


การคำนวณพื้นที่ที่มีโอกาสถูกฟ้าผ่าโดยวิธี attractive volume concept สำหรับระบบป้องกันฟ้าผ่า



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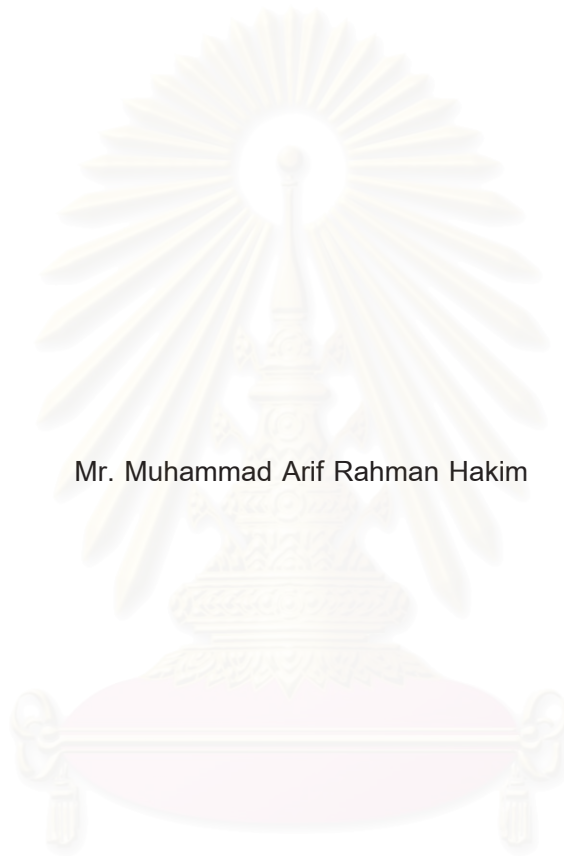
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CALCULATION OF ATTRACTIVE AREA BY USING ATTRACTIVE VOLUME CONCEPT  
FOR LIGHTNING PROTECTION SYSTEMS



Mr. Muhammad Arif Rahman Hakim

สถาบันวิทยบริการ  
จุฬาลงกรณ์มหาวิทยาลัย  
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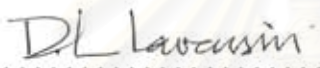
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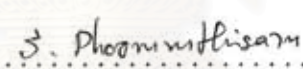
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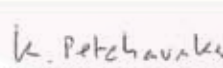
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จุฬาลงกรณ์มหาวิทยาลัย

มุฮัมมัด อริฟ ราห์แมน ฮาคิม: การคำนวณพื้นที่ที่มีโอกาสถูกฟ้าผ่าโดยวิธี attractive volume concept สำหรับระบบป้องกันฟ้าผ่า (Calculation of Attractive Area Using Attractive Volume Concept for Lightning Protection Systems), อาจารย์ที่ปรึกษา: ดร.คมสัน เพ็ชรรักษ์, 74+xi หน้า ISBN 974-53-2898-7

ฟ้าผ่าสามารถทำให้เกิดความเสียหายต่อสิ่งปลูกสร้างได้ทั้งทางตรงและทางอ้อม ดังนั้นเราจึงมักติดตั้งระบบป้องกันฟ้าผ่าให้กับสิ่งปลูกสร้างของเราเพื่อไม่ให้เกิดฟ้าผ่าโดยตรงลงบนสิ่งปลูกสร้าง โดยปกติสิ่งปลูกสร้างจำเป็นที่จะต้องมียระบบป้องกันฟ้าผ่าเมื่อความเสี่ยงที่จะเกิดความเสียหายกับสิ่งปลูกสร้างจากฟ้าผ่ามีค่ามากกว่าความเสี่ยงที่จะเกิดความเสียหายกับสิ่งปลูกสร้างที่เรายอมรับได้ ความเสี่ยงที่จะเกิดความเสียหายกับสิ่งปลูกสร้างสามารถประเมินได้จากการหาจำนวนที่สิ่งปลูกสร้างอาจถูกฟ้าผ่าในรอบหนึ่งปี ซึ่งขึ้นอยู่กับพื้นที่ที่มีโอกาสถูกฟ้าผ่าของสิ่งปลูกสร้างและความหนาแน่นของฟ้าผ่าในบริเวณนั้นในรอบหนึ่งปี การหาพื้นที่ที่มีโอกาสถูกฟ้าผ่าของสิ่งปลูกสร้างทำได้หลายวิธี แต่ในวิทยานิพนธ์นี้จะใช้วิธีแนวคิดปริมาตรที่มีโอกาสถูกฟ้าผ่าซึ่งเป็นปริมาตรที่รวมจุดต่างๆ ในอากาศที่เมื่อหัวฟ้าผ่าอยู่ที่ปริมาตรนี้จะทำให้สิ่งปลูกสร้างถูกฟ้าผ่า และพื้นที่ใดๆที่อยู่ในปริมาตรนี้จะเรียกว่าพื้นที่ที่มีโอกาสถูกฟ้าผ่าซึ่งสามารถคำนวณได้จากการแบ่งปริมาตรดังกล่าวออกเป็นส่วนๆ โดยผลการคำนวณความเสี่ยงที่จะเกิดความเสียหายกับสิ่งปลูกสร้างด้วยการใช้แนวคิดนี้อาจมีความถูกต้องมากกว่าการใช้วิธีอื่น

ในวิทยานิพนธ์ได้รายงานถึงการพัฒนาโปรแกรมเพื่อคำนวณพื้นที่ที่มีโอกาสถูกฟ้าผ่าของอาคารรูปสี่เหลี่ยมผืนผ้าทั้งในกรณีอาคารรูปสี่เหลี่ยมผืนผ้าที่ติดตั้งระบบป้องกันฟ้าผ่าและไม่ติดตั้งผลการวิเคราะห์แสดงให้เห็นว่าอาคารที่ติดตั้งระบบป้องกันฟ้าผ่าจะมีพื้นที่ที่มีโอกาสถูกฟ้าผ่น้อยกว่าอาคารที่ไม่มีระบบป้องกันฟ้าผ่า ดังนั้นอาคารที่ติดตั้งจึงมีความเสี่ยงที่จะเกิดความเสียหายน้อย นอกจากนั้นผู้ทำวิทยานิพนธ์ยังได้เสนอรูปแบบของระบบป้องกันฟ้าผ่าไว้ 8 แบบ พร้อมแสดงรายละเอียดในการคำนวณพื้นที่ที่มีโอกาสถูกฟ้าผ่าของระบบป้องกันฟ้าผ่าแต่ละแบบ โปรแกรมที่พัฒนาขึ้นแสดงภาพของพื้นที่ที่มีโอกาสถูกฟ้าผ่าของระบบป้องกันฟ้าผ่าแต่ละแบบเมื่อเทียบกับพื้นที่ที่มีโอกาสถูกฟ้าผ่าของอาคารรูปสี่เหลี่ยมผืนผ้า ทำให้ผู้ใช้สามารถตัดสินใจได้ว่าระบบป้องกันฟ้าผ่าแบบใดจะเหมาะสมกับอาคารมากที่สุด

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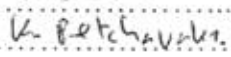
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ATTRACTIVE VOLUME CONCEPT

MUHAMMAD ARIF RAHMAN HAKIM: CALCULATION OF ATTRACTIVE  
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Lightning protection system is needed at a structure if its possible risk due to lightning strikes is greater than accepted risk. The possible risk can be acquired by calculating frequency of lightning strikes to the structure. The frequency of lightning strikes itself, needs a calculation of attractive area of the structure to be done first. There are several methods available for calculating the attractive area of the structure, but this thesis only concern about attractive volume concept which can give better risk assessment than the other methods.

An attractive volume is a volume that contains all possible orientation point from which lightning can strike our structure. The area within this volume is called attractive area, and it can be calculated easily by dividing this volume into several sections. Based on this method, we build a computer program to make the calculation of attractive area of a square roof building. At each section of the attractive volume of the building, its horizontal cross section area will be calculated. For a rectangular roof building that has lightning rods installed on its roof, the horizontal cross section area of the building will be reduced by the horizontal cross section of the lightning rods. Thus, the arrangement of the rods should be noticed. There are 8 arrangement of the rods discussed in this thesis. The arrangement figure and the detail information on how we calculate the horizontal cross section area are given in this thesis. Aside from giving the predicted frequency of lightning strike to the structure, the program also show figures of horizontal cross section area at certain orientation distance. This picture can help the user of the program from deciding which arrangement of the rods that is suitable for their building.

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Student's signature .....   
Advisor's signature ..... 

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Lastly, I am foremost grateful to ALLAH, for giving me the Islam as the light of my life.

*Those who remember ALLAH (always, and in prayers) standing, sitting, and lying down on their side and think deeply about creation of the heavens and the earth, (saying): “Our LORD! You have not created (all) this without purpose, glory to You! (Exalted are You above all that they associate with You as patners). Give us salvation from the torment of the Fire.” [Al Qur’an 3:(191)]*

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# CHAPTER 1

## INTRODUCTION

### 1.1 Motivation

Lightning has been a problem since long time ago, not only because it can cause damage if it strikes directly to a structure, but its electromagnetic and electrostatic pulses can also cause interruption to our communication, electronic and electrical systems. Thus, an assessment of the risk of damage due to lightning must be performed, to know whether we need to install a LPS or not, and if we do, what is the degree of protection level should be chosen [1]. The risk of damage depends on some parameters, with the annual frequency of lightning strikes,  $N$ , as its main parameter. This annual frequency of lightning strikes is depending on the attractive area,  $A_{eq}$ , as well as Ground Flash Density (GFD) of the structures. So, it is important to get the accurate value of these parameters to achieve a good risk assessment.

The first aim of lightning protection system is to intercept the lightning strikes, thus avoiding direct contact between the lightning channel and the object to be protected. The part of the lightning protection system which fulfills this function is termed air termination system. The air termination system is considered to be the main part of the lightning protection system, because interception failure or shielding failure happens if the air termination system fails to intercept the lightning strikes. Thus, the placement of air termination system, such as air terminal on our structure, is important. There are two aspects that have to be considered during the design phase, which are (i) the placement of air terminals should guarantee the safety of our protected structure. It means that the number of interception failure must not exceed the accepted frequency of lightning strikes to the structure,  $N_c$ , as defined in the IEC Standard; (ii) the number of air terminals installed on the structure must be efficient as over design means more money to be expensed.

There are several lightning protection design methods for this design purpose, but only the attractive volume concept, provides an accurate calculation of the attractive area of the structure, will be considered, as it is proved to be protective and efficient

among all. These are the reasons why we are interested in applying this concept for the real structure defined in the scope of this thesis.

## 1.2 Problem Statement

A fundamental aspect of lightning protection system is the lightning protection design method used to identify the most suitable location for the air terminal, based on the area of protection afforded by each terminal. These air terminal placement methods typically fall into one of four categories (see figure 1.1):

- (a) Pure geometrical constructions, such as the Cone of Protection or Protective Angle Method, which is commonly found in national and international standards [2,3,4].
- (b) Faraday Cage concepts, in which a meshwork of conductors or air terminations is placed at set intervals over a structure [5].
- (c) Electro-geometrical Model (EGM), in which empirical relationships for striking distance and lightning peak current are invoked. The most common example is the Rolling Sphere Method, which is also partly a geometric construction [6].
- (d) Physical models, where air breakdown mechanisms are applied to the lightning scale. These models have been derived from laboratory investigations of long sparks and, to a lesser extent, field studies of natural lightning.

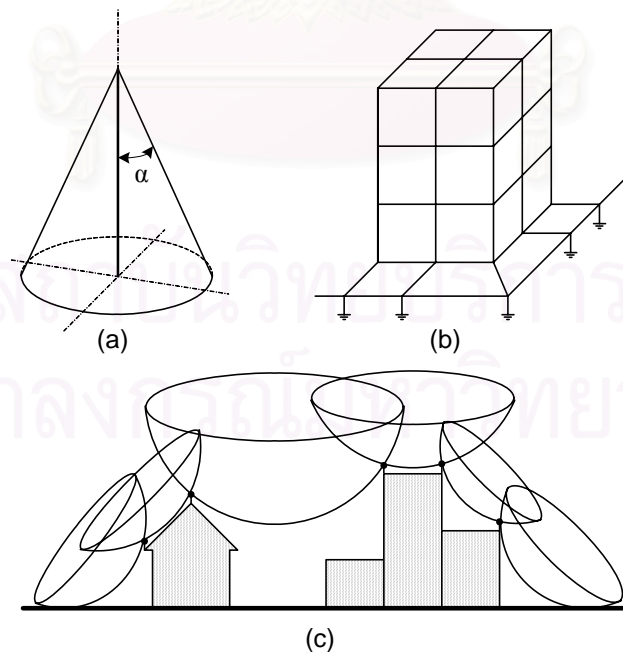


Figure (1.1): Air terminal Placement Methods  
 (a) Cone of protection; (b) Faraday cage; (c) Rolling sphere method

The methods in (a)-(c) are conceptually simple and relatively easy to apply. However, many scientists and engineers agree they have inherent limitations that make them difficult to apply reliably across a wide range of structures, particularly over tall structures [7,8,9].

The Cone of Protection Method is a result of poorly applied and unquantifiable physics principle. Indeed on structures protected by Franklin rods using this design method, it is not unusual to find places where lightning has struck well within the hypothetical zone of protection.

There is no guarantee that metallic strips used in the Faraday Cage method will be struck by lightning in preference to some other nearby exposed point. The dielectric strength of construction materials is such that the lightning strike may flash over to the nearest element of the structural steel, with unpredictable consequences. Furthermore, protection of exposed items such as communication dishes is difficult.

The Rolling Sphere method is undoubtedly the most common technique recommended in Codes of Practice. It originated from the electric power transmission industry, i.e., lightning strike attachment to phase and shield wires of lines and is based on the well-known Electro-geometrical Model (EGM). The EGM relates striking distance to the prospective peak stroke current. To apply this technique, an imaginary sphere, typically 45 m (150 ft) in radius, is rolled over the structure. All surface contact points are deemed to require protection, whilst the unaffected surfaces and volumes are deemed to be protected.

It is claimed that the main advantage of the Rolling Sphere method is the simplicity of its application. This may be the case for simple structures but for more complex ones it is difficult to apply by hand, requiring sophisticated 3D numerical modeling software. The main weakness of this method is that it assigns equal leader initiation ability to all contact points on the structure. That is, for a given prospective peak stroke current or, alternatively, protection level, the striking distance is a constant value. This over-simplification results in over-design on flat horizontal and vertical surfaces and under-design when structural points with significant electric field intensification are outside the sphere radius in a so-called protected zone.

An attractive volume concept proposed by Tibor Horvath, is based on the assumption that the point of strike is only determined near the earth [10]. The point from which the lightning turn definitely toward the point of strike is called the orientation point and the attractive volume is a volume that consists of all possible orientation point of considered structure. This concept is considered to be efficient for the design method, but the applications of this method are rare to see. Thus, in this thesis we will try to apply this method to a structure described in the scope of this thesis. We will use this method to calculate the frequency of lightning strike to considered structure, with and without lightning protection system installed on the structure. For the

design phase, we will let the user of the program to choose the location of air terminal, and let them decide whether the design is good enough to protect their structure or not.

### **1.3 Objective**

The objective of this research is to apply the attractive volume concept for the calculation of the attractive area of a structure defined by the scope of this thesis, through a computer program. The program will also allow us to design an appropriate Lightning Protection System (LPS) for the structure. It will then tell us whether our design is good enough to protect the structure against lightning or not.

### **1.4 Scope of Thesis**

1. The protected structure is a rectangular flat roof building which dimension can be defined through the program. It is assumed that no object is installed on the roof, so the roof will be definitely flat.
2. This building is located alone in a flat ground to make the calculation easier.
3. The placement of air terminals is considered only for the rooftop, so the side flashes are not considered.

### **1.5 Research Procedure**

This thesis will be conducted in several steps to fulfill its objective, which are:

1. Study related IEC Standard on LPS. Two kinds of IEC standard will be studied: (i) IEC 61662 describes a method to calculate risk of damage due to lightning; (ii) IEC 61024-1 describes about protection of structures against lightning. This study is important as its give a basic view about lightning protection system, that we are dealing with.
2. Study the attractive volume concept. The study will be mainly based on the book written by Tibor Horvath entitled Computation of Lightning Protection. He is the one who proposed the attractive volume concept and explained about the concept in his book, so we will get a clear explanation about the concept.
3. Develop a small program for calculation of the attractive area of basic structure, such as a horizontal line above plane and a point above plane. In this simple program, we will apply the attractive volume concept to perform an accurate

calculation of the attractive area. The program will be used further as a procedure in the main program.

4. Develop the main program to calculate frequency of lightning strikes to the structure. This program will also allow us to design the placement of air terminals above our protected structure. The placement of air terminals is done step by step to get an appropriate design.
5. Write the thesis book.

## 1.6 Contribution

1. A program that can calculate the attractive area of a structure accurately, which leads to more accurate risk assessment.
2. An effective lightning protection system design of a structure using the developed program.
3. This developed program can also be used as a basis for further lightning protection system study.



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## CHAPTER 2

### LITERATURE REVIEW

#### 2.1 Risk of Damage due to Lightning Strikes

Lightning strike, whether it strikes directly or indirectly, can cause damages in our system. Thus, we should be able to evaluate the losses (humans or goods) in our system due to lightning strikes, to know whether our system is safe or need a LPS to protect them. We call these losses as risk of damage,  $R_d$ , and usually they are evaluated annually. According to IEC 61662, the risk of damage to the structure can be calculated by using this equation:

$$R_d = (1 - e^{-Npt})\delta \quad (2.1)$$

where

- N is the expected average annual number of lightning strikes to the structure, in strike/year
- p is the probability of damage to the structure (dimensionless)
- $\delta$  is a measure of the amount of possible losses of the structure or of its contents (dimensionless)
- t is the time of observation, in year

The product  $F = N.p$  is the expected average annual number of damages to the structure. If the time observation is  $t = 1$  year, in the case of  $N.p \ll 1$ , the preceding formula may be simplified as follows:

$$R_d = N.p.\delta \quad (2.2)$$

If a LPS, as a measure of damage limitation, is applied, the risk of damage is reduced according to its efficiency.

Protection against lightning aims to reduce the risk of damage,  $R_d$ , below a maximum acceptable one,  $R_a$ .

$$R_d \leq R_a \quad (2.3)$$

Values of  $R_a$  are to be fixed by national bodies concerned if the lightning causes losses involving human, cultural or social values. Representative values of  $R_a$  are listed in table (2.1) below.

Table (2.1): Representative values of acceptable risk [1]

Type of damage	$R_a$	
1	$10^{-5}$	Annual loss of life
2	$10^{-3}$	Annual loss of service
3	$10^{-3}$	Annual loss of heritage

The values  $R_a$  can be fixed by the owner of the structure or by the lightning protection design engineer when losses due to lightning are relevant to private values only.

If the  $R_d$  should be less than  $R_a$ , the frequency of damage to the structure should be limited to the value  $F_a$  accepted as tolerable damage for the structure:

$$F = N \cdot p \leq F_a \quad (2.4)$$

where

$$F_a = \frac{R_a}{\delta} \quad (2.5)$$

Therefore, the lightning flash frequency to the structure should be limited to the value  $N_c$  accepted as tolerable number of lightning strikes to the structure:

$$N \leq N_c \quad (2.6)$$

where

$$N_c = \frac{F_a}{p} \quad (2.7)$$

From above equations, we can see that to know whether our structure is safe or not against lightning strikes, we can just compare the calculated frequency of lightning strike to our structure  $N$  with the accepted one  $N_c$  instead of comparing risk of damage  $R_d$  with the accepted one  $R_a$ . By comparing  $N$ , we can also define a proper degree of

protection level should we need to apply LPS to protect our structure. We avoid of using high protection level of LPS if we can protect our structure with lower protection level of LPS, because higher protection level mean higher cost for installation of LPS.

According to IEC 61024-1-1, the protection level indicates the efficiency of LPS which is the ratio of the average annual number of direct lightning strikes which cannot cause damage to the structure to direct lightning strikes. The protection level and its efficiency can be seen in table (2.2) below.

Table (2.2): LPS efficiency corresponding with protection level [3]

Protection level	LPS efficiency
I	0.98
II	0.95
III	0.90
IV	0.80

From above explanation, we can see that an accurate calculation of  $N$  is needed to achieve a good risk assessment. We can also use this value to define the degree of protection level of LPS we should apply to our structure. That is why we will concern more about the calculation of  $N$  among the others parameter of risk of damage.

The average annual frequency of lightning strikes to the structure is the product of the annual ground flash density  $N_g$  and the attractive area of the structure  $A_{eq}$ :

$$N = N_g \cdot A_{eq} \quad (2.8)$$

The ground flash density is a meteorological parameter of the country and it is measured in ground flash/km<sup>2</sup> per year. Sometimes it is known from direct measurements of lightning counters, but if it is not, then it can be estimated using the following relationships [11]:

$$N_g = 0.04T_d^{1.25} \quad (2.9a)$$

$$N_g = 0.023T_d^{1.3} \quad (2.9b)$$

$$N_g = 0.0086T_d^{1.45} \quad (2.9c)$$

where  $T_d$  is the annual number of thunderstorm days, which is known for most territories of the world from long-term observations.

$N_g$  is a fixed values and it is depend on the location where our structure stand. So, in our program later, we will assess  $N_g$  as the input of the program for calculation of

annual frequency of lightning strikes. The program will mainly focused on the calculation of  $A_{eq}$  using attractive volume concept described in chapter 3.

## 2.2 Protected Volume Concept

The first idea of lightning protection assumed that there is a protected volume into which neither the lightning channel nor its effects can penetrate to cause damage. According to this concept, every structure inside this volume is protected against direct lightning strikes.

In the last century, many authors defined the protected volume by the protective angle. This angle is either produced by lightning rod or horizontal conductor and is at the top of them as shown in figure (2.1).

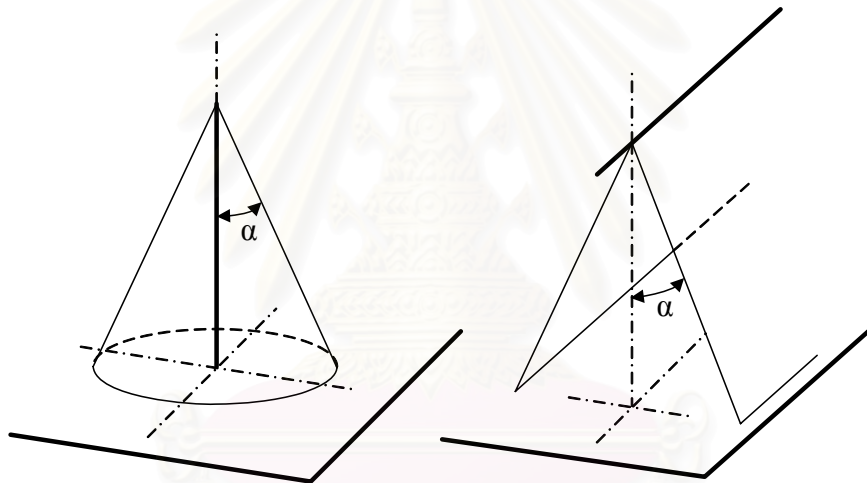


Figure (2.1): Application of the protective angle at a vertical rod and a horizontal conductor

The border surface of the protected volume can be produced by moving a straight line which has a constant angle to the vertical. The motion is for example, rotation around a vertical rod or parallel translation along a horizontal conductor. Schwaiger as written in [10] said that the protective angle has changed from  $7.1^\circ$  to  $83.6^\circ$  as the result of observations made over more than a hundred years.

According to IEC 61024-1-2, the principle of protection by the protective angle is that the air-termination which can be horizontal conductors or lightning rods, should be positioned so that all parts of the structure to be protected are inside the envelope surface generated by projecting points on the air-termination conductors to the reference plane, at an angle  $\alpha$  to the vertical in all directions.

Table (2.3): Positioning of air termination according to the protection level [2]

Protection level	h(m) R(m)	20	30	45	60
		$\alpha^{(o)}$	$\alpha^{(o)}$	$\alpha^{(o)}$	$\alpha^{(o)}$
I	20	25	*	*	*
II	30	35	25	*	*
III	45	45	35	25	*
IV	60	55	45	35	25

\* Rolling sphere only apply in these cases

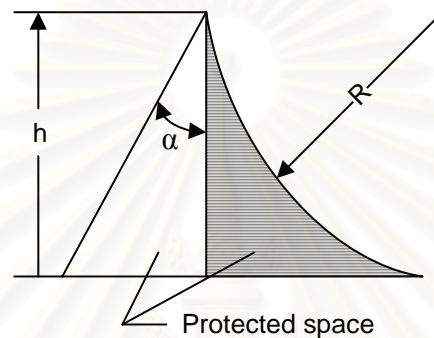


Figure (2.2): Principle of protection by protective angle and rolling sphere

The protective angle  $\alpha$  should comply with IEC 61024-1, which can be seen in table (2.3) (see also figure 2.2),  $h$  being the height of the air-termination above the surface to be protected.

The protective angle method has geometrical limits and shall not be applied if  $h$  is larger than the rolling sphere radius  $R$  as defined in table (2.3). At this condition, we can apply rolling sphere method to protect our structure. However, protective angle method can still be applied successfully to high voltage transmission lines. They have a very simple geometrical structure because the conductors are represented by points in a two-dimensional cross section. Only one parameter, the angle, determines the relative position of the earthed protective conductor to any energized conductor to be protected. A protective angle of  $45^\circ$  produced good results for transmission lines of voltage less than 100 kV. Since about 1930 the protective angle has been decreased and  $30^\circ$  was applied for up to 220 kV. Later  $15^\circ \dots 20^\circ$  was found to be suitable for voltage above 300 kV. The reason for this change was actually the increasing height of the lines and not their nominal voltage.

The third decade of this century was the start of a period of model studies. At this time many scientists set out to solve the problem of the protective effect of air terminations. Although they were not as effective for protection, volumes with curved borders were used in practice as well as the protective angle. The arc of a circle is

applied most frequently in construction. The Schwaiger method (as in [10]) represents the most effective requirements for the protective wires, as shown in figure (2.3a). Later, the centre was assumed to be higher, e.g. twice the height of the line, as shown in figure (2.3b). These figures also highlight the problem of model studies that the protected volume depends on the choice of the orientation point [10]. As a first approximation its worst position was assumed to be in the centre of the circle. This method also involves a subjective moment leading to divergent results.

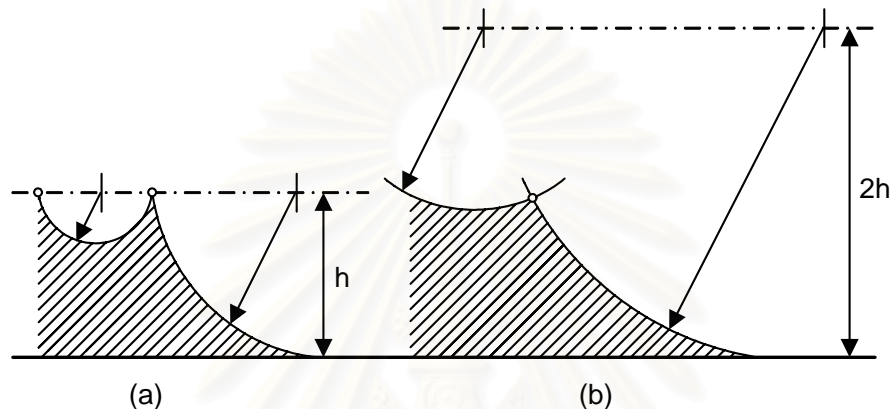


Figure (2.3): Protected volumes show by border arcs  
 (a) centre for the level of earth wires  
 (b) centre for twice height of the line

The use of protected volume was initiated for investigations with high voltage transmission lines. The protective angle or the circle as a border was suitable for this purpose but not for three-dimensional arrangements such as a flat roof protected by a network of horizontal conductors or by vertical rods. The protective angle proved a failure in this case; therefore it must be combined with other arbitrary principles of construction. The circle became a sphere but its radius was not constant if the centre was at a given level as shown in figure (2.4). This problem can be eliminated by introducing the principle of the rolling sphere method. The volume to be protected is never intersected when the sphere moves over the air termination.

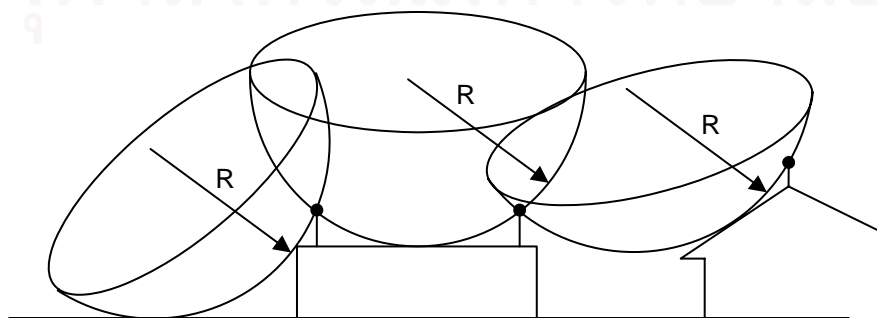


Figure (2.4): Principle of the rolling sphere method

The rolling sphere method is based on an assumption that the point of strike of a lightning is determined when the downward leader approaches the earth or a structure with a striking distance. Another assumption is that the lightning strikes the nearest earth object from the orientation point and so its worst position is the center of a sphere which attaches several earth objects. These previous assumptions allow the conclusion that no lightning will strike the structure to be protected if its striking distance is greater than the radius of the sphere.

Because the striking distance and so the radius of the sphere is related to the lightning current, it is often assumed that the efficiency is equal to the probability of occurrence of the corresponding lightning current. But, some authors have demonstrated that the radius of the sphere doesn't determine the efficiency of the air termination system.

The principle of application of the rolling sphere construction method is shown in figure (2.4). Protection is adequate when the sphere never intersects the volume to be protected without effect on the air termination or the earth surface. In case of intersection, we need to install a LPS. The position, at which we should install the LPS, can be obtained by following the IEC standard related to this topic. Rolling sphere method has an advantage over the protective angle in that it can be applied, without any limitation, either on one side or between air termination conductors. The rolling sphere method should be used to identify protected space of parts and areas of a structure when table (2.3) which derived from IEC 61024-1, excludes the use of the protective angle method.

According to the standard, when we apply this method, the positioning of an air-termination system is adequate if no point of the space to be protected is in contact with a sphere with radius  $R$  rolling on the ground, around and on to top of the structure in all possible directions. Therefore the sphere shall touch only the ground and/or the air-termination system. The radius of the rolling sphere should comply with selected protection level of the LPS according to table (2.2).

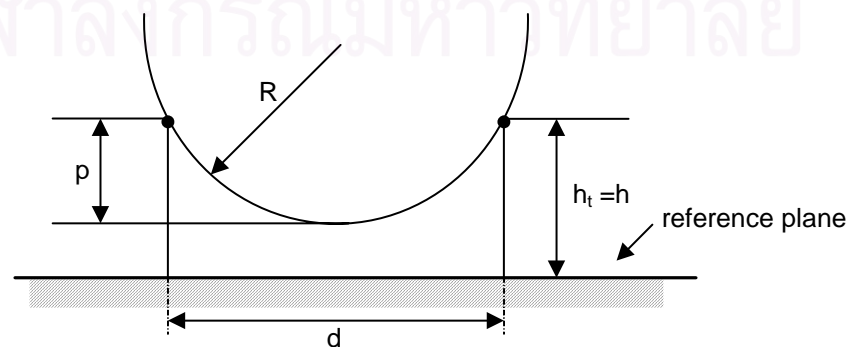


Figure (2.5): Space protected by two air termination rods

In the case of two parallel horizontal LPS air-termination conductors placed above the horizontal reference plane in figure (2.5), the penetration distance  $p$  of the rolling sphere below the level of the conductors in the space between the conductors should be calculated:

$$p = R - \left[ R^2 - \left( \frac{d}{2} \right)^2 \right]^{\frac{1}{2}} \quad (2.10)$$

In the figure (2.5),  $d$  is distance separating two air termination rods, and  $h$  is height of the air termination according to table (2.3). We can see that the penetration distance should be less than  $h$ , physical height of the air-termination rods above the reference plane, to avoid intersection with our protected structure, or reference plane in figure above.

The Rolling Sphere method is undoubtedly the most common technique recommended in Codes of Practice. It is claimed that the main advantage of the Rolling Sphere method is the simplicity of its application. This may be the case for simple structures but for more complex ones it is difficult to apply by hand, requiring sophisticated 3D numerical modeling software. The main weakness of this method is that it assigns equal leader initiation ability to all contact points on the structure, or in other word, this method only uses single orientation distance value to evaluate the striking process. That is why, for a given prospective peak stroke current or, alternatively, protection level, the radius of the sphere is a constant value. This method is too simple.

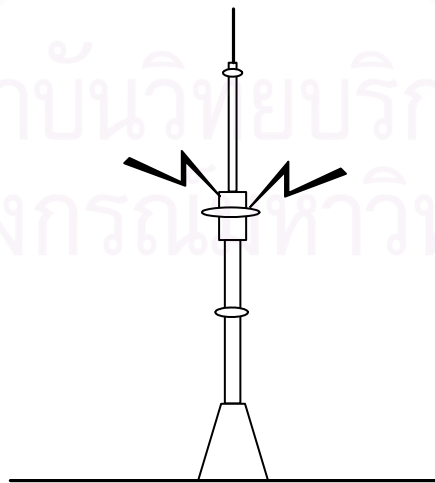


Figure (2.6): The point of strike on the Onstankio television tower in Moscow



Later we will find out that every object has a lot of orientation point around them, and we should concern all of these orientation points in the striking process to know better whether our protected structure is safe or not by the lightning strikes. The over-simplification of the method will results in over-design on flat horizontal and vertical surfaces and under-design when structural points with significant electric field intensification are outside the sphere radius in a so-called protected zone.

In overall, the most important conflict of the protected volume concept is the observed lightning strikes which penetrated any possible protected volume. Typical cases are the lightning strikes on the side of thin high objects, e.g. on the Monte San Salvatore in Switzerland the point of strike was on the side of a steel tube 15 m below its top. The tube formed the upper 18 m of a 70 m high tower. The 540 m high television tower in Moscow was struck twice in its middle part, where there are technical installations and a restaurant between the levels of 320 m and 360 m, as shown in figure2.6 [10]. These cases mean that a rod or tower cannot protect even its own side.



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## CHAPTER 3

### ATTRACTIVE VOLUME CONCEPT

#### 3.1 Basic Principles

Attractive volume concept was proposed by Tibor Horvath of the Technical University of Budapest in 1971 and 1988. He assumed an attractive volume as a basis of estimation of the risk of lightning strikes or the protective effect of air termination system. It is a fundamental statement that the downward leader approaches the earth on a stochastically path and the point of strike is only determined near the earth. The critical point from which the lightning turns definitely toward the point of strike can be taken as an orientation point. This point is determined by the criterion that at least one connecting leader start from a structure or from the earth.

The gap between the orientation point and the earth can be called the orientation distance. It is determined by the field strength at the earth, thus it is a function of the specific charge on the leader channel. This charge is to be neutralized by the charge running up to the plasma channel and so the lightning current is related to the charge on the leader channel. Thus a relationship also exists between the orientation distance and the lightning current.

According to the other theories [10], the point of strike occurs at a position where the voltage reaches the breakdown value of the air gap between the leader and the earth. The potential of the leader is equal to the voltage drop produced by the current of the main strike. The breakdown voltage is estimated by the extrapolation of laboratory results. The final gap determined on this principle is usually called the striking distance. This is similar to the previously mentioned orientation distance, but its definition has a different basis.

The orientation distance or the striking distance is a function of the peak value of the lightning current, which can be expressed by the general equation:

$$\frac{I}{I_m} = \left( \frac{r}{r_m} \right)^p \quad (3.1)$$

where,

$I$  is the peak value of the lightning current, in kA

$r$  is the orientation distance belonging to the value  $I$ , in m

$I_m$  is median values of lightning current occurring with 50% probability, in kA

$r_m$  is median values of orientation distance, in m

$p$  is estimated as 1.2 to 2 by several authors (dimensionless)

The median value of the orientation distance,  $r_m$ , will be expressed as:

$$r_m = \mu \cdot h \quad (3.2)$$

where the coefficient  $\mu$  is a function of the polarity of lightning and the height  $h$  of the object struck by the lightning.

The measured peak values of lightning current are usually recorded on a graph whose abscissa has a logarithmic scale and whose ordinate is scaled according to the Gaussian error function. The distribution functions are indicated by straight lines as shown in figure (3.1). From this graph, the probability that the lightning current exceeds the value on the abscissa can be determined [10].

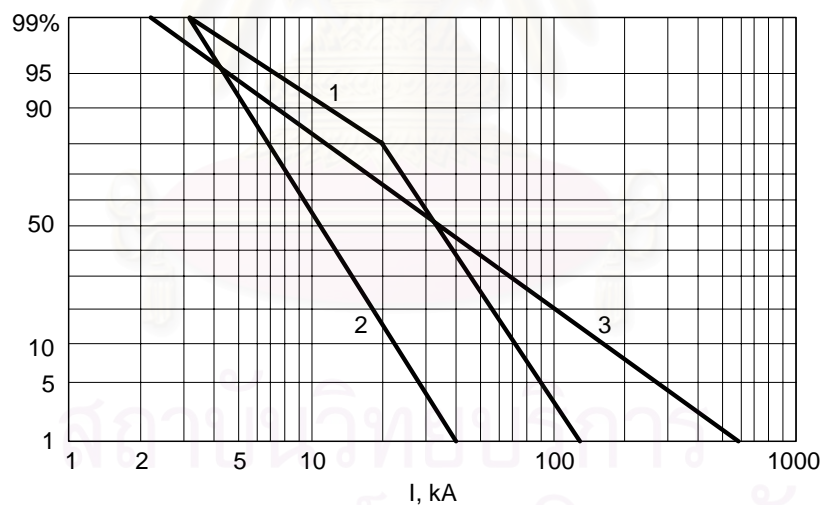


Figure (3.1): Distribution function of the peak value of (1) negative first strikes; (2) subsequent strikes; (3) positive strikes

In this graph the straight lines represent logarithmic normal distributions. The distribution function can be expressed by the equation:

$$P(i \leq I) = \Phi \left( \frac{I}{s} \ln \left( \frac{I}{I_m} \right) \right) \quad (3.3)$$

which expresses the probability that the lightning current  $i$  is less than the value  $I$  on the abscissa. In contrast to this definition, figure (3.1) indicates the function  $1-P$ , but for mathematical evaluation, equation (3.2) is more convenient. As describe above,  $I_m$  is the median value of the lightning current occurring with 50% probability and  $s$  represents the deviation but it is not equal to the well known standard deviation of log-normal distribution.

The symbol  $\Phi$  represents the Gaussian error function, which defined by the following integral:

$$\Phi(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^x e^{-\frac{t^2}{2}} dt \quad (3.4)$$

Characteristic values of this function are:

$$\Phi(-\infty) = 0 \quad \Phi(0) = 0.5 \quad \Phi(+\infty) = 1$$

For calculation, the following equation is used [10]:

$$Q(x) = u(x) \cdot (a_1 v^1 + a_2 v^2 + a_3 v^3 + a_4 v^4 + a_5 v^5) \quad (3.5)$$

where,

$$u(x) = \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}} \quad v = \frac{1}{1+bx} \quad (3.6)$$

$$\begin{aligned} a_1 &= 0.31938153 & a_2 &= -0.356563782 \\ a_3 &= 1.781477937 & a_4 &= -1.821255978 \\ a_5 &= 1.330274429 & b &= 0.2316419 \end{aligned}$$

Using the result of equation (3.5), the error function is expressed by:

$$\begin{aligned} \text{if } x \leq 0 & \quad \text{then } \Phi(x) = Q(|x|) \\ \text{if } x > 0 & \quad \text{then } \Phi(x) = 1 - Q(x) \end{aligned}$$

Values of  $I_m$  and coefficient  $s$  in equation (3.3) are shown in table (3.1). These constants are derived from the straight lines in figure (3.1).

Table (3.1): Coefficient of equation (3.3)

Polarity and type of lightning strike		Median value $I_m$ (kA)	Coefficient $s$
Positive strike		35	1.215
Negative	$I \leq 20$ kA	61*	1.325
	$I > 20$ kA	34	0.592
Negative subsequent strike		12	0.578

\*A hypothetical value only

By application of the distribution function expressed by equation (3.3), it is possible to determine the distribution function of the orientation distances. For this purpose, equation (3.1) must be substituted into equation (3.3):

$$P(x \leq r) = \Phi \left( \frac{I}{s} \ln \left( \frac{r}{r_m} \right) \right) \quad (3.7)$$

This equation expresses the probability that the orientation distance  $x$  is less or equal than the value  $r$ . This orientation distance is then be used to define the attractive volume.

The attractive volume of an object consists of all point from which the object will be struck by lightning if the orientation point is included. The attractive volume can be related to the whole object, the lightning protection system, a part of a structure, or even the earth. The extent of the attractive volume gives an outline of the expected frequency of lightning striking to the structure or to the parts to be protected, but it is a rough estimation. A more informative result can be obtained only by taking into account the fact that the orientation point occurs with the different probabilities at several points inside the attractive volume.

It must be mentioned that the attractive volume is not identical with the attractive area often used in the literature to express the lightning strike hazard [10]. The attractive area of an object is the extent of earth object. Instead of the attractive area, the attractive radius and the attractive band have also been mentioned. These are not to be confused with the orientation distance or the striking distance.

According to the fundamental conditions of the applied model, two questions have to be answered. First, what is the expected frequency that a volume element includes the orientation point? Second, what is the probability that the lightning strikes the considered object from this orientation point?

It is a plausible statement that a rectangular area of the earth surface will be struck by lightning with a frequency which is proportional to the flat area  $\Delta x \Delta y$  and to

the ground flash density,  $N_g$ . In this case the attractive volume is a prism rising above the area to infinity, as shown in figure (3.2).

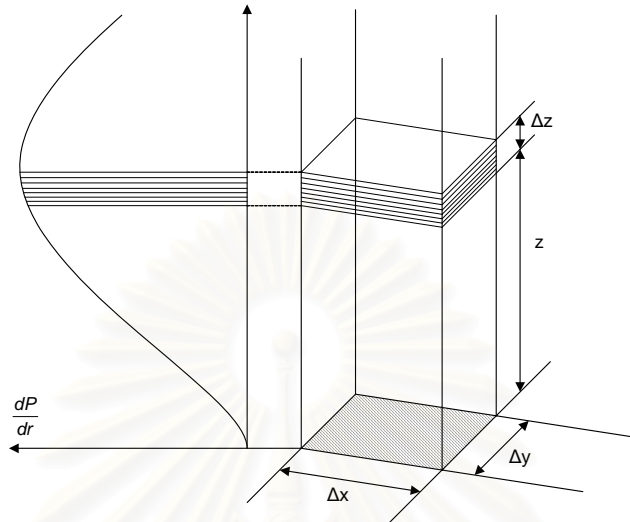


Figure (3.2): The attractive volume of a rectangular area

In the figure (3.2), the orientation points are distributed along the z axis according to equation (3.7). The expected frequency that it occurs in a volume element of height  $\Delta z$  may be expressed by the relationship:

$$\Delta N(z) = N_g \Delta x \Delta y \frac{\delta P}{\delta z} \Delta z \text{ strike/year} \tag{3.8}$$

where  $\frac{\delta P}{\delta z}$  is the density function of the orientation distances according to equation (3.7).

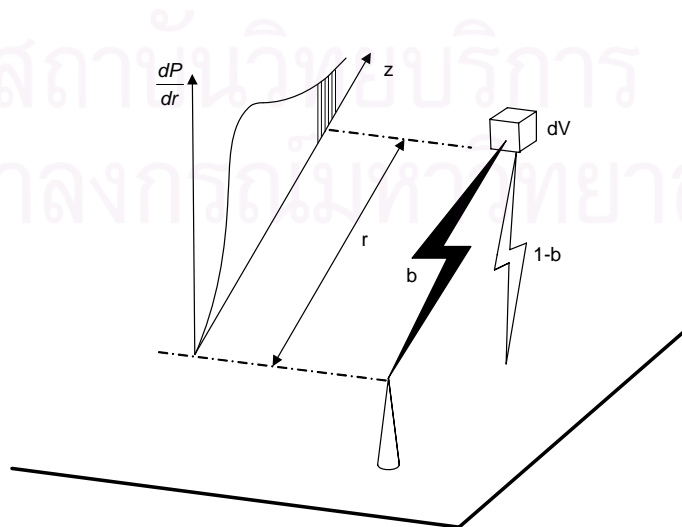


Figure (3.3): Position of the volume element

Consider a structure on flat country, the position of the volume element is shown in figure (3.3). If the sizes  $\Delta x$ ,  $\Delta y$  and  $\Delta z$  tend toward zero, their product maybe replaced with a symbol  $\delta V$  as a differential volume element. The equation then expresses a differential value of frequency that this volume element includes the orientation point,  $\delta N$ .

Returning to the second fundamental question, the lightning may strike the structure with probability  $b$  or not strike with probability  $1-b$ , as shown in figure (3.3). If we include the orientation point into volume element, we have to include this  $b$  into the equation. This  $b$  value is not used in the equation directly but it is used to define which orientation point should be included in the volume element. It shows contour line of the attractive volume where from all of orientation point inside this volume, lightning will strike the object with probability greater than  $b$ . For example, if  $b = 0.5$  then at the contour line, there are orientation points from which lightning will strike the object with probability 0.5. Inside the attractive volume, lightning will strike the object with probability greater than 0.5

$$\delta N = N_g b \frac{\delta P}{\delta z} \delta V \text{ strike/year} \quad (3.9)$$

To obtain the expected frequency of all lightning striking to the structure, the integral of the differential quantity  $\delta N$  must be calculated theoretically on the infinite space. The integration is really extended on the attractive volume of the structure only, so the expected frequency can be expressed by:

$$N = N_g \int_{V_a} b \frac{\delta P}{\delta z} \delta V \text{ strike/year} \quad (3.10)$$

where the integral has a dimension of  $m^2$ . It means that the integral represents an area which is identical to the equivalent area. Considering the relationship in (3.10), the equivalent area is:

$$A_{eq} = \int_{V_a} b \frac{\delta P}{\delta z} \delta V \text{ m}^2 \quad (3.11)$$

We see that in equation (3.9)-(3.11)  $b$  still be written, because we want to show that we also use probability value  $b$  in the calculation of attractive area when we construct the attractive volume. But later, this  $b$  will be omitted. To determine the probability  $b$  for any point inside the attractive volume, a possible method is a model

study. Although the validity of such results is often regarded as doubtful, the conditions of the orientation points are applicable to a model study. The definition of the orientation point requires that two discharges are running towards each other, namely the downward and the connecting leaders. A similar situation can be produced using standard lightning impulses (1.2  $\mu$ s front time). The standardized switching impulse is not adequate because a long leader discharge may propagate from the positive electrode without the existence of an opposite one. The most suitable voltage is slightly above the breakdown voltage of the gap, because this is the best approximation of natural condition.

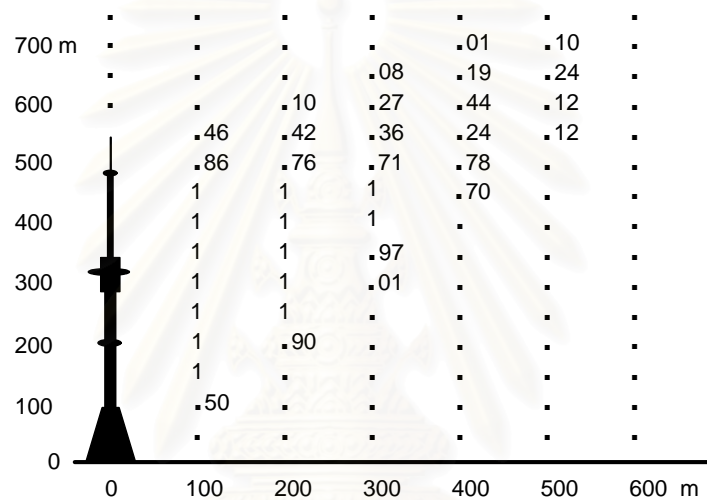


Figure (3.4): The probability  $b$  of the side of the Moscow television tower

The experiment should be conducted so that a high voltage electrode represents the upper part of the leader channel up to the orientation point. Its base is the position of the orientation point where the value  $b$  is to be determined. For this purpose the electrode is moved above the model and at each point the discharges which strike the considered object must be counted. The probability  $b$  is the ratio of these charges to the total. Applying a suitable coordinate network, this is a method which can give a result independent of the complexity of the arrangement. A disadvantage is that it is time-consuming and the cost of construction of the model may be expensive.

The result of such experiment with a model of the television tower in Moscow is given in figure (3.4). The considered object is the side of the tower. Considering the rotation symmetry, the volume element is in this case:

$$\Delta V = 2\pi x \Delta x \Delta z \quad (3.12)$$



where  $\Delta x$  and  $\Delta z$  are the distances between the points of measurement. Equation (3.11) is transformed so that the integral is changed into a summation as follows:

$$A_{eq} = \sum b(z, r) \frac{\delta P}{\delta r} \Delta V \quad m^2 \quad (3.13)$$

This calculation can be performed by computer. The measured values of  $b$  are input data and the system of coordinates, as well. The density function must be calculated by equation (3.7) at each point.

As explained before,  $b$  in equations (3.9)-(3-11) and (3.13) represents the contour lines of the attractive volume. The model study can be used to obtain general relationships. Figure (3.5) indicates the results of experiments with a simple rod rising from a metal plate. Contour lines represent levels changing from  $b = 0$  to  $b = 1$ . Remarkable differences can be seen between the extents of the attractive volumes depending on the polarity.

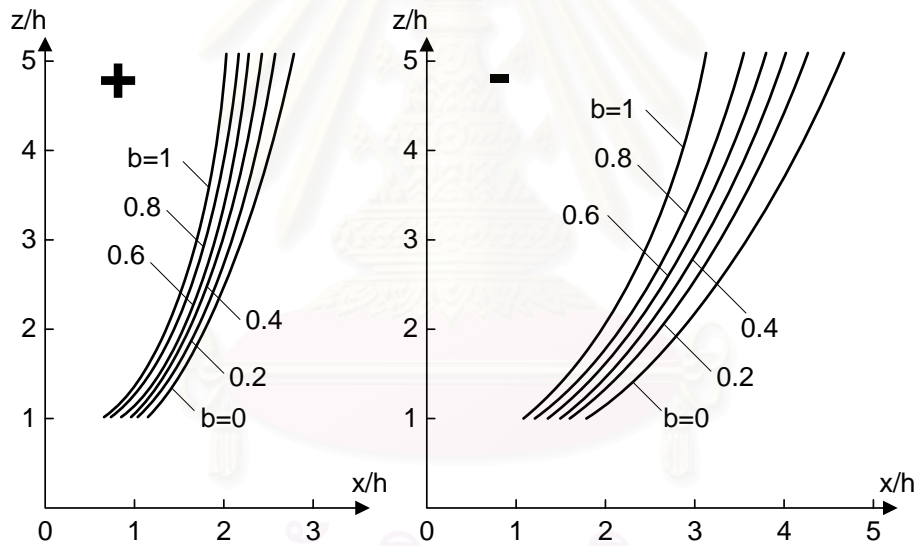


Figure (3.5): Contour lines of constant  $b$  values for positive and negative strikes [10]

The contour lines may be approximated with the following equation (see figure (3.6)):

$$\cos \varphi = \varepsilon - \frac{h}{r} \quad (3.14)$$

where,

$$\varepsilon = \frac{z}{r} \quad (3.15)$$

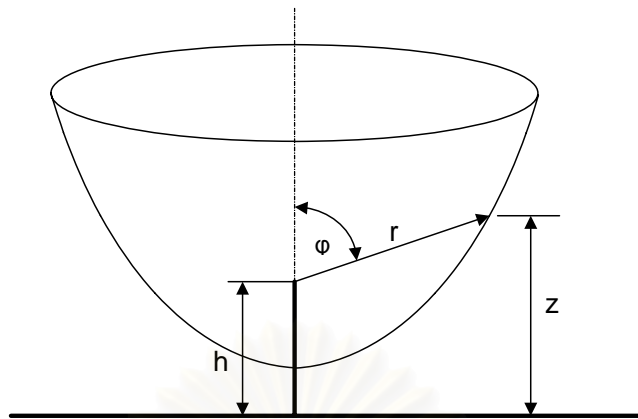


Figure (3.6): The border of the attractive volume of a rod above a flat surface

The notation used in equations (3.14) and (3.15) are marked in figure (3.6):  $h$  is height of the building,  $z$  is height of orientation point from the reference plane,  $r$  is the orientation distance which is the line connecting the orientation point with the point of strike at the object, and  $\varphi$  is the angle between the orientation distance line and line which is perpendicular to the reference plane. The value  $\varepsilon$  is depending on the probability  $b$  as well as the polarity of lightning strike. From figure (3.5), for  $b = 0.5$  and 0, the constant  $\varepsilon$  has the following values:

for	$b = 0.5$	positive: $\varepsilon = 1.06$	negative $\varepsilon = 0.88$
	$b = 0$	positive: $\varepsilon = 1.00$	negative $\varepsilon = 0.75$

Equation (3.14) represents a hyperbola if  $\varepsilon < 1$ , a parabola if  $\varepsilon = 1$  and an ellipse if  $\varepsilon > 1$ . This equation can be used to describe the borders of the attractive volume using analytical relationships in the computer programs. For this purpose, the middle of the zone of transition will be usually taken as the border of the attractive volume. This condition is identical with  $b = 0.5$ . Replacing the adequate value of  $\varepsilon$ , relationship (3.14) can be applied in the case of a rod or a tower if it is rotated around the vertical axis. In the case of a horizontal line, the attractive volume is created by parallel displacement. The attractive volume can also be used to evaluate the protective effect of a lightning protection system. In this case, the attractive volume which belongs to the object to be protected has to be considered. In equations (3.10) or (3.11), the integral is calculated only on this attractive volume. This method can be applied generally without any modification for calculation of the expected frequency, either of all strikes or the interception failures. The difference includes the borders of the attractive volumes.

This method produces the expected frequency expressed as strikes per year, which is a distinctly defined quantity and can be compared with the observed data. The protective effect can also be expressed as a relative value which is the frequency of the interception failures relative to that all strikes.

The attractive volume can be used to evaluate the protective effect of a lightning protection system also. In this case, the attractive volume of the air termination system, the object to be protected and the earth in most cases should be considered separately. The frequency which concerns the object to be protected is the expected frequency of interception failures or shielding failure, and this can be calculated by define an attractive area of protected structure,  $A_{eq}'$ , which is simply subtraction of attractive area of the structure without a LPS installed,  $A_{eq}$  and attractive area of lightning rods,  $A_{eq-LPS}$ :

$$A_{eq}' = A_{eq} - A_{eq-LPS} \quad (3.16)$$

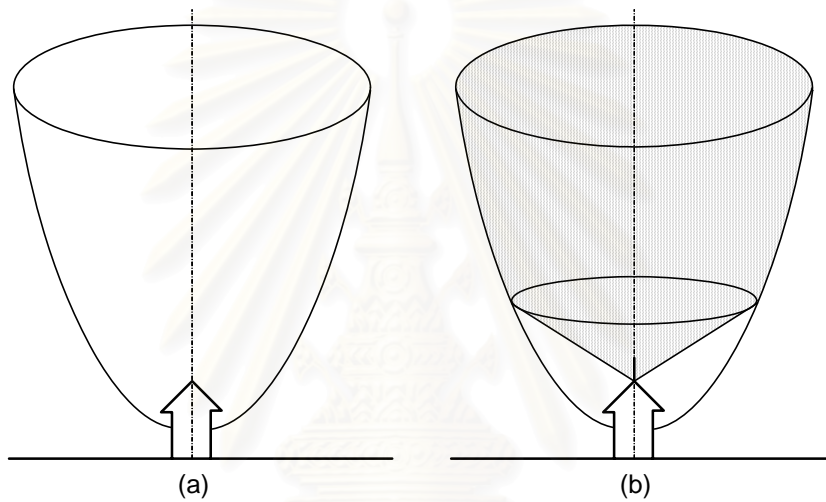


Figure (3.7): The attractive volume of a building (a) without, (b) with LPS

Figure (3.7a) shows the attractive volume of a building without any lightning protection. According to figure (3.7b), a lightning rod on the top of the roof removes a considerable part of this volume. The reduction of the attractive volume of the structure to be protected represents a lower lightning strike frequency, not only because its extent is decreased, but also because it does not approach infinity. The value of  $\frac{\delta P}{\delta r}$  is lower inside the left volume in figure (3.7b), and so equation (3.10) or (3.11) result in a considerably lower expected frequency than without lightning protection.

### 3.2 Attractive Volume of a Simple Object

Many objects and air terminations can be substituted by simple geometrical figures which are points, planes, vertical or horizontal straight lines as well as a circle. For example, a transmission line can be replaced by a horizontal line above a plane and

a point above a plane for a lightning rod. We will only discuss about a point above a plane and a horizontal line above a plane, because the structure considered in this thesis is a rectangular roof building which can be replaced by combination of them. By defining the attractive volume of these simple objects, we can calculate attractive area of the object through calculation of its cross section area. In such cases, the relationship between the area of the cross section of the attractive volume and the orientation distance can be expressed by analytical equations.

For a point above a plane, the surface which is equidistant from the point is a sphere from which the border of the attractive volume cuts out like a calotte-like shape as shown in figure (3.8).

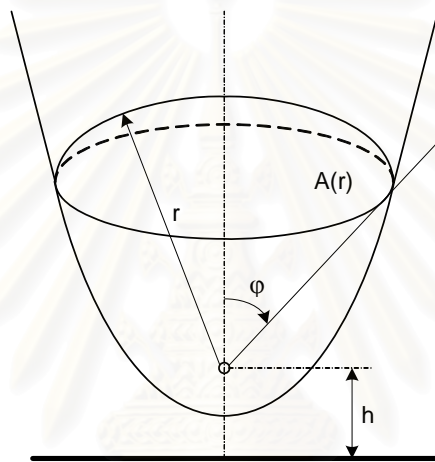


Figure (3.8): The attractive volume of a point above a plane

The border can be generated by rotation of a curve, which is described by equation (3.14). For positive strikes, the attractive volume is a rotated ellipsoid and in the case of negative ones a rotated hyperboloid

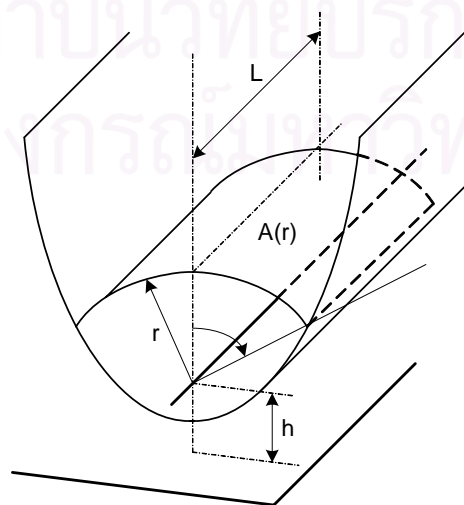


Figure (3.9): The attractive volume of a horizontal line above a plane

For a horizontal line above a plane, the attractive volume is similar to a trough which is produced by parallel displacement of a curve determined by equation (3.14). The cross section of the attractive volume is a sector of a cylindrical surface, as shown in figure (3.9). This surface has a distance  $r$  from the line.

### 3.3 Calculation of the Attractive Area

According to IEC 61024-1-1 or IEC 61662, the equivalent collection area or attractive area, is defined as an area of ground surface which has the same annual frequency of direct lightning strikes as the structure.

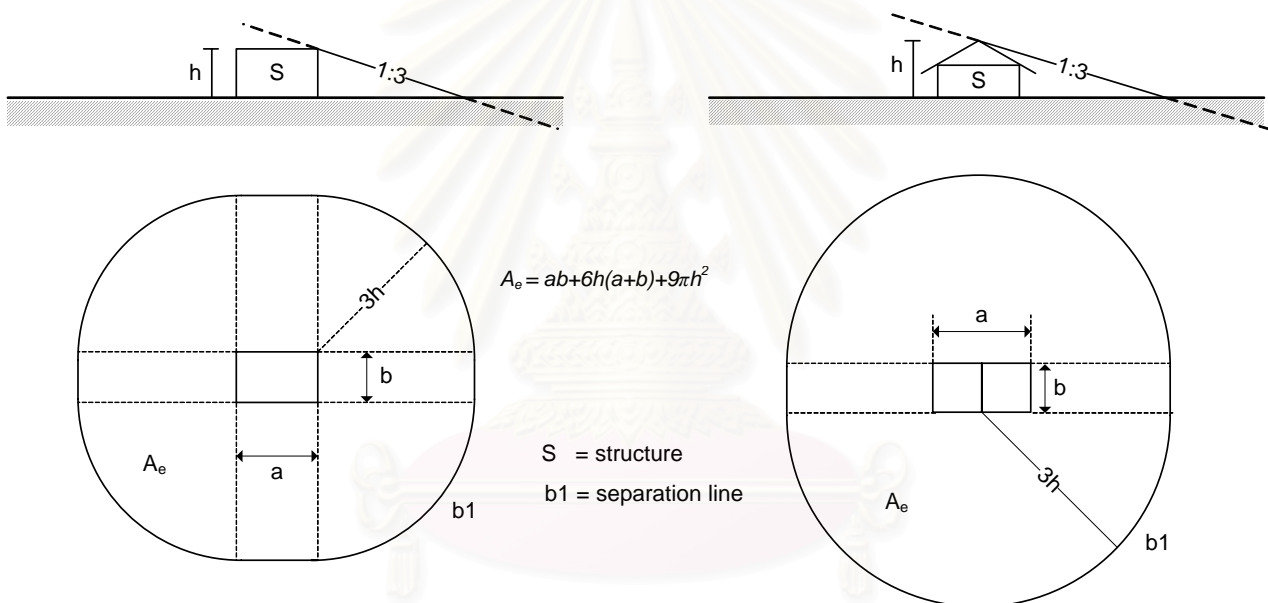


Figure (3.10): The attractive area of a structure in flat terrain

For isolated structure, the attractive area is the area enclosed within the border line  $b1$  obtained from the intersection between the ground surface and a straight line with 1 : 3 slope which passes from the upper parts of the structure (touching it there), and rotating around it. For flat terrain, the attractive area can be seen in figure (3.10). The standard uses a simple way to calculate the attractive area. It only considering one value of orientation distance for the calculation, and this might be not enough, because we know that there are many orientation points around a structure as discussed previously. So, the value we get from the calculation is only estimation, not an accurate one.

Using the attractive volume concept, we can achieve an accurate calculation of this attractive area through a computer program as we consider all possible value of orientation distance in this concept. As we state before, we will omit  $b$  from equation (3.11), because now we already integrate  $b$  in the construction of the attractive volume:

$$A_{eq} = \int_{V_a} \frac{\delta P}{\delta z} \delta V \quad m^2 \quad (3.17)$$

Because the density function  $\frac{\delta P}{\delta r}$  depends on the orientation distance,  $r$  can be a suitable independent variable to express the volume element  $\delta V$ :

$$A_{eq} = \int_{V_a} \frac{\delta P}{\delta r} A(r) \delta r \quad m^2 \quad (3.18)$$

In above equation,  $A(r)$  is the area of the cross section of the attractive volume at a distance  $r$  from the object. The function  $A(r)$  can be expressed either by an analytical equation or by values of  $A(r)$  and  $r$  which belong together.

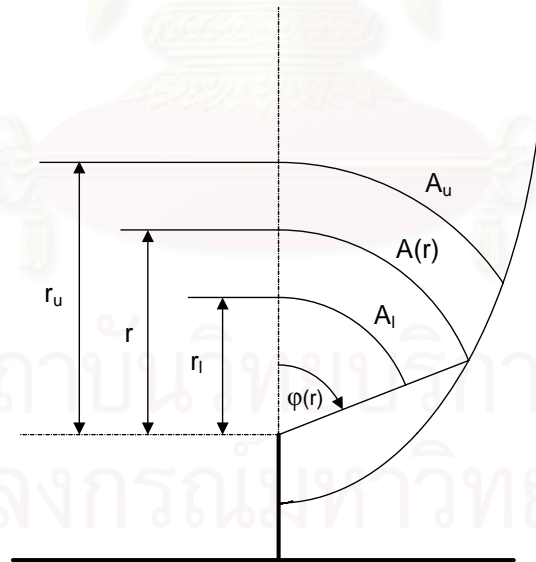


Figure (3.11): Division of the attractive volume into sections

To calculate the integral, the attractive volume is divided into sections, as shown in figure (3.11). At the lower limit of a section, the orientation distance is  $r_l$  and at the upper value is  $r_u$ . The cross section can vary continuously from  $A_l$  to  $A_u$  according to different function. For calculations, a general equation can be used, as follows [10]:

$$A(r) = K_1 r^c + K_2 r^{c+1} \quad (3.19)$$

where,

$$K_1 = \frac{A_{cs-l} r_u - A_{cs-u} r_l}{r_u - r_l} \quad \text{and} \quad K_2 = \frac{A_{cs-u} - A_{cs-l}}{r_u - r_l} \quad (3.20)$$

In these equations,  $A_{cs-u}$  and  $A_{cs-l}$  are the values of  $A_{cs}(r)$  at the upper and the lower limit of the section. The function  $A_{cs}(r)$  is a horizontal cross section area at orientation distance  $r$  as shown in figure (3.12). In the figure,  $z$  is the height of the cross section area from the reference plane and  $\delta z$  is the width of the section of the attractive volume. The program will calculate the horizontal cross section area from minimum height that related to orientation distance minimum,  $z_{min}$ , to maximum height,  $z_{max}$ .

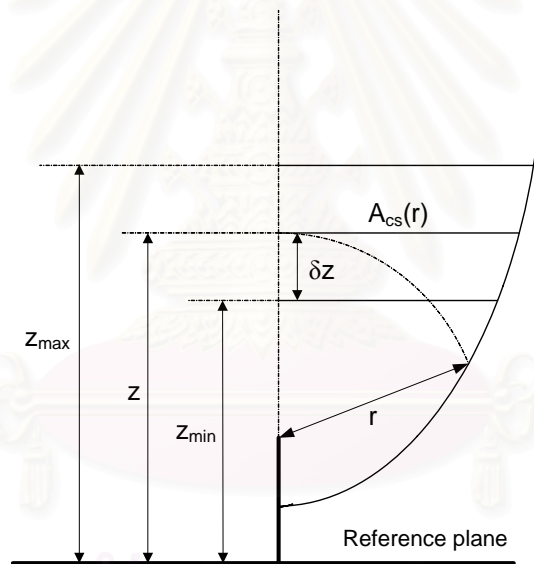


Figure (3.12): Horizontal cross section area

After substituting equation (3.19) into equation (3.18), the component of the equivalent area which belongs to the section  $r_l$  to  $r_u$  is expressed by:

$$A_{eq} = K_1 \int_{r_l}^{r_u} \frac{\delta P}{\delta r} r^c \delta r + K_2 \int_{r_l}^{r_u} \frac{\delta P}{\delta r} r^{c+1} \delta r \quad m^2 \quad (3.21)$$

Both integrals in equation (3.21) has the same form, only the exponent of  $r$  may change from  $c = 0$  to  $c+1 = 3$ . The indefinite form of these integrals can generally be written as:

$$\int \frac{\delta P}{\delta r} r^n \delta r = \frac{P}{s\sqrt{2\pi}} \int r^{n-1} e^{-\frac{1}{2}\left(\frac{p \ln \frac{r}{r_m}}{s}\right)^2} \quad (3.22)$$

This type of indefinite integral can be solved by analytical method. Taking 0 and r as integration limits, the following equation will be derived:

$$\int_0^r \frac{\delta P}{\delta r} r^n \delta r = r_m^n e^{\frac{1}{2}\left(\frac{n \cdot s}{p}\right)^2} \Phi\left(\frac{p \ln \frac{r}{r_m}}{s} - \frac{n \cdot s}{p}\right) \quad (3.23)$$

From above equations, we can easily calculate the equivalent area of the structure by using a computer program.



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## CHAPTER 4

### STRUCTURE OF THE COMPUTER PROGRAM

#### 4.1 Basic Parameter

The distribution function of the peak values of the lightning currents can be expressed by equation (3.3). It includes the median value  $I_m$  and the coefficient  $s$  as parameters. Their values related to high objects are given in table (3.1). We have to modify these values to suit condition where lightning strike a flat territory of the earth not a high object. The suggested original values are indicated in table (4.1). Since the subsequent strike have no influence on the striking process and the point of strikes, their parameters are omitted. These data are fixed at the beginning of the computer program as constants, but they can be replaced with another one if required.

Table (4.1): Coefficient of equation (3.3) related to lightning striking a flat territory

Polarity and type of lightning strike		Median value $I_m$ (kA)	Coefficient $s$
Positive strike		16	1.360
Negative	$I \leq 20$ kA	24	1.520
	$I > 20$ kA	20	0.645

Probability of lightning strikes,  $b$ , will affect the border of the attractive volume. So, the value should be input first before we run the program. Lower value of  $b$  means that we included more possibility of lightning strikes to the attractive volume. This will make the considered object has higher risk, thus it needs higher protective level of LPS to protect it. In the program, probability value of 0 and 0.5 is given as an option where probability of 0.5 as the default value.

The ratio of positive to negative strikes is also an important parameter for the calculation of the attractive area. The observed value is about 10%:90% (positive: negative) for strikes at high objects. But the percentage of positive strikes is certainly higher than 10% because influences of the object will increase the ratio of positive strikes relative to the original one occurring on flat territory. The suggested original ratio of positive to negative strikes is between 10%:90% and 50%:50%. The computer

program assumes initially 30% positive and 70% negative strikes, but it can be changed if required.

Another important constant is the exponent  $p$  in equation (3.1), because it determines the relationship between the orientation distance and the lightning current. At the present time it is usually assumed that  $p = 1.5$  [10], but it can be changed later if necessary.

The ground flash density,  $N_g$ , shows the numbers of lightning strikes in an area per year. We need the value to calculate the frequency of lightning strike to the structure, thus we should input it before we run the program. A default value of 1 flash/km<sup>2</sup> per year is given, but users can change this value according to the ground flash density in the area where his/her considered building stands. The considered minimum lightning current,  $I_0$ , must also be assumed as input data. This value shows the maximum lightning current that still not damage the structure. Giving the right value will protect the structure, because the program will ensure that any lightning current it sustains will be below the level that causes damage.

One of the fundamental relationships between the median value of the orientation distance and the height of the object is given by equation (3.2). In this relationship, the coefficient  $\mu$  can be expressed by general equation [10]:

$$\mu = \left( \frac{I_m}{I_n} \right)^q \left[ (C.h)^{0.1} + \left( \frac{D}{h} \right)^{0.7} \right] \quad (4.1)$$

where,

$I_m$  is the median value of lightning current, kA

$I_n = 20$  kA

For positive:  $C = 1 \text{ m}^{-1}$        $D = 31.6 \text{ m}$

For negative:  $C = 644 \text{ m}^{-1}$        $D = 32.6 \text{ m}$

For the calculation of the attractive area, the attractive volume must be divided into several sections between the minimum  $r_o$  and the maximum  $r_{max}$  of the orientation distance. The number of sections is depending on the width of each section called step,  $\delta r$ , given by the user. Two point of view of step size are considered. Very small steps are inconvenient because they require a lot of calculation time. On the other hand, the accuracy is affected when the steps are too large. At the old time, it was a problem to decide a suitable step value, because of the processor speed of computer at that time is not too fast as right now. The number of sections at that time should not be too high. This is the reason why some author [10] only limits them to only 16. Nowadays, we can rely on the processor speed. So, higher number of sections is not a problem to us. In the

program, the value of step is given 0.01 m as the default value, but later user can change this value.

## 4.2 Flowchart of the Program

The flowchart of the program is shown in figure (4.1), which can be used to calculate the frequency of lightning strike to our structure,  $N$ . The inputs of the program are Ground Flash Density (GFD),  $N_g$ , ratio of positive to negative strikes and the attractive area of considered structure,  $A_{eq}$ . GFD and ratio of positive to negative strikes are inputted before we run the program while the attractive area is calculated within the program by using Procedure  $A_{eq}$ .

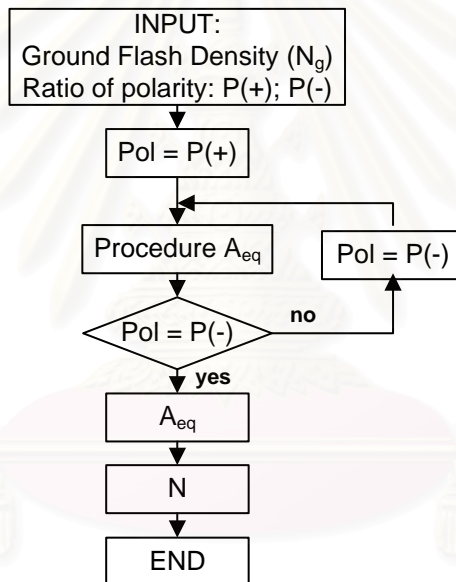


Figure (4.1): Flowchart of program for calculation of the expected frequency of lightning strike

The attractive area of positive polarity of lightning strikes,  $A_{eq}(+)$ , will be calculated first and then the program will loop back to calculate the attractive area of negative polarity,  $A_{eq}(-)$ . At this time we know the attractive area of both polarities, thus the total attractive area can be calculated by using this equation:

$$A_{eq} = P(+)\mathcal{A}_{eq}(+) + P(-)\mathcal{A}_{eq}(-) \text{ m}^2 \quad (4.2)$$

where  $P(+)$  represents the proportion of the positive ground strikes and  $P(-)$  that of negative ones. After that, we can calculate the expected frequency of the lightning striking the considered object by using this equation:

$$N = N_g \cdot A_{eq} \quad \text{strike/year} \quad (4.3)$$

Users can use the result of the program to determine whether it is required to install a LPS or not by comparing it with the accepted frequency of lightning strike,  $N_a$ .

The flowchart of procedure  $A_{eq}$  is shown in figure (4.2). This procedure can be used to calculate the attractive area of only one polarity.

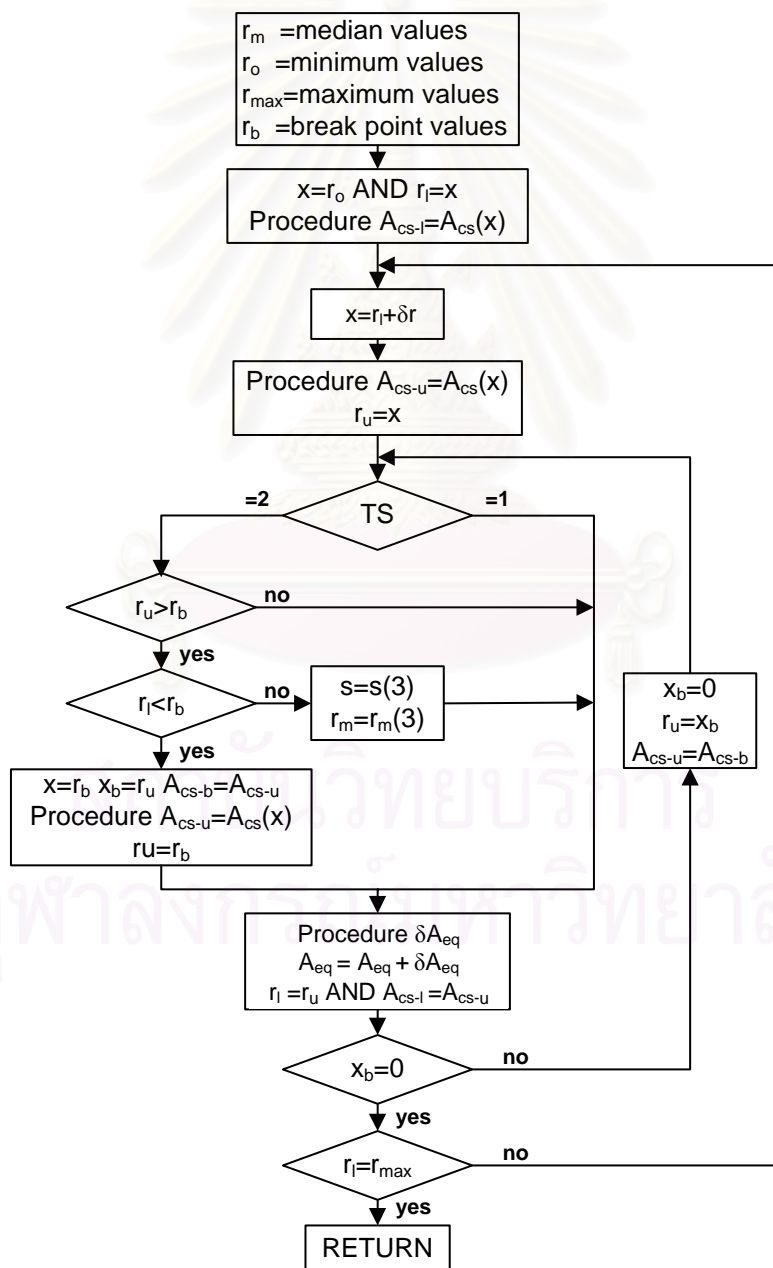


Figure (4.2): Flowchart of Procedure  $A_{eq}$

The inputs of this procedure are the minimum lightning current that will cause no damage to the object,  $I_o$ , maximum lightning current,  $I_{max}$ , and lightning current related to the breaking value of lightning strikes probability in figure (3.1),  $I_b$ . The breaking value is only happen for the negative first strike, and has value of about 20 kA. The value of  $I_{max}$  relate to the upper limit of the attractive volume. We can extend the limit up to infinity or just limit it at certain distance according to the lightning current value. Even though user can input any maximum lightning current value to the program, we limit this lightning current value to 500 kA, because usually lightning that strike to earth object has lightning current value of less than 500 kA. For minimum lightning current value, user can input any value and we do not limit this value as for the maximum one.

At the beginning, the median values for the orientation distances,  $r_m$ , are determined by using equation (3.1) and (3.2). Next, we calculate all orientation distance that will be needed in the program such as maximum orientation distance,  $r_{max}$ , minimum orientation distance,  $r_o$ , and orientation distance related to the breaking value of lightning strikes probability in figure (3.1),  $r_b$ , using equation (3.1).

After we set all initial quantities, the value of the function  $A_{cs}(r)$  will be calculated at the lower as well as at the upper limit. This function is characteristic of the air termination and the object, thus it is depend on the typical arrangement of the object. In the program, function  $A_{cs}(r)$  will give horizontal cross section of the attractive volume at the orientation distance  $r$ . This value together with its orientation distance can be used to calculated cross section area  $A(r)$  using equation (3.19) and (3.20).

For the calculation, a variable  $x$  is initially introduced as  $x = r_o$ . In the case of the first section, this value also represents the lower limit and so  $r_l = x$ . Substituting this value in  $A_{cs}(r)$  results in  $A_{cs-l}$  which is related to the lower limit. After that we increase  $x$  in step by adding  $\delta r$ .  $A_{cs}(r)$  will give  $A_{cs-u}$  which is related to the upper limit of the section. The values obtained can be substituted into equation (3.1), but the break point of the distribution must be considered in the case of negative lightning. If  $x$  should exceed the maximum, then  $x = r_{max}$ .

The type of the strike may be either positive (TS =1) or negative (TS = 2) and this condition determines its parameters according to table (4.1). For negative lightning which has break point at 20 kA on its distribution function, it has to be divided into two parts. Upper part become TS = 3 and the parameters are those which concern the negative strike,  $I > 20$  kA according to table (4.1).

At this point in the program, information is available for the calculation of the equivalent area related to a section between the limits  $r_l$  and  $r_u$ . For this purpose, a subroutine called procedure  $\delta A_{eq}$  is applied. The flowchart is shown in figure (4.3). The calculation of  $\delta A_{eq}$  is based on equations (3.19)-(3.23). For the calculation,  $c = 0$  has to be considered. The result of this procedure is the attractive area from lower section limit to upper section limit of the step.

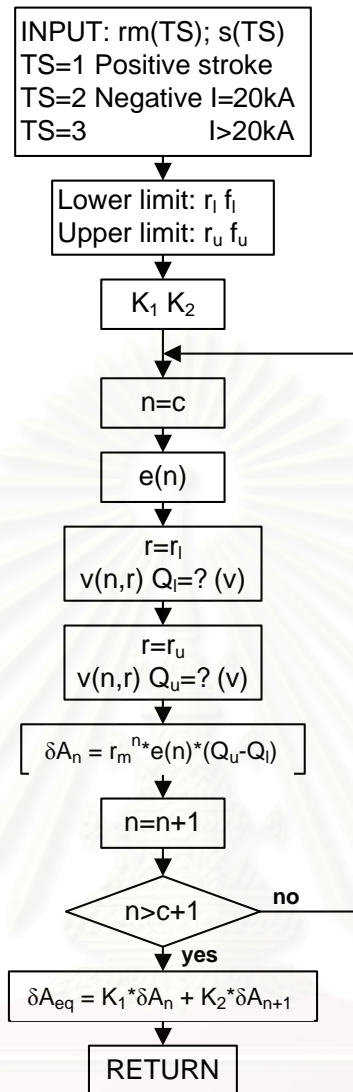


Figure (4.3): Flowchart of Procedure  $\delta A_{eq}$  for calculation of the attractive area from a lower up to an upper limit

In the main program, the result of this procedure is added to the equivalent area, and so the integral is calculated according to equation (3.21). The values related to the lower limit will be replaced by those of the upper limit. The program turns back to the break point if it was inside the section, or the step is increased. The calculation will be completed, if the upper limit reaches the maximum.

### 4.3 Calculation of the Horizontal Cross Section Area

We need a horizontal cross section area to calculate the cross section area  $A(r)$  of attractive volume. This can be done by using procedure  $A_{cs}(r)$ .

The flowchart of this procedure can be seen in figure (4.4).

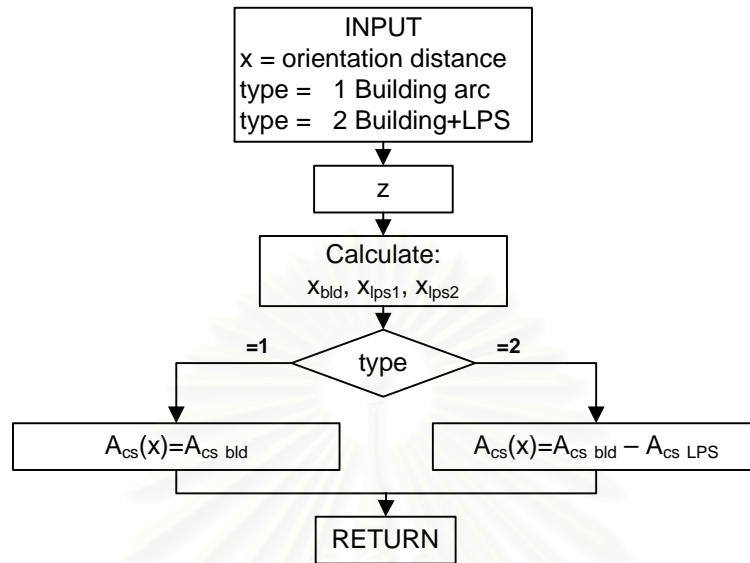


Figure (4.4): Procedure  $A_{cs}(r)$

The input of this procedure is only orientation distance of the building,  $r_{bld}$ . Using equation (3.15), we can calculate the height of horizontal cross section of the building,  $z_{bld}$ . From  $z_{bld}$ , we can calculate the radius of cross section area of building,  $x_{bld}$ , and of LPS in case where we install them on the building.

For the LPS, there are 2 radii of cross section area,  $x_{lps1}$  and  $x_{lps2}$ , because we consider two different heights of LPS from different reference plane. For the first reference plane, which is the earth, the height of LPS is  $h_{LPS1}$  and for the other reference, the height of LPS is  $h_{LPS2}$  as shown in figure (4.5).

To calculate radius of cross section area,  $x$ , we should first know for the lowest height of the attractive volume, because below this value  $x$  is zero and we can ignore them. The lowest height of the attractive volume is reached when  $\varphi$ , the angle between  $r$  and  $z$ , is  $180^\circ$  and in general, it can be calculate using this equation:

$$z_{lowest} = \frac{\varepsilon h}{\varepsilon + 1} \quad (4.4)$$

where:

$h$  is height of considered object, in m

$\varepsilon$  is probability of lightning strike (dimensionless)

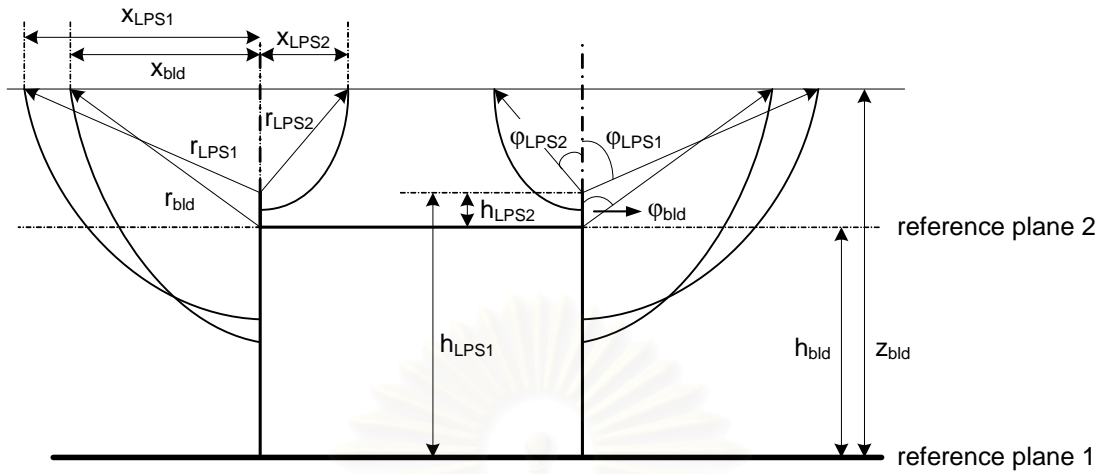


Figure (4.5): Side-view of attractive volume of a building

Applying this equation to building and LPS, we get:

$$z_{bld\ lowest} = \frac{\varepsilon h_{bld}}{\varepsilon + 1} \quad (4.5)$$

$$z_{LPS1\ lowest} = \frac{\varepsilon h_{LPS1}}{\varepsilon + 1} \quad (4.6)$$

$$z_{LPS2\ lowest} = \frac{\varepsilon h_{LPS2}}{\varepsilon + 1} + h_{bld} \quad (4.7)$$

In figure (4.5), we can see a  $90^\circ$  triangle form by orientation distance,  $r$ , radius of cross section area,  $x$ , and subtraction of height of cross section area,  $z$ , with height of considered object,  $h$ , thus  $x$  is:

$$x = \sqrt{r^2 - (z - h)^2} \quad (4.8)$$

Considering  $r = \frac{z}{\varepsilon}$  and applying this to building and LPS we get:

$$x_{bld} = \sqrt{\left(\frac{z_{bld}}{\varepsilon}\right)^2 - (z_{bld} - h_{bld})^2} \quad (4.9)$$



$$x_{LPS1} = \sqrt{\left(\frac{z_{bld}}{\varepsilon}\right)^2 - (z_{bld} - h_{LPS1})^2} \quad (4.10)$$

$$x_{LPS2} = \sqrt{\left(\frac{(z_{bld} - h_{bld})}{\varepsilon}\right)^2 - (z_{bld} - h_{LPS1})^2} \quad (4.11)$$

The theoretical border of the attractive volume of positive strike is ellipsoid. Thus, we have a breaking height,  $z_{break}$ . The calculation with  $z > z_{break}$  will result in a decreasing value of radius of cross section area. For practical application, we modify this border by replacing the radius of cross section area above the breaking height with the radius of cross section area at the breaking height as shown in figure (4.6) below. The radius will be a constant value start from this breaking height. This modification is based on the large transitional zone in the high region. The ellipsoid is associated with 50% probability but 0% yields a much enlarged volume. The constant radius represents a probability between 0% and 50% nearer to the latter one. For negative strikes, there will be no modification, thus the border of the attractive volume will be the same as the theoretical one.

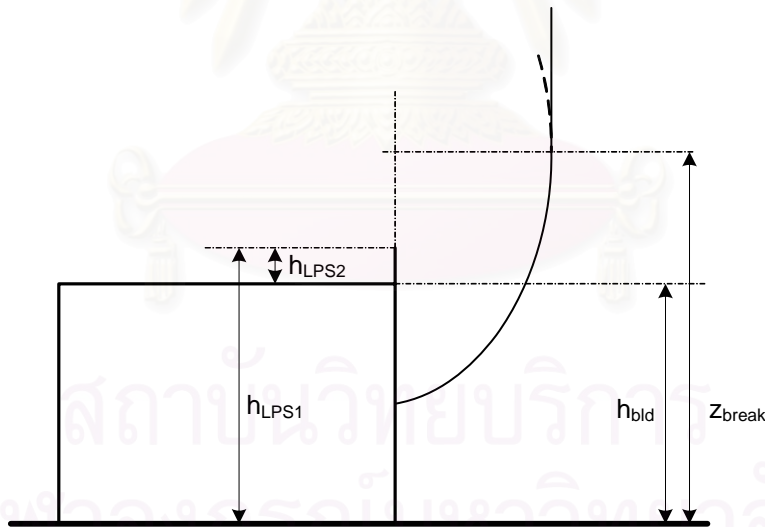


Figure (4.6): Modification of the border of the attractive

The maximum radius of the cross section area can be calculated from equation (4.9)-(4.11). The equations are quadratic equations with the form:

$$a^2x + bx + c = 0 \quad (4.12)$$

Thus, they will reach maximum value at  $x = \frac{-b}{2a}$ . Applying this to the equations, we can calculate the breaking height value:

$$z_{bld\ break} = \frac{h_{bld}}{1 - \left(\frac{1}{\varepsilon^2}\right)} \quad (4.13)$$

$$z_{LPS1\ break} = \frac{h_{LPS1}}{1 - \left(\frac{1}{\varepsilon^2}\right)} \quad (4.14)$$

$$z_{LPS2\ break} = \frac{(h_{bld} + h_{LPS2})\varepsilon^2 - h_{bld}}{\varepsilon^2 - 1} \quad (4.15)$$

Above this breaking height value, the radius of the cross section area will be constant, the same as the maximum radius at the breaking height value. We can calculate the maximum radius by substituting equations (4.13)-(4.15) into equations (4.9)-(4.11):

$$x_{bld\ max} = \sqrt{\left(\frac{z_{bld\ break}}{\varepsilon}\right)^2 - (z_{bld\ break} - h_{bld})^2} \quad (4.16)$$

$$x_{LPS1\ max} = \sqrt{\left(\frac{z_{LPS1\ break}}{\varepsilon}\right)^2 - (z_{LPS1\ break} - h_{LPS1})^2} \quad (4.17)$$

$$x_{LPS2\ max} = \sqrt{\left(\frac{(z_{LPS2\ break} - h_{bld})}{\varepsilon}\right)^2 - (z_{LPS2\ break} - h_{LPS1})^2} \quad (4.18)$$

To calculate the horizontal cross section area of a structure, we should know the attractive volume of the structure. Most structures extend in two horizontal directions. The attractive volume of a rectangular structure is shown in figure (4.7). It consists of three parts. The first part is the prismatic above the roof. It represents an equivalent area equal to the area of the roof  $A_r$ , as shown in figure (4.8). The second part of the attractive volume is that of the straight edges which are similar to that of a horizontal line above a plane show in figure (3.9). The third part is corner part which can be regarded as a point above a plane as in figure (3.8)

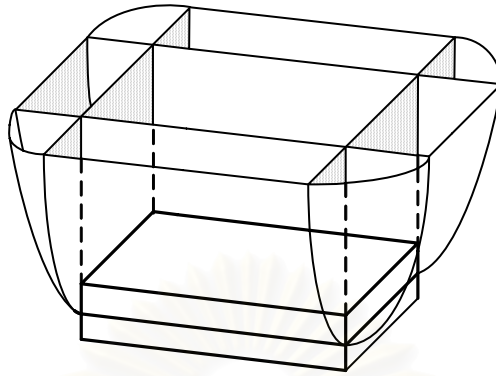


Figure (4.7): The Attractive volume of a rectangular structure

For the second part, the equivalent area is proportional to its length and the width of attractive band,  $B_a$ . The length is usually equal to the perimeter of the edge of the structure, but there are exceptions.

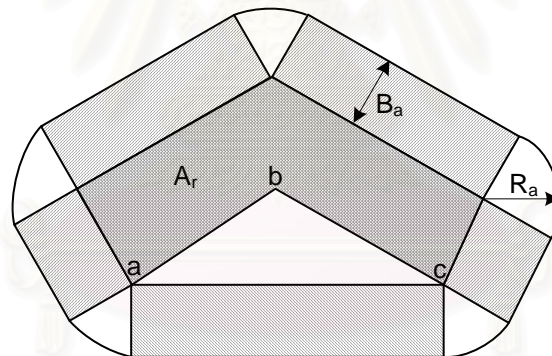


Figure (4.8): The components of the equivalent area of a cornered structure

Figure (4.8) shows such a case where the concave parts of the edge,  $ab-bc$ , are replaced by the shortest line,  $ac$ , and so the parameter is equal to the shortest length of a string which encloses the structure. The width of attractive band,  $B_a$ , is related to equivalent attractive area on one side of the line through this equation:

$$A_{eq} = L.B_a \quad (4.19)$$

where,  $L$  is the length of the perimeter. There are many authors that try to define  $B_a$  through their own formulae. Some of them are written below.

$$\begin{aligned}
\text{by Horvath: } & B_a = (10.2h)^{0.7} + (0.46h)^{1.3} \quad m \\
\text{by CCITT: } & B_a = 4.h \quad m \\
\text{by Eriksson: } & B_a = 14.h^{0.6} \quad m \\
\text{by Golde: } & B_a = 2.h \quad m \\
\text{by IEEE: } & B_a = 2.h^{1.09} \quad m
\end{aligned}$$

The third part of the attractive volume is associated with the corners. This consists of sectors of a rotation volume similar to that of a point according to figure (3.8). We can represent the corners as a point above a plane, and its equivalent area can be computed. To express the frequency of lightning strikes, some authors use an attractive radius,  $R_a$ , instead of attractive area. This radius is defined as the radius of a round field whose area is equal to the equivalent area of the tower, and so the following equation is valid:

$$A_{eq} = \pi R_a^2 \quad (4.20)$$

These following equations are commonly used for the calculation of the attractive radius:

$$\begin{aligned}
\text{by Horvath: } & R_a = \sqrt{\frac{(188h)^{1.02} + (4.68h)^{2.05}}{\pi}} \\
\text{by CCITT: } & R_a = 4.h \\
\text{by Eriksson: } & R_a = 16.6h^{0.55} \\
\text{by Golde: } & R_a = 2.h
\end{aligned}$$

The total equivalent area of the structure can be expressed by:

$$A_{eq} = A_r + p.B_a + \pi R_a^2 \quad m^2 \quad (4.21)$$

where,

$p$  is the perimeter of the structure, in m

$A_r$ ,  $B_a$  and  $R_a$  were defined previously, in m

The calculation of attractive area can be faster if using the above equation, but the result is only the approximation value. Thus, instead of using those equations, we will calculate the attractive area using the attractive volume concept.

Knowing the attractive volume shape, we can easily define the horizontal cross section of the attractive volume. For a rectangular roof building, the horizontal cross section area is as shown in figure (4.9) below:

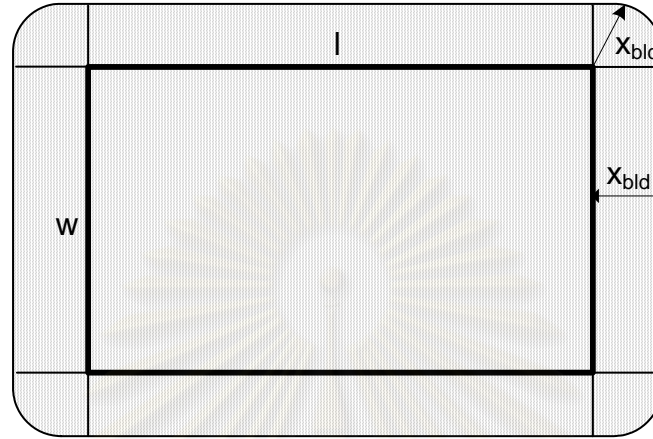


Figure (4.9): Horizontal cross section area of a rectangular roof

As in the attractive area, the horizontal cross section area also consists of three part. The first part is the area of the roof which is the product of building length,  $l$ , and building width,  $w$ . The second part is the area of the perimeter of the building. The area is equal to the multiplication of the perimeter of the building and the width of the area which is radius of the horizontal cross section area,  $x_{bld}$ , defined previously. The third part is the area of the corner. This area is a quarter of a circle with radius of  $x_{bld}$ . For four corners, the total area is same with the area of a full circle. Summarizing, the total area of horizontal cross section area of a rectangular roof building can be calculate using this relationship:

$$A_{cs}(r) = lw + 2(l + w)x_{bld} + \pi x_{bld}^2 \quad (4.22)$$

For a building on which has a LPS installed, the horizontal cross section area is a subtraction of horizontal cross section area of a building defined above, and horizontal cross section area of a LPS. Thus, the attractive area of a building will be reduced if we install a LPS.

Lightning rod as a main part of the LPS has an attractive volume similar to that of a point above a plane. The horizontal cross section area is a circle, but there is an exception. If we install a lightning rod at the corner of the building, it will have two heights depend on the reference plane as shown in figure (4.5). In this case, there will be a union of two circles forming the horizontal cross section area of a lightning rod, as we

can see in figure (4.10). The radii of the circle are different because they are related to different height of lightning rods due to different reference plane, as we can see in figure (4.5). The first circle will have a radius of  $x_{LPS1}$  and the other of  $x_{LPS2}$ . The smaller circle is related to the height of lightning rod of  $h_{LPS1}$ , and the other of  $h_{LPS2}$ .

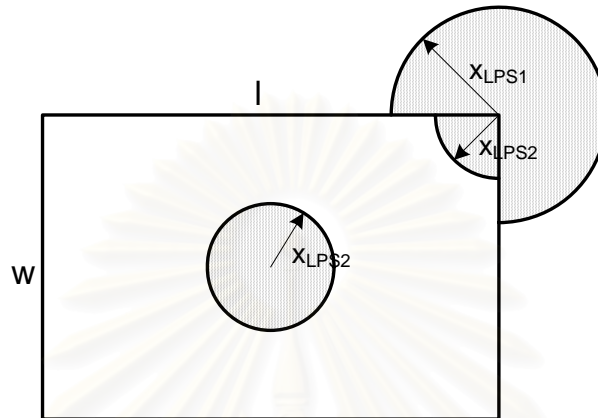
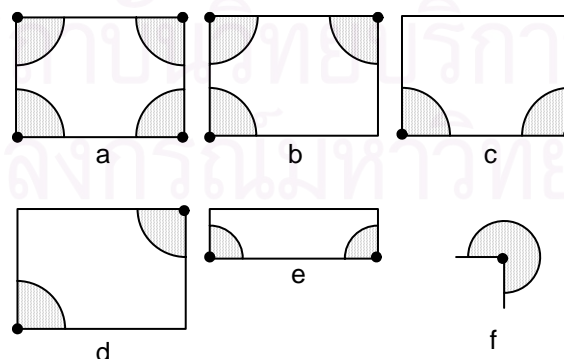


Figure (4.10): Horizontal cross section area of a LPS

If there is a LPS installed on top of a rectangular roof building, its horizontal cross section area will depend on the arrangement of lightning rods on top of building and sometimes it may be difficult to calculate the area. To make the calculation easier, we divide the horizontal cross section area into two parts, inner part and outer part. Inner part is a part of horizontal cross section area of a building which is enclosed by the projection of perimeter of the building. LPS will have a radius of  $x_{LPS2}$  for inner part a radius of  $x_{LPS1}$  for outer part. We will use notation  $A_{cs1}(r)$  for inner part and  $A_{cs2}(r)$  for outer part in the explanation later.



- a. Inner part, 4 lightning rods installed;
- b. Inner part, 3 lightning rods installed;
- c. Inner part, 2 lightning rods installed next to each other;
- d. Inner part, 2 lightning rods installed in front of each other;
- e. Perimeter part;
- f. Corner part

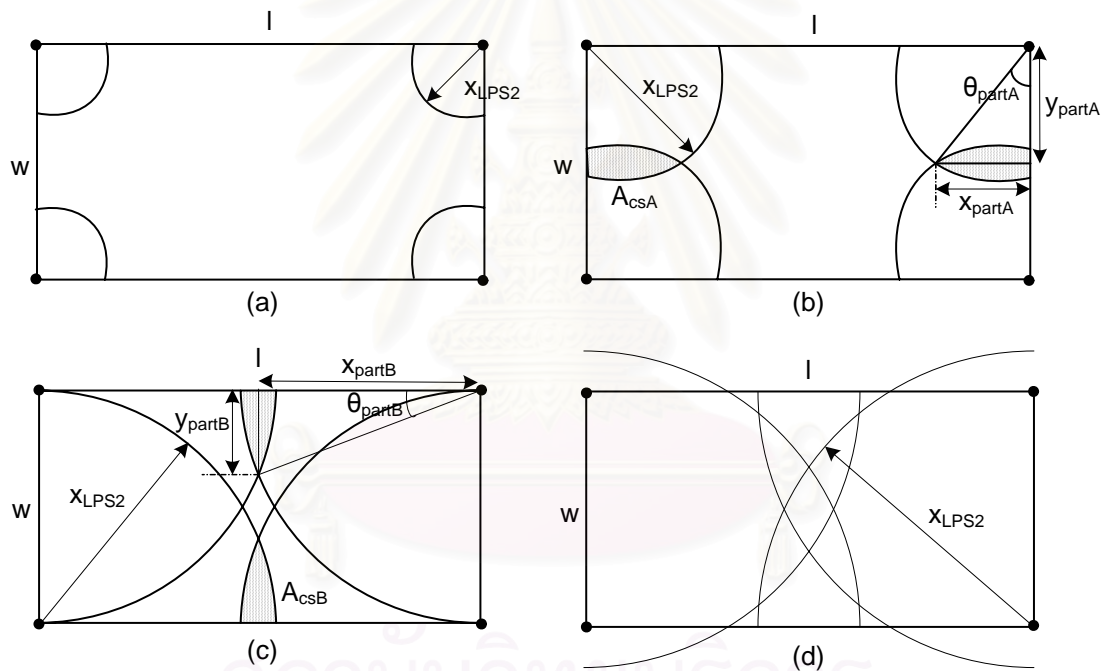
Figure (4.11): Simple parts of horizontal cross section area of a building:

Usually, the horizontal cross section area formed by the arrangement of lightning rods can be represented as a combination of simple parts of cross section area as shown in figure (4.11). There are 6 possible parts which can be divided into 3 categories, which are inner part, perimeter part and corner part. For inner part, there may be 2 to 4 LPS installed in this part, thus 4 combinations of the LPS is obtained. The combinations are 4 lightning rods installed, 3 lightning rods installed, 2 lightning rods installed next to each other and 2 lightning rods installed in front of each other.

For 4 lightning rods installed, the inner part calculation of horizontal cross section area of the building can fall into one of these categories as shown in figure (4.12):

(a) If  $x_{LPS2} \leq 0.5 w$

$$A_{cs1-1}(r) = lw - \pi x_{LPS2}^2 \quad (4.23)$$



The notation (a), (b), (c) and (d) show the category as in the explanation

Figure (4.12): Categories on 4 installed lightning rods

(b) If  $x_{LPS2} > 0.5 w$  and  $x_{LPS2} \leq 0.5 l$

$$y_{partA} = \frac{1}{2} w$$

$$x_{partA} = \sqrt{x_{LPS2}^2 - y_{partA}^2}$$

$$\theta_{partA} = \arctan\left(\frac{x_{partA}}{y_{partA}}\right)$$

$$A_{csA} = 2\left[\left(\frac{\theta_{partA}}{2} x_{LPS2}^2\right) - \frac{1}{2} x_{partA} y_{partA}\right] \quad (4.24)$$

$$A_{cs1-1}(r) = lw - \pi x_{LPS2}^2 + 2A_{csA} \quad (4.25)$$

(c) If  $x_{LPS2} > 0.5 l$  and  $x_{LPS2} \leq \frac{1}{2}\sqrt{l^2 + w^2}$

$$x_{partB} = \frac{1}{2}l$$

$$y_{partB} = \sqrt{x_{LPS2}^2 - x_{partB}^2}$$

$$\theta_{partB} = \arctan\left(\frac{y_{partB}}{x_{partB}}\right)$$

$$A_{csB} = 2\left[\left(\frac{\theta_{partB}}{2} x_{LPS2}^2\right) - \frac{1}{2} x_{partB} y_{partB}\right] \quad (4.26)$$

$$A_{cs1-1}(r) = lw - \pi x_{LPS2}^2 + 2A_{csA} + 2A_{csB} \quad (4.27)$$

(d) If  $x_{LPS2} > \frac{1}{2}\sqrt{l^2 + w^2}$

$$A_{cs1-1}(r) = 0 \quad (4.28)$$

For 3 lightning rods installed, the inner part calculation of horizontal cross section area of the building can fall into one of these categories as shown in figure (4.13):

(a) If  $x_{LPS2} \leq 0.5 w$

$$A_{cs1-2}(r) = lw - 0.75\pi x_{LPS2}^2 \quad (4.29)$$

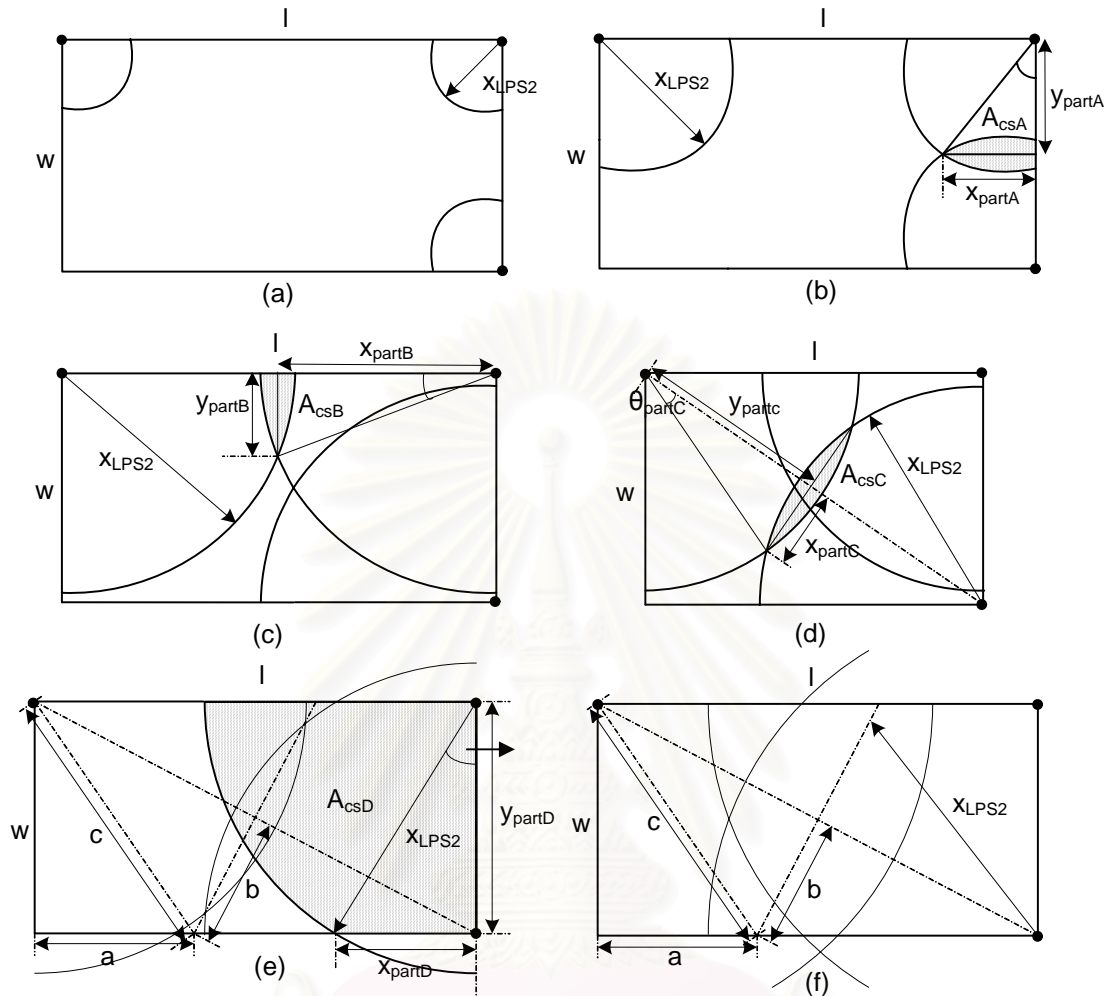
(b) If  $x_{LPS2} > 0.5 w$  and  $x_{LPS2} \leq 0.5 l$

$$A_{cs1-2}(r) = lw - 0.75\pi x_{LPS2}^2 + A_{csA} \quad (4.30)$$

(c) If  $x_{LPS2} > 0.5 l$  and  $x_{LPS2} \leq \frac{1}{2}\sqrt{l^2 + w^2}$

$$A_{cs1-2}(r) = lw - 0.75\pi x_{LPS2}^2 + A_{csA} + A_{csB} \quad (4.31)$$





The notation (a), (b), (c), (d), (e) and (f) show the category as in the explanation

Figure (4.13): Categories on 3 installed lightning rods

(d) If  $x_{LPS2} > \frac{1}{2}\sqrt{l^2 + w^2}$  and  $x_{LPS2} \leq w$

$$y_{partC} = \frac{1}{2}\sqrt{l^2 + w^2}$$

$$x_{partC} = \sqrt{x_{LPS2}^2 - y_{partC}^2}$$

$$\theta_{partC} = \arctan\left(\frac{x_{partC}}{y_{partC}}\right)$$

$$A_{csC} = 4 \left[ \left( \frac{\theta_{partC}}{2} x_{LPS2}^2 \right) - \frac{1}{2} x_{partC} y_{partC} \right] \quad (4.32)$$

$$A_{cs1-2}(r) = \frac{1}{2} \left( lw - \frac{1}{2} \pi x_{LPS2}^2 + A_{csC} \right) \quad (4.33)$$

(e) If  $x_{LPS2} > w$  and  $x_{LPS2} > \frac{1}{2} \sqrt{l^2 + w^2}$  and  $x_{LPS2} \leq \text{limit}$

*Limit* =  $c$  in figure (4.13e), and to calculate it we have to know  $b$  value which can be calculate using these equations:

$$0.5lw = 0.5 \left( wa + b\sqrt{l^2 + w^2} \right) \quad (4.34)$$

$$c^2 = a^2 + w^2 = \left( 0.5\sqrt{l^2 + w^2} \right)^2 + b^2 \quad (4.35)$$

Combining equation (4.34) and (4.35) we get a quadratic equation:

$$4l^2b^2 + 8lw\sqrt{l^2 + w^2}b + 3(lw)^2 + 3w^4 = 0 \quad (4.36)$$

Solving this equation, we will get 2 values of  $b$  and considering that  $b$  should be less or equal to the width of the building,  $w$ , we will get a true value of  $b$ . The *limit* or  $c$  can be calculated:

$$c = \sqrt{b^2 + \left( 0.5\sqrt{l^2 + w^2} \right)^2} \quad (4.37)$$

$$y_{partD} = w$$

$$x_{partD} = \sqrt{x_{LPS2}^2 - y_{partD}^2}$$

$$\theta_{partD} = \arctan \left( \frac{x_{partD}}{y_{partD}} \right)$$

$$A_{csD} = \frac{1}{2} x_{partD} y_{partD} + \left( \frac{\pi - \theta_{partD}}{2} x_{LPS2}^2 \right) \quad (4.38)$$

$$A_{cs1-2}(r) = \frac{1}{2} (lw + A_{csC} - 2A_{csD}) \quad (4.39)$$

(f) If  $x_{LPS2} > \text{limit}$

$$A_{cs1-2}(r) = 0 \quad (4.40)$$

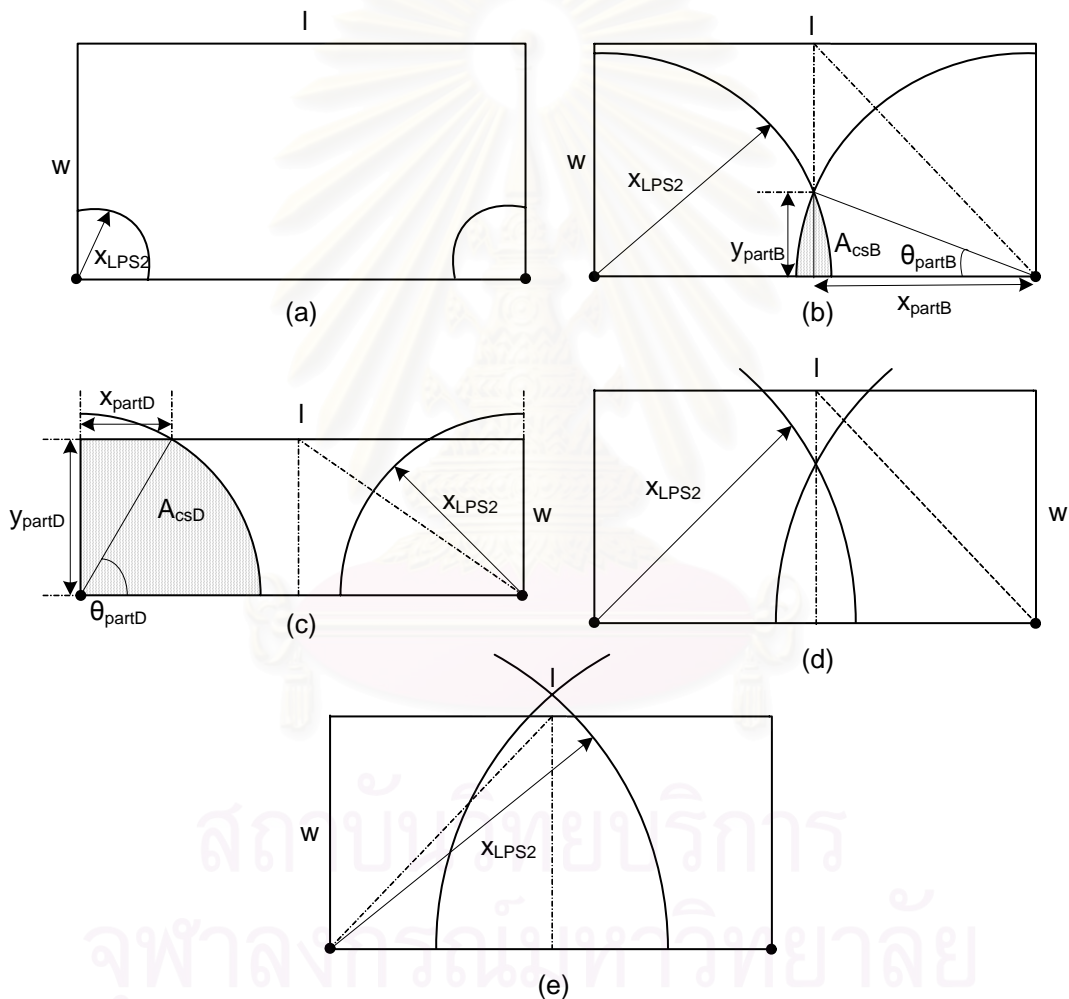
For 2 lightning rods installed next to each other, the inner part calculation of horizontal cross section area of the building can fall into one of these categories as shown in figure (4.14):

(a) If  $x_{LPS2} \leq w$  and  $x_{LPS2} \leq 0.5l$

$$A_{cs1-3}(r) = lw - 0.5\pi x_{LPS2}^2 \quad (4.41)$$

(b) If  $x_{LPS2} \leq w$  and  $x_{LPS2} > 0.5l$

$$A_{cs1-3}(r) = lw - 0.5\pi x_{LPS2}^2 + A_{csB} \quad (4.42)$$



The notation (a), (b), (c), (d) and (e) show the category as in the explanation

Figure (4.14): Categories on 2 lightning rods installed next to each other

(c) If  $x_{LPS2} > w$  and  $x_{LPS2} \leq 0.5l$

$$A_{cs1-3}(r) = lw - 2A_{csD} \quad (4.43)$$

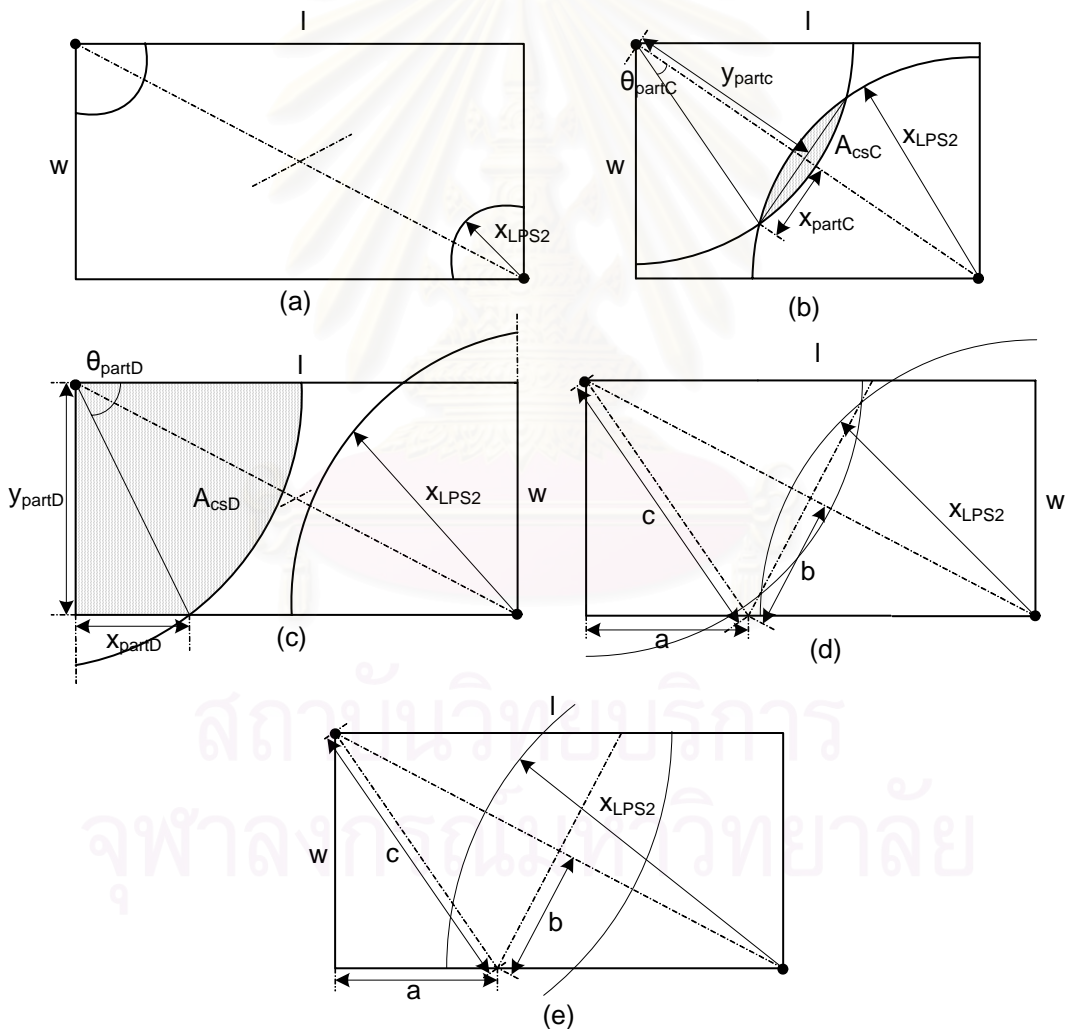
(a) If  $x_{LPS2} > w$  and  $x_{LPS2} > 0.5 l$  and  $x_{LPS2} \leq \sqrt{(0.5l)^2 + w^2}$

$$A_{cs1-3}(r) = lw - 2A_{csD} + A_{csB} \tag{4.44}$$

(b) If  $x_{LPS2} > \sqrt{(0.5l)^2 + w^2}$

$$A_{cs1-3}(r) = 0 \tag{4.45}$$

For 2 lightning rods installed in front of each other, the inner part calculation of horizontal cross section area of the building can fall into one of these categories as shown in figure (4.15):



The notation (a), (b), (c), (d) and (e) show the category as in the explanation

Figure (4.15): Categories on 2 lightning rods installed in front of each other

(a) If  $x_{LPS2} \leq w$  and  $x_{LPS2} \leq \frac{1}{2}\sqrt{l^2 + w^2}$

$$A_{cs1-4}(r) = lw - 0.5\pi x_{LPS2}^2 \quad (4.46)$$

(b) If  $x_{LPS2} \leq w$  and  $x_{LPS2} > \frac{1}{2}\sqrt{l^2 + w^2}$

$$A_{cs1-4}(r) = lw - 0.5\pi x_{LPS2}^2 + A_{csE} \quad (4.47)$$

(c) If  $x_{LPS2} > w$  and  $x_{LPS2} \leq \frac{1}{2}\sqrt{l^2 + w^2}$

$$A_{cs1-4}(r) = lw - 2A_{csF} \quad (4.48)$$

(d) If  $x_{LPS2} > w$  and  $x_{LPS2} > \frac{1}{2}\sqrt{l^2 + w^2}$  and  $x_{LPS2} \leq \text{limit}$

*Limit* = *c* in figure (4.15d), and to calculate it we can use equations (4.34)-(4.37). Thus, we can continue to calculate part of horizontal cross section area using equation below:

$$A_{cs1-4}(r) = lw - 2A_{csD} + A_{csC} \quad (4.49)$$

(e) If  $x_{LPS2} > \text{limit}$

$$A_{cs1-4}(r) = 0 \quad (4.50)$$

For perimeter part which is one of the outer part of the horizontal cross section area of the building, its calculation can fall into one of these categories as shown in figure (4.16). Because this part is in pair with the same part in opposite direction, thus the calculation already combines this. The cross section area will be 2 times than of the figure (4.11e). The categories in the calculation of cross section area are:

(a) If  $x_{LPS1} \leq x_{bld}$  and  $x_{LPS1} \leq 0.5l$

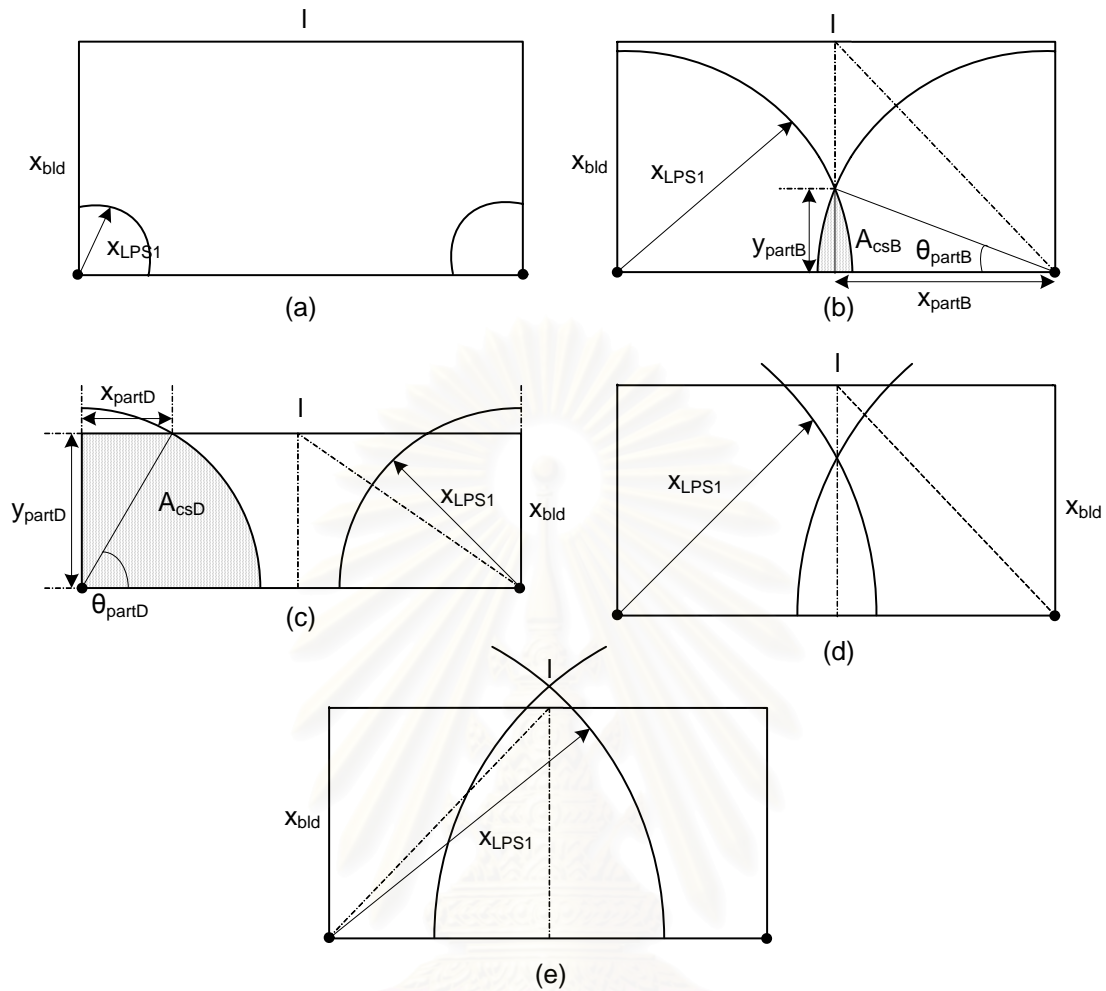
$$A_{cs2-1}(r) = 2lx_{bld} - \pi x_{LPS1}^2 \quad (4.51)$$

(b) If  $x_{LPS1} \leq x_{bld}$  and  $x_{LPS1} > 0.5l$

$$A_{cs2-1}(r) = 2lx_{bld} - \pi x_{LPS1}^2 + 2A_{csB} \quad (4.52)$$

(c) If  $x_{LPS1} > x_{bld}$  and  $x_{LPS1} \leq 0.5l$

$$A_{cs2-1}(r) = 2lx_{bld} - 4A_{csD} \quad (4.53)$$



The notation (a), (b), (c), (d) and (e) show the category as in the explanation

Figure (4.16): Categories on parameter part of cross section area

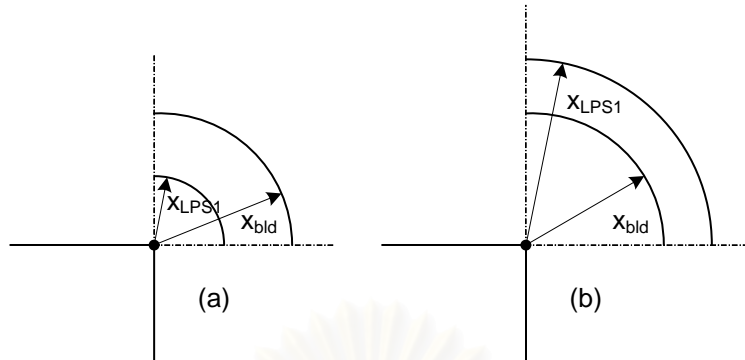
$$(a) \text{ If } x_{LPS1} > x_{bld} \text{ and } x_{LPS1} > 0.5l \text{ and } x_{LPS1} \leq \sqrt{(0.5l)^2 + x_{bld}^2}$$

$$A_{cs2-1}(r) = 2lx_{bld} - 4A_{csD} + 2A_{csB} \quad (4.54)$$

$$(b) \text{ If } x_{LPS1} > \sqrt{(0.5l)^2 + x_{bld}^2}$$

$$A_{cs2-1}(r) = 0 \quad (4.55)$$

For the corner part, there will be only 2 possible categories of horizontal cross section area as we can see in figure (4.17). The calculation will involve 4 corner of the rectangular roof building, thus the cross section area is just a subtraction of 2 circles which radii are  $x_{LPS1}$  and  $x_{bld}$ .



The notation (a) and (b) show the category as in the explanation

Figure (4.17): Categories on corner part of cross section area

(a) If  $x_{LPS1} \leq x_{bld}$

$$A_{cs2-2} = \pi(x_{bld}^2 - x_{LPS1}^2) \tag{4.56}$$

(b) If  $x_{LPS1} > x_{bld}$

$$A_{cs2-2} = 0 \tag{4.57}$$

In the program, all simple parts of cross section area described above can be represented in a function so that we can easily select which part of cross section area is needed and which part is not needed.

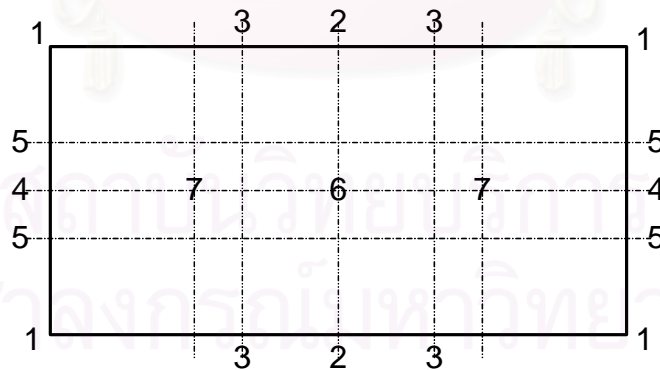


Figure (4.18): Several arrangements of lightning rods on top of building

There are several arrangements of lightning rods that can be calculated using the program. The arrangement can be constructed by combination of a lightning rod and/or group of lightning rods indicated by number as shown in figure (4.18). We only limit the arrangement up to 8 arrangements which are: “1”, “1+2”, “1+3”, “1+2+4”, “1+3+4”,

“1+3+5”, “1+6” and “1+2+7”. As explained above, the horizontal cross section area of each arrangement is combination of simple parts of cross section area. For example, with the arrangement of 1+3+4, top of building will be divided into 6 smaller areas whose length is equal to  $\frac{1}{3}l$  and width equal to  $\frac{1}{2}w$  as in figure (4.19).

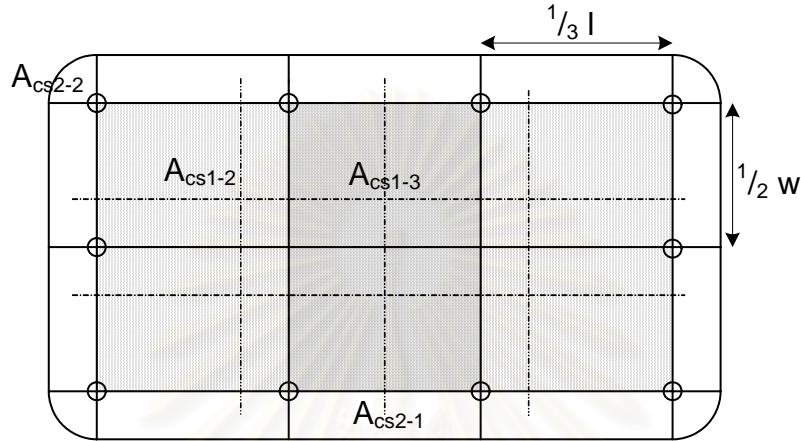


Figure (4.19): Lightning rods arrangement of “1+3+4”

The length  $\frac{1}{3}l$  can either be longer or shorter than  $\frac{1}{2}w$ , there are 2 possible calculations of cross section area. If  $\frac{1}{3}l < \frac{1}{2}w$ , we set the length of constructed area to  $\frac{1}{2}w$ . If on the contrary happened,  $\frac{1}{3}l$  is set to be the length of constructed area. Then, the cross section area can be calculated using one of these equations:

$$A_{cs}(r) = 4A_{cs1-2}\left(\frac{1}{3}l, \frac{1}{2}w\right) + 2A_{cs1-3}\left(\frac{1}{3}l, \frac{1}{2}w\right) + 3A_{cs2-1}\left(\frac{1}{3}l\right) + 2A_{cs2-1}\left(\frac{1}{2}w\right) + A_{cs2-2} \quad (4.58)$$

or

$$A_{cs}(r) = 4A_{cs1-2}\left(\frac{1}{2}w, \frac{1}{3}l\right) + 2A_{cs1-3}\left(\frac{1}{3}l, \frac{1}{2}w\right) + 3A_{cs2-1}\left(\frac{1}{3}l\right) + 2A_{cs2-1}\left(\frac{1}{2}w\right) + A_{cs2-2} \quad (4.59)$$

The calculation of cross section area for others arrangements can be performed in same manner as describe above. The results are:

- For “1” arrangement:

$$A_{cs}(r) = A_{cs1-1}(l, w) + A_{cs2-1}(l) + A_{cs2-1}(w) + A_{cs2-2} \quad (4.60)$$



- For “1+2” arrangement:

$$A_{cs}(r) = 2A_{cs1-1}(0.5l, w) + 2A_{cs2-1}(0.5l) + A_{cs2-1}(w) + A_{cs2-2} \quad (4.61)$$

or

$$A_{cs}(r) = 2A_{cs1-1}(w, 0.5l) + 2A_{cs2-1}(0.5l) + A_{cs2-1}(w) + A_{cs2-2} \quad (4.62)$$

- For “1+3” arrangement:

$$A_{cs}(r) = 3A_{cs1-1}\left(\frac{1}{3}l, w\right) + 3A_{cs2-1}\left(\frac{1}{3}l\right) + A_{cs2-1}(w) + A_{cs2-2} \quad (4.63)$$

or

$$A_{cs}(r) = 3A_{cs1-1}\left(w, \frac{1}{3}l\right) + 3A_{cs2-1}\left(\frac{1}{3}l\right) + A_{cs2-1}(w) + A_{cs2-2} \quad (4.64)$$

- For “1+2+4” arrangement:

$$A_{cs}(r) = 4A_{cs1-2}(0.5l, 0.5w) + 2A_{cs2-1}(0.5l) + 2A_{cs2-1}(0.5w) + A_{cs2-2} \quad (4.65)$$

- For “1+3+5” arrangement:

$$A_{cs}(r) = 4A_{cs1-2}\left(\frac{1}{3}l, \frac{1}{3}w\right) + 2A_{cs1-3}\left(\frac{1}{3}w, \frac{1}{3}l\right) + A_{cs1-1}\left(\frac{1}{3}l, w\right) + 3A_{cs2-1}\left(\frac{1}{3}l\right) + 3A_{cs2-1}\left(\frac{1}{3}w\right) + A_{cs2-2} \quad (4.66)$$

or

$$A_{cs}(r) = 4A_{cs1-2}\left(\frac{1}{3}l, \frac{1}{3}w\right) + 2A_{cs1-3}\left(\frac{1}{3}w, \frac{1}{3}l\right) + A_{cs1-1}\left(w, \frac{1}{3}l\right) + 3A_{cs2-1}\left(\frac{1}{3}l\right) + 3A_{cs2-1}\left(\frac{1}{3}w\right) + A_{cs2-2} \quad (4.67)$$

- For “1+6” arrangement:

$$A_{cs}(r) = 4A_{cs1-4}(0.5l, 0.5w) + 2A_{cs2-1}(0.5l) + 2A_{cs2-1}(0.5w) + A_{cs2-2} \quad (4.68)$$

- For “1+2+7” arrangement:

$$A_{cs}(r) = 8A_{cs1-4}(0.25l, 0.5w) + 4A_{cs2-1}(0.25l) + 2A_{cs2-1}(0.5w) + A_{cs2-2} \quad (4.69)$$

or

$$A_{cs}(r) = 8A_{cs1-4}(0.5w, 0.25l) + 4A_{cs2-1}(0.25l) + 2A_{cs2-1}(0.5w) + A_{cs2-2} \quad (4.70)$$

#### 4.4 Protection of a Building Using the Attractive Volume Concept

Some example of calculation are performed by using the program (program manual is shown in Appendix A). There are only 4 kinds of variation considered in the example, which are probability value  $b$ , ratio of positive to negative strikes, arrangement of lightning rods and height of lightning rods. The considered building is a rectangular roof building which dimension is defined by user. There are others inputs to the program such as ground flash density,  $I_{max}$ ,  $I_o$ , ratio of positive to negative strikes, probability of lightning strikes, lightning rod's height and rod's arrangement, but we will only vary some of this input as an example of calculation using the program.

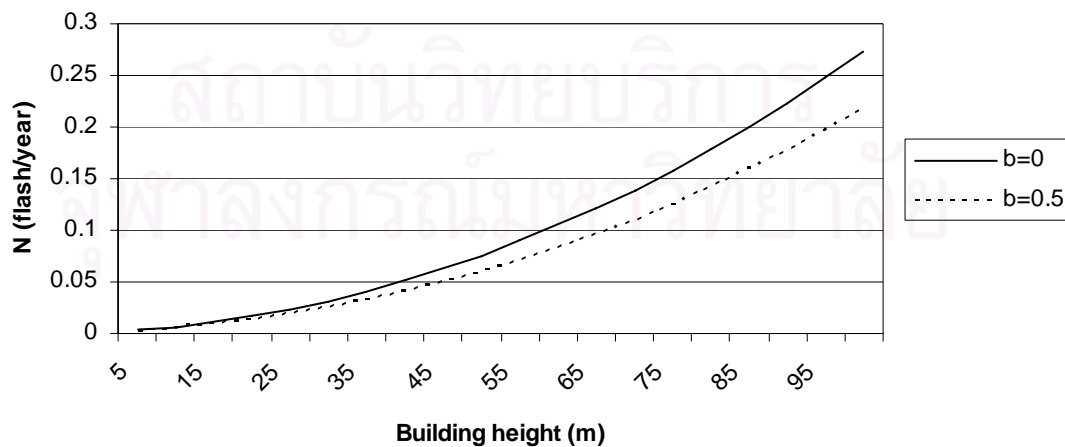


Figure (4.20):  $N$  of  $10 \times 20 \text{ m}^2$  building at different probability value  $b$

Without lightning rods installed on the top of the building, we can calculate the attractive area of the building and the frequency of lightning strikes to the building which is the product of ground flash density of the area where the building stands and the attractive area of the building. Setting the ground flash density to 1 flash/km<sup>2</sup> per year,  $I_{max}$  to 100 kA,  $I_o$  to 1 kA and building's dimension is 10x20 m<sup>2</sup>, we will vary the building height at different probability of lightning strikes values. There are 2 options of probability value which are  $b = 0$  and  $b = 0.5$ . The result of the calculation is shown in figure (4.20) (see table B.1 in Appendix B).

We can see that for all variation of building height, frequency of lightning strikes,  $N$ , for probability value  $b = 0$  is higher than for  $b = 0.5$ . Lower probability value means that we add more possible orientation point inside the attractive volume, thus the attractive volume will be larger. Larger attractive volume will result in larger attractive area. That is why we see that frequency of lightning strike for  $b = 0$  is always higher than that of  $b = 0.5$ . There is positive side and also negative side of setting the probability value to a low value. The positive side is that if we set  $b$  to a low value, we will get higher  $N$  value. Higher value of  $N$  will make us think carefully on whether we should install a LPS or not. This is good because we will reduce the risk of damage of our building. But, installation of LPS is of course costs more money to spend in the design phase of the protection system. This is the negative side of having a higher value of  $N$ .

The knowledge on how important of the building depends on the users of the program, because they must choose by themselves the appropriate  $b$  value. If the building is important, they can choose a low value of  $b$  so they can think more carefully about the protection of the building.

With probability value of 0.5, we will vary the ratio of positive to negative strike. Horvath suggested the value around 10%:90% to 50%:50%, so the variation is between this range. The result of calculation is shown in figure (4.21) (see table B.2 in Appendix B).

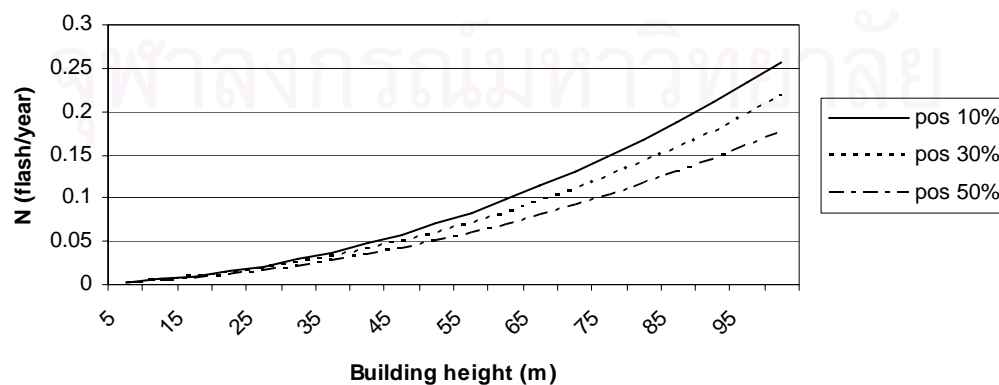


Figure (4.21):  $N$  at different ratio of positive to negative strikes

From figure (4.21) above, we can see that the frequency of lightning strike of the building without any LPS installed on top of it is higher for lower value of positive polarity. This means that the negative strikes take an important role in the calculation of  $N$ . From equation (3.15), we know that negative strike has lower value of  $\varepsilon$  than that of positive one at same probability value. Lower  $\varepsilon$  means that the border of the attractive volume is wider and resulting in higher value of attractive area. That is why the attractive area of the negative strike is always larger than the positive one, and it will give more contribution to the total attractive area as we can see in figure (4.21).

There are 8 options available for the arrangement of the rods as we can see in figure (4.18). Using the same input as the first example, we will vary the height of the building at different arrangement of the lightning rods and calculate the frequency of lightning strikes to the building. The result of calculation on the arrangements is shown in figure (4.22) (see table B.3 in Appendix B).

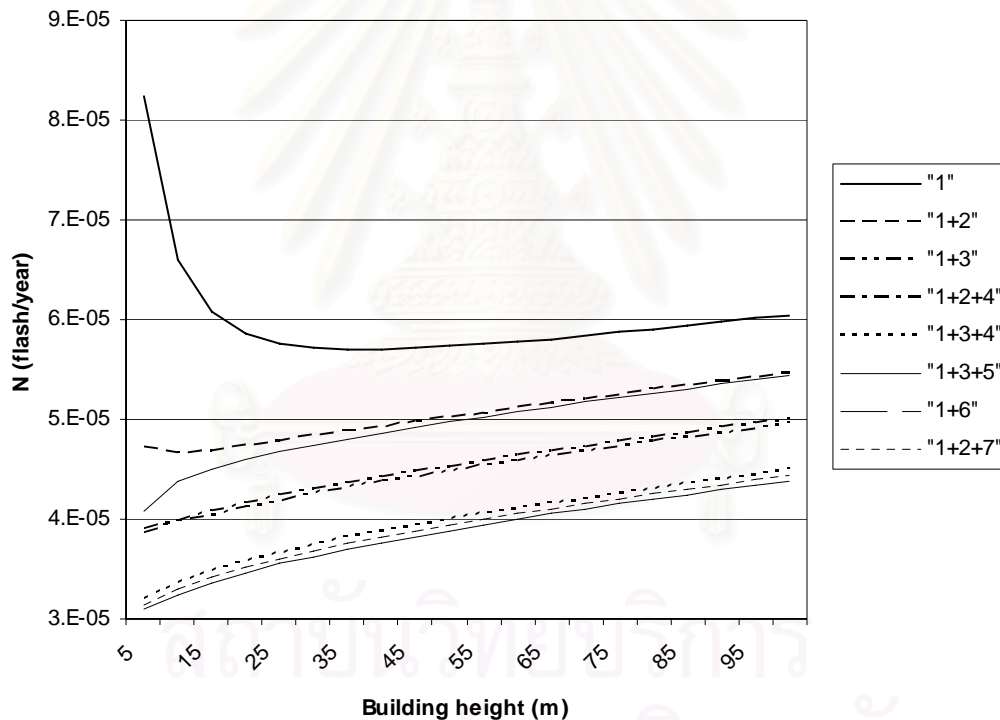


Figure (4.22):  $N$  of different arrangements of lightning rods

We can see that all values of  $N$  for all arrangements are smaller compared with the values before we install any LPS on the building. On the average, by install a LPS of such arrangement, the frequency of lightning strike to the building is reduced by 98-99%. Using arrangement "1" with only 4 lightning rods installed at the corner, frequency of lightning strikes to the  $10 \times 20 \text{ m}^2$  building which has height of 20 m is reduced by 99.56%, from 0.013 flash/year to 0.000059 flash/year. Thus, we can

conclude that for a rectangular roof building, installation of lightning rods to its corner is first priority on the design phase.

From figure (4.22), we also know that higher number of lightning rods will result in lower value of  $N$ . This is good, but we have to consider that higher number of lightning rods will cost more money to spend in the installation. It is up to the user of the program to choose an appropriate arrangement of lightning rods for his building. Installation of lightning rods at a non-perimeter section of the building will reduce more the frequency of lightning strikes to the building than the installation on the perimeter section. But, installation of such arrangement will be difficult, because we need to bring the down conductor to the perimeter section first before we can connect it to the earth electrode. Once more it depends on the designer of LPS to decide whether he will install some rods at the non-perimeter section or not.

Using default value for input data in general information page, and choose arrangement “1” in design information page, we will vary height of lightning rods. Four heights are considered in the calculation, which are 0.1 m, 1 m, 3 m and 5 m. The result of calculation is shown in figure (4.23) (see table B.4 in Appendix B).

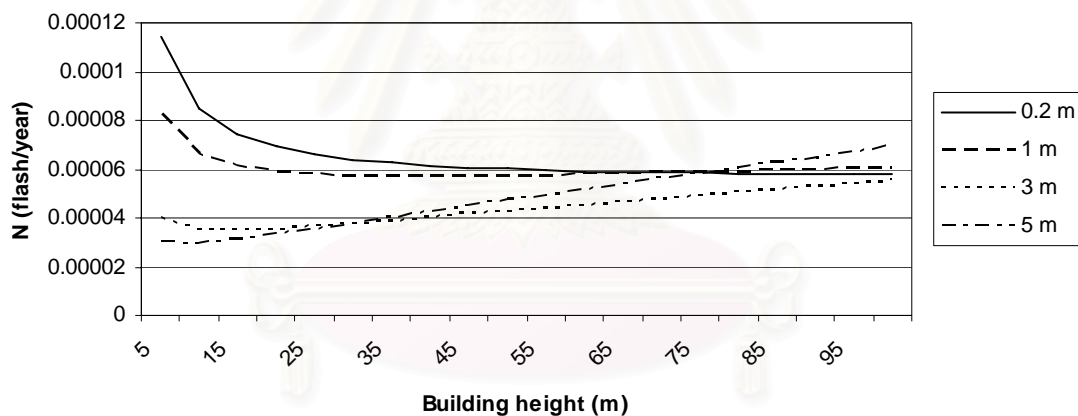


Figure (4.23):  $N$  at different height of lightning rods

We can see from figure (4.23) that at lower building, choosing higher lightning rods is more benefit, because the frequency of lightning strike to the building will be lower. This is because attractive volume of the lightning rods can cover whole attractive volume of the building at both polarities. Using the default value which is 1 m, at positive strike, there is a center part of the building which not covered yet as we can see in figure (4.24a). The contour of the attractive volume will reach its breaking height value before all attractive volume of lightning rods intersects each others. This will lead to unprotected region in the center of the roof. Using higher value, which is 5 m, all attractive volume will intersect each others before they reach their breaking height values as we can see in figure (4.24b).

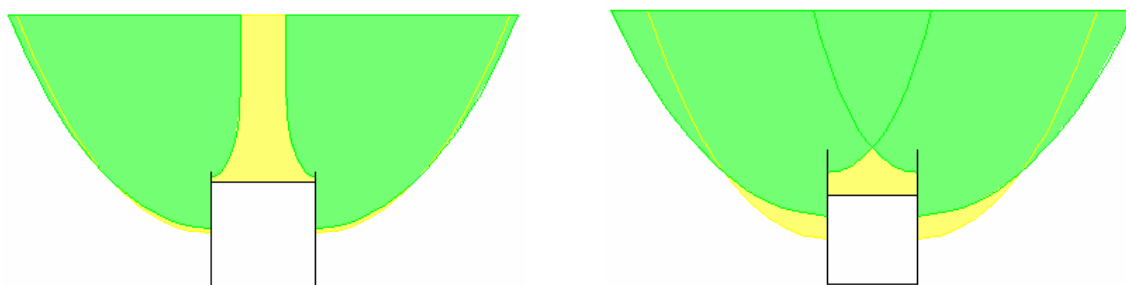


Figure (4.24): Front view of attractive volume of a 10 m building  
(a)  $h_{LPS} = 1$  m (b)  $h_{LPS} = 5$  m

At higher building, the choosing of higher lightning rods should be considered first, because at some building height, the frequency of lightning strike can be higher than if we use lower lightning rods. This frequency of lightning strike will be rising slowly with increasing height of the building as we can see in figure (4.23). At higher building, there will be more attractive volume of the building to be protected and there will be larger unprotected volume at the bottom part of attractive volume of the building as well as at the part above the roof. This will lead to higher frequency of lightning strike for higher building. Even though the situation is the same at lower building, contrary result is obtained. This is because of the difference of the attractive area of the building without LPS installed is very large. At building height of 10 m, the attractive area is only  $5068.91 \text{ m}^2$  which is smaller compared to  $217032.02 \text{ m}^2$  obtained for building height of 100 m. That is why at lower building, the frequency of lightning strike will be lower if we use a higher lightning rods.

## CHAPTER 5

### CONCLUSIONS

#### 5.1 Summary of Thesis

This thesis concerns with the calculation of attractive area of a structure using attractive volume concept. There are many methods to calculate the attractive area, but only attractive volume concept that gives better risk assessment which are needed for designing the protection of the structure. In chapter 2, risk of damage due to lightning strikes is discussed. It is necessary because it tells us about the risk of damage of the structure. Protective volume concept is applied after that. This subchapter tells the history of lightning protection system from protection angle method to attractive volume method which were developed by Tibor Horvath.

Chapter 3 deals with the attractive volume concept itself. Attractive volume is a volume which contains all possible orientation point from which lightning turns toward the point of strike. This volume has a border that depends on the probability of lightning strike,  $b$ , of the orientation point. Every orientation point has a probability  $b$  from which lightning can strike a structure. Attractive volume of simple object such as a horizontal line above a plane and a point above a plane is discussed afterward. Knowledge regarding attractive volume of this simple object is important, because our considered structure, a rectangular roof building, can be substituted by them in the calculation of attractive area. After knowing the attractive volume of a basic structure, we go to the calculation of attractive area which is area within the border of attractive volume. A step by step approach is suitable for the calculation, thus we use a computer program in the calculation. This subchapter also compares the calculation of attractive area using attractive volume concept and the one given in IEC standard. It is shown that IEC standard only consider a single orientation distance value, a distance between orientation point and a point of strike. This is a simplification because we know that every object has many orientation points depend on probability of lightning strike.

Structure of the computer program we developed is given in chapter 4. The first subchapter is discussed about input parameters that should be set before we run the program. The choice of these parameters is important to give the calculation value as close to the real value. Flowchart of the program is given after that. The program is

divided into several functions and the flowchart of all function is given. Using the flowchart, attractive area of a structure from lower lightning current limit to upper limit can be calculated. One of the functions is used to calculate the horizontal cross section area of the attractive volume, thus the subchapter will explained about it. The horizontal cross section area of a building we need is the horizontal cross section area of the building itself (subtracted with the horizontal cross section area of a LPS in case we install LPS on our building). Arrangement of lightning rods take important role on it, thus a discussion about horizontal cross section of some arrangement is given. There are 8 arrangement discussed in this subchapter which should be choose first before we run the program.

Results of some calculations are given in the next subchapter. In this subchapter, we calculate the frequency of lightning strikes of different probability value and of different ratio of positive to negative strikes. It was shown that lower probability value will give higher frequency of lightning strikes,  $N$ , because lower probability value will give wider border of attractive volume. In the second calculation, it is shown that lower ratio of positive polarity will result in higher value of  $N$ . Negative strike has a wider border of attractive volume than the positive strike. That is why such a result was obtained. Last calculation in this subchapter is calculation of attractive area of several lightning rods arrangement. Higher number of lightning rods installed will decrease frequency of lightning strike to the structure. This is also happen for installation of lightning rods on the non-perimeter section of the building. But, such arrangement is sometimes difficult to be installed and it will cost more expense than the other arrangement.

## 5.2 Recommendations for Future Works

The program developed in this thesis is just a beginning for further studies. There are only few aspects considered in the program, thus this program will be very useful for improving lightning protection system studies. Works that can be done to improve the program are:

- Consider other shapes of the building:  
The program developed in this thesis is only for a rectangular roof building. So, application of the program is limited. If users can input by themselves the shape of the building such us L shape or circle, it will make the program more applicable.
- Consider other arrangements of lightning rods:



In the program, only 8 available arrangements can be choose for designing the appropriate LPS. Sometimes this is not enough. So other arrangements are needed, whether by adding more option to the program or user can select manually the location of lightning rods he prefer.

- Add an option of horizontal conductor beside the available lightning rods  
For designing the LPS of the building, the program only consider lightning rods only. It will give more flexibility if we add an option of horizontal conductor in the program. Usually, to protect the perimeter of the building, a horizontal conductor is easier to be applied and it also gives better artistic view of the building than the lightning rods.
- Improve the graphic of attractive volume to 3D view  
Nowadays, 3D application is widely used. By improving the graphic of attractive volume to 3D, it will give extra information about the attractive volume. It will also make the program more attractive.
- Programming efficiency:  
In this work, the computational time was rather long when a higher building was considered. This can be caused by too small step chosen or too long script written. Therefore, if we can reduce number of line in the script by making the program more compact, the calculation time can be shorter.

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## **APPENDICES**

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## APPENDIX A

### Program Manual

The program consists of two screens, calculation screen and drawing screen. Calculation screen will be displayed the first time when we start the program. We can input the data we have through this screen. Calculation screen has 2 filling page, general information and design information. General information page contain basic information needed for the calculation of attractive area of a structure such as, Ground Flash Density (GFD), ratio of positive to negative lightning strike polarity,  $I_{max}$ ,  $I_o$ , step size, probability of lightning strike, and building dimension. Figure (A.1) shows the general information page of the calculation screen.

Figure (A.1): General information page

Explanation of the input is given below:

- *GFD* (strikes/km<sup>2</sup> per year):

Indicates ground flash density of the area where the building stands. The default value is 1 strikes/km<sup>2</sup> per year. If the users only know the thunderstorm day value,  $T_d$ , they can calculate by themselves GFD value using one of these equations.

$$N_g = 0.04T_d^{1.25}$$

$$N_g = 0.023T_d^{1.3}$$

$$N_g = 0.0086T_d^{1.45}$$

- *Ratio of positive polarity (%)*:  
Indicates the ratio of positive to negative lightning strike polarity assigned for the calculation of attractive area. The suggested value is between 10:30 and 50:50. The default value is 30:70.
- $I_{max}$  (kA):  
Shows the maximum lightning current for the calculation of the attractive area. This value is related to the upper limit of the attractive volume. The program will calculate the attractive area up to this value. The default value of  $I_{max}$  is 100 kA. User can input value up to 500 kA.
- $I_o$  (kA):  
Shows the maximum lightning current that will not cause damage to the building.  $I_o$  is related to the lower limit of the attractive volume. The default value is 1 kA. User can input any value but the value must be less than  $I_{max}$  value.
- *Step size (m)*:  
For the calculation of the attractive area, attractive volume will be divided into several sections and step size indicates the width of the section of the attractive volume. The value should not be too small because it can lengthen the calculation time. The default value is 0.01 m.
- *Probability of lightning strike*:  
Indicate all orientation points from which lightning has probability to strike the object. The collection of orientation points will form the border of attractive volume. Lower probability value will give wider border of attractive volume. There are two options available for the probability value, i.e. 0 and 0.5. The default value is 0.5.

- *Building dimension (m):*

The considered structure is a rectangular roof building. User can input the building height, length and width into this field. The default value for building height, length and width are 10 m, 20 m and 10 m respectively.

The second page is LPS design information page. In this page, user can design the appropriate lightning rods arrangement. The design information page is shown in figure (A.2). The data that should be inputted in this page is only lightning rods height and their arrangement:

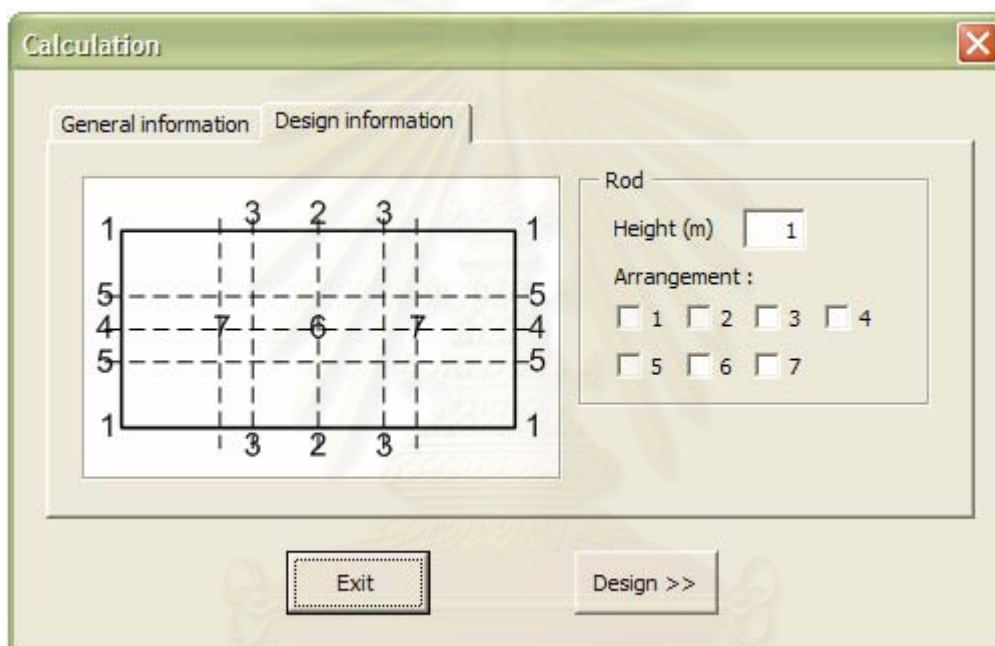


Figure (A.2): Design information page

- *Height (m):*

Indicate the height of lightning rods to be installed to the building. The default value is 1 m. User can input value up to 5 m.

- *Arrangement:*

There are 7 check boxes available. Checking one of the check boxes will install lightning rods at the position show by number in the figure beside the check box. There are 8 arrangement that can be chosen, which are “1”, “1+2”, “1+3”, “1+2+4”, “1+3+4”, “1+3+5”, “1+6”, and “1+2+7”. Uncheck all means that no LPS installed and program will calculate attractive area of building only. Besides these

arrangements, warning message will be displayed to user to change their arrangement.

In the calculation screen, there are 2 buttons which are exit button and design button:

- Exit button:  
By clicking this button, the program will be ended.
- Design button:  
A click on this button will run the calculation based on the data inputted by the user in the calculation screen. Program will also draw the related attractive volume. Drawing results screen will be shown after the calculation finish.

Result of the calculation including the drawing will be shown in the drawing screen. To explain the screen, an example of calculation of the attractive area of a building will be shown. Using default value in the general information page, and pick the arrangement of “1+2” in the design information page the program were run. The result of the calculation is shown in drawing screen as in figure (A.3).

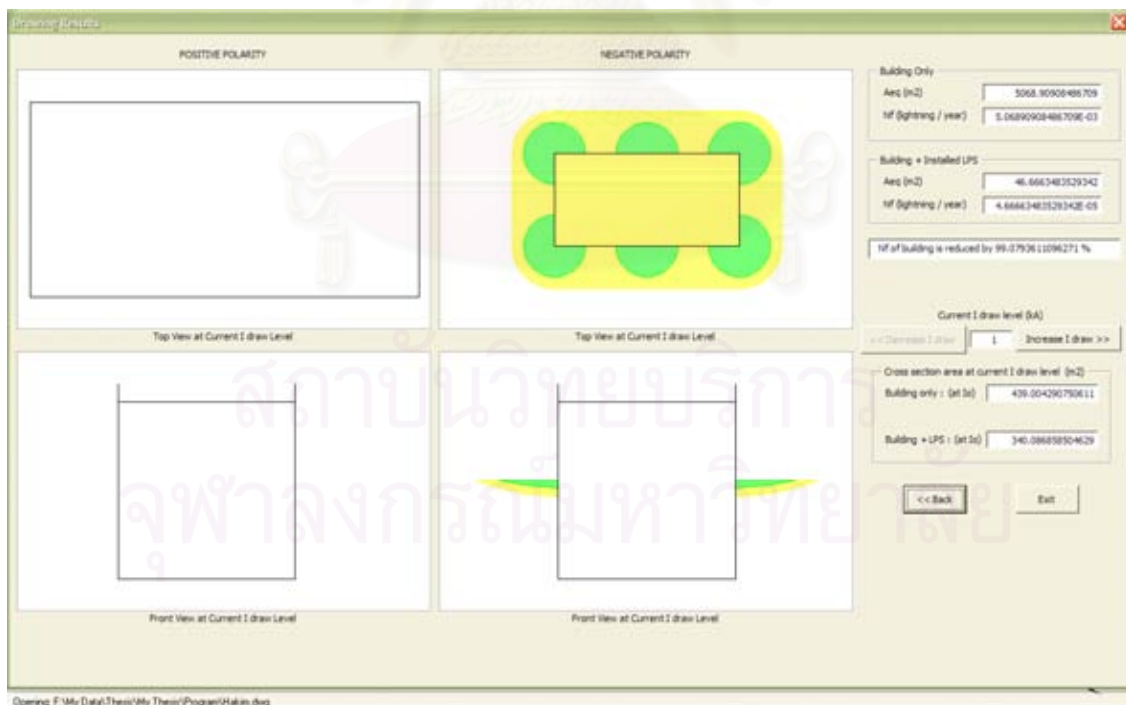


Figure (A.3): Drawing results screen

The drawing screen consists of two main part, drawing part and calculation part:

- Drawing part:

The drawing part is shown by 4 picture windows in rectangular arrangement. Two pictures on the left are for positive polarity and two on the right for negative polarity. Upper picture show top view of the attractive volume. Side view is shown in the lower picture. Basically, the object in the picture has 2 kinds of colors, which are:

Yellow : indicate attractive volume of the building

Green : indicate attractive volume of LPS

The pictures shown on the screen are related to the lightning current value which can be seen in the text box before increase-I draw button. We can draw another picture of attractive volume by clicking this button.

- Calculation part:

Show two results of calculation, the attractive area ( $A_{eq}$ ) of building and attractive area of building+LPS. The related frequency of lightning strike values ( $N_f$ ) are also shown in the same frame with the attractive area.

Below these result, a text box indicated result of calculation on how much frequency of lightning strike are reduced is shown. This text box together with building+LPS frame will not be shown if no arrangement of LPS in the design information page is chosen.

Current I draw level (kA)	
<< Decrease I draw	11.894
Increase I draw >>	
Cross section area at current I draw level (m2)	
Building only :	3607.63774353311
(IEC Current Level)	4827.43338823081
Building + LPS :	44.7495502252923
<< Back	Exit

Figure (A.4): IEC Calculation result

Program also calculates the horizontal cross section area of building and building+LPS at current lightning current level. The result of calculation will show inside frame below increase-I draw button. At the first run, program will tell that calculation of horizontal cross section is at  $I_o$  level, but if we increase the level the label (at  $I_o$ ) will not be shown. Clicking increase-I draw button several time will



give us result of calculation using IEC method. Program will tell this by showing the label (IEC Current Level) beside the result of calculation, as we can see in figure (A.4). This result will only be shown at IEC current level.

In general, drawing results screen has 4 buttons which are:

- *Decrease I draw*  
Clicking this button will reduce current  $I_{draw}$  level by 5 kA until  $I_o$  level, except if between two current levels there is IEC current level.  $I_{draw}$  will reduce to this value first before go to the lower current level if we click the button again. Calculation of horizontal cross section area of building and building+LPS together with the drawing of attractive volume is also being update by clicking this button. This button will not active at  $I_o$  level.
- *Increase I draw*  
Clicking this button will increase current  $I_{draw}$  level by 5 kA until  $I_{max}$  level, except if between two current levels there is IEC current level.  $I_{draw}$  will increase to this value first before go to the upper current level if we click the button again. Calculation of horizontal cross section area of building and building+LPS together with the drawing of attractive volume is also being update by clicking this button. This button will not active at  $I_{max}$  level.
- Back  
A click in this button will hide the drawing result screen and show the calculation screen again
- Exit  
If we click this button, the program will be ended.

## APPENDIX B

### Calculation Results

Table (B.1):  $N$  at different probability of lightning strikes value

h	N (flash / year)	
	b = 0	b = 0.5
5	0.003003775	0.002322083
10	0.006475193	0.005068909
15	0.011033829	0.008690276
20	0.016714459	0.013207931
25	0.0235409	0.018637731
30	0.031532987	0.024993908
35	0.040708598	0.024993908
40	0.051084207	0.040534981
45	0.062675161	0.049742309
50	0.075495851	0.059921242
55	0.089559846	0.071081331
60	0.104879994	0.083231608
65	0.121468497	0.096380648
70	0.139336983	0.110536611
75	0.158496561	0.125707288
80	0.178957873	0.14190013
85	0.200731128	0.159122286
90	0.223826147	0.17738062
95	0.248252388	0.196681741
100	0.274018979	0.217032018

Table (B.2):  $N$  at different ratio of positive polarity

h	N (flash/year)		
	10%	30%	50%
5	0.002665659	0.002322083	0.001978507
10	0.005840791	0.005068909	0.004297027
15	0.010054191	0.008690276	0.007326361
20	0.015333685	0.013207931	0.011082177
25	0.021699122	0.018637731	0.015576341
30	0.029168132	0.024993908	0.020819685
35	0.037756407	0.032289120	0.026821833
40	0.047478335	0.040534981	0.033591628

45	0.058347301	0.049742309	0.041137318
50	0.070375836	0.059921242	0.049466649
55	0.083575733	0.071081331	0.058586928
60	0.097958137	0.083231608	0.068505080
65	0.113533617	0.096380648	0.079227679
70	0.130312227	0.110536611	0.090760995
75	0.148303560	0.125707288	0.103111016
80	0.167516786	0.141900130	0.116283475
85	0.187960698	0.159122286	0.130283874
90	0.209643739	0.177380620	0.145117502
95	0.232574032	0.196681741	0.160789451
100	0.256759405	0.217032018	0.177304632

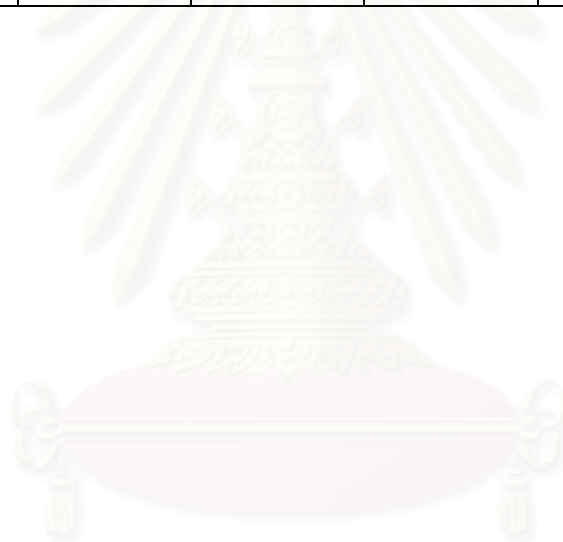
Table (B.3):  $N$  on different arrangement of lightning rods

h	N (flash/year)							
	"1"	"1+2"	"1+3"	"1+2+4"	"1+3+4"	"1+3+5"	"1+6"	"1+2+7"
5	8.25E-05	4.72E-05	3.90E-05	3.85E-05	3.20E-05	3.10E-05	4.08E-05	3.13E-05
10	6.60E-05	4.67E-05	3.97E-05	3.99E-05	3.37E-05	3.25E-05	4.38E-05	3.30E-05
15	6.08E-05	4.69E-05	4.05E-05	4.08E-05	3.48E-05	3.36E-05	4.51E-05	3.42E-05
20	5.87E-05	4.73E-05	4.12E-05	4.16E-05	3.58E-05	3.46E-05	4.60E-05	3.52E-05
25	5.77E-05	4.78E-05	4.19E-05	4.23E-05	3.67E-05	3.55E-05	4.68E-05	3.60E-05
30	5.72E-05	4.83E-05	4.25E-05	4.30E-05	3.74E-05	3.63E-05	4.75E-05	3.68E-05
35	5.70E-05	4.88E-05	4.31E-05	4.36E-05	3.81E-05	3.70E-05	4.81E-05	3.75E-05
40	5.70E-05	4.93E-05	4.37E-05	4.42E-05	3.88E-05	3.77E-05	4.87E-05	3.82E-05
45	5.71E-05	4.98E-05	4.43E-05	4.48E-05	3.94E-05	3.83E-05	4.92E-05	3.88E-05
50	5.73E-05	5.02E-05	4.48E-05	4.53E-05	4.00E-05	3.89E-05	4.97E-05	3.94E-05
55	5.75E-05	5.07E-05	4.53E-05	4.58E-05	4.05E-05	3.94E-05	5.03E-05	4.00E-05
60	5.78E-05	5.11E-05	4.58E-05	4.63E-05	4.11E-05	4.00E-05	5.08E-05	4.05E-05
65	5.81E-05	5.16E-05	4.63E-05	4.68E-05	4.16E-05	4.05E-05	5.12E-05	4.10E-05
70	5.84E-05	5.20E-05	4.68E-05	4.73E-05	4.21E-05	4.10E-05	5.17E-05	4.15E-05
75	5.87E-05	5.25E-05	4.73E-05	4.77E-05	4.26E-05	4.15E-05	5.22E-05	4.20E-05
80	5.91E-05	5.29E-05	4.77E-05	4.82E-05	4.31E-05	4.20E-05	5.26E-05	4.25E-05
85	5.94E-05	5.33E-05	4.82E-05	4.87E-05	4.35E-05	4.25E-05	5.31E-05	4.30E-05
90	5.98E-05	5.38E-05	4.86E-05	4.91E-05	4.40E-05	4.30E-05	5.35E-05	4.35E-05
95	6.01E-05	5.42E-05	4.91E-05	4.96E-05	4.45E-05	4.34E-05	5.40E-05	4.39E-05
100	6.05E-05	5.46E-05	4.95E-05	5.00E-05	4.49E-05	4.39E-05	5.44E-05	4.44E-05

Table (B.4):  $N$  on different height of lightning rods

h	N (flash/year)			
	0.2	1	3	5
5	0.000114162	0.000082458	0.000040214	0.000030353
10	0.000084920	0.000065974	0.000035412	0.000029518
15	0.000074438	0.000060834	0.000034896	0.000031058

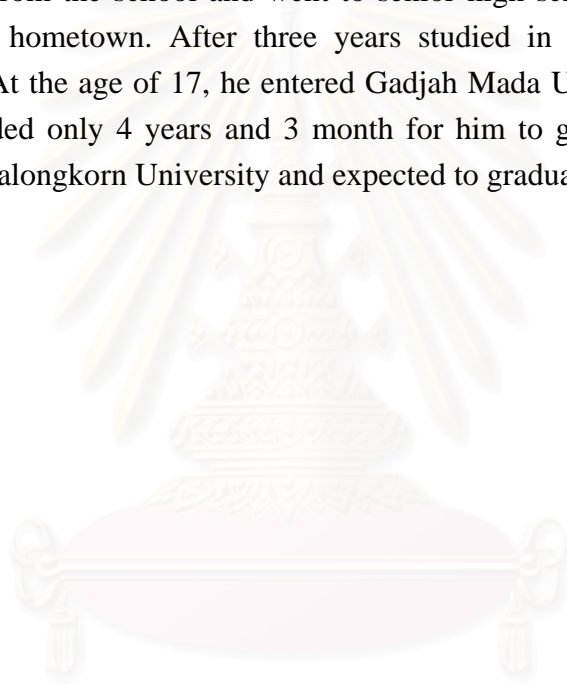
20	0.000069148	0.000058689	0.000035472	0.000033176
25	0.000065993	0.000057684	0.000036432	0.000035457
30	0.000063921	0.000057218	0.000037557	0.000037783
35	0.000062474	0.000057041	0.000038763	0.000040114
40	0.000061420	0.000057036	0.000040009	0.000042434
45	0.000060628	0.000057140	0.000041277	0.000044739
50	0.000060021	0.000057316	0.000042555	0.000047025
55	0.000059546	0.000057542	0.000043838	0.000049293
60	0.000059172	0.000057805	0.000045123	0.000051545
65	0.000058874	0.000058094	0.000046407	0.000053780
70	0.000058635	0.000058404	0.000047689	0.000056000
75	0.000058443	0.000058729	0.000048967	0.000058205
80	0.000058289	0.000059066	0.000050243	0.000060398
85	0.000058165	0.000059413	0.000051514	0.000062577
90	0.000058068	0.000059768	0.000052782	0.000064746
95	0.000057991	0.000060129	0.000054046	0.000066903
100	0.000057932	0.000060494	0.000055306	0.000069050



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จุฬาลงกรณ์มหาวิทยาลัย

## BIOGRAPHY

Muhammad Arif Rahman Hakim was born in Tuban, a city in East Java, Indonesia on January 15<sup>th</sup>, 1982. He followed his parents to move to Jogjakarta, a city in Central Java where his parents stayed until right now, at the age of 2. In 1987, he studied primary high school in a local school near his home. Six years later he graduated and he continued study in junior high school 5, which is a good school in Jogjakarta. In 1996 he graduated from the school and went to senior high school 1, which is also a good school in his hometown. After three years studied in senior high school he graduated in 1999. At the age of 17, he entered Gadjah Mada University as a bachelor student. And it needed only 4 years and 3 month for him to graduate. Right now he study master at Chulalongkorn University and expected to graduate on May, 2006.



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