Consideration of protection angle method and lightning protection rules for sides of high-rise buildings in IEC 62305 standard

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***Abstract*-- The protection angle and protection rules for lightning flashes to the sides of tall buildings described in the IEC 62305 standard were considered. The penetration depth of a rolling sphere into the cone of the protection angle is estimated. Non-negligible flash frequency to the unprotected sides is indicated.**

Key words: lightning protection, IEC 62305, protection angle, rolling sphere, collection volume, high-rise building

I. INTRODUCTION

Since the late 1960's, we have seen the verticalization of buildings in the urban areas of Japan continue to rise. As a result, external lightning protection systems (external LPSs) technology for high-rise buildings is needed.

In Jan. 2006, IEC TC81 issued a new lightning protection standard, IEC 62305[1], which integrated the previous lightning standards. Although the rolling sphere method (RSM), the protection angle method(PAM) and the mesh method(MM) are included in this standard, the rolling sphere method is considered to be the best tool for designing lightning protection systems[2].

The protection angle under the new standard, IEC 62305, is precisely defined to approximate the protected regions defined by the RSM method. However, this method has a problem in that the rolling sphere penetrates into the presumed protected area in comparison with the risk posed by using the RMS method, this introduces an additional risk of lightning strikes.

Although the former standard, IEC 61024-1, which is applicable to structures with heights up to 60 m, stipulates that the sides of structures for LPL I to LPL III (LPL= lightning protection level) be protected, the new standard regards the risk of strikes to the sides as negligible for heights up to 60 m, requires the protection of the upper part of structures taller than 60 m (i.e. the topmost 20% of the height of the structure), and recommend the protection of all the parts which may be endangered above 120 m for structures over 120 m.

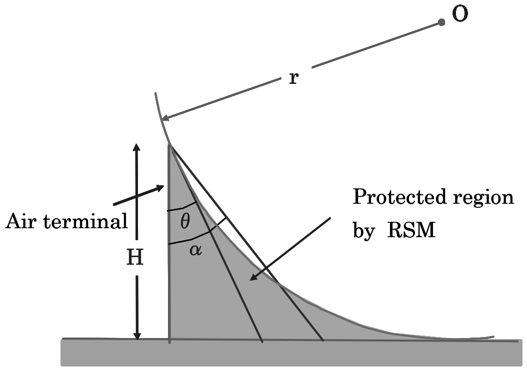

Fig. 1 Description of protection angle α and angle θ with protected region by RSM. ($H < r$)

The equations for the penetration depths of a rolling sphere into the protected region presumed by the PAM method are considered here. The estimated results on the validity of the protection rules for the sides of a high-rise building, when using the 'Probability Modulated Collection Volume' (PMCV) method[3] for rectangular structure models, are described.

II. ESTIMATION OF PENETRATION DEPTH OF ROLLING SPHERE

Some relational expressions for the striking distance r (m) with the peak value of lightning current I (kA) are proposed in the following form[4]:

$$r = A \cdot I^b , \qquad (1)$$

where A = 10 and b = 0.65 in the IEC 62305 standard.

The protection angle that satisfies the RSM method conditions is given by the angle θ between the perpendicular line drawn from the contact point, which is made when a rolling sphere contacts with the top of an air terminal, and the tangent plane of the sphere at the contact point. However, the boundary line of the presumed protected region by the angle would be too different from that of the RSM method in the point far away from the contact point.

The protection angle in the German standard, DIN VDE 0185 Part 100, is defined[5] so that the area of the protected region presumed by the PAM method is equal to that presumed by the RSM method (Fig. 1). This may be a realistic method for defining the protection angle.

By this definition, the protection angle can be expressed as follows:

$$\alpha = arctan\left[\left(\frac{1}{H}+\frac{r}{H^2}\right)\sqrt{2rH-H^2}-\left(\frac{r}{H}\right)^2 arccos\frac{r-H}{r}\right], \quad (2)$$

where r is the radius of a rolling sphere, H is the height of an air terminal (m), and α is the protection angle (rad).

This angle α *is* described in Fig. 2, using angle θ for comparison, where each curve corresponds to an LPL level.

As this angle α coincides with the value of the plotted protection angle in IEC 62305-3 within an error of reading (±0.5°), it is assumed that the protection angle in IEC 62305-3 is defined by Eq. (2), although the values of the plotted protection angle in IEC 62305-3 are a little different within about ±3° than those in Table 1 of IEC 61024-1.

However, as this method defines a protection angle larger than the angle θ, the rolling sphere should penetrate the protected area presumed by this method.

If the penetration depth from the surface of the cone produced by the protection angle is denoted as d, this is expressed by the following equation (Fig. 3):

$$d = r\left(1 - cos\left[\alpha - arcsin\frac{r-H}{r}\right]\right) \qquad (3)$$

The dependency of d onto the height of an air terminal estimated by using Eq. (3), is described in Fig. 4. The penetration depth d is almost proportional to the height for heights under 10 m. It is 0.65-0.70 m for LPL I to IV when the height is 10 m, and is 7−8 % of the height when the height is under 20 m.

Although this protection angle is based on the existence of a sufficiently large real reference plane to support the sphere, the PAM method is independent of the RSM method in the standard and does not need this condition.

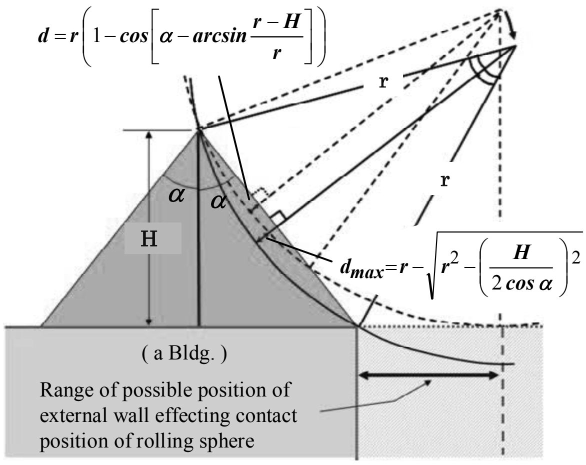

Fig. 2 Explanation of penetration depth of rolling sphere. （H < r）

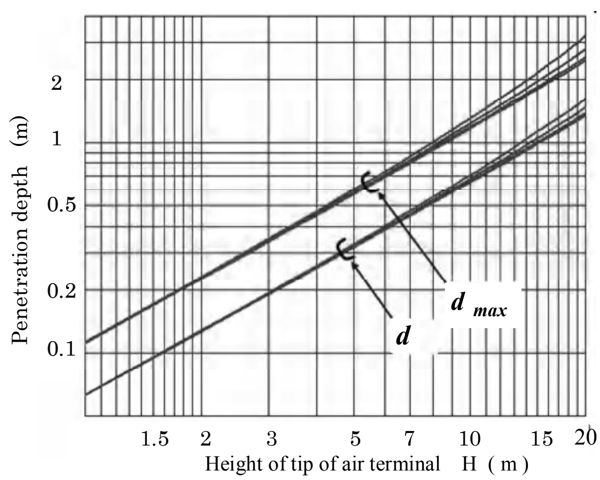

Fig. 3 Penetration depth of rolling sphere into presumed protected region. Each line corresponds to LPL I to IV.

Therefore, if the distance of the ridge of the reference plane from the air terminal is short enough for the rolling sphere to contact with both the top of the air terminal and the ridge as expected for high-rise buildings, the penetration depth is larger than that determined by using Eq. (3) (Fig. 3).

The maximum penetration depth in this condition, is given by the following equation:

$$d_{max} = r - \sqrt{r^2 - \left(\frac{H}{2\ cos\ \alpha}\right)^2} \qquad (4)$$

The dependency of the penetration depth d onto the height of an air terminal estimated by Eq. (4), is also described in Fig. 3. The maximum penetration depth of a rolling sphere is almost proportional to the height for heights under 10 m. It is 1.2 to 1.3 m for LPL I to IV when the height is 10 m, and is 11 to 16 % of the height when the height is under 20 m.

Consequently, in the worst case, the penetration depth of the rolling sphere is about twice as large as when the reference plane is large enough to support the sphere.

In the IEC 62305 standard, the height limit of a structure, which was 60 m in the former IEC standard, is removed. Therefore, when the PAM method is applied to a high-rise building that might be high in flash frequency, the point described above should be kept in mind. Therefore, the penetration depth should be taken as a margin to design an air temination system.

III. Estimation of Lightning Flash Frequency to Side of Structure

A. Conditions

Equation (1) is assumed for the relation of the striking distance and the peak current of a lightning stroke, without discriminating the concerned structure or ground. From this assumption, the loci of the center of the rolling sphere with a radius equal to the striking distance around the structure defines the surface $S(I)$, termed as the exposure area, for the lightning stroke peak current I.

The unique probability density distribution of the first short stroke current which is very important in lightning protection, is assumed to be at any point in the space around the structure.

According to the IEC 62305 standard, in which a polarity ratio of 10 % of positive and 90 % of negative flashes is assumed, the probability density distribution of the first stroke current is expressed as follows:

$$\overline{\rho}(I) = 0.9\rho_n(I) + 0.1\rho_p(I), \qquad (5)$$

where $\rho_n(I)$ is the distribution function of the negative first short stroke current and $\rho_p(I)$ is the distribution function of the positive first short stroke current.

It is informed in the standard that the probabilities of lightning current parameters are subject to log normal distributions, and the mean value μ and dispersion $\sigma_{\log}$ for the common logarithm of the value of the current parameter are given in it. The given values for the set of (μ, $\sigma_{\log}$) are (61.1kA, 0.576) (< 20kA) and (33.3kA, 0.263) (> 20kA) for the negative first short stroke current, and (33.9kA, 0.527) for the positive first short stroke current.

B. Equations for estimation

The mean annual flash frequency to a structure N_d and the mean annual flash frequency above the minimum peak current to the structure $N_{d,\, I \geqslant Imin}$ are expressed as follows:

$$N_d = N_g\ A_d\ C_d \times 10^{-6} \quad \text{(flashes / year)} \qquad (6)$$

$$N_{d,\, I \geq Imin} = N_d \frac{\int_{Imin}^{\infty} S(I)\, \overline{\rho}(I)\, dI}{\int_{0}^{\infty} S(I)\, \overline{\rho}(I)\, dI} \qquad (7)$$

where N_g is the mean annual ground flash density ($N_g \cong 0.1 \cdot T_d$; T_d is the annual number of thunderstorm days), C_d is the environmental factor, and A_d is the collection area (*W*: width, *L*: length, *H*: height)

The mean annual flash frequency to the unprotected sides of a structure $N_{d,\, UP\, side}$ and the mean annual flash frequency above the minimum peak current to the unprotected sides of a structure $N_{d,\, UP\, side,\, I \geqslant Imin}$ are expressed similarly, although the maximum current in the integral is limited for the sides of a structure.

Thus, the ratio of $N_{d,\, UP\, side,\, I \geqslant Imin}$ to $N_{d,\, I \geqslant Imin}$ is expressed as follows:

$$P_{UPside,\, I \geq I\min} = \frac{\int_{Imin}^{Imax} S_{UPside}(I)\, \overline{\rho}(I)\, dI}{\int_{Imin}^{\infty} S(I)\, \overline{\rho}(I)\, dI} \qquad (8)$$

C. Collection area

Although the collection area is considered for some models concerning the striking distance[6], the next expression is adopted in this paper as defined in the IEC 62305 standard:

$$A_d = W \cdot L + 6\, H \cdot (W + L) \ + 9\, \pi H^2, \qquad (9)$$

However, the next expression for the collection area is also possible as the striking distance is defined in Eq. (1):

$$A'_d = k \int_0^{\infty} S(I)\, \overline{\rho}(I)\, dI \qquad (10)$$

A'_d is composed of $A'_{d,top}$ for the top of a structure and $A'_{d,side}$ for the sides of the structure. The factor k is the coefficient for relating to A_d. Although it must be equal to 1 for self-consistency as is evident when $H = 0$ m, it becomes 2.12 when A'_d is set to be equal to A_d for when H = 60m, W = L = 50m. With the height H increasing, $A'_{d,top}$ converges to a little large value than $W \cdot L$, and $A'_{d,side}$ increases linearly for large values of H (Fig. 4).

D. Estimated results

1) Flash frequency to a structure

The mean annual flash frequency to a structure N_d is estimated for a variety of areas, two different ratios between the width W and the length L (1:1 and 10:1), and the height up to 200m at a T_d = 25 (typical value in Japan) and C_d = 1. For high-rise structures, the flash frequency is proportional to the second power of the height when $H > W$, L, which is manifested from the function form of A_d. The flash rate for structures with $W = L = 50$ m, H = 60 and 150 m, are estimated to be 0.35 flashes/year (H = 60 m) and 1.82 flashes/year (H = 150 m).

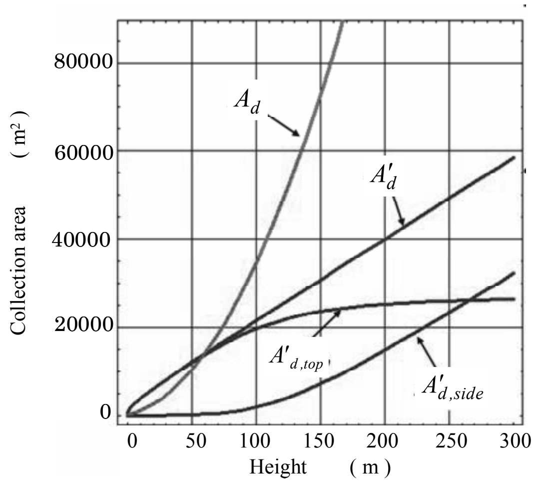

Fig. 4 Collection area A'_d is set to be equal to A_d at H = 60 m (W = L = 50m).

The ratio of the mean annual flash frequency above the minimum peak current to a structure $N_{d,\, I \geqslant Imin}$ to the mean annual flash frequency to the structure N_d is estimated to be as follows:

a) If $H > r_{Imin}$, it is almost constant with the height.

b) If $H > r_{Imin}$, it's dependency to the ratio between the width W and length L is low and the difference is within 1 %.

c) If $H > r_{Imin}$, for each LPL level, it is > 99 % (LPL I), 98-99% (LPL II), 94-97% (LPL III), 89-93% (LPL IV).

Where r_{Imin} is the radius of the rolling sphere for a LPL.

Thus, the difference between N_d and $N_{d,\, I \geqslant Imin}$ is within about 10% of N_d, which is relatively small as expected.

2) Flash frequency to the sides of a structure and the effect of countermeasures

The protection of upper parts of high-rise buildings is found to have a pronounced effect. When taking flashes with lightning currents above the minimum lightning current (3kA) for LPL I into account, the ratio of the flash frequency to the sides of a structure to that to the whole structure for currents above the minimum peak current $P_{UP\, side,\, I \geqslant Imin}$ is basically under 6 % for a structure shorter than 90 m. However, it begins to increase at a rate of 0.3% / m with the heights over about 90 m (Fig. 5). This result basically comes from the ratio $A'_{d,side} / A'_d$, where $A'_{d,side}$ and A'_d are explained in the section *C*, although the current is limited in the lowest level here. If the topmost 20 % of the height of a structure is protected, the increasing rate is suppressed to 2/3 (0.2 % / m). The increasing rates for both ratios between the width W and the length L (1:1 and 10:1), coincide within 0.5 %. Thus, it may be said that high-rise structures with different ratios

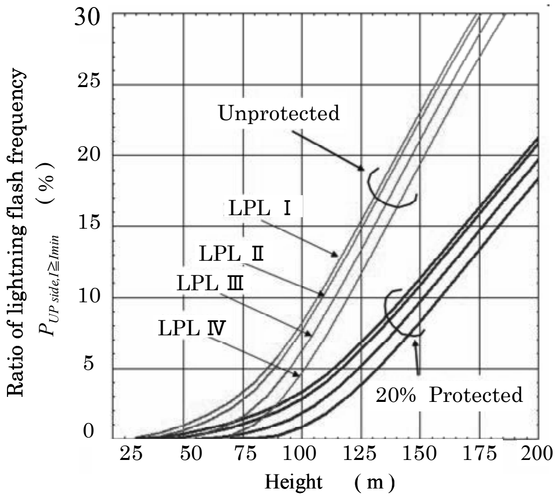

Fig. 5 Effect of topmost 20% of protection on side of building on ratio of frequency of lightning flashes to unprotected side of building (W=L= 50 m). Each line corresponds to LPL level.

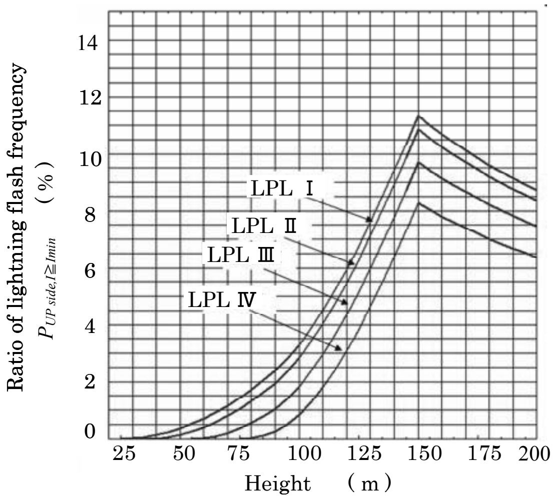

Fig. 6 Effect of protection of area above 120 m with topmost 20% of protection on side of building (W=L= 50 m). Each line correspond to LPL level.

between their widths W and lengths L are nearly equal in the effect of topmost 20 % protection.

For structures with heights under 150 m, owing to the 20 % protection rule, the reduction rate of lightning flashes with currents above the minimum peak current to the unprotected sides is 51-59 % for LPL I to LPL IV (Fig. 5). Namely, this rule is estimated to have the effect of reducing the ratio of flash frequency to the unprotected sides of a structure to the flash frequency to the whole structure to under 50 %.

The recommended rule of the protection for all parts above 120 m is effective for structures taller than 150 m (Fig. 6).

However, for structures that are 150 m high ($W = L = 50$ m) with topmost 20% protection, the mean annual flash frequency N_d is 1.82 flashes/year and the flash frequency of the unprotected side $N_{d,UP\,side}$ is 0.21 flashes/year, so that the rate of $N_{d,\,UP\,side}$ to N_d is 11.5%. This rate alone is larger than the tolerable rate of shielding failure, which is 2-10%, when the any level of LPL I to III is applied to the whole structure.

Consequently, if this estimation described above is justified, although the postulates for the calculation model are simple, then the lowest position for the protected parts of the sides of a structure should be lowered. Moreover, the difference between the protection efficiencies of LPL I to IV should be taken into account.

IV. CONCLUSION

The protection angle of the PAM method and protection rules for flashes to the sides of a structure in the new IEC lightning protection standard were considered here. The results are summarized as follows:

1) For the PAM method

a) The penetration depth of the rolling sphere into the presumed protected region may, in a worst case scenario, be about twice as large as that intended in the standard.

b) It is preferable to design an air terminal system using the penetration depth as a margin.

2) Protection from lightning flashes to the sides of a structure

a) The flash frequency to a high-rise building ($H > W, L$) sharply increases with the height in proportion to the second power of the height because of the function form of A_d.

b) Structures under 150 m in height with the topmost 20 % protection rule are estimated to effectively reduce the flashes to the unprotected sides of a structure to under 50 %.

c) The recommended rule which demands the protection of all the parts above 120 m is effective for structures taller than 150 m because of the topmost 20% protection rule.

d) The estimated flash frequency to the sides of structures 150 m high with topmost 20% protection is not sufficiently small compared to the protection efficiency of the LPS assigned in the standard. This indicates the need to lower the lowest position stipulated/recommended in the IEC 62305 standard for the protected parts of the sides of a high rise building.

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