, which protect the object of the height y, is two, then the plan view of the protective zone looks like as shown in Fig. 2.3. The closer the masts are, the higher the height of the object is protected. The curve 1 with color of green bounds the protected zone for the height $y = 0$. The curve 2 with color of blue bounds the protected zone for the height $y > 0$. The height h is computed in a same way as in the case of one mast, see (2.6), (2.7), and (2.8).
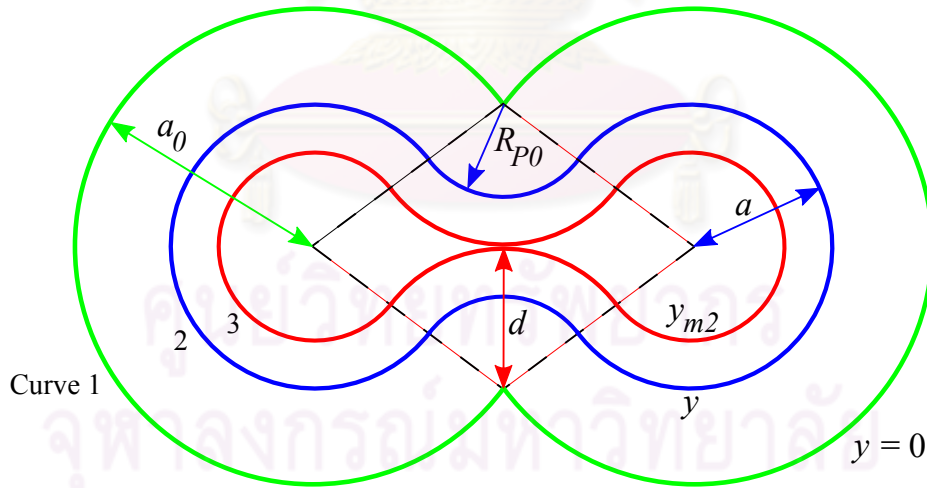
Figure 2.3: Protected zone of two masts

The value y_{m2} should be considered here, see (2.9). The protected zone by both masts is inside curve 2 and outside the curve 3. The area inside the curve 3 is protected by only one mast.

$$y_{m2} = r_g - \sqrt{r_c^2 - d^2} \tag{2.9}$$

3. **Three Masts**

Assuming there are three masts with the equal height h. They form a triangle as in Fig. 2.4. Three spheres, which have the centers at the tops of the masts and the equal
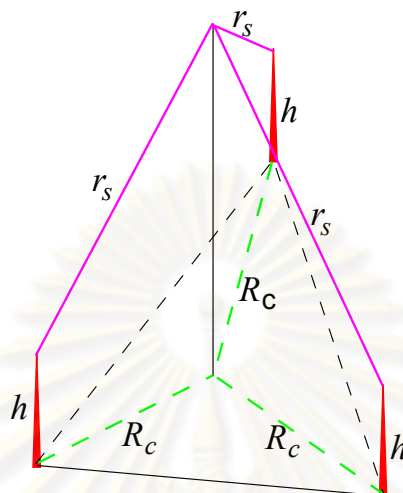
Figure 2.4: Determination of the radius of the circumscribed circle

radius r_s, intersect at a point whose plan view is the center of the circumscribed circle of the triangle. R_c is the radius of this circle. 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 (see Fig. 2.5), then R_c is determined from the following equation

$$R_c = \frac{a_2 \times a_3}{2h_1} \tag{2.10}$$

or the equation

$$R_c = \frac{a_2}{2 \sin \alpha} \tag{2.11}$$

where α is the angle opposite to the side a_2.
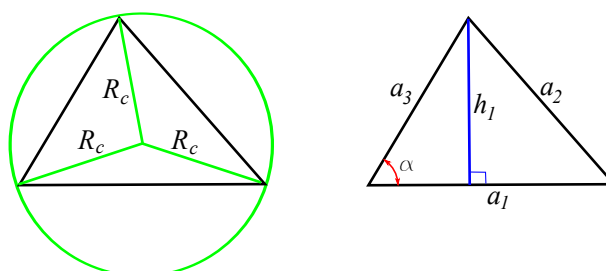
Figure 2.5: Parameters of a triangle

In addition, if the locations of three masts and the object are given then the distance from the object to the center of the circumscribed circle, R_{PC}, is known, see Fig. 2.6. As a result, the height of the masts is determined as follow

$$h = y + \sqrt{r_c^2 - R_{PC}^2} - \sqrt{r_s^2 - R_c^2} \qquad (2.12)$$

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

According to [7], the minimum height of the protected zone of three masts, y_{mc} (see Fig. 2.6), should be considered and be computed by using the following equation

$$y_{mc} = h - r_c + \sqrt{r_s^2 - R_c^2} \qquad (2.13)$$
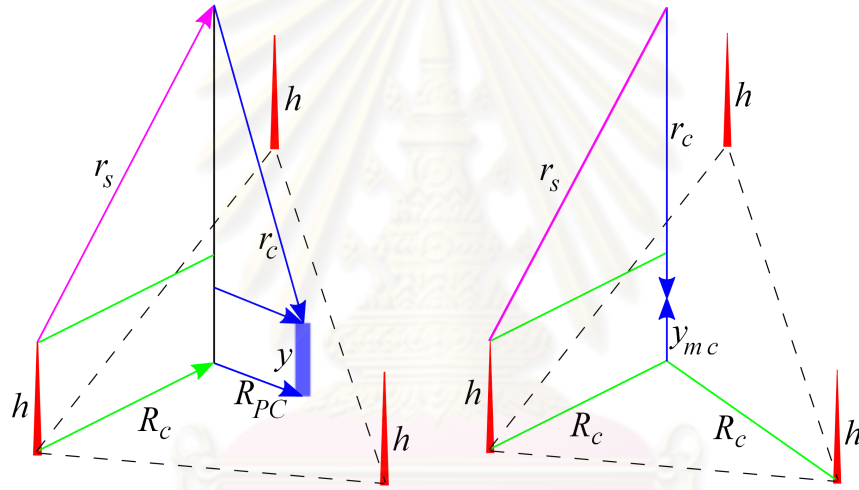
Figure 2.6: Determinations of R_{PC} and y_{mc}

However, for the existence of three-mast configuration, there are two conditions based on the method

- R_c must be less than a_0, where $a_0 = \sqrt{r_c^2 - (r_g - h)^2}$.
- The center of the circumscribed circle of the triangle, which is formed by the masts, must be within the triangle.

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

- There is not any mast inside the triangle, which is formed by the three-mast group (those four masts have the same voltage level). This condition bases on the optimal criterion because a mast inside a three-mast group is meaningless in lightning protection.

To imagine more easily about the protected zone of three masts, Fig. 2.7 shows the protected zone within the triangle formed by three masts of height of h. This zone is a part of a sphere. Values y_{mc}, y_1, y_2, y_3, y_4, and y_5 represent heights of devices to be protected; they increase respectively, i.e. $y_{mc} < y_1 < y_2 < y_3 < y_4 < y_5$. At the center of the circumscribed circle of the triangle, the maximum height of the object, which is protected by three masts, is y_{mc}; and the more a device is far from this center, the more maximum height of the device is.
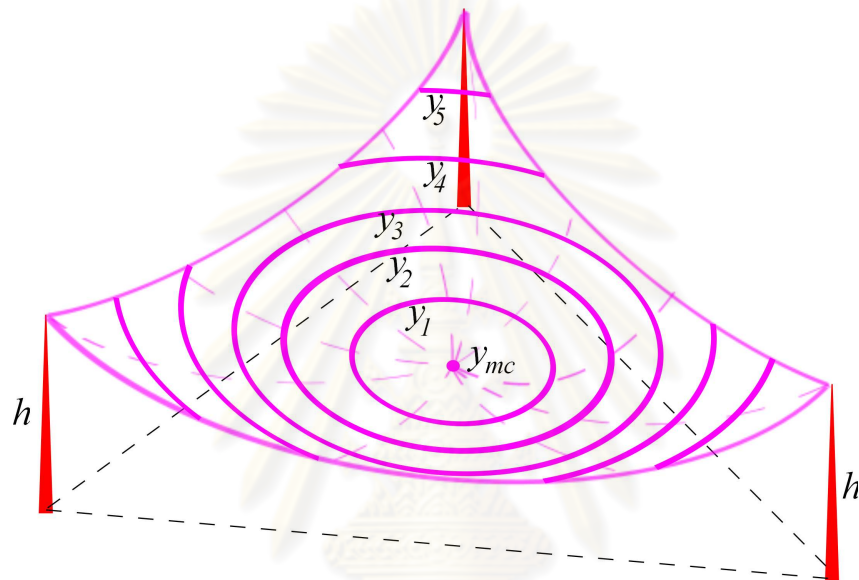
Figure 2.7: Protected zone within three masts

4. **More than Three Masts**

This case bases on cases of one mast, two masts, and three masts. The mast heights are computed by grouping them into three-mast configurations. The heights of the masts will be calculated by the determining heights of three-mast cases; so a mast height will be the maximum value which satisfies all three-mast groups containing this mast.

From (2.8) and (2.12), the required height of the mast h is based on the striking distance to the mast, r_s. Since (2.1), (2.3), and (2.4), in case of either Young's equations, or CIGRE equations, or IEEE-1992 equations, the value r_s depends on the mast height h, iteration is required; but not necessary for Love's equations and IEEE-1995 equations [7]. Furthermore, Love's equations and IEEE-1995 equations look very similar, but the value of the striking distance to ground r_g, i.e. the maximum mast height, is higher for Love's equations [7]. Thus, if Love's equations are applied, lightning protection ability is possibly lower, but the construction cost is not as high as in a case where IEEE-1995 equations are applied.

2.4   The Economical Criterion

As we already know, once the technical goal is satisfied, the economical function is always the next goal of the designing, i.e. the cost of construction, should be considered [1]. In our case, the summation of all mast heights calculated should be as low as possible.

On the other hand, determination of mast heights is not easy especially in case of a substation, as the number of masts required to protect a substation against lightning is not small. The larger the number of masts is, the more complicated determination of mast heights.

To obtain economical criterion when electrical devices and locations of masts are given, the simplest way is that a designer figures out all possible options to group the masts into three-mast configurations in case of more than two masts (in cases of one mast and two masts, there is only one option). From mast heights calculated with these options, the designer compares and choose the economical option whose the sum of the mast heights is smallest. However, it would take a long time if it is done by hand-calculation; because the larger number of masts is, the larger number of options. A manual calculation is normally applied to a substation with a few masts; in case of a substation with a large number of masts, as shown in chapter 5, a software is needed.

Therefore, a computational tool, based on MATLAB$^{®}$ [9], is developed to design LPSs for substations. With this computational tool, the effect of the striking distance formulae on the LPSs can also be investigated.

2.5   Summary

1. Currently, the EGM is a preferred method to design LPSs for substations.

2. The most important parameters in the EGM are three striking distances. However, the equations of striking distances differed from one investigator to another. As a result, there are various results when various equations of striking distances were applied. In this work, there are five equation sets applied: Young's equations, Love's equations, CIGRE equations, IEEE-1992 equations, and IEEE-1995 equations.

3. Once the technical goal was satisfied, the economical function must be considered.

CHAPTER III

The Computational Tool

3.1 Introduction

MATLAB$^{\circledR}$ [9] is a powerful software for a simulation in electrical study. Some applications of MATLAB$^{\circledR}$ in electrical research have been presented in [32–37]. Therefore, a computational tool based on MATLAB$^{\circledR}$ has been developed [38]. The purpose of this tool is to design an LPS for a substation by applying different equations, i.e. Love's, Young's, CIGRE, IEEE-1992, and IEEE-1995 equations. However, the tool cannot cover all cases of LPS design, because there are some limited conditions which still remain.

This chapter presents the manner to use this tool and some examples to explain this tool. All LPSs designed in these examples were computed by applying Love's equations.

3.2 Computational Tool Description

3.2.1 Limited Conditions

In case of more than two masts, for a certain nominal system voltage, two limited conditions are considered.

Firstly, please keep in mind that a three mast group must satisfy a condition: the triangle which is formed by the three masts is not an obtuse triangle. Let's see Fig. 3.1 to define 'outside mast'.
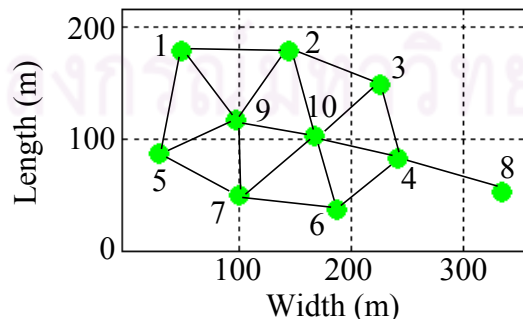
Figure 3.1: Masts lay-out to define 'outside mast'

There are ten masts in Fig. 3.1 which may be formed into three-mast configurations.

However, the mast #8 is not contained by any three-mast group because there is not any acute triangle with this mast. As a result, this mast can be formed into single-mast configuration or two-mast configuration with the mast #4. The seven masts, from #1 to #7, may be formed into single-mast configuration, or two-mast configuration, or three-mast configuration. The two masts #9 and #10 are formed into only three-mast configuration. As a consequence, the eight masts, from #1 and #8 are called outside masts, which can be formed into *single-mast configuration*, or *two-mast configuration*, or *three-mast configuration*. The masts #9 and #10 are not outside masts because **only** *three-mast configuration* contains them.

Next, we define 'neighbor mast'. The outside masts #1 and #2 are *two ends of a side of a three-mast group* (#1,#2,#9). They are called two neighbor masts. Similarly, pairs of masts (#2,#3), (#3,#4), (#4,#6), (#6,#7), (#7,#5), and (#5,#1) are pairs of neighbor masts.

Thus, the two limited conditions are as follows

- Each mast of a certain voltage level is contained by at least one three-mast group.

- Each outside mast has **only** two neighbor masts.

In Fig. 3.1, the first limited condition is trespassed, because the mast #8 is not contained by any three-mast group.

To explain the second limited condition, we consider a masts lay-out as shown in Fig. 3.2.
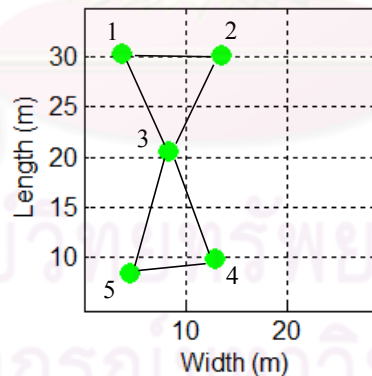
Figure 3.2: To explain the second limited condition

There are two three-mast groups (#1,#2,#3) and (#3,#4,#5) here. Please note that (#1,#3,#5) and (#2,#3,#4) cannot be three-mast groups because they do not form acute triangles. Hence, the mast #3 has four neighbor masts #1, #2, #4, and #5, i.e. the second limited condition is broken.

According to the limited conditions, masts will be placed by the user. After that, the computational tool will show the mast heights, which can properly protect all devices within

the substation. This result satisfies the economical criterion, of course. The next part of this chapter will show how the tool is applied.

3.2.2   Usage and Graphic Interface of the Computational Tool

To explain how to use the computational tool and its application, we consider a substation with the following information

1. The dimension of the substation is 30×40 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 tool, there are two steps to input information: the substation boundary in step 1; and the location of equipment within the substation, and the desired location of masts and step 2. The last step is to show the mast heights computed to protect the substation properly.

   Flow charts of the tool are shown in Appendices.

Step 1

Inputting substation boundary is shown as in Fig. 3.3. Two opposite apices of the substation boundary are entered by two buttons 'Apex 1' and 'Apex 2'.
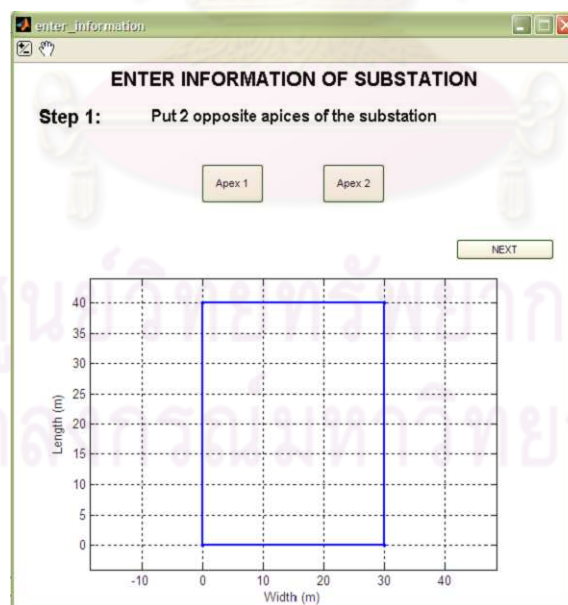
Figure 3.3: Input the substation boundary

After the apices were located, the tool would automatically draw the substation boundary as a rectangle. The purpose of the substation boundary is to bound all devices and masts, i.e. there is no device or mast outside the substation boundary.

Step 2

Inputting equipment and masts information is shown as in Fig. 3.4. For equipment, the information needed is apex locations, voltage level, and height. For masts, the required information is location and voltage.
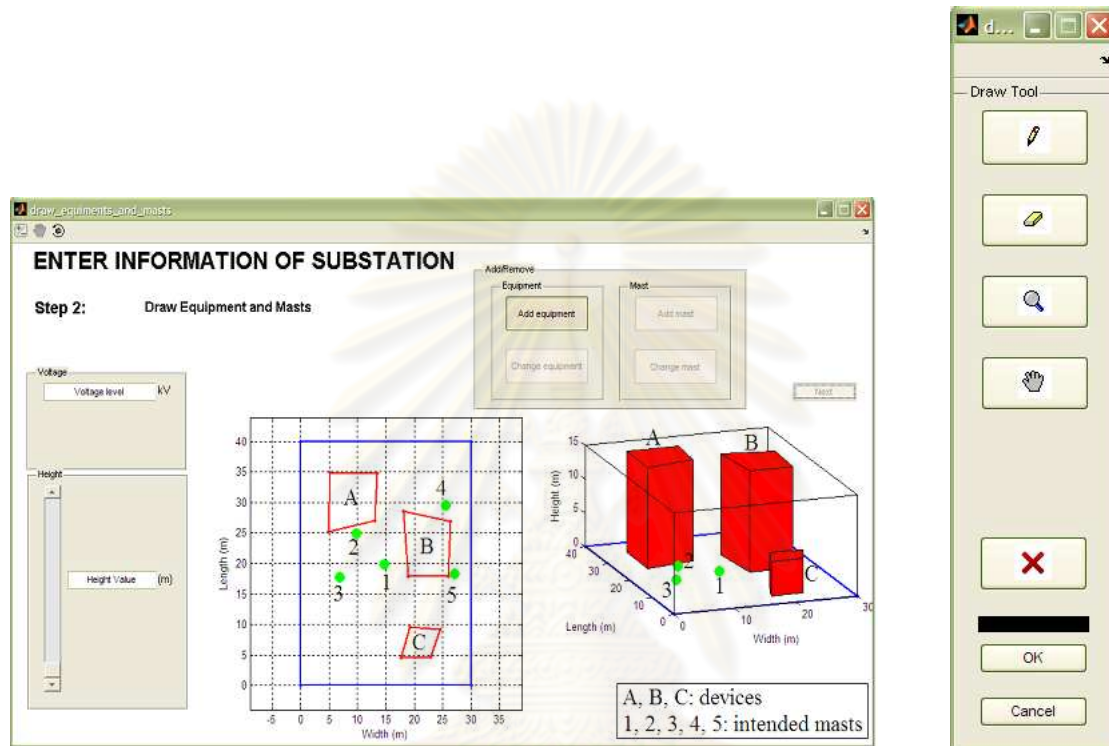
Figure 3.4: Input equipment and masts information

Here, we assigned five masts:

- The masts #1 and #2 are used to protect the 230 kV and 500 kV devices.

- The masts #3, #4, and #5 are used to protect the 500 kV device. The locations of the devices and the masts are shown in Fig. 3.4.

The location of the desired masts and the apices of the devices were drawn in the plan view graph through buttons of the draw tool. The devices are shown as the red polygons. The locations of the desired masts are green points. Here, the 3-D graph is just helping to imagine the substation lay-out more easily. The purposes of the panel 'Voltage' and 'Height' are to input voltage levels of the devices and masts, and heights of the devices. It's noted that a mast may be used to protect more than one voltage level; so in case of more than one voltage level protected by a mast, the voltage of the mast should be input by the form '$V_1/V_2/V_3$', where V_1, V_2, and V_3 are three voltage levels to be protected by the mast.

Step 3

This step shows the result of computation, e.g. as shown in Fig. 3.5.
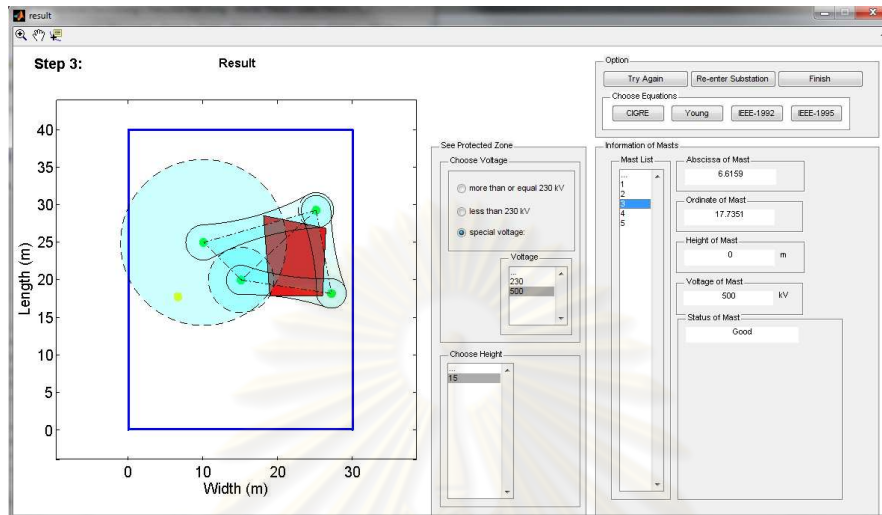
Figure 3.5: Step 3 graphic interface

Here, once the step appears, the mast heights computed by applying Love's equations are shown. In cases of other kind of equations, there are four buttons: 'CIGRE', 'Young', 'IEEE-1992', and 'IEEE-1995'.

Next, protected zone for a certain voltage and a certain height can be chosen by the user to be shown in the graph. Due to the design method in choosing the design current I_d (see chapter 2), there are three manners to see protective zones: according to voltages higher than or equal 230 kV, according to voltages less than 230 kV, or according to a certain voltage level. The blurred green areas are protective zones. A solid line green area is a protective zone by two masts; a dashed line green circle is a protective zone by a mast; and a dash-dot line triangle is a protective zone by three masts. There are intersection parts of the protected zones. However, the green color of the protected zone was blurred to reveal the devices. It is helpful for engineers to know whether the devices are protected properly or not. If the protected zones cover entire devices then the devices are protected, conversely, if there is a device which is not covered by any protected zones then this device is not protected.

In addition, the calculated mast heights, as well as the mast coordinates and mast voltages, are shown in the panel 'Information of Masts'. When the user chooses one mast from the panel 'Information of Masts', the color of the mast is changed from green to a color which is combined by green and yellow; and the user can see information of this mast. In this panel, there is a convenient sub-panel 'Status of Mast'. This sub-panel supports the graph to remind whether the masts protect the substation properly or not. If a mast has the status 'Not good' then the location of this mast should be adjusted, or the user should add more

mast. Together with the status 'Not good', the sub-panel also shows the voltage level which the mast cannot protect properly.

According to the computational tool with Love's equations, the calculated mast heights are 21 m, 41 m, 0 m, 18 m, and 17 m, for the masts #1, #2, #3, #4, and #5, respectively. Here, the height of the mast #3 is 0 m, i.e. the mast #3 is not necessary. All devices can be protected by the remaining masts.

Finally, there are three options for user to finish the design. The button 'Try Again' can be chosen when the user would like to change or add some devices and masts, i.e. returning to step 2. The button 'Re-enter Substation' is used in case of adjusting the substation boundary, i.e. when the user would like to return to step 1. Otherwise, the user can choose the button 'Finish' to complete designing LPSs.

Plan views of protected zones for the devices of the voltage level 230 kV and various device heights are shown as in Fig. 3.6, Fig. 3.7.
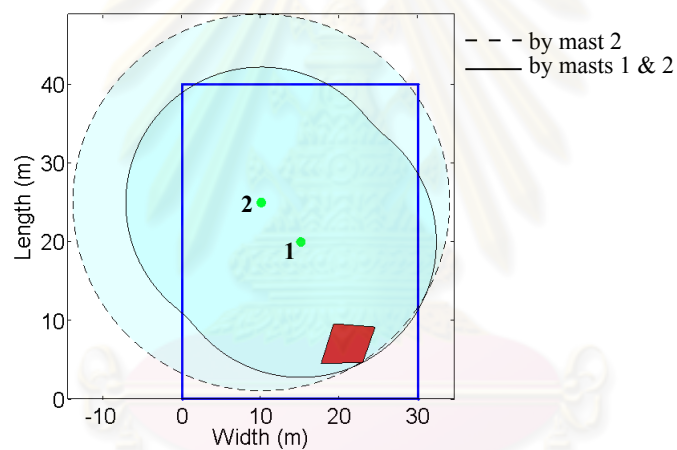
Figure 3.6: Plan view of the protected zones for a 230 kV device with a height of 5 m
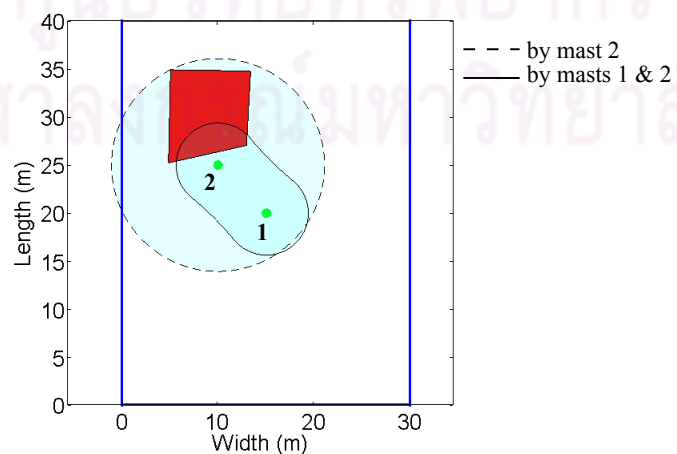
Figure 3.7: Plan view of the protected zones for a 230 kV device with a height of 15 m

Also, a plan view of protected zones for the device of the voltage level 500 kV and the device height of 15 m is shown as in Fig. 3.8.
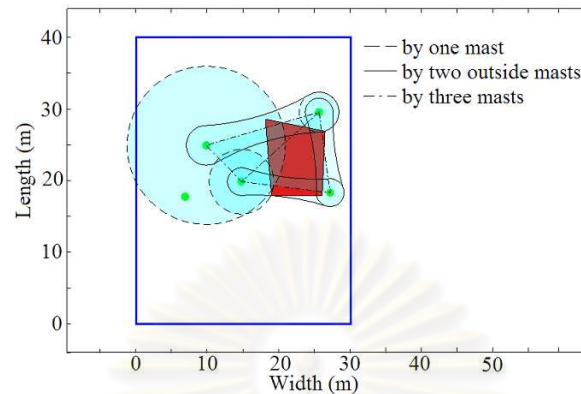
Figure 3.8: Plan view of the protected zone for a 500 kV device with a height of 15 m.

From previous figures, it is evident that all devices (the red ones) are inside the protected zones (the green ones), i.e. all devices are protected by those masts. Moreover, each device is very close to its corresponding protected zones. As a result, the mast heights cannot decrease because if not, the protected zones would be narrowed, and some parts of the devices would be outside the protected zones, i.e. those masts could not protect the devices. In summary, the mast heights are as small as possible to properly protect the substation.

3.2.3 Economical Criterion Achievement of the Computational Tool

The computational tool was developed to compute mast heights from possible LPS cases of a substation. After that, the sums of the mast heights of the cases would be compared with each other to choose the lowest one.

However, can we decrease a mast height when a three-mast configuration option is given? The answer is *'No'*, because if a mast height is decreased, those masts could not protect the devices in the substation, as stated above. As a result, the mast heights calculated by the tool are the smallest. Hence, we achieved an LPS which satisfies the economical criterion through this computational tool.

To explain the applicability of this computational tool, some examples are shown in next section. The tool was implemented with various characteristics of substation area, devices, desired masts, and voltage level. Of course, please concentrate on results: whether mast lay-out can protect all equipment or not, and whether the program can calculate for a mast lay-out or not (i.e. the limited conditions are broken or not). Note that, the following examples were computed based on Love's equations.

3.3 Examples

Briefs of the examples are shown in Table 3.1.

Table 3.1: Example briefs

Example	Mast number	Purpose
1	1	To represent a protected zone of a single mast
2	2	To consider the first adjustment alternative which would be stated in example 1
3	2	- To consider the second adjustment alternative which would be stated in example 1 - To represent a protected zone of two masts
4	3	To strive for reduction of mast heights when a greater number of masts is used in comparison with examples 3
5	3	Limited condition trespass
6	5	Limited condition trespass

3.3.1 Example 1

The purpose of this example is to represent a protected zone of a single mast.

The dimension of the substation is 30×40 m^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. Only one mast is used to protect all devices, as shown in Fig. 3.9.
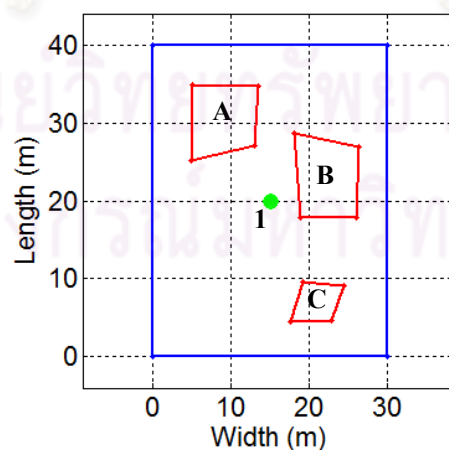
Figure 3.9: Lay-out of the substation in example 1

The mast height calculated is 44.6683 m which equal to the striking distance to ground r_g, when Love's equations were applied. Please do not forget that the maximum height of

mast is r_g (see chapter 2). Therefore, one mast cannot be used to protect the substation against lightning. It is demonstrated by Fig. 3.10. There are some devices which are outside the protected zone. In addition, status of the mast is 'Not good' on the panel 'Information of Masts' to refer that this mast cannot protected effectively.
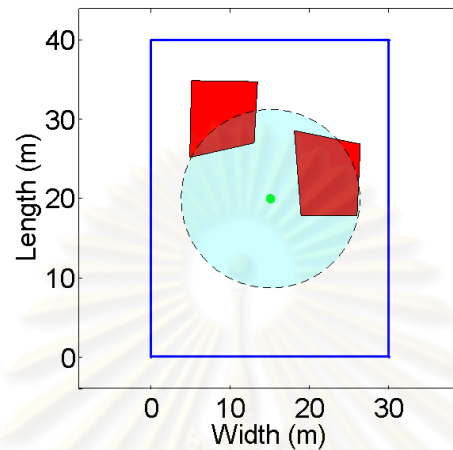
Figure 3.10: Protected zone for voltage $\geq$ 230 kV and devices of 15 m in example 1
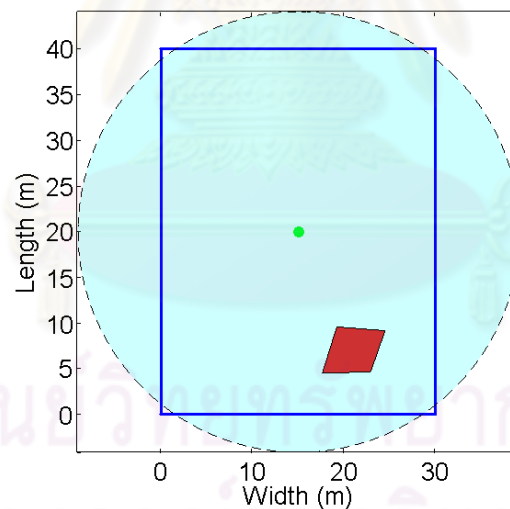
Figure 3.11: Protected zone for voltage $\geq$ 230 kV and a device of 5 m in example 1

Accordingly, in order to protect the substation properly, there are two alternatives

- Change the location of this mast.

- Add more mast.

They will be considered respectively in the following examples.

3.3.2 Example 2

The purpose of this example is to consider the first adjustment manner about mast lay-out, as was stated in the example 1. The desired mast was moved to other location as shown in Fig. 3.12.
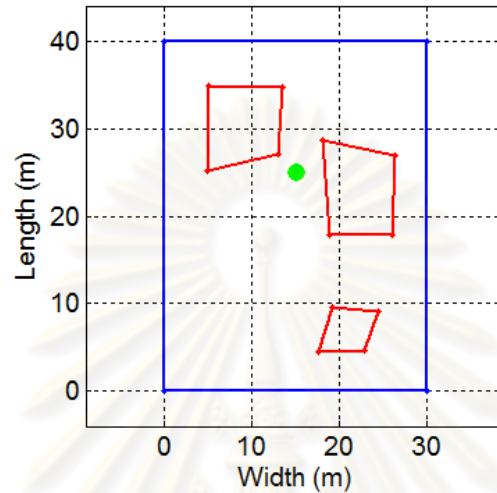
Figure 3.12: Lay-out of the substation in example 2

However, the mast height calculated is still 44.6683 m, or r_g; and the mast still cannot protect for some devices, as in Fig. 3.13. Thus, we have to add more mast to protect the substation from lightning strike, as shown in example 3.
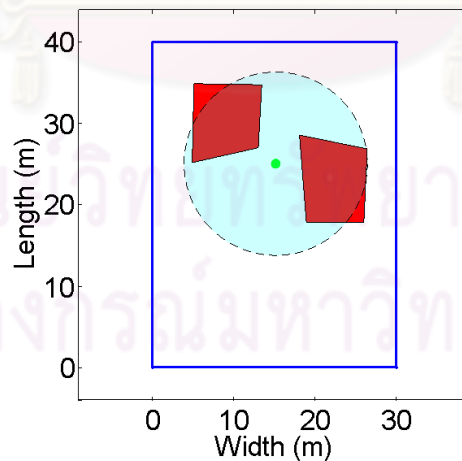
Figure 3.13: Protected zone for voltage $\geq$ 230 kV and devices of 15 m in example 2

3.3.3 Example 3

The purpose of this example has twofold

- To consider the second adjustment manner about mast lay-out, as was stated in the example 1 and the example 2.

- To represent a protected zone of two masts.

With the same devices as in example 1, there are two desired masts as shown in Fig. 3.14.
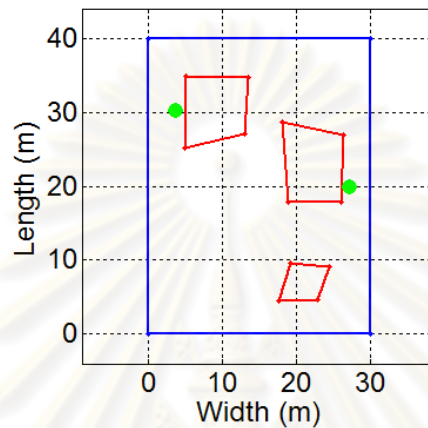
Figure 3.14: Lay-out of the substation in example 3

The masts height calculated is about 33 m. The protected zones for the devices of 15 m and 5 m are shown in Fig. 3.15. It is evident that all devices are properly protected by the two masts; because each device is inside a corresponding protected zone.

(a) For the height of 5 m

(b) For the height of 15 m
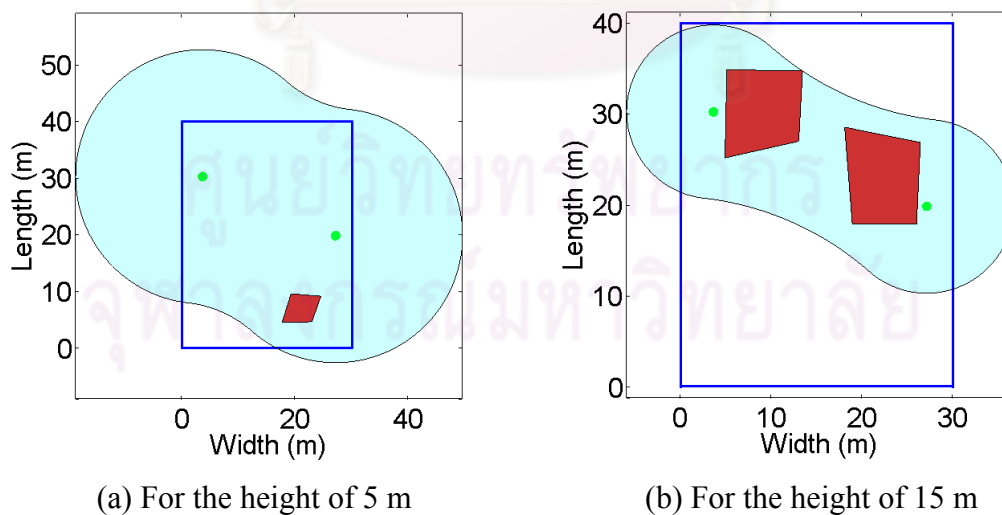
Figure 3.15: Protected zones for voltage level $\geq$ 230 kV and device heights of 5 m and 15 m in example 3

3.3.4   Example 4

Objective of this example is to strive for reduction of mast heights when a greater number of masts is used in comparison with the previous examples; because manufacturing and construction of a short mast are easier than a high mast, so a large number of short masts is sometime preferred to a small number of high masts. Three masts are used in this example, see Fig. 3.16.
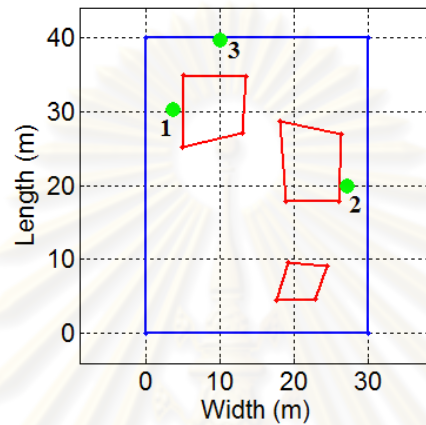
Figure 3.16: Lay-out of the substation in example 4

We see that the mast heights calculated are reduced to about 25 m, 25 m, and 23 m, for the masts #1, #2, and #3, respectively. Fig. 3.17 shows the protected zones for 230 kV and the device of 5 m; where a solid line area is protected zone by two masts, a dashed line area is protected zone by single mast, and a dash-dot line triangle area is protected zone by a three-mast group.
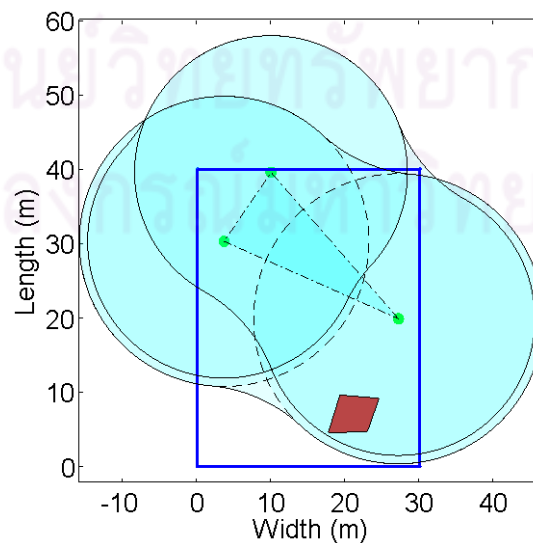
Figure 3.17: Protected zones for voltage 230 kV and a device of 5 m in example 4

Also, Fig. 3.18 shows the protected zones for the devices of 15 m.
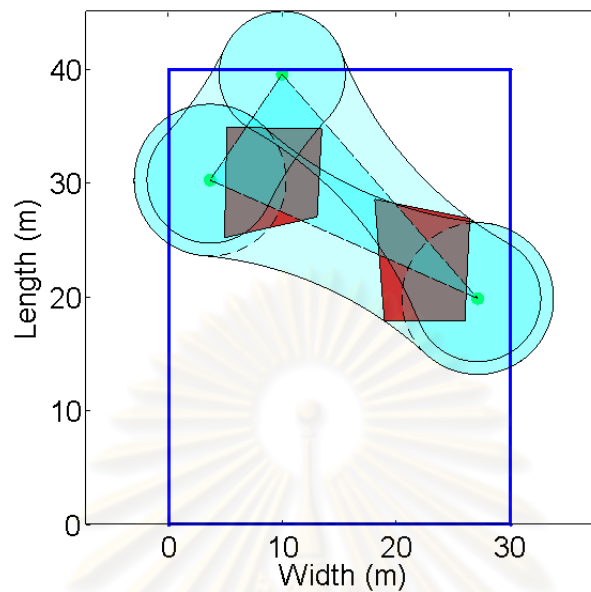
Figure 3.18: Protected zones for voltage $\geq$ 230 kV and devices of 15 m in example 4

3.3.5 Example 5

Objective of this example, as well as example 6, is to show some cases of trespassing limited conditions; the program thus cannot calculate for those cases. Please keep in mind that the limited conditions are just broken if we consider case of more than two masts.

In this example, the devices are the same as in example 1. There are three masts desired as shown in Fig. 3.19.
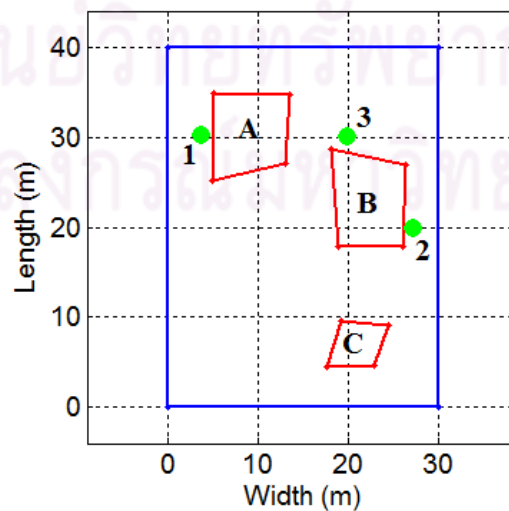
Figure 3.19: Lay-out of the substation in example 5

When the program is executed, an announcement will appear as in Fig. 3.20. Why cannot the program be used for this situation? Which limited condition was broken?

Figure 3.20: The announcement in example 5

Here, two limited conditions are

- Each mast of a certain voltage level is contained by at least one three-mast group.

- Each outside mast has **only** two neighbor masts.

On the other hand, if a three-mast group is existed then this group must satisfy the condition: The center of the circumscribed circle of the mast group must be within the triangle, see chapter 2. However, the triangle, which is formed by three masts in this case, is an obtuse triangle (there is an obtuse angle at the mast #3), i.e. the center of the circle is outside the triangle. It means, there is not any three-mast group in this example. Therefore, the masts #1, #2, and #3 are not contained by any three-mast group. The first limited condition is broken. To protect for the substation, we have to change the mast locations (as in example 4) or add more mast.

3.3.6 Example 6

This example represents the case of trespass of the second limited condition. Figure 3.21 shows substation lay-out.
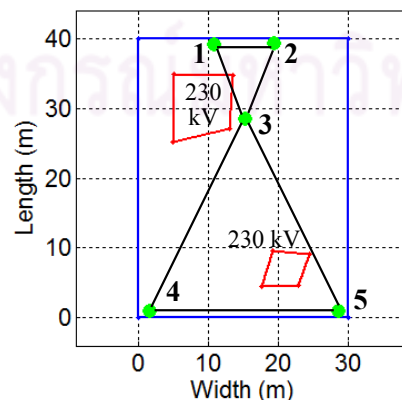
Figure 3.21: Lay-out of the substation in example 6

Here, the substation has two 230 kV devices and is protected by five desired masts. In case of three-mast groups being (#1, #2, #3) and (#3, #4, #5), the program cannot operate because the second limited condition is broken, the mast #3 has four neighbor masts: #1, #2, #4, and #5.

3.4   Summary

1. A computational tool was developed to design LPSs for substations. However, some limited conditions have still existed.

2. The tool can be used to design LPSs based on various kinds of equations: Young's equations, Love's equations, CIGRE equations, IEEE-1992 equations, and IEEE-1995 equations.

3. An LPS designed satisfies the economical criterion, i.e. total of mast heights is the smallest.

CHAPTER IV

Effect of Different Striking Distance Formulae on the Design of LPSs for Substations

4.1 Introduction

As stated before, applications of the EGM are different because different formulae to determine striking distances can be used. Thus, there are two questions for LPS designer: "How do different formulae affect on the LPS design?" and "Which kind of formulae should be used for LPS design?".

As a result, this chapter presents an investigation on the effect of various striking distance equations, including Love's, Young's, IEEE-1992, IEEE-1995, and CIGRE equations, on the design of an LPS of a substation by using masts. Some recommendations about the applications of the striking distance equations are also suggested. [39]

4.2 Simulation and Discussion

Here, we present the calculation results of mast heights for 5 substation layouts. The system voltage of all devices within the substations is 230 kV.

Firstly, two substation lay-outs in Fig. 4.1 were computed in three cases: a number of masts used is 1, 2, and 3.

● desired locations of the masts A,B,C
▬ Polygons are devices so that:
(1): 7 m   (2): 10 m   (3): 12 m
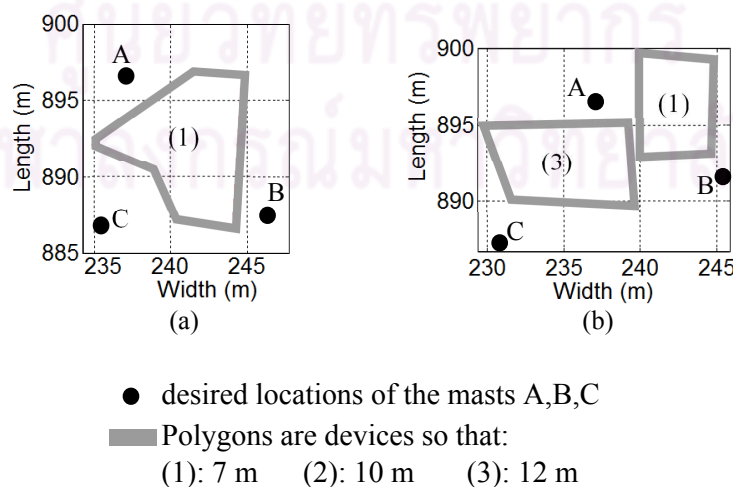
Figure 4.1: Substation lay-outs in cases of 1 mast, 2 masts, and 3 masts

In addition, three substation lay-outs in Fig. 4.2 were computed in cases of a number of masts used more than 2.

(a) (b) (c)

● desired locations of the masts A,B,C,D,E,F

▬ Polygons are devices so that:

(1): 7 m   (2): 10 m   (3): 12 m
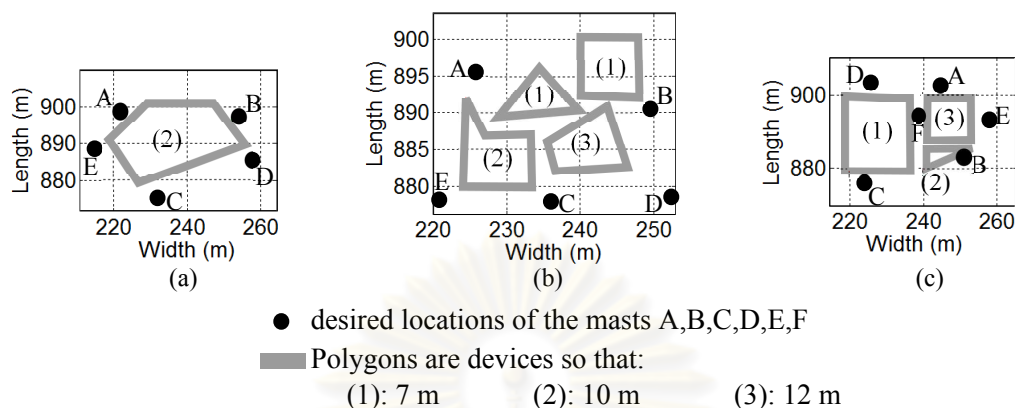
Figure 4.2: Lay-outs substations in cases of more than 2 masts

As a result, there are 15 scenarios for the substation layouts, as shown in Table 4.1 (number of masts used are varied)

Table 4.1: Scenarios and mast heights calculated

Scenario	Lay-out	Masts	Total of mast heights (m)				
			Love	Young	CIGRE	IEEE 1992	IEEE 1995
1		A	18.3	15.9	20.5	16.6	22.8
2	Fig. 4.1(a)	A,B	23.4	21.7	25.5	22.4	25.6
3		A,B,C	31.6	29.7	34.1	30.6	34.2
4		A	23.0	19.9	23.1	20.3	30.1
5	Fig. 4.1(b)	A,B	44.2	38.9	44.8	39.5	55.6
6		A,B,C	49.7	46.8	52.3	47.2	54.7
7		A,B,C	53.4	48.5	58.3	49.5	62.0
8	Fig. 4.2(a)	A,B,C,D	64.9	59.3	71.2	60.7	74.6
9		A,B,C,D,E	71.8	66.7	78.0	68.2	79.9
10		A,B,C	62.3	54.5	65.5	55.7	83.8
11	Fig. 4.2(b)	A,B,C,D	74.0	65.2	78.5	66.9	96.8
12		A,B,C,D,E	69.5	65.0	75.7	66.5	76.5
13		A,B,C,D	72.6	66.3	75.4	67.2	85.4
14	Fig. 4.2(c)	A,B,C,D,E	74.0	70.9	78.4	71.6	78.6
15		A,B,C,D,E,F	83.8	80.8	90.3	81.4	90.6

From Table 4.1, comparisons of total mast heights calculated by using different equa-

tions are shown in Fig. 4.3. In the figure, the result determined by using Love's equations is selected as a value-based of 100 %.
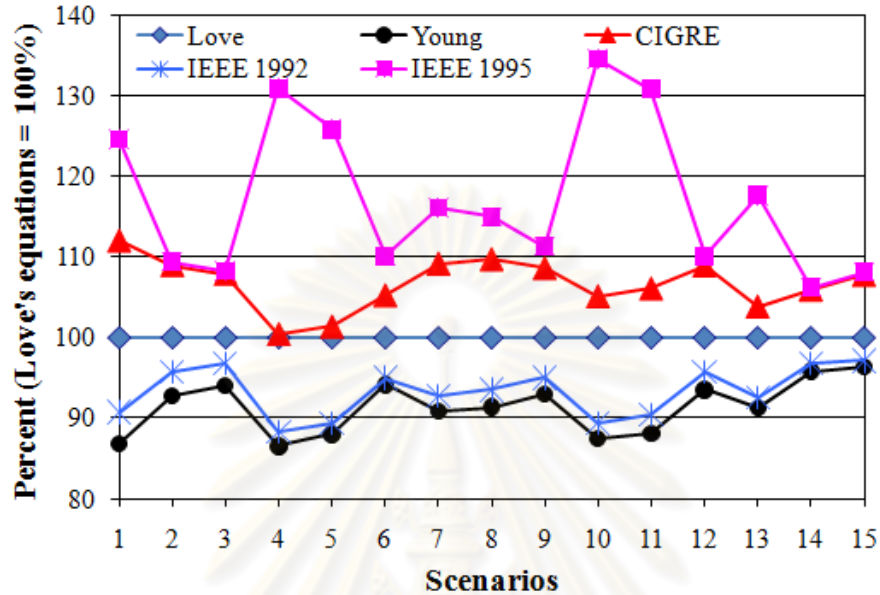
Figure 4.3: Total of mast heights due to equations used

From Fig. 4.3, we can see that large differences in LPSs designed are caused by the selections of the striking distance equations. The method which results in the highest quantity of material used is IEEE-1995. The methods which give the lowest quantity of material used are Young's equations and IEEE-1992.

An engineer who wants to design an LPS for a substation should consider which equations should be applied because of two reasons as follows

Firstly, a cost of a construction depends on the quantity of the material. Here, the engineer can choose a kind of equations based on the relationship between the LPS cost and the importance of the substation, as well as a lightning ground flash density at the location of the substation. If the substation is very important and lightning usually strikes the substation, then the cost is not an important factor. A proper method is selected the one that gives the largest values of mast heights.

Secondly, as the maximum value of a mast height is the striking distance to ground, r_g (see chapter 2); in many cases, a method which gives high values of mast heights may not a good LPS as there are some masts whose heights are higher than r_g. A method which results in lower values of mast heights should be used.

4.3   Summary

1. The total mast heights calculated bases on various proposed striking distance equations has been presented. An LPS with the largest material quantity is resulted from the using of IEEE-1995. In cases of CIGRE, Love's, IEEE-1992, and Young's equations, the cost decreases.

2. A method, which is applied in the designing of LPS for a substation, should be considered based on cost of the LPS, importance of the substation, and lightning flash density. However, in a case where the calculated mast height is greater than r_g, we should use other method which gives lower values of mast heights.

CHAPTER V

Application of the Computational Tool for a Real Substation

5.1 Introduction

Ha Dong is a district of Ha Noi city - the capital of Vietnam, and is an important point in Vietnamese electrical system map. At Ha Dong substation, there are some in-coming lines and out-going lines, including 220 kV and 110 kV, to supply electrical energy for Ha Noi and other cities. This substation is thus large and has three voltage levels: 220 kV, 110 kV, and 35 kV. Here, the computational tool is applied to the 220 kV area within the substation.

This chapter presents an application of the computational tool to design an LPS for this area, as well as check the ideas which were stated in chapter 4.

5.2 Substation Topologies

Figure 5.1 shows electrical devices, such as busbars, lines, and transformers, and desired mast locations of this area. Two electrical device heights that must be protected are 11 m and 17 m. In Fig. 5.1, the 11 m devices are in black and green; and the 17 m devices are in red. There are 15 desired locations of masts in blue, from M1 to M15. The out-going feeders are not necessary to be protected by LPS since they, together with transmission lines outside the substation, are protected by shielding wires.

Firstly, we should make a consideration about possible three-mast configuration options to demonstrate the idea *"the larger number of masts is, the larger number of options"* in chapter 2, such that

- The group which contains four masts M2, M3, M4, and M5 can create 2 options: an option including two three-mast group (M2,M3,M4) and (M3,M4,M5), and an option including two three-mast group (M2,M3,M5) and (M2,M4,M5).

- Similarly, in cases of the 5 four-mast groups (M2,M3,M6,M7), (M3,M5,M8,M9), (M3,M7,M9,M10), (M8,M9,M11,M12), and (M9,M10,M12,M13), each case can create 2 options.

- As the result, a number of possible options is at least $2^6 = 64$. With such large number, a hand-calculation is very complicated. Thus, the computational tool was applied to design an LPS for the substation.
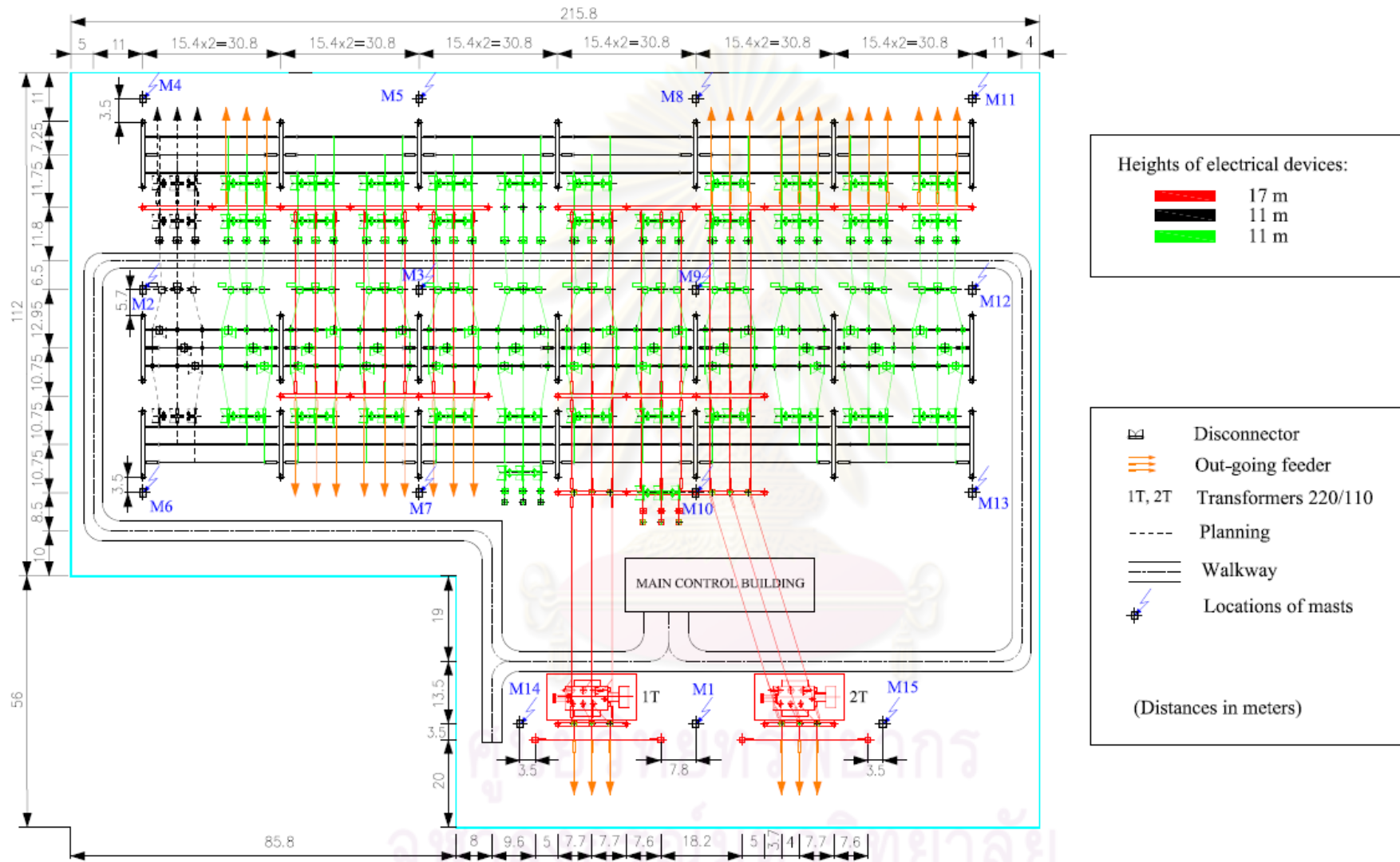
Figure 5.1: Plan view of the 220 kV area of the Ha Dong substation

5.3 The LPS Design

First of all, please keep in mind that the methodology was developed according to research in electrical power systems containing a voltage level of 230 kV instead of 220 kV (see chapter 2). Nevertheless, the methodology does not need to be corrected when it is applied to 220 kV systems; and ideas for 220 kV is the same as case of 230 kV by following reasons

- Firstly, the determinations of striking distances are based on value of design current I_d. However, the values of the design current for practical designs, 5 kA and 10 kA, are approximate. For example, Andrew R. Hileman stated that the design current may be 8 kA for 230 kV, but its value for practical designs is 10 kA [7].

- Secondly, the nearest lower voltage of 230 kV is 138 kV [7]. Therefore, the idea of *"If nominal system voltage < 230 kV, I_d is 5 kA. If the voltage ≥ 230 kV, I_d is 10 kA"* is the same as *"the value 5 kA should be used for voltage ≤ 138 kV and the value 10 kA should be used for voltage ≥ 230 kV"*.

- Lastly, the value 220 kV is nearer to 230 kV than 138 kV. Thus, the suggested design current for 220 kV should be similar to the case of 230 kV, rather than the case of 138 kV.

Even though the tool was developed based on the idea of 230 kV, the application for 220 kV devices and masts is just input all objects as they are the 230 kV equipment.

Moreover, drawing exactly every devices takes a long time of a engineer. This matter is not necessary because the devices can be gathered in group, as shown in Fig. 5.2.
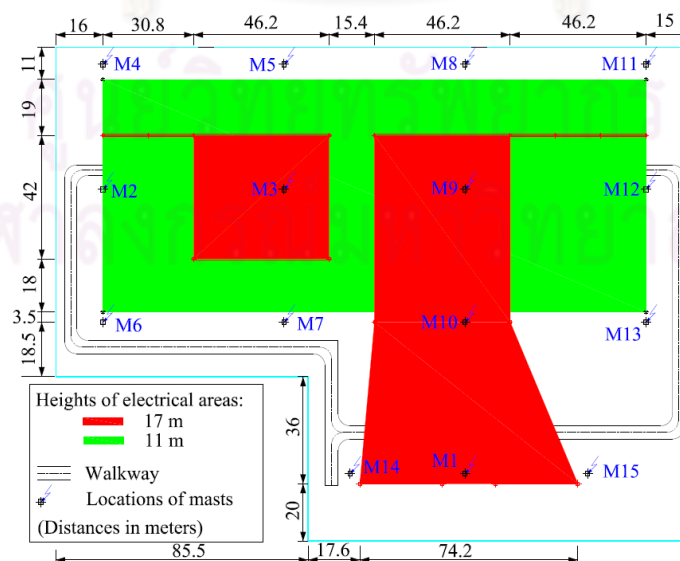
Figure 5.2: Grouping of electrical devices in the 220 kV area of the Ha Dong substation

Here, the red areas are groups of devices with the height of 17 m; and the green area is a group of devices with the height of 11 m. The desired locations of the masts are the positions M1, M2, M3, M4, M5, M6, M7, M8, M9, M10, M11, M12, M13, M14, and M15.

As a result, the substation lay-out is shown in Fig. 5.3 when the computational tool is applied to design an LPS for the substation.
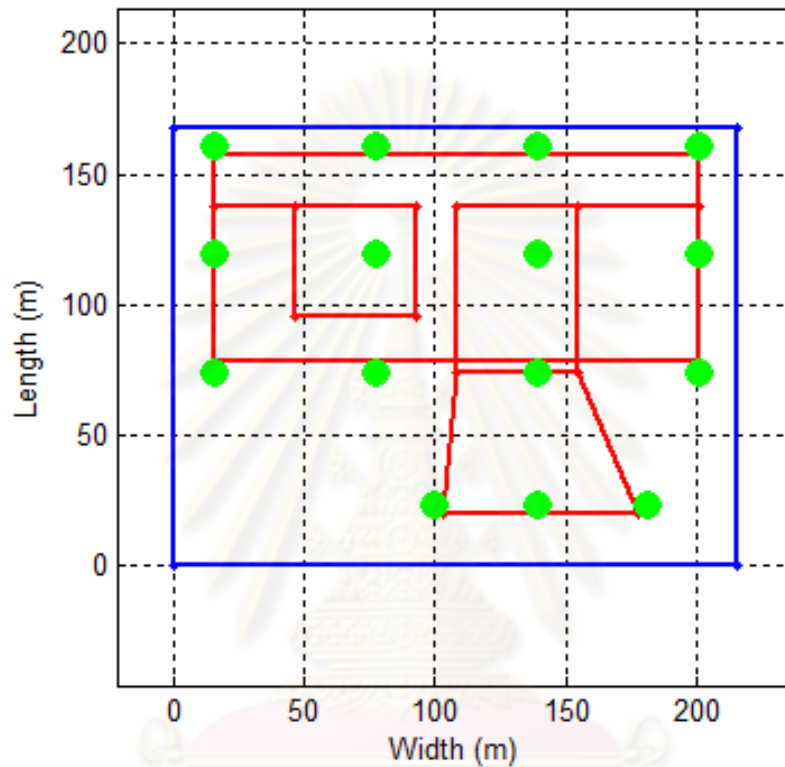
Figure 5.3: The substation lay-out in the computational tool

In this figure, the substation boundary is the blue rectangular; the desired locations of the masts are the green points; the electrical areas, which are protected, are the red polygons.

After running time is about one hour, the mast heights based on Love's equations are shown in Table 5.1.

Table 5.1: Mast heights based on Love's equations

Mast	M1	M2	M3	M4	M5	M6	M7	M8
Height (m)	36.4	38.5	38.5	36.4	36.5	38.5	38.5	36.5
Mast	M9	M10	M11	M12	M13	M14	M15	
Height (m)	38.5	38.5	36.4	36.5	34.2	34.1	36.4	
Mast height total	554							

Figures 5.4 and 5.5 show the protected zones for the device heights of 11 m and 17 m. Entire electrical areas are inside the protected zones. That is, those mast heights satisfy for the protection of the substation.
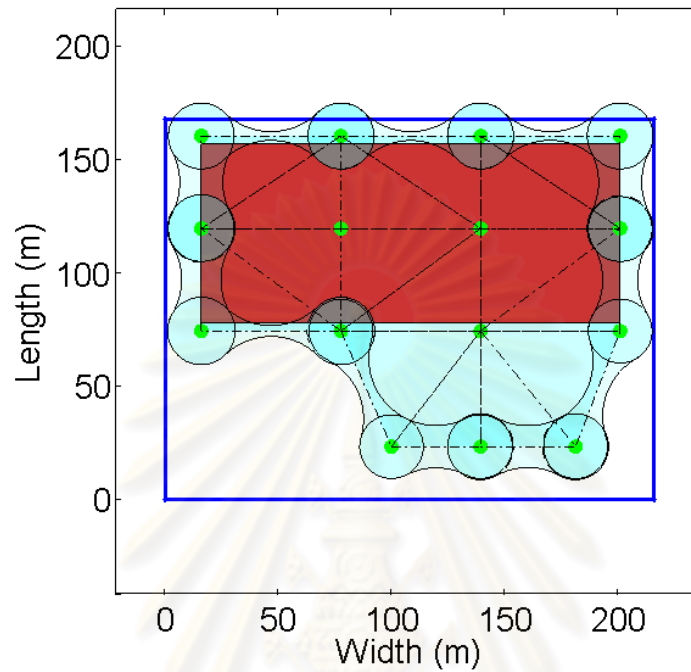
Figure 5.4: The protected zones for the device height of 11 m
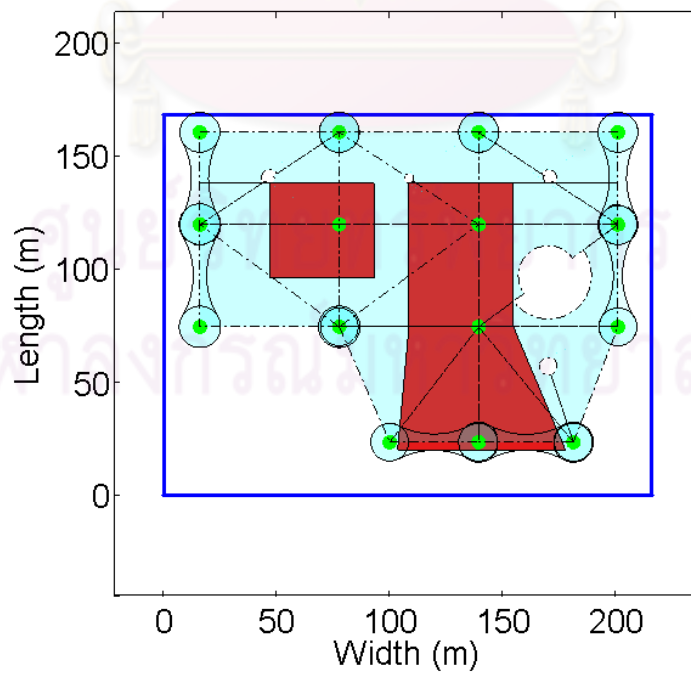
Figure 5.5: The protected zones for the device height of 17 m

Similarly, Table 5.2 shows mast heights when IEEE-1992 and Young's are applied.

Table 5.2: Mast heights based on IEEE-1992 and Young's equations

	Mast	M1	M2	M3	M4	M5	M6	M7	M8
IEEE-1992	Height (m)	26.4	29.1	29.1	28.3	28.4	29.1	29.1	28.4
	Mast	M9	M10	M11	M12	M13	M14	M15	
	Height (m)	29.1	29.1	28.3	28.4	27.2	27.4	27.2	
	Mast height total	425							
Young	Mast	M1	M2	M3	M4	M5	M6	M7	M8
	Height (m)	26.3	29.8	29.8	28.8	28.9	29.8	29.8	28.9
	Mast	M9	M10	M11	M12	M13	M14	M15	
	Height (m)	29.8	29.8	28.8	28.9	27.4	27.7	27.4	
	Mast height total	432							

From Table 5.1 and Table 5.2, total of mast heights for Love's equations is 554 m which is higher than the cases of IEEE-1992 and Young's equations. Also, the totals for IEEE-1992 and Young's equations are nearly the same. These comparisons completely agree with the ideas previously stated in chapter 4.

On the other hand, in cases of CIGRE and IEEE-1995 equations, the computational tool cannot bring out any LPS because

- As stated in chapter 4, mast heights calculated in cases of CIGRE and IEEE-1995 equations are higher than the case of Love's equations. Furthermore, mast heights are limited by a value of a striking distance to ground r_g, as was stated in chapter 2. Consequently, regarding the mast lay-out, even if mast heights are the maximum value r_g, some three-mast groups could not protect devices inside the triangle which is formed by the three masts. As a result, all masts cannot be grouped into three-mast configurations, i.e. there are some masts which are not contained by any three-mast group. That is, the first limited condition is trespassed; and there is not any LPS designed by the tool.

As a consequence, these results for CIGRE and IEEE-1995 equations are completely agree with the ideas that are mentioned in chapter 4.

5.4 Summary

1. From the application of the computational tool on the 220 kV area of the Ha Dong substation, it proves that the computational tool is helpful to design LPSs for substations.

2. The results also prove that the ideas which were stated in chapter 4 are correct. Thus, the engineer is recommended that effect of striking distance equations should be considered to design an appropriate LPS.

CHAPTER VI

Conclusions and Future Work

6.1 Conclusions

For lightning protection problem regarding substations, there are some methods which have been investigated since about 200 years ago. However, the EGM is currently preferred for LPS design. The method bases on the ideas about striking distances and attempts to produce a perfect protection. In this work, five striking distance equations were applied. They are Love's, Young's, CIGRE, IEEE-1992, and IEEE-1995 equations. In addition, scope of this work is confined to the design of LPSs for substations by using only masts.

The contribution of this work has twofold

- Develop a computational tool with graphic interface to help engineers who design substation protection systems against lightning.

- Give some suggestions to engineer about choosing proper kind of striking distance equations in LPS design.

The idea about developing computation tool arose from a fact that in LPS design, a hand design spends a long time; and it is not easy when an economical criterion is considered. Therefore, we created the tool based on MATLAB$^{®}$ to design a LPS which satisfies as small as possible the quantity of the used material. The tool was applied to design a LPS for the 220 kV area within the Ha Dong substation, Vietnam.

Moreover, one more advantage of the tool is to check an existent LPS, or only some masts, that whether they can be salvaged or not. For example, if there are some masts with certain heights, and the engineer wants to use those masts for lightning protection, he can use the tool to calculate the required mast heights. The heights of existent masts are then compared with the calculated mast heights. The engineer will know that which installed masts can be salvaged and which masts must be freshly installed.

According to the describing of the tool in chapter 3, we see that the tool can be applied for any area, not limited to substations.

As a consequence of the tool application, the author investigated about effect of various striking distance formulae on LPSs designed. Suggestions are

- A LPS with the largest material quantity is resulted from the using of IEEE-1995. The lower are CIGRE and Love's equations, respectively. In case of IEEE-1992 and Young's equations, the mast heights are nearly the same and are the smallest.

- A kind of equations applied in the designing of LPS for a substation should be considered based on cost of the LPS (through the sum of the mast heights), importance of the substation, and lightning flash density. However, in a case where the calculated mast height is greater than the striking distance to ground r_g, we should use other method which gives lower values of mast heights.

    Nevertheless, two limited conditions of the tool still remain as follows

- Each mast of a certain voltage level is contained by at least one three-mast group.

- Each outside mast has **only** two neighbor masts.

    In spite of these limitations, this tool is helpful for engineers in LPS design for substations; the application of this tool on the Ha Dong substation is an example.

6.2 Future Work

The author intends to apply this tool in practice. Yet, there are two matters, which the author desire to do first, as follows

1. Eliminating the limited conditions of the tool.

2. As the running time in the chapter 5 is about one hour, the author want to reduce this time. Apart from consideration about computer configurations, two feasible solutions are recommended: attempting to reduce time of commands, functions, and loops in the procedure of the tool; or using other software instead of MATLAB$^{\circledR}$.

On the other hand, a computational tool which can compute lightning protection probability of substation protection using masts (risk assessment) is also suggested for future work. With this tool, engineers can evaluate effect of different striking distance equations on LPSs designed more accurately.

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APPENDICES

Appendix A: Flow Chart of the Computational Tool

```
                          ┌──────────────┐
                          │    START     │
                          └──────┬───────┘
                                 │
                                 ▼
              ┌──────────────────────────────────────┐
       ┌─────▶│     Input substation boundary        │
       │      │  (step 1 of the tool, see chapter 3)  │
       │      └──────────────────┬───────────────────┘
       │                         │
       │                         ▼
       │      ┌──────────────────────────────────────┐
       │ ┌───▶│       Input devices and masts         │
       │ │    │  (step 2 of the tool, see chapter 3)  │
       │ │    └──────────────────┬───────────────────┘
       │ │                       │
       │ │                       ▼
       │ │       ╱────────────────────────────╱
       │ │      ╱   Determine mast heights    ╱   Appendix B
       │ │     ╱────────────────────────────╱
       │ │                       │
       │ │                       ▼
       │ │       ╱────────────────────────────╱
       │ │      ╱       Show result            ╱
       │ │     ╱ (step 3 of the tool, see chapter 3)╱
       │ │    ╱────────────────────────────╱
       │ │                       │
       │ │                       ▼
       │ │  Y      ◇───────────────────────────◇
       │ └────────◇   Return to step 2 of the tool   ◇
       │          ◇ ('Try Again' button, see chapter 3)◇
       │          ◇───────────────────────────◇
       │                        │ N
       │                        ▼
       │  Y       ◇───────────────────────────◇
       └─────────◇   Return to step 1 of the tool   ◇
                  ◇('Re-enter Substation' button, see chapter 3)◇
                  ◇───────────────────────────◇
                              │ N
                              ▼
                        ┌──────────┐
                        │   END    │
                        └──────────┘
```
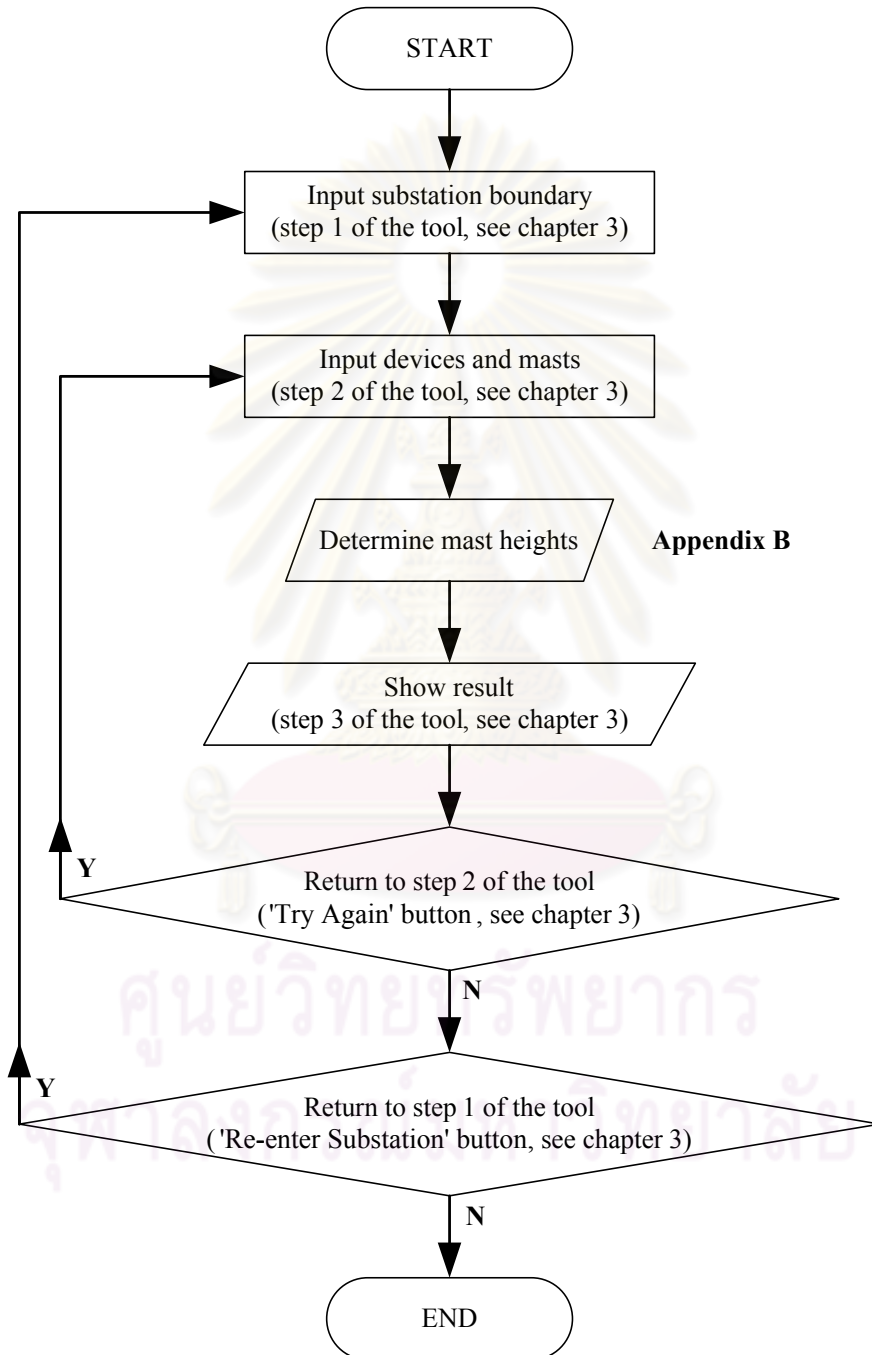
Appendix B: Flow Chart for Determination of Mast Heights

```
                        ┌─────────────┐
                        │    START    │
                        └──────┬──────┘
                               ↓
              ┌────────────────────────────────┐
              │ Assume that there are m voltage │
              │      levels to be protected     │
              └────────────────┬───────────────┘
                               ↓
    N ←──────────────────◇  i=1:m  ◇──────────────────────────┐
                               │ Y                             │
                               ↓                               │
              ┌────────────────────────────────┐               │
              │ A number of masts of this voltage│   Appendix C │
              │           level is n            │               │
              └────────────────┬───────────────┘               │
                               ↓                               │
                         Y    ┌──────────────────────────┐     │
               ◇  n > 2  ◇───→│ Determine mast heights in │────→│
                         │    │ case of more than two masts│    │
                        N│    │  for a certain voltage level│   │
                         ↓    └──────────────────────────┘     │
                         Y    ┌──────────────────────────┐     │
               ◇  n = 2  ◇───→│ Determine mast heights in │────→│
                         │    │     case of two masts      │     │
                        N│    │  for a certain voltage level│    │
                         ↓    └──────────────────────────┘     │
                         Y    ┌──────────────────────────┐     │
               ◇  n = 1  ◇───→│ Determine mast height in  │────→┘
                         │    │     case of single mast    │
                        N│    │  for a certain voltage level│
                         ↓    └──────────────────────────┘
                   ┌──────────┐
                   │Impossible│
                   └──────────┘

              ┌────────────────────────────────┐
              │    Recapitulate mast heights    │
              │ which satisfy all voltage level │
              └────────────────┬───────────────┘
                               ↓
                        ┌─────────────┐
                        │     END     │
                        └─────────────┘
```

Appendix C: Flow Chart for Determination of Mast Heights in Case of More than Two Masts and for A Certain Voltage Level

```
                        ┌──────────────┐
                        │    START     │
                        └──────┬───────┘
                               │
               ┌───────────────▼───────────────┐
               │  Assume that there are n options to │
               │   group masts into three-mast  │
               │         configuration          │
               └───────────────┬───────────────┘
                               │
                        ◇──────┴──────◇   N
                        │   i=1:n     │──────────────────────┐
                        ◇──────┬──────◇                      │
                               │ Y                           │
```

Assume that there are n options to group masts into three-mast configuration

i=1:n N / Y

With each three-mast group: Determine a height of masts to protect devices which are inside the triangle formed by the three masts.

With each pair of two neighbor masts: Determine a mast height to protect devices which are protected by both two masts and are not inside any triangle formed by a three-mast group.

With each outside mast: Determine a mast height to protect devices which are protected by only this mast and are not inside any triangle formed by a three-mast group.

Recapitulate mast heights which can protect all devices.

If there is not any option which satisfies the limited conditions N / Y

Choose an option which satisfies the economical criterion

Return to step 2 of the tool (see chapter 3)

END

BIOGRAPHY

Lê Việt Dũng was born in Thanh Hoa, Vietnam, in 1985. He received his Bachelor's degree in electrical engineering from Hanoi University of Technology, Vietnam, in 2008. He has been granted a scholarship by the AUN/SEED-Net (www.seed-net.org) to pursue his Master's degree in electrical engineering at Chulalongkorn University, Thailand, since 2008. He conducted his graduate study with the High Voltage Research Laboratory, Department of Electrical Engineering, Faculty of Engineering, Chulalongkorn University. His research interest includes lightning protection and insulation coordination.