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A Comparative Analysis of External Lightning Strike Protection Area Determined by Using Protection Angle and Rolling Sphere Methods

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***Abstract*—The lightning phenomenon is a natural disaster that endangers human life. The nature of grabbing objects closest to the cloud can cause fires, damage to electrical equipment, and even fatalities. The Padang Institute of Technology is a campus that has tall buildings, such as buildings B, C, D, E, and F, without an adequate lightning protection system. This is certainly a concern regarding security and safety for building users on the ITP campus. This research was conducted to reduce the risk of being hit by a lightning strike on the ITP campus. The protection system design process refers to the IEC 62305-3 standard comparing the protection angle and rolling sphere methods. Meanwhile, the procedure for calculating building requirements for a protection system or building protection level refers to the PUIPP and IEC 1024-1-1 standards. After analyzing the lightning rods in 5 ITP campus buildings by comparing the protection angle and rolling sphere methods, it can be concluded that there are still parts of the building that are not protected by the size of the installed air terminal. To overcome this, adding or adjusting the air terminal level is necessary so that all buildings are in the protection area. In addition, in conducting the analysis, the method considered the best to provide clear information on the part of the building that needs protection and the amount of the building that has been protected is the Rolling sphere method**.

***Keywords*— Lightning; rolling sphere; protection angle.**

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I. INTRODUCTION

High rainfall accompanied by lightning is a natural phenomenon that often occurs in Indonesia because it is in a tropical climate [1]. Indonesia is categorized as having very high lightning or thunder days compared to other countries, namely 100-200 thunder days per year [2], [3]. In addition, based on data from BMKG Indonesia in 2020, lightning occurrences continue to increase compared to the previous year [4]. This condition needs to be considered because lightning strikes endanger human life, causing fires, damaging equipment, and even causing fatalities [5].

The lightning phenomenon occurs due to the discharge of charge in the cloud to the earth to be neutralized [6], [7]. Often this discharge strikes objects closest to the cloud, such as tall buildings [8]. To improve the security aspect of the building, it is necessary to install an external protection system. Installation of an external lightning strike protection system is the most widely used standard solution in overcoming lightning strikes. This lightning strike protection system consists of an air terminal, a down conductor, and grounding [9]. The process of designing a lightning strike protection system depends on the height of the building, the building area, and the frequency of lightning strikes per year [10]. The taller the building and the greater the frequency of lightning strikes, the greater the risk of being struck by lightning and the higher the need for a protection system [11]. The building's needs for lightning protection can be determined by the value of the PUIPP standard index to the condition of a building and calculations using the thunder day parameters according to the IEC1024-1-1 standard [12].

In addition to determining the need for lightning protection, a design process for placing a lightning strike protection system is required. Several previous studies have shown the methods used to analyze the design and placement of external protection systems based on the IEC 62305-3 standard [13]. This standard has several methods for determining lightning protection systems' placement, such as rolling spheres and protection angles. Based on that research, the rolling sphere method is a method that uses a sphere in analyzing the protection area of an air terminal in a building [14], [15], [16]. Meanwhile, the protection angle analyzes the location of the protected area using the angle form between the height of a finial and the reference plane [17].

Institut Teknologi Padang is an engineering campus located in West Sumatra, Indonesia. This campus has tall buildings without a good lightning protection system. To reduce the risk of lightning strikes on on-campus buildings, this research was conducted on five campus buildings, namely buildings B, C, D, E, and F, by comparing the protection angle and rolling sphere methods according to the IEC 62305-3 standard [18], [19].

II. Materials and Method

A. The Need for a Building to Have a Lightning Protection System and Implementation

A good lightning protection installation system can reduce and prevent the occurrence of danger and damage due to lightning strikes in buildings. This, of course, must be considered when building a tall building or getting closer to the clouds [20]. A building should have an external protection system in the form of air terminals, down conductors, and adequate grounding [21]. In addition, it is supported by the accuracy of the installation of a protection system in reaching a large lightning protection area.

Institut Teknologi Padang has several high buildings, such as buildings B, C, D, E, and F, which may be exposed to the risk of external lightning strikes. These tall buildings are often used for practical activities, lectures, and campus data centers. However, these buildings do not have a lightning protection system. So, activity in the building may be disrupted due to lightning strikes. This is the basis for comparing the lightning protection system on the Institut Teknologi Padang campus building with the rolling sphere and protection angle methods. Tests and analysis will be carried out to determine the coverage area, the number of installed water terminals, and the accuracy of the method in analyzing a good lightning protection system, as for determining the level of building needs for a protection system [16], [22].

1) PUIPPP (Installation General Regulation of Lightning Protection): According to the PUIPPP standard, the need for lightning strike protection in a building can be determined by taking into account the indexes that have been determined according to the condition of the building's standing. Estimated lightning strike hazard (R) can be defined as follows.

$$R = A + B + C + D + E \quad (1)$$

2) IEC 1024-1-1 (International Electrotechnical Commission): The level of protection is based on the value of the number of local direct lightning strikes (Nd) and the allowed number of local annual lightning strikes (Nc) [17] [23]. Mathematically the calculation of the frequency of lightning strikes to the ground in the regional yearly average is as follows.

$$Ng = 0{,}04\ x\ Td^{1{,}25} \quad (2)$$

$$Nd = Ng\ x\ Ae\ x\ 10^{-6} \quad (3)$$

$$Ae = ab + 6h\,(a + b) + 9.\,\pi\, h2) \quad (4)$$

The estimated risk of installing a protection system in buildings depends on the values of Nd and Nc as follows [26]:

- If Nd > Nc, there is no need for a lightning protection system.
- If Nd>Nc, a lightning protection system is required with efficiency:

$$E = \left(1 - \frac{Nd}{Nc}\right) x\ 100\% \quad (5)$$

TABLE I
PROTECTION LEVELS

Protection Level	Efficiency
I	98%
II	95%
III	90%
IV	80%

B. Design of Air Termination Placement with IEC Standard 62305-3

1) Protective Angle Method: The protective Angle Method is suitable for simple-shaped buildings [24]. However, this method only applies to a height equal to the Rolling sphere radius of the appropriate lightning protection level [27] [25]. Mathematically it can be formulated as below:

$$tan\, \alpha = \text{rp/h} \quad (6)$$

In addition, the formula for calculating the protected area mathematically is as follows.

$$Ap = \pi\, rp^2 \quad (7)$$

The protected part is inside the cone as in Fig below.

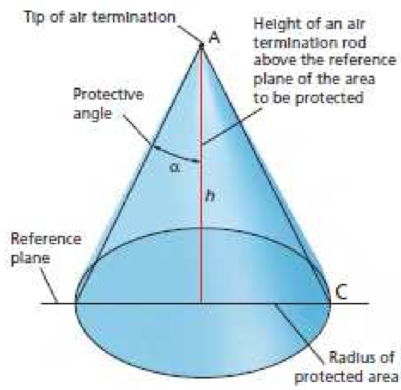


Fig. 1 Protection angle method

The calculation of the air protection angle depends on the distance between the height of the shield and the reference plane to be protected, such as the roof and the ground. An example can be seen in the Figure below.

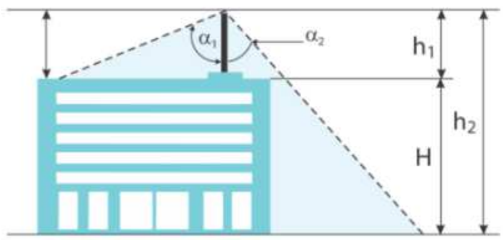


Fig. 2 Angle of protection against a reference plane

Figure 2 above shows that angle 1 is generated from h1 with the roof reference plane. Angle 2 is the result of h2=H+h1 with ground reference.

TABLE II

PROTECTION ANGLE VALUE

Height (m)	Level I		Level II		Level III		Level IV	
	Angle α	Distance (m)	Angle α	Distance (m)	Angle α	Distance (m)	Angle α	Distance (m)
1	71	2.90	74	3.49	77	4.33	79	5.14
2	71	5.81	74	6.97	77	8.66	79	10.29
3	66	6.24	71	8.71	74	10.46	76	12.03
4	62	7.52	68	9.90	72	12.31	74	13.95
5	59	8.32	65	10.72	70	13.74	72	15.39
6	56	8.90	62	11.28	68	14.85	71	17.43
7	53	9.29	60	12.12	66	15.72	69	18.24
8	50	9.53	58	12.80	64	16.40	68	19.80
9	48	10.00	56	13.34	62	16.93	66	20.21
10	45	10.00	54	13.76	61	18.04	65	21.45
11	43	10.26	52	14.08	59	18.31	64	22.55
12	40	10.07	50	14.30	58	19.20	62	22.57
13	38	10.16	49	14.95	57	20.02	61	23.45
14	36	10.17	47	15.01	55	19.99	60	24.25
15	34	10.12	45	15.00	54	20.65	59	24.96
16	32	10.00	44	15.45	53	21.23	58	25.91
17	30	9.81	42	15.31	51	20.99	57	26.18
18	27	9.17	40	15.10	50	21.45	56	26.68
19	25	8.86	39	15.39	49	21.86	55	27.13
20	23	8.49	37	15.07	48	22.21	54	27.53
21			36	15.26	47	22.52	53	27.87
22			35	15.40	46	22.78	52	28.16
23			36	16.71	47	24.66	53	30.52
24			32	15.00	44	23.18	50	28.60
25			30	14.43	43	22.31	49	28.76
26			29	14.41	41	22.60	49	29.91
27			27	13.76	40	22.66	48	29.99
28			26	13.66	39	22.67	47	30.03
29			25	13.52	38	22.66	46	30.03
30			23	12.73	37	22.61	45	30.00
31					36	22.52	44	29.94
32					35	22.41	44	30.90
33					35	23.11	43	30.77
34					34	22.93	42	30.61
35					33	22.73	41	30.43
36					32	22.50	40	30.21
37					31	22.23	40	31.50
38					30	21.94	39	30.77
39					29	21.62	38	30.47
40					28	21.27	37	30.14
41					27	20.89	37	30.90
42					26	20.48	36	30.51
43					25	20.05	35	30.11
44					24	19.59	35	30.81
45					23	19.10	34	30.35
46							33	29.87
47							32	29.37
48							32	29.99
49							31	29.44
50							30	28.87
51							30	29.44
52							29	28.82
53							28	28.18
54							27	27.51
55							27	28.02
56							26	27.31
57							25	26.58
58							25	27.05
59							24	26.27
60							23	25.47

3) Rolling sphere Method: The rolling sphere method is geometrically used for all building structures, including complex ones (Fig 3). Air terminations are installed at rolling ball test points in the protected building [28]. The rolling sphere method is expressed in the form of R, which is the distance of lightning to the tip of the lightning rod. Mathematically the value of R is related to the magnitude of the lightning current, as below:

$$rp = I^{0.75} \tag{8}$$

If the lightning current < I, then the building can still withstand lightning strikes.

If the lightning current > I, then the lightning strike will be caught by the air terminal.
Find the area of protection:

$$Ap = \pi \, x \, rp^2 \quad (9)$$

In addition, angles can be found using the Hasse and Wiesinger equations below:

$$\alpha = sin^{-1}(1 - h/rp) \quad (10)$$

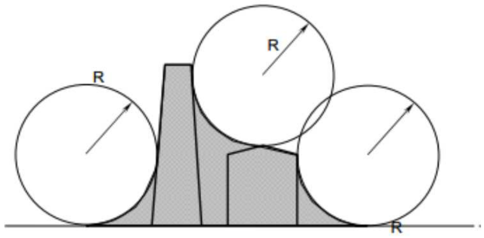


Fig. 2 Rolling sphere method

In addition, one of the determining factors in designing a building air termination system is knowing the depth of penetration of the Rolling sphere between the two water terminals [29].

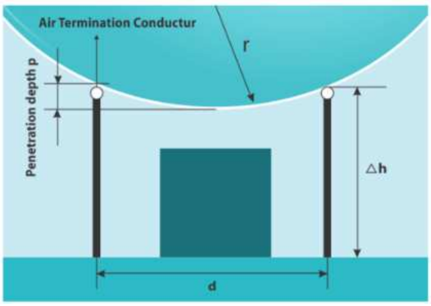


Fig. 3 Penetration depth of rolling sphere

To find out the depth of penetration of the rolling sphere, you can perform the following calculations.

$$p = rp - \sqrt{r^2 - \left(\frac{d}{2}\right)^2} \quad (11)$$

The following is a table of rolling sphere radius based on protection level.

TABLE III
PROTECTION LEVEL

Protection Level	Radius Rolling sphere (m)
I	20
II	30
III	45
IV	60

C. *Data Collection Method*

The data collection methods used in this research were observation, interview, and literature study. The researchers observed objects to be analyzed, such as building data (length, width, and height) and the frequency of Padang thunder day. Then, the interview was administered to related parties, such as Institut Teknologi Padang staff, to complete the test data and to Padang Panjang Geophysics BMKG regarding the lighting conditions in Padang. Furthermore, previous journals or studies were analyzed to acquire the standards set as a reference in the analysis and evaluation process. The standards included IEC 62305-3-3, PUIP 1983, IEC 1024-1-1, and SNI 03-7015-2004.

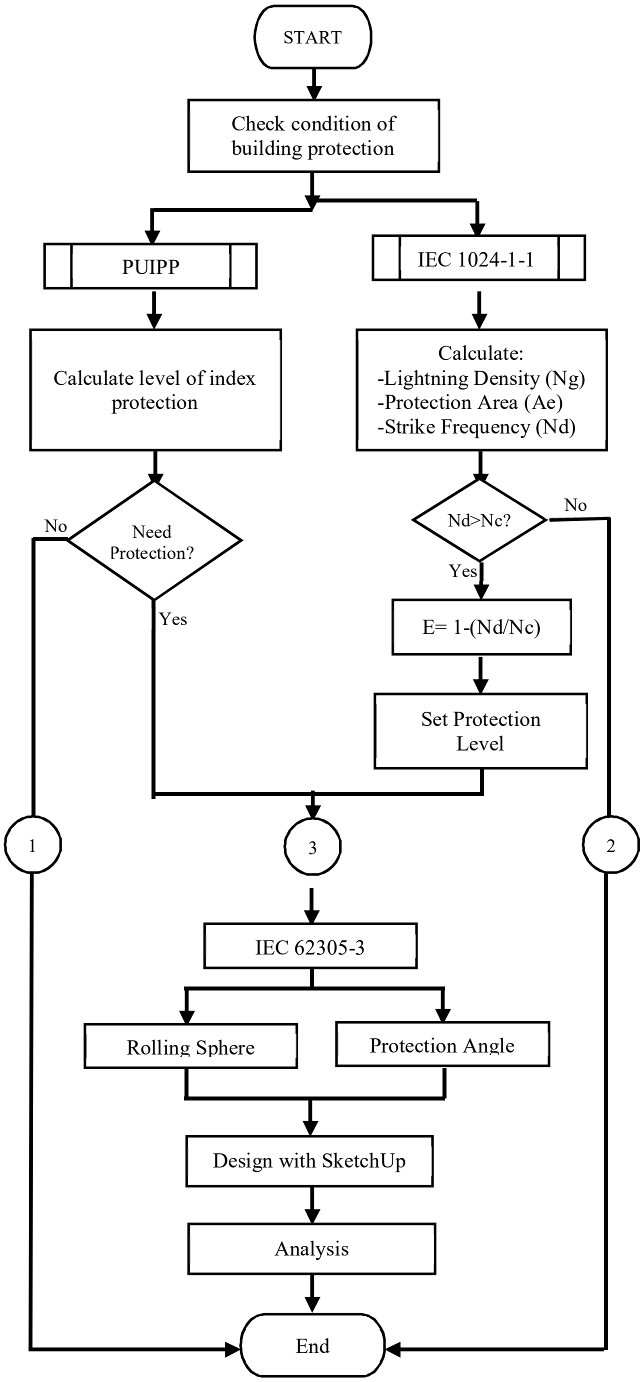


Fig. 4 Research flow chart

III. Results and Discussion

Institut Teknologi Padang is geographically located at 0.900155°S and 100.36397° E [30]. Based on the geographical location, it can be seen that the average number of thunder days/year is 286/km2/year. This data was taken in 2018-2020 at the BMKG Padang Panjang Station.

A. *Specifications of Lightning Protection*

In this study, the air terminal height is assumed to be the same in each building, namely the Splitzen type of trident with a size of 40 cm and a support pole height of 60 cm. Thus, the total height of the lightning rod used is 100 cm or 1 meter.

TABLE IV
LIGHTNING ROD

Specification	Information
Brand	Split Zen Trisula
Length size	30-40 cm
Ingredients	Copper plated brass
Support Pipe Size	60 cm

B. Building Data

The buildings used in the research on lightning rods were buildings B, C, D, E, and F. These buildings were the tallest and had essential functions in campus activities. The following table shows the characteristics of the building.

TABLE V
BUILDING CHARACTERISTICS

Building	Size (meter)			Utility
	P	L	T	
B	32	14	15.3	Classrooms, Lecturers room, and Civil Eng. laboratory.
C	31	15	11.54	Library, Head of Department offices
D section I	44	20	13.70	Rectorate, office room
D section II	20	6	13.70	Campus Hall, and Hall Archives
E	24	12	15.50	Classroom, Electrical Eng. Laboratory Computer Laboratory
F	42	14	10.80	Class, Lecturer room, Machine Eng. Laboratory

C. Calculation of ITP Building Protection Needs Level

1) PUIPP: From the results of the calculation of the R-value on the PUIPP standard, the level of protection needed for each building is obtained.

TABLE VI
LEVEL OF BUILDING PROTECTION BASED ON PUIPP

No	Building	Index summation result (R)	Protection Needs
1	B	16	Required
2	C	15	Required
3	D (sections I and II)	16	Required
4	E	16	Required
5	F	15	Required

2) IEC 1024-1-1: Calculations with the IEC 1024-1-1 standard using data on the Padang city thunder day can be seen in the following table.

TABLE VII
BUILDING PROTECTION LEVEL BASED ON IEC1024-1-1

Building	IEC 1024-1-1 dan SNI 03-7015-2004					Protected Level
	Ng	Ae	Nd	Nc	E %	
B	47,04	11286,18	0,53	0,1	81,2	III
C	47,04	7413,47	0,35	0,1	71,3	IV
D sect I	47,04	11561,03	0,54	0,1	81,6	III
D sect II	47.04	7654,63	0.36	0,1	72,2	IV
E	47,04	10425,47	0,49	0,1	79,6	IV
F	47,04	7513,05	0,35	0,1	71,7	IV

D. Air Terminal Placement Analysis

Based on Table VI, a calculation application was designed using the GUI feature of MATLAB R2009a. This application helped in determining the angular size of the protection angle and the rolling sphere radius.

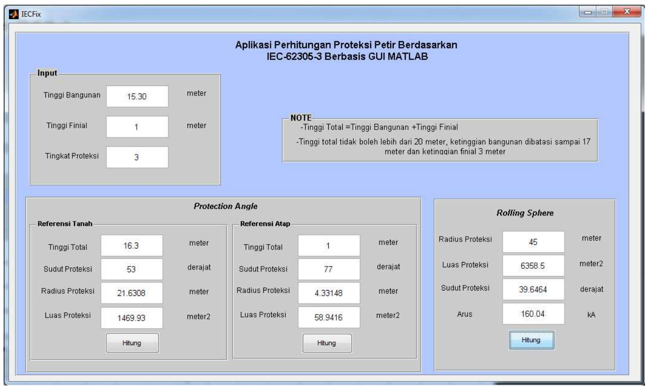


Fig. 7 Application for calculating the rolling sphere and protection angle method

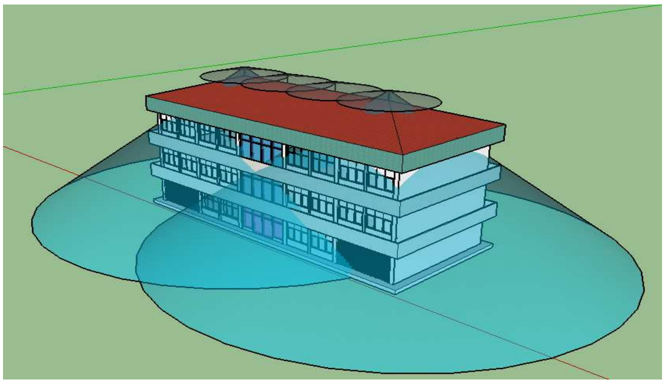
From the application calculation on the MATLAB GUI feature, the resulting angle and radius of protection are as follows.

TABLE VIII
ANGLE VALUE AND RADIUS

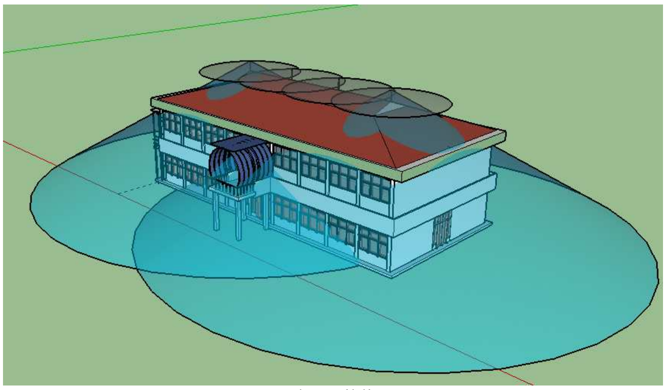
Building	**Protection Angle**		**Rolling Sphere**
	Angle h1	**Angle h2**	**Radius sphere**
B	77°	53°	45 m
C	79°	61°	60 m
D sect I	77°	54°	45 m
D sect II	79°	59°	60 m
E	79°	57°	60 m
F	79°	62°	60 m

Notes: h_1 = air terminal level, h_2 = total height (building height + air terminal height)

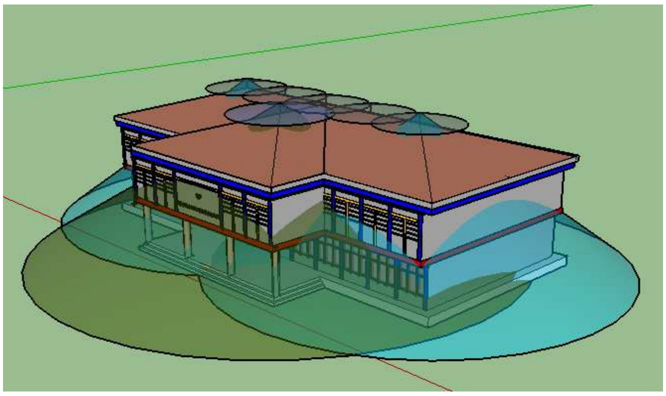
1) Protection Angle: Protection for a building with the protection angle method showed by how many areas in the building can be covered by an air terminal. From Figure 8, as shown below, it can be seen that there are four air terminals installed in buildings B, C, and E. Then, five air terminals in building D section I, only one air terminal in building D section II and six air terminals in building F. However, the installed air terminal could not provide overall protection to the building because the coverage of the protection area of the protection angle method was narrow, so the angle did not cover parts of the building. The protection angle method is a simplification of the rolling sphere method. It depends on the angle formed between the height of an object and the reference plane. Thus, the protection area is smaller than the rolling sphere. The higher the air terminal installation, the wider the protection coverage area. Regarding this theory, it is necessary to add or adjust the air terminal level so that all buildings are in the protection area.



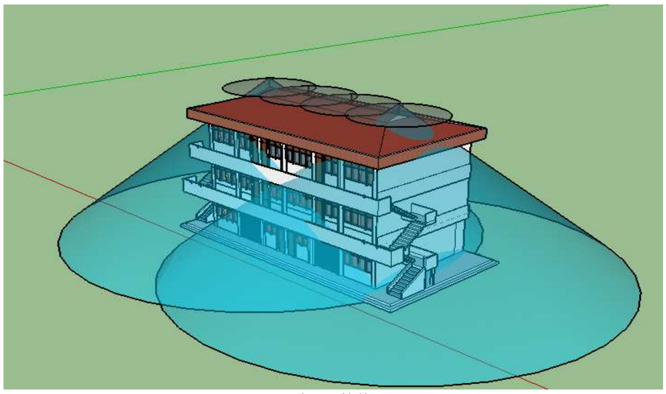
a. Building B



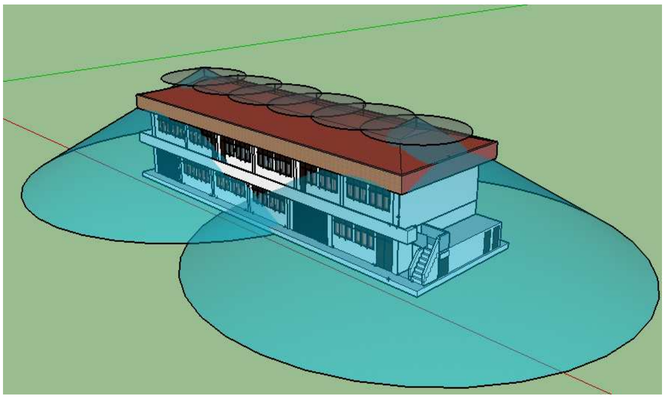
b. Building C



c. Building D



d. Building E



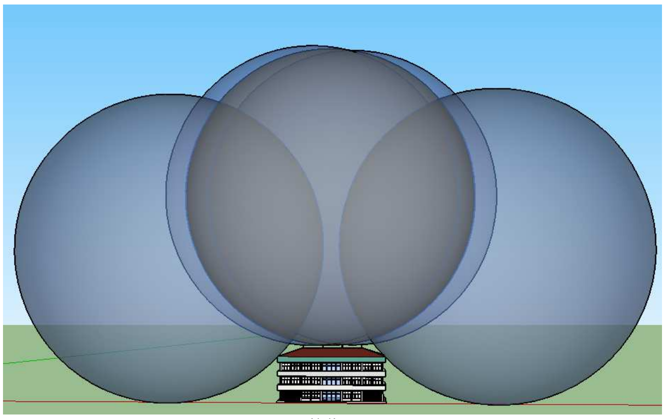
e. Building F

Fig. 8 Buildings protection area with protection angle method

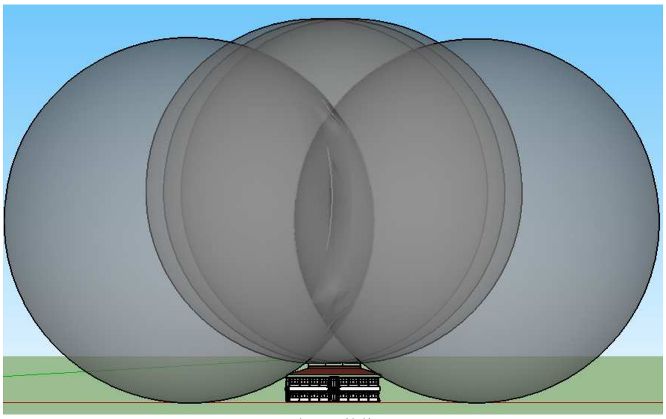
2) Rolling Sphere: Using the same number and size of air terminals, Figure 9 shows the protection area rolling sphere method. There are parts of the ball contact points touching the roof of the building. At the same time, the concept of a rolling sphere considers the sphere as the range of a lightning strike. The sphere will roll following the structure of the building, starting from the ground and ending on the ground again. If the rolling sphere touches a part of the building, the building is likely to be hit by a lightning strike. If it is not touched, then the building is in a protected area. Therefore, the rolling sphere method is considered better for analyzing a lightning rod's protected and unprotected areas.

The illustration of the area protection using the rolling sphere and protection angle methods shows the protected and unprotected parts of the building from a lightning strike. Based on the illustration, it is known that the installation of the same size air terminals, namely a height of 1 meter in five buildings, has not been able to protect the building as a whole. This is evidenced by the presence of parts of the building outside the protected angle area or the presence of parts of the roof of the building that are still touched by the sphere. Therefore, it is necessary to adjust the air level of the terminal used to protect the building as a whole.

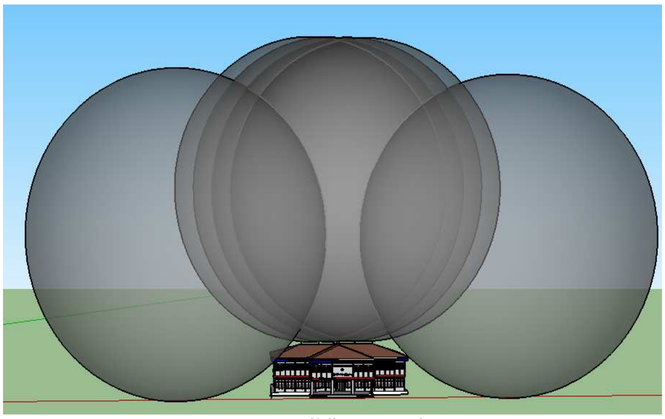
In terms of accuracy in analyzing the protected and unprotected building, the rolling sphere method is considered better than the protection angle. This is because the touchpoint of the sphere used as a medium for determining protection can clearly show the protected and unprotected parts of the building compared to the angle of protection.



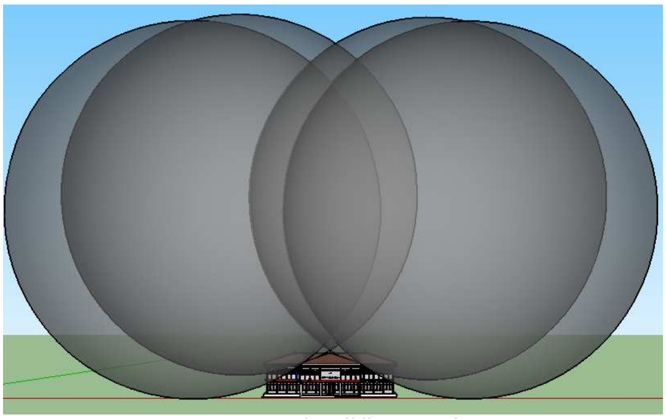
a. Building B



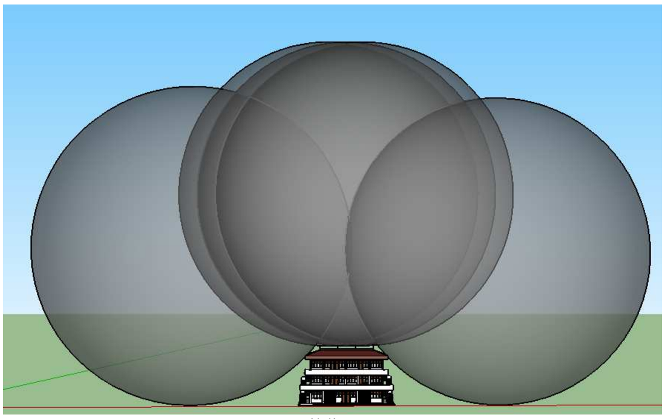
b. Building C



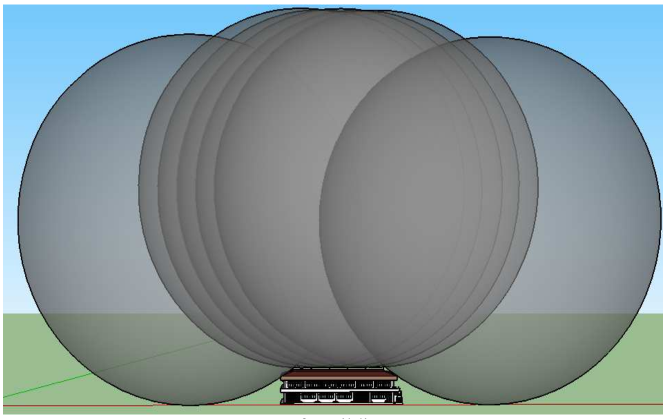
c. Building D section I



d. Building D section II



e. Building E



f. Building F

Fig. 9 Buildings protection area with rolling sphere method

IV. CONCLUSION

A comparative analysis of the external lightning strike protection area was determined using protection angle and rolling sphere methods. Comparing the protection angle and rolling sphere methods, it can be shown that there are still parts of the building that are not protected by the size of the installed air terminal where it is necessary to add or adjust the air terminal level so that all buildings are in the protection area. Conducting the analysis, the method that is considered the best to provide clear information on the part of the building that needs protection and the amount that has been protected is the Rolling sphere method.

NOMENCLATURE

R	lightning hazard assessment	
A	building contents	
B	building construction	
C	building height	
D	building situation	
E	thunder day/Year	
A	the length of the roof of the building	m
B	building roof width	m
h	building roof height	m
Ae	Coverage area of Structure	m2
Td	number of Groh Days	km2year-1
Ng	the density of lightning to the year ground	

Nd	frequency or number of strikes year local lightning per year	
rp	protection radius	m
phi	22/7 or 3.14	
Ap	Protected area	m2
I	lightning strike current	kA
P	penetration distance	m
d	distance between two air termination rods	mm

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