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A Quantitative Evaluation Method for Failure Risk of the Lightning Attachment System on Wind Turbine

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***Abstract*—The lightning damage seriously affects the normal operation of wind turbines, but there is currently few quantitative analysis methods for the failure risk of the lightning attachment system on wind turbine. Based on leader development model, this paper proposes the definition and calculation method of the lightning shielding failure rate (LSFR) of the lightning attachment system on wind turbine. Taken into the influence of the blade orientation, the LSFR of the blades regarding different lightning attachment systems were comparatively analyzed. The proposed assessment method can provide a theoretical basis for the optimal design and failure risk assessment of the lightning attachment system on wind turbines.**

Keywords—lightning shielding failure rate, wind turbine, lightning attachment system, long gap discharge

I. INTRODUCTION

In recent years, wind power has developed rapidly and has broad prospects. With the continuous increase of the capacity of single wind turbine, the blade length of the wind turbine is continuously increasing, which brings great threat to lightning protection. After lightning strikes the wind turbine, it will bring huge economic losses. In order to reduce the losses caused by lightning to the wind turbine, quantitative study is needed to evaluate the failure risk of the lightning protection system on wind turbine.

According to the international standard IEC61400-24, there are several designs of lightning protection system on wind turbine blade, such as receptor and down conductor structure and blade beam covered with copper mesh. However, the lightning protection systems cannot provide enough protection for blades. According to the lightning records of 508 wind turbines in the US wind farm, 304 blades have been struck by lightning in 5 years[1]; Arinaga has compared the interception efficiency of different receptors. The tip receptor has the highest interception efficiency, thus can provide a better protection for the blade[2]; Garolera points out that the metal parts inside the blade affect the electric field distribution on the blade surface[3], and it is believed that the down conductor will increase the risk of lightning strike of the blade. In order to protect the blades from lightning strikes, new lightning protection systems will continue to emerge. Therefore, for different types of lightning protection systems, quantitative analysis of failure risk of the lightning inception is needed to provide a theoretical basis for optimizing the lightning protection system on the blade.

For the failure risk assessment of lightning protection system on the blade, researchers have carried out many experimental studies, in which the real blade tips or scale wind turbines are employed[4-6]. The efficiency of the blade lightning protection system can be obtained by statistical analysis. However, due to the limited number of experiments, these results often have certain contingency.

Based on the self-consistent leader inception propagation model (SLIM)[7-8], Guo has given the calculation method to evaluate the lightning strike probability on the blade surface[9]. Wang introduced the concept of dynamic striking distance, proposed an electrical geometric model suitable for wind turbine blades, and analyzed the influence of blade orientation on the efficiency of blade lightning protection system[10], but it is difficult to analyze different types of lightning protection systems.

In this paper, the definition and calculation method of the lightning shielding failure rate(LSFR) of the lightning attachment system on wind turbine are proposed. This method can be used to evaluate the LSFR of different lightning attachment systems, which provides a theoretical basis for the optimization design for the lightning protection system on wind turbines.

II. DEFINITION AND CALCULATION OF LSFR

A. Definition of the LSFR of lightning attachment system on wind turbines

The LSFR is proposed to quantitatively evaluate the failure risk of the lightning attachment system on wind turbine blade. Since the blade tip and the receptors are metal

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components (area S_a as shown in Fig. 1), it is easy to initiate upward leader and connect with the lightning downward leader under the effect of the space electric field and the downward leader. At this point, it is considered that the lightning attachment system effectively protect the blade. When the attachment system fails to incept the lightning downward leader, that is, the downward leader hits directly on the insulation part of the blade (area S_b shown in Fig. 1), it is believed that the lightning attachment system fails to shield the blade.

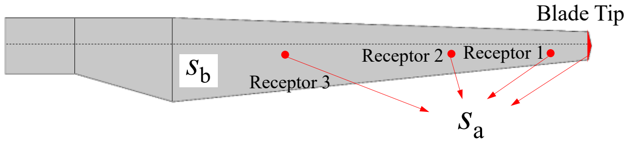


Fig. 1 Partition of the blade surface

The lightning attachment process is related to the average field density (E_{av}) between the tip of downward leader and the potential attachment point on the blade surface[11].

The average field density characterizes the difficulty of initiating a stable upward leader at a certain point on the blade surface. It's considered that the larger the E_{av}, the easier it is to initiate a stable upward leader. And E_{av} corresponding to point i on the blade surface is calculated by (1):

$$E_{\text{av}} = \frac{U_{\text{down}} - U_i}{d} \tag{1}$$

Being U_{down} the potential of the tip of downward leader, U_i the potential of the point probably to initiate stable upward leader, d the distance between the downward leader tip and the point i on blade.

When there is one stable upward leader initiating at a certain point on blade surface, the ratio of E_{av} at each point and the maximal average field density E_{max} is adopted to characterize the possibility of lightning strike on the blade surface, which can be interpreted by (2):

$$\rho = \frac{E_{\text{av}}}{E_{\text{max}}} \tag{2}$$

ρ is introduced to quantitatively describe the probability at a certain point on blade surface. Therefore the ratio of the integral of ρ of a certain area on blade surface and the proportion of this area is adopted to characterize the overall lightning risk of this area. When the blade is at a specific orientation, the LSFR of the blade is defined as:

$$R_\theta = \frac{\int_{S_b} \rho(s)ds / s_b}{\int_{S_a} \rho(s)ds / s_a + \int_{S_b} \rho(s)ds / s_b} \tag{3}$$

Where S_a refers to the proportion of the lightning attachment area on the blade, S_b to the insulation area of the blade.

R_θ refers to the LSFR of a single blade at a certain angle θ (versus horizontal plane). Thus for the three-blade rotatory wind turbine, the LSFR can be calculated by (4):

$$R_3 = \frac{1}{3} \cdot \frac{1}{2\pi} \sum_{b=1}^{3} \left[\int_0^{2\pi} \frac{\int_{S_b} \rho(s,\theta)ds / s_b}{\int_{S_a} \rho(s,\theta)ds / s_a + \int_{S_b} \rho(s,\theta)ds / s_b} d\theta \right] \tag{4}$$

Where: b refers to the blade number ranging as 1, 2 and 3.

It is noted that this method is not limited by the shape of the lightning attachment system on the blade, meanwhile it is available for the evaluation of different lightning attachment systems.

B. *Calculation method of the LSFR of lightning attachment system on wind turbines*

For the calculation of LSFR, it is necessary to describe the process of the leader development numerically. Thus a leader development model SLIM[7-8] is adopted in this paper. Adopting finite element calculation method, the calculation process of LSFR is interpreted as follows:

a) Build the wind turbine model, enter the blade orientation angle, the parameters of thundercloud and lightning current.

b) Develop the lightning leader for one step toward the ground and calculate the space potential distribution.

c) Calculate the lightning strike probability distribution on blade surface combining equations (1) and (2) if there is one stable upward leader initiating successfully on blade surface. If not, return to step *b)*.

d) Calculate the LSFR of the wind turbine according to equation (4) while the calculation of $\rho(s, \theta)$ at every angle is completed, otherwise return to step *a)* to start the calculation of next angle.

III. Experimental Verification of LSFR Calculation Method

A. *Experiment Setup*

In this paper, to verify the validation of the calculation method of LSFR, a physical experiment platform is established.

Comparing the scale of lightning evolution and the size of wind turbine blade, assume that the shape of blade has little effect on lightning attachment. A simplified blade model corresponding with the real blade is adopted in this experiment. It consists with a glass fiber reinforced plastic(GFRP) board 0.6m×0.4m×0.01m as blade body, an aluminum-made panel 0.4cm by 0.0cm with a thickness of 1cm as tip receptor, an aluminum wire adhering to the back side of the board as down conductor. The down conductor and the tip receptor are bolted together.

The experiment platform shown in Fig. 2 was built to carry out the discharge experiments. Since the wind turbine blades are rotating during operation, each blade will rotate ranging from 0° to 360°. In general, the typical angle is selected for analysis. Place the model horizontally on an insulation support and connect the down conductor to grounding terminal. A 0.2m long copper electrode is fixed 0.6 m above the center of the model. Standard lightning impulse (1.2/50μs) with the amplitude of +500kV is applied, while the discharge breakdown rate is 100%. Three groups discharge experiment were set up, namely, blade without salt fog, 1/2 of the blade covered with salt fog and full blade covered with salt fog. The discharge was repeated 15 times in each group. Pollute the blade surface with salt fog according to solid layer method[12]. Still camera is adopted to record the discharge paths. To be corresponding with the experiment, the accumulation mechanism of surface charge on salt fog [11] in considered while calculating the LSFR.

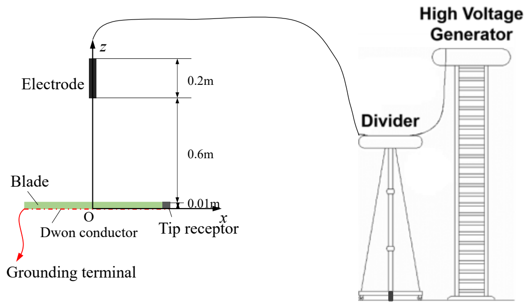
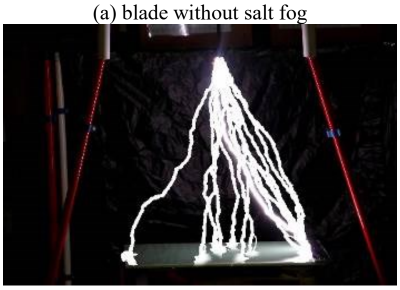


Fig. 2 Schematic diagram of experiment platform

B. Verification Result

The discharge paths captured by the still camera were collected on each picture, respectively. The creeping discharges on the blade surface in the collection pictures were removed in order to discern the attachment points on the blade surface, as shown in Fig. 3. It is only considered as a successful interception when the discharge hit directly on the metal receptor.

(a) blade without salt fog



(b) 1/2 of the blade covered with salt fog

(c) full blade covered with salt fog

Fig. 3 The discharge collections of different blade surface

According to the definition of LSFR in section II.A, the LSFR in this experiment can be calculated with the failing attachment time divided by the total discharge time. Therefore the LSFRs are 0.333, 0.533 and 0.867 in accordance with Fig. 3(a), (b) and (c). The comparison of the LSFRs obtained by the discharge experiments and calculated by the proposed method in section II is demonstrated in Fig.4, where it is shown an agreement of experiment result and proposed method.

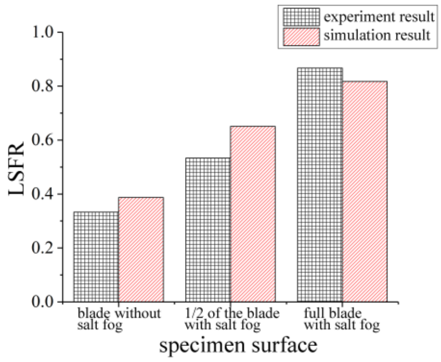


Fig. 4 Comparison of the experimental the calculation results

IV. Application of LSFR on Different Lightning Attachment Systems

In this paper, the calculation method of LSFR was applied to the real-size wind turbine to quantitatively evaluate the failure risk of the lightning protection systems. The typical parameters of 1.5MW wind turbine with the height 80m were adopted while modelling. The blade which consists of one aluminum tip and 3 body receptors was modeled according to type SINOMA42.2 offered by Sinoma Wind Power Blade Co., Ltd. The blade sketch is shown as Fig. 5, in which the red line through the blade refers to the down conductor.

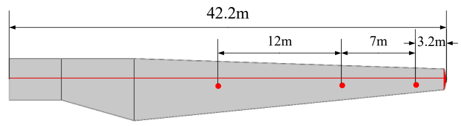


Fig. 5 Receptor-down conductor setup of the blade

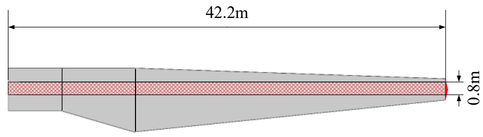


Fig. 6 Blade with beam copper mesh

In addition to the structure mentioned as Fig. 5, it is also adopted that the surface of blade beam covered with copper mesh, as shown in Fig. 6. One typical type of copper mesh adopted is with width of 800mm and weight of 420g/m^2. The copper mesh is to some extent a shielding layer for the inner structure of the blade which can eliminate the attraction of the inner metal component such as down conductor to lightning leaders.

However, about 95% of the lightning accidents of blade occurred within 5m of the blade tip known from the literature. It is indicated that the first 5 meters of the blade is vulnerable to lightning. This paper proposed a new structure of lightning attachment system shown as Fig. 7. The copper mesh is covered only the first 5 meters of the blade while the down conductor is placed inside the rest of the blade, grounding at the blade root.

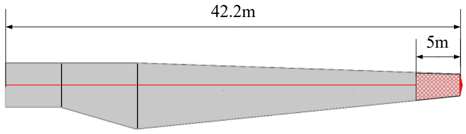


Fig. 7 Blade with tip copper mesh

For some typical blade angles, the LSFRs of the 3 blades mentioned above were calculated, results shown in Fig. 8.

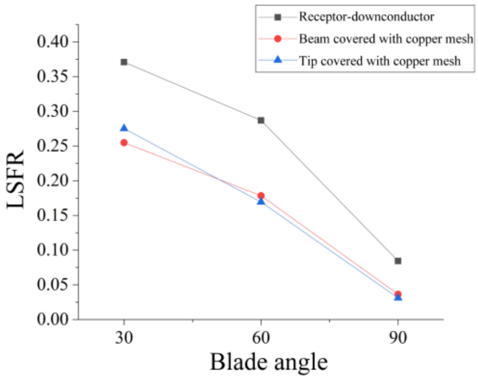


Fig. 8 Lightning shielding failure rate of the blade with different attachment systems

It can be seen from Fig. 8 that the LSFRs of the three structures decrease while the blade angle increases. For the most severe cases, when the blade is at 30 degree, the LSFR of receptor-type blade is close to 0.4 while the LSFRs of the other 2 blades are less than 0.3. At 90 degree, the LSFRs of the two mesh-type blades are lower than 0.05 while the receptor-type is still near 0.1.

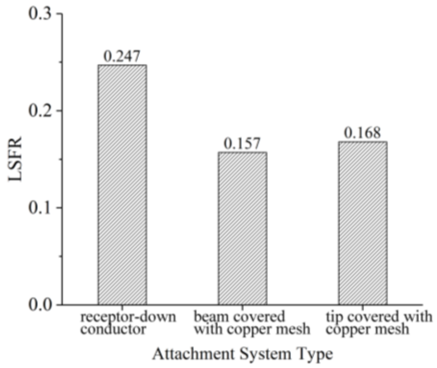


Fig. 9 Lightning shielding failure rate of the blade with different attachment systems

According to equation (4), the LSFRs of wind turbines corresponding to the three types of blades were calculated presenting in Fig. 9. The LSFRs of the two mesh-type blades are obviously lower than the receptor-type. However, considering the low cost, the tip-mesh-type is recommended even its LSFR is only about 0.01 higher compared to the beam-mesh-type.

V. Conclusion

This paper proposes a calculation method of lighting shielding failure rate to quantitatively evaluate the failure risk of the lightning attachment system on wind turbine. The validity of the method is verified by a physical simulation experiment.

A design of lightning attachment system on wind turbine is introduced, with the blade tip covered with copper mesh. And the LSFRs of three types of wind turbines, namely receptor-type, beam-mesh-type and tip-mesh-type were calculated. The LSFR of the beam-mesh-type is the lowest while the tip-mesh-type is with less copper mesh which can achieve the similar LSFR with the beam-mesh-type. Therefore the tip-mesh-type blade is recommended by comprehensive consideration.

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