Risk Evaluation of Lightning Damage to Wind Turbines with the Electro-Geometrical Method

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Keywords: striking distance, lightning striking angle, distribution of lightning current, equivalent collection area

The electro-geometrical method (EGM) has been adopted for lightning protection design of transmission lines. The expected frequency at which the conductors will be damaged by lightning can be calculated by the following equations.

$$\left. \begin{aligned} N_F &= N_g A_e \\ A_e &= \int_{I_{\min}}^{I_{\max}} a_e(I) \frac{-dP(I)}{dI} dI \end{aligned} \right\} \dots\dots\dots (1)$$

where N_g is the ground flash density per m^2 per year; $a_e(I)$, the collection area on the ground surface; A_e , the equivalent collection area; and $P(I)$, the cumulative distribution of the peak value of the lightning current.

In the case of transmission lines, the exposed surface is considered to be cylindrical. However, it should be mainly considered to be spherical in the case of wind turbines, as shown in Fig. 1.

The lightning stroke does not always occur in the vertical direction with respect to the plane of the ground. We assumed the lightning striking angle in three dimensional space to simplify the calculation of the equivalent collection areas, as shown in Fig. 2.

The distributions of the peak value of the lightning current mentioned in various documents are based on observational results of the

lightning that has struck structures. These distributions are different from those corresponding to lightning strokes from a thundercloud to the ground surface. We estimated the peak value of the current for all lightning strokes from a thundercloud to the ground surface by using the EGM, as shown in Fig. 3.

Observational results of the lightning strokes to a wind turbine and a lightning tower at Uchinada wind generation site on the coast of the Sea of Japan has been reported. We compared the calculated result with the observational results, using the observed data at the Uchinada site.

Figure 4 shows the comparison between the calculated and observation results. According to the comparison, the expected rate of lightning stroke seems to be reasonably good.

Fig. 1. Exposed surface

Fig. 2. Assumed lightning striking angle

Fig. 3. Estimated cumulative distribution used by EGM

Fig. 4. Comparison of calculated and observational results

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The electro-geometrical method (EGM) has been adopted for lightning protection design of transmission lines. In this paper, probability calculations of direct lightning strokes to wind turbines are carried out by using the EGM. The distributions of the peak values of lightning current mentioned in various documents are based on observational results of lightning strokes onto structures. These distributions are different from those corresponding to lightning strokes from a thundercloud to the surface of the ground. Therefore, we have estimated the peak value of the lightning current and the probability of shielding failure by using the EGM. In addition, the equivalent collection areas of structures were calculated on the basis of an assumed lightning striking angle in three-dimensional space.

Keywords: striking distance, lightning striking angle, distribution of lightning current, equivalent collection area

1. The Electro-geometrical Method

The electro-geometrical method (EGM) has been adopted for lightning protection design of transmission lines. According to this method, a relation exists between the striking distance and the lightning current. This relation can be expressed as follows⁽¹⁾⁽²⁾:

$$\left. \begin{aligned} r_s(I) &= AI^b \\ r_g(I) &= k_g r_s(I) \end{aligned} \right\} \dots\dots\dots (1)$$

where $r_s(I)$ is the striking distance from a conductor; $r_g(I)$, the striking distance from the ground; A , b , and k_g , the coefficients; and I , the peak value of the lightning current.

According to Fig. 1, which illustrates the EGM, the exposure arc is determined from the lightning current and the positional relation between the conductors and the ground. The maximum value of the lightning current, $I_{\max}$, is related to the striking distance, assuming that the lightning does not strike a conductor, and the minimum value, $I_{\min}$, is related to the overvoltage that the transmission line must withstand.

The statistical distribution of the lightning current can be considered to be a logarithmic normal distribution. The following equation provides the probability P that the actual value i is greater than or equal to the lightning current I ⁽¹⁾.

$$P(i \geq I) = 1 - \frac{1}{\sqrt{2\pi}\sigma_{\log i}} \int_{-\infty}^{\log I} \exp \frac{-(x - \mu_{\log i})^2}{2\sigma_{\log i}^2} dx \Bigg\}_{x = \log i} \dots\dots\dots (2)$$

where $\sigma_{\log i}$ is the standard deviation of $\log i$, and $\mu_{\log i}$ is the average value of $\log i$.

The expected frequency at which that the conductors will be damaged by lightning can be calculated by the following equations.

$$\left. \begin{aligned} N_F &= N_g A_e \\ A_e &= \int_{I_{\min}}^{I_{\max}} a_e(I) \frac{-dP(I)}{dI} dI \end{aligned} \right\} \dots\dots\dots (3)$$

where N_g is the ground flash density per m^2 per year; $a_e(I)$, the collection area on the ground surface; and A_e , the equivalent collection area.

The equivalent collection area of a structure is defined as the area of ground surface that has the same annual frequency of direct lightning flashes as that of the structure⁽³⁾. Furthermore, the collection area is related to not only the lightning

Fig. 1. Exposure arc of the conductors and the ground

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Fig. 2. Exposed surface

current but also the lightning striking angle, as mentioned later.

2. The EGM in the Case of Wind Turbines

In the case of transmission lines, the exposed surface⁽⁴⁾⁽⁵⁾ is considered to be cylindrical. However, it should be mainly considered to be spherical in the case of wind turbines.

According to Fig. 2, the exposed surface changes due to not only the lightning current but also the direction and orientation of the blades. It is necessary to calculate the equivalent collection areas considering all the situations and probabilities. However, such a study would be time consuming. Therefore, in this paper, we assumed that each of the cases (1)–(4) shown in Fig. 3 has a 25% probability. We then calculated the equivalent collection areas by using the following equation.

$$A_e = 0.25 \sum_{i=1}^4 A_{ei} \dots \dots \dots (4)$$

where A_{ei} is the equivalent collection area in each situation.

3. Lightning Striking Angle in Three-dimensional Space

The lightning stroke does not always occur in the vertical direction with respect to the plane of the ground. According to the EGM, the probability distribution of the lightning striking angle in the case of transmission lines is assumed to be given by the following equation⁽¹⁾.

$$\left. \begin{aligned} f(\alpha) &= K_m \cos^m \alpha \\ K_m &= \frac{1}{\int_{-\pi/2}^{\pi/2} \cos^m \alpha d\alpha} \end{aligned} \right\} \dots \dots \dots (5)$$

Here, α is the lightning striking angle in the vertical section, and m is a fixed number.

In the case of wind turbines, the lightning striking angle in three-dimensional space should be considered because the exposed surface is spherical and not cylindrical. As shown in Fig. 4, we assumed the lightning striking angle in three-dimensional space to simplify the calculation of the equivalent collection areas.

Fig. 3. Directions and orientations of blades

Fig. 4. Assumed lightning striking angles

Fig. 5. Comparison of cumulative probability

We converted the assumed probability distribution into a vertical section distribution and compared it with the distribution given by Eq. (5). According to Fig. 5, which shows the result of the conversion, the difference does not seem to be significant.

4. Calculation of Equivalent Collection Area

The equivalent collection area can be found comparatively easily because the lightning striking angle is considered in only nine directions. The equivalent collection area can be calculated by using the following equations.

$$A_e = 0.25 \sum_{i=1}^4 \sum_{j=1}^9 F_j \int_{-\infty}^{\infty} a_{eij}(I) \frac{-dP(I)}{dI} dI \left\} \dots\dots\dots (6)$$

$$a_{eij}(I) = \frac{a_{pij}(I)}{\cos \alpha_j}$$

where i is the suffix of the position of a blade, as shown in Fig. 3; j , the direction of the lightning stroke, as shown in Fig. 4; F_j , the probability of the assumed lightning striking direction for the ground plane, as shown in Fig. 4; a_{eij} , the collection area of a structure; a_{pij} , the projected area of the exposed surface; α_j , the lightning striking angle, as shown in Fig. 4.

Figure 6 shows the relation between an exposed surface, its projected area, and its collection area.

Although it is possible to calculate the projected areas, in this paper, we drew exposed surfaces by using a CAD software to measure the projected areas. Figure 7 illustrates an example of the exposed surfaces, as seen from the direction of propagation of lightning, and Fig. 8 shows the projected areas.

The value of the projected area can be determined from

Fig. 6. Projected area and collection area

Fig. 7. Example of exposed surfaces

Fig. 8. Example of projected areas

Fig. 8, and Eq. (6) provides the value of the equivalent collection area.

5. Distribution of the Peak Value of the Lightning Current

The distributions of the peak value of the lightning current mentioned in various documents are based on observational results of the lightning that has struck structures. These distributions are different from those corresponding to lightning strokes from a thundercloud to the ground surface because lightning tends to strike a structure when the value of the lightning current is high, as shown in Fig. 9. Therefore, we estimated the peak value of the current for all lightning strokes from a thundercloud to the ground surface by using the EGM.

For the estimation of the peak value of the current distribution for all the lightning strokes from thunderclouds to the ground surface, we adopted the distribution given by Eq. (7) as the distribution of the lightning from the thunderclouds to the structures⁽¹⁾. Moreover, we used the approximated distribution as shown in Fig. 10 to simplify the integration calculation.

In addition, we adopted Eq. (8) for calculating the striking distance⁽⁷⁾.

$$\frac{-dP(I)}{dI} = \frac{1}{\sqrt{2\pi}\sigma_{\log i}} \exp \left\{ \frac{-(x - \mu_{\log i})^2}{2\sigma_{\log i}^2} \right\} \dots\dots\dots (7)$$

$$x = \log i$$

$$\mu_{\log i} = 1.415(26 \text{ kA})$$

$$\sigma_{\log i} = 0.325$$

$$\left. \begin{aligned} r_s(I) &= 10I^{0.65} \\ r_g(I) &= r_s(I) \end{aligned} \right\} \dots\dots\dots (8)$$

Figures 11 and 12 show the estimated result of the distribution of the peak value of the current for all the lightning

Fig. 9. Comparison of exposure arcs

Fig. 10. Distribution according to Eq. (7) and approximated distribution

Fig. 11. Estimated density distribution used by the EGM

Fig. 12. Estimated cumulative distribution used by the EGM

strokes from thunderclouds to the ground. This estimated distribution shifts to the lower-current side, and the difference in the median values is about 11 kA.

6. Comparison with the Observational Result

Observational results of winter lightning striking a wind turbine and a lightning tower at Uchinada wind generation site on the coast of the Sea of Japan has been reported by S. Minamimura *et al.*⁽⁸⁾⁽⁹⁾. Figure 13 shows the arrangement of the Uchinada site, which is composed of a wind turbine and a lightning tower. The heights of the wind turbine and the lightning tower are 100.25 m and 104.99 m, respectively. The lightning tower stands 45.5 m to the northwest of the wind turbine. We compared the calculated result with the observational results, using the observed data at the Uchinada site.

It has been reported that the current characteristics of winter lightning on the coast of the Sea of Japan are different from those of summer lightning. In addition, the probability of lightning strokes in the winter season greatly depends on the direction from which the thundercloud approaches.

We removed half data observed during a period of strong winds to reduce the influence of the direction of thundercloud movement from all observed data at the Uchinada site. Figure 14 shows the distribution of the peak value of the lightning currents, which we extracted and assumed an examination object. Figure 15 shows the estimated result of the distribution of the peak value of the current for all the lightning strokes from thunderclouds to the ground used in the EGM.

Figure 16 shows an equivalent collection area for every position of the blades shown in Fig. 3. The equivalent collection

Fig. 13. Arrangement of Uchinada site

Fig. 14. Lightning strokes at Uchinada site

Fig. 15. Estimated cumulative distribution at Uchinada site

Fig. 16. Equivalent collection area

Fig. 17. Comparison of calculated and observational results

area of a wind turbine varies somewhat due to a change in the position of its blades.

In addition, if the blades are stopped when a thundercloud approaches, the probability of lightning striking the wind turbine has a minimum value at position (3).

Figure 17 shows a comparison between the calculated and observational results. According to the comparison, the expected rate of lightning strokes seems to be reasonably good. However, it is necessary to consider that a considerable number of upward lightning strokes are included in the lightning observed at the Uchinada site.

Recently, the EGM has been adopted as a method for lightning protection design of transmission lines, including upward lightning⁽¹⁾. We think that the favourable results obtained in this study suggest the possibility for the use of the EGM in lightning shielding examinations, including upward lightning, in three-dimensional space. Therefore, it will be necessary to collect many data and to check the possibility for the use of the EGM as a method for lightning protection design in three-dimensional space in the future.

7. Conclusions

The EGM has been adopted for lightning protection design of transmission lines. In this paper, probability calculations of direct lightning strokes to wind turbines have been carried out by using the EGM, considering a wind turbine as a structure in three-dimensional space. Although there are still some issues to be considered, the probability calculation results at the Uchinada site appear to be good. In addition, the results suggest the possibility of adopting the EGM to lightning protection design, including protection against upward lightning on a wind turbine.

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