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# The Simulation of a Lightning Protective Area through the Protective Angle Method and the Rolling Sphere Method

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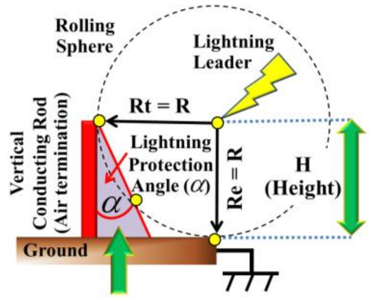
***Abstract*— The protective angle method (PAM) and the rolling sphere method (RSM) are the popular lightning protection concepts for the impact avoidance of a lightning flash by using the installation of a vertical conducting rod (or Air termination) which can appropriately be utilized to analyze the external lightning protection. Moreover, these methods (PAM & RSM) are approved through the international standard IEC62305. Especially, the lightning protective area (LPA) is demonstrated if and only if the vertical conducting rod is installed which directly concerns the PAM and RSM respectively. However, the LPA of PAM and RSM are different configurations. As mentioned above, this article presents the simulation and comparison result of the lightning protective area (LPA) between the protective angle method (PAM) and the rolling sphere method (RSM). Also, the mathematical correlations of the LPA based on PAM & RSM are clearly shown for evaluation in this article.**

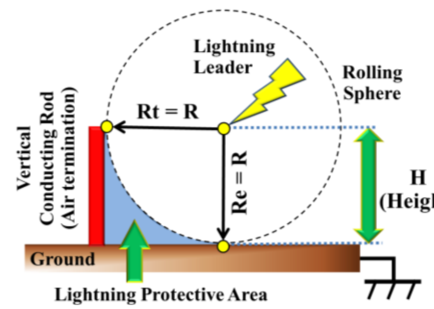
***Keywords — lightning protective area, protective angle method, rolling sphere method, Air termination***

## I. INTRODUCTION

The lightning protection concepts can be divided into three methods as follows: the mesh method (MM), the protective angle method (PAM), and the rolling sphere method (RSM) respectively [1]. Especially, the implementation of a vertical conducting rod (we can call an Air termination or Franklin's rod) for analysis of the lightning protective area, directly relates to the protective angle and the rolling sphere method because the effective results of these methods (PAM & RSM) occur through the installation of a vertical conducting rod above the ground as shown in Figure 1 (a) and Figure 1 (b).




(a) The lightning protective area due to the protective angle method.




(b) The lightning protective area due to the rolling sphere method.

Fig.1. The lightning protective area based on 2-Dimensions.

According to Figure 1 (a), the correlation of a protective angle method (PAM) can be shown in the mathematical parameter as a lightning protection angle ( $\alpha$ ), the processing analytical of this parameter was illustrated by the novel equation (Reference: Arnon Singhasathein and et al.) [2-3] which lightning protection angle ( $\alpha$ ) can be utilized to calculate the protective area easily. Moreover, the configuration of a lightning protective area through the protective angle method (PAM) is equivalent to the simple triangle area (or an approximate area).

While, the lightning protective area due to the rolling sphere model in Figure 1 (b) is a complete realistic configuration, which can be analyzed by using the total area below the boundary curves between a rolling sphere and a vertical conduction rod above the ground level that must utilize the upper and lower limit of integration in the calculus theorem for evaluation. Therefore, the rolling sphere method (RSM) is a complex calculation for analysis of the lightning protective area.

The calculation of the lightning protective area can be implemented to evaluate the quantity of a protective region through a vertical conducting rod (Air termination) which can generate the safety area to cover the interesting object such as the solar rooftop, the solar farm, the tall building, and so on.

As mentioned above, the lightning protection angle ( $\alpha$ ) of PAM is easy to implement in the practical. However, it delivers the approximate lightning protective area which must be compared the result with the realistic lightning protective area through the rolling sphere. During in the past decade, this comparison is never illustrated in the researches. Therefore, this article presents the analysis and comparison of the lightning protective area between the protective angle method (PAM) and the rolling sphere method (RSM) respectively. Moreover, we can show the proof of mathematical correlation for the lightning protective area in the condition of PAM and RSM based on the international standard IEC 62305. However, this research focuses on the 2-dimensions (2D) area only.

The remainder of this article is prepared as follows. The structure of a lightning protective area through the analysis of PAM is explained in section II. Also, the topics of the relationship between a rolling sphere method and the realistic lightning protective area, and the simulation and comparison of lightning protective areas, are illustrated in section III and section IV respectively.

And finally, the conclusion is summarized in section V.

## II. THE STRUCTURE OF A LIGHTNING PROTECTIVE AREA TROUGH THE ANALYTICAL OF A PAM

The mathematical correlation of the lightning protection angle ( $\alpha$ ) was demonstrated to analyzed the protective angle method (PAM) [2-3] as shown in Figure 3 and an equation (1). The PAM is a solution and popular implementation for the avoidance of lightning flash in the IEC standard. The correlation of equation (1) is depended on the striking distance, the striking distance to the vertex, the striking distance to the ground (all the striking distance is equivalent ($R = R_t = R_e$) based on the IEC 62305 as shown in equation (2)), the lightning current (I), and the object height (H) respectively.

Moreover, the lightning protection angle ( $\alpha$ ) can be utilized to evaluate the lightning protective area (LPA) which can be approximately analyzed to a simple triangle area. This area consists of the vertical distance (as an object height, H) and the horizontal distance (as a significant distance, S). The important correlation can be illustrated in equations (3) and (4) respectively.

$$\alpha = 0.5 \bullet \left( \arctan(\frac{\sqrt{2RH\text{-}H^2}}{H}) + \arcsin(\frac{R\text{-}H}{R}) \right) \quad (1)$$

$$R = 10 \bullet I^{0.65} \quad (2)$$

$$S = \tan(\alpha) \bullet (\sqrt{2RH}) \bullet \sin\left( \arccos\left( \sqrt{\frac{2R\text{-}H}{2R}} \right) \right) \quad (3)$$

$$\text{Lightning Protective Area of PAM} = \frac{1}{2} \bullet S \bullet H$$

$$= \frac{1}{2} \bullet \left( \tan(\alpha) \bullet (\sqrt{2RH}) \bullet \sin\left( \arccos\left( \sqrt{\frac{2R\text{-}H}{2R}} \right) \right) \right) \bullet H \quad (4)$$

The correlation of a lightning protective area (LPA) in equation (4) can imply the quantity of an approximate protective region which is limited by the horizontal boundary within the significant distance (S) as illustrated in Figure 3.

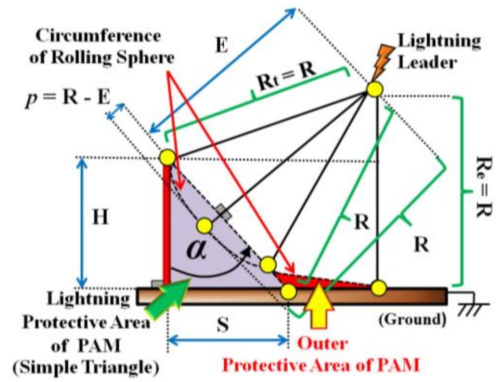



Fig.3. All the structures of a lightning protective area (LPA) due to PAM.

However, the realistic lightning protective area based on the rolling sphere method (RSM) has a horizontal limit more than the significant distance (S) because the circumference of a rolling sphere can above cover the protective region and the outer protective area of PAM as shown on Figure 3. Particularly, the outer protective area cannot be directly determined through the PAM.

In the Figure 3, illustrates the penetration distance ($p$) as shown in the correlation in equation (5) [4]. The penetration distance ($p$) is a disadvantage of the PAM because this distance is a maximum dangerous length which the lightning flash can strike into the protective area and it is influenced to reduce the protective area of PAM. However, this article neglects the impact of a penetration distance for the analysis of the LPA.

$$p = R \text{ - } E = R \bullet \left( 1 - \cos(\alpha - \arcsin(\frac{R-H}{R}) \right) \quad (5)$$

As mentioned above, The PAM is easily utilized because it delivered the basic correlation (as shown in equation (1)) and it can be directly converted to a simple triangle of the protective area. However, the lightning protective area (LPA) of PAM which was analyzed through the equation (4) has many constraints for the application (such as the horizontal boundary, the outer protective area of PAM, and so on). Therefore, it must be compared to the quantity of protective region with the LPA of an RSM that can be illustrated in the next sections.

## III. THE RELATIONSHIP BETWEEN A ROLLING SPHERE METHOD AND THE REALISTIC LIGHTNING PROTECTIVE AREA

The rolling sphere method (RSM) is analyzed based on the realistic physics of the striking distance (R) and the lightning current (I), was shown in equation (2) which is approved through the IEC 62305. Moreover, the striking distance (R) is equivalent to a radius of the rolling sphere model [5] that can be divided into levels 1-4 as demonstrated in Table I.

In this section, we can determine the lightning protective area (LPA) of RSM by using the analysis of a geometric theorem in Figure 4 and the integral technique which can be shown the mathematical correlation in the equation (6) to (9) respectively.

TABLE I. THE STANDARD STRIKING DISTANCE BASED ON IEC 62305 [1]

| LEVEL | Minimum Lightning Current. $I_{min}$, (kA) | Striking Distance IEC Standard. R, (meters) |
|---|---|---|
| 1 | 3 | 20 |
| 2 | 5 | 30 |
| 3 | 10 | 45 |
| 4 | 16 | 60 |

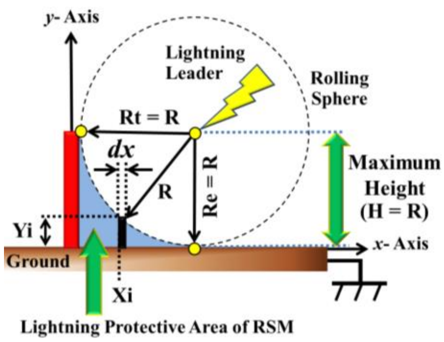


Fig.4. The geometric concept of RSM for analysis of the LPA.

$$(x-R)^2+(y-R)^2=R^2 \tag{6}$$

$$y=-\sqrt{R^2-(x-R)^2}+R \tag{7}$$

$$\text{Lightning Protective Area of RSM}=\int_{Xi}^{R}\left(-\sqrt{R^2-(x-R)^2}+R\right)dx \tag{8}$$

$$X_i=-\sqrt{R^2-(Y_i-R)^2}+R \tag{9}$$

Where

- $x$ is the variable of a horizontal axis (x-axis)
- $y$ is the variable of a direct axis (y-axis)
- R is the striking distance in the detail of Table I
- $X_i$ is the interesting horizontal distance for a calculation
- $Y_i$ is the interesting height of a vertical conducting rod

From the calculation of using the equation (6) to (9), it can be appeared all the results of the realistic lightning protective area, which can be utilized to evaluate the trend line and approximate correlation for easy implementation through the relationship of the polynomial least square equation which is defined the R-Square ($R^2$) as 1 only. As mentioned earlier, we can show the approximate correlation of the LPA of RSM as demonstrated in equation (10) to (13) respectively.

$$\text{LPA of RSM}_{LEVEL1}=-0.0142H^3+0.3439H^2+3.1888H-1.8269 \tag{10}$$

$$\text{LPA of RSM}_{LEVEL2}=-0.0096H^3+0.3505H^2+4.6852H-3.7088 \tag{11}$$

$$\text{LPA of RSM}_{LEVEL3}=-0.0065H^3+0.3577H^2+6.8825H-7.7236 \tag{12}$$

$$\text{LPA of RSM}_{LEVEL4}=-0.0049H^3+0.356H^2+9.1957H-13.334 \tag{13}$$

Where H is the object height for calculation

The correlation in this section focuses on the evaluation of LPA based on the RSM concept which can be analyzed to compare the results with the LPA of the protective angle method (PAM) as shown in section IV.

## IV. THE SIMULATION AND COMPARISON OF LIGHTNING PROTECTIVE AREAS

As mentioned in the previous sections, the lightning protective area (LPA) was demonstrated that the mathematical correlation which can be divided into the two concepts: such as the LPA of a protective angle method (PAM) and the LPA of a rolling sphere method (RSM). These correlations were obviously shown in equations (4) and (8) respectively.

According to the equations (4) and (8), can be simulated to compare the results of the LPA of PAM and RSM as illustrated in Figure 5 to Figure 8 based on the condition levels 1-4 of international standard IEC 62305 as shown in Table1. Also, the maximum height conditions are defined as follows: 20, 30, 45, and 60 meters (H = R) at levels 1 to 4 respectively.

In accordance with the simulation results of Figure 5 to Figure 8, it can be explained as follows: The trend of the LPA curves between PAM and RSM at all the levels are corresponding. Besides, the LPA curves of PAM closely match the results of the RSM if and only if the height is no more than 50 percent of maximum height such as 10, 15, 22.5, and 30 meters based on levels 1-4 respectively (all the absolute errors are less than 0.8 percent). While, the height exceeds 50 percent of maximum height can illustrate the absolute error as between 0.8 to 3.5 percent.

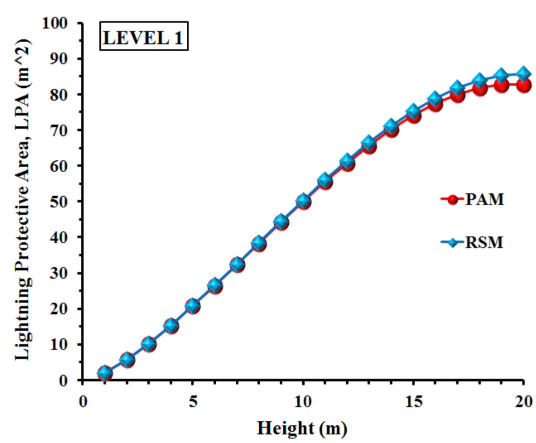


Fig.5. The simulation results of the lightning protective area (LPA) between PAM and RSM based on the level 1 of IEC 62305 (Maximum height = R = 20 meters).

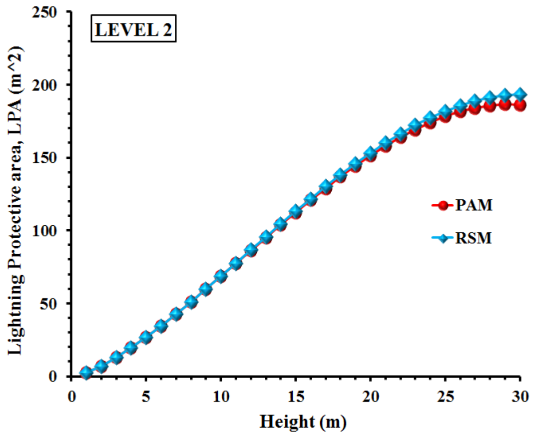



Fig.6. The simulation results of the lightning protective area (LPA) between PAM and RSM based on the level 2 of IEC 62305 (Maximum height = R = 30 meters).

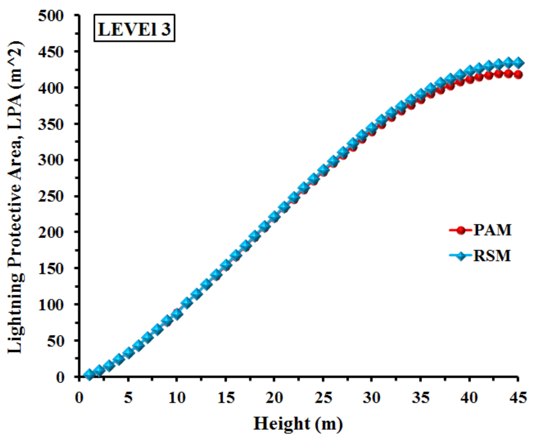



Fig.7. The simulation results of the lightning protective area (LPA) between PAM and RSM based on the level 3 of IEC 62305 (Maximum height = R = 45 meters).

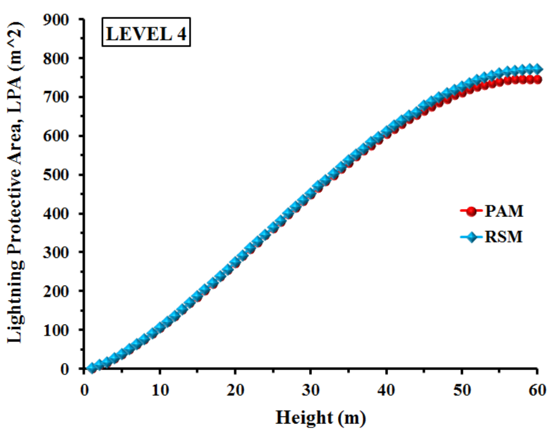



Fig.8. The simulation results of the lightning protective area (LPA) between PAM and RSM based on the level 4 of IEC 62305 (Maximum height = R = 60 meters).

As a result, the LPA curves of PAM and RSM at levels 1-4 are nearly perfectly equal. While, the absolute errors can be slightly demonstrated because all the results of LPA of PAM were analyzed through the novel equation (as shown in equation (1)) which was renovated to a simplified correlation [2]. Thus, the effect of a simplified form can show off the few error percent when calculating the LPA. However, it is insignificant to the practice which can consider the LPA of PAM to be equivalent to the LPA of RSM.

From the analytical as above, the protective angle method (PAM) is a suitable solution for implementation in practice because it can be easily calculated the result by using the basic mathematical correlation (as shown in the novel equation) and it has the lightning protective area (LPA) which is quasi-equivalent to the realistic lightning protective area due to the rolling sphere method (RSM). Therefore, the PAM can be appropriately utilized to analyze for avoidance lightning flash according to the recommendation of IEC 62305. However, the implementation of PAM must be considered to the penetration distance which is a weak point of this method.

Finally, the advantage of the lightning protective area (LPA) can utilize to evaluate the protective region. Especially, the object above ground (such as a tall building or tall structure) can avoid danger due to the lightning, if and only if, it is inside the boundary limit of the LPA (PAM or RSM) and the area of an object has a lower quantity than the LPA respectively.

## V. Conclusion

This article presents a focus on the lightning protective area (LPA) between protective angle method (PAM) and rolling sphere method (RSM) respectively. All the mathematical correlations of LPA (due to the PAM & RSM) are clearly proved for implementation. Also, this article analyzes the result of LPA which can summarize as follows: the LPA is dependent on the height of a vertical conducting rod and the multi-levels (1-4) based on the IEC standard. And finally, the LPA of PAM is equivalent to the LPA of RSM.

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