Flashover Probability of Wind Turbine Blade and Impact of Strong Electromagnetic Pulse from Lightning Strikes on Wind Turbine Safety

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Abstract This paper systematically studies the flashover probability of wind turbine blade lightning arrester and the impact of strong electromagnetic pulses on the local and surrounding wind turbines during lightning strikes. The research results indicate that the flashover probability of direct lightning strikes by the wind turbine blade lightning arrester is almost negligible, and the strong electromagnetic pulse of wind turbine blade during lightning strikes has a serious impact on the electronic equipment of the machine, while the impact on the surrounding wind turbine is relatively small. At the same time, the calculation formula for the reflection of lightning current on the carbon brush between the wind turbine hub and the engine compartment during the flashing of the wind turbine blades is provided, and the calculation method for calculating the spatial gradient distribution of electromagnetic field intensity using Biot – Savart Law theorem is applied. The limitations of using wind turbine blades for lightning protection are pointed out, and a technical route for achieving wind turbine lightning safety is proposed, which can be used as a reference for wind turbine lightning protection technicians.

Key words Wind turbine; Flashover probability of blade lightning arrester; Spatial gradient of electromagnetic field intensity; Technical route

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The lightning protection technology for wind turbines in wind farms is mainly divided into protection technology against direct lightning strikes of wind turbines (overhead and side lightning strikes) and strong electromagnetic pulses caused by lightning strikes. The two complement and cooperate with each other, which is the main technical means for wind farms to achieve the goal of "zero lightning damage". For technical methods for preventing lightning damage to wind turbines by wind turbine blade lightning arresters, which are commonly used both domestically and internationally, this paper introduces the five types of existing wind turbine blade lightning arresters, and calculates the flashover probability of direct lightning strikes caused by wind turbine blade lightning arresters. It also analyzes the shortcomings and deficiencies of wind turbine blade lightning arresters in preventing direct lightning strikes, the physical process of strong electromagnetic pulses generated by lightning current during the flashing of the wind turbine blade lightning arrester, harm to the internal electromagnetic field environment of wind turbines at lightning strike points and impact on wind turbines around wind farms[1]. The analysis results indicate that the technical method of using wind turbine blade lightning arresters to protect the safety of wind turbine is not feasible, which is consistent with the provision in Article 4.2.3 "Rotating Equipment Should not be Used as Lightning Arresters" of the current *Design Code for Lightning Protection of Petrochemical Equipment* (GB 50650)[2].

1 Basic types of wind turbine blades

The types of blades depend on the control and braking mechanisms used, as well as the use of insulation and conductive composite materials. Currently, the five main types are shown in Fig. 1[3].

1.1 A type The blade uses flaps (ailerons) on the outer side of leading edge for braking. On A-type blades, lightning attachment points are often found on the flap steel hinges. Due to the cross-sectional area of the steel wires used to operate the flaps insufficient to conduct lightning currents, serious damage often occurs.

1.2 B type The blades use a pointed brake retained by springs

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and released at high speed through centrifugal force. For B-type blades, lightning attachment points mainly occur within a few tens of centimeters from the outermost tip, or on both sides of the tip at the outermost end position. Starting from the attachment point, a lightning arc is formed inside the blade tip section, reaching the outermost end of the blade tip axis. From the other end of the axis, an arc is formed inside the main blade, and down to the steel mounting flange at the blade root. This internal arc always causes catastrophic damage to the blade. A-type and B-type blades are commonly used for older wind turbines up to 100 kW.

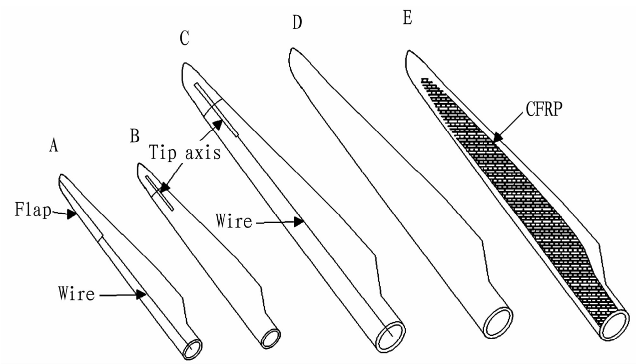


Fig. 1 Basic types of wind turbine blades

1.3 C type A blade with a pointed brake controlled by a steel wire. For C-shaped blades, the lightning attachment point is mainly within a few tens of centimeters from the tip of the outermost layer of the blade, or on both sides of the tip at the outermost end position of the tip. Like B-type blades, C-type blades form a lightning arc at the tip between the attachment point and the outermost end of the axis, causing serious damage. When the steel wire cannot carry lightning current on C-shaped blades, most of the main blades will be damaged. The minimum diameter of the steel wire used for this purpose is 10 or 12 mm, with a 17 m long of blade. This type of wire can conduct most lightning currents, thereby protecting the main blades from damage.

1.4 D type Blades are made entirely of non-conductive materials. Like other types of blades, lightning attachment points are mostly located near the tip of non-conductive blade. Compared with other types of blades, attachment points can also be randomly distributed at other positions along the length of the blade.

1.5 E type Some building components are made of carbon fiber reinforced plastic (CFRP) because that it has high stiffness under a given weight. CFRP can be used for strengthening blade skins and carrying building components, such as internal pillars. Due to the electrical performance of CFRP, careful coordination should be made with lightning protection devices to ensure necessary separation distance, electrical insulation, and current carrying capacity.

2 Flashover probability of wind turbine blade lightning arrester

2.1 Wind turbine blade lightning arrester The wind turbine blade lightning arrester consists of an M20 screw at the end of the wind turbine blade and a lightning conductor inside the blade.

2.2 Flashover probability of wind turbine blade lightning arrester for overhead lightning The phase angle difference of the three blades of the wind turbine is 120°, and circular motion is performed. Its spatial position is a function of time, and its instantaneous value function is as below:

$$i = Im\sin(\omega t + \Psi) \tag{1}$$

The wind turbine blades reach the top every 120°, with a value equal to 1. When the blade rotates once, it reaches the top of the wind turbine three times. Setting the rotation rate of wind turbine is 20 times/min, the time for each rotation is 3 s. Reaching the vertex once in 1 s is equivalent to 3 ωt of a blade. Assuming a blade length of 50 m, the circumference of its 1 s motion is 314 m[4]. If the diameter of the screw at the end of the lightning arrester is 20 mm, the arc length of blade motion in 1 s is 2 π, $dl/dt = 314$ mm/ms. The time required to move a 20 mm of distance $t_0 = 20/314$ ms; the flashover probability of time it stays at the vertex is:

$$P = \lim_{T \to 1\,000} \frac{t_0}{T} \times 100\% = \lim_{T \to 1\,000} \frac{\frac{20}{314}}{T} \times 100\% = 0.006\,31\% \tag{2}$$

The above calculation of flashover probability shows:

1) The wind turbine blade lightning arrester has a low flashover probability against overhead lightning strikes, and is almost ineffective against overhead lightning strikes. The flashover probability of lightning striking from the side of the wind turbine is zero.

2) When the movement velocity of wind turbine blades is 20 times/min, it reaches the top position once per second instead of being fixed at the top, and the time of staying at the top is $P = 0.006\,3\%$. The high-power wind turbine has lower speed, longer time, and lower flashover probability.

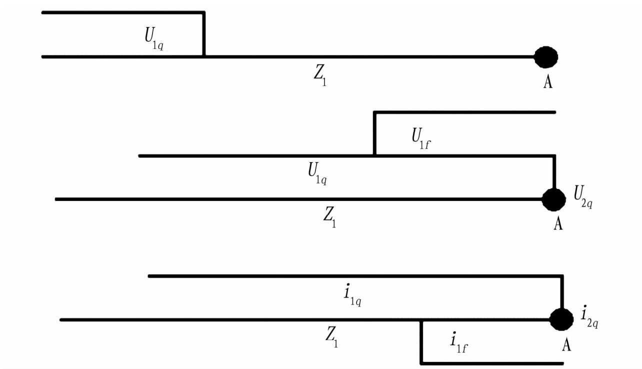
3) The flashing end of wind turbine blade adopts M20 screws, and the electric field strength required to generate corona is about 20 times of the standard lightning rod tip with a curvature radius of 1 mm.

4) A large number of cases have shown that when the blade lightning arrester is not receiving lightning, the physical damage to the blade end caused by non main channel branch lightning is a soybean sized hole; side lightning strikes will cause the blades to burst and break; flashover of lightning current inside the wheel hub can cause the wind turbine to burn out[5].

3 Impact of blade lightning arrester on the local machine

3.1 Carbon brush reflection effect The lightning current generated by the flashing of the wind turbine blades needs to be discharged into the ground after being connected to the carbon brush through hub copper ring. However, lightning discharge is a wave process. When encountering a sudden change in impedance at the carbon brush, reflection will inevitably occur[6].

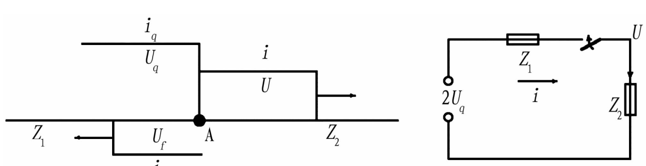
3.1.1 Load open circuit can generate 2 times of overvoltage. When U_{1q} reaches the end of the open circuit, a total reflection occurs. The reflected voltage wave is equal to the incident voltage wave, and the refracted voltage (namely terminal voltage) is twice the voltage of the incident wave, and the terminal current is zero. The reflected wave propagates backwards from the end, causing the voltage to double and the current to decrease to zero wherever it reaches. The voltage at the location where the reflected wave reaches doubles because all the magnetic field energy established by the incident and reflected waves there is converted into electric field energy. Where the reflected wave has not yet reached, the voltage and current are still U_{1q} and U_{1f}[7]. The physical process is shown in Fig. 2. It can be seen that when the circuit is open, the terminal voltage is twice the incident voltage.



Note: U_{1q} is incident wave voltage (V); i_{1q} is incident wave current; U_{1f} is reflected wave voltage; i_{1f} is reflected wave voltage; Z_1 is surge impedance of a line; U_{2q} is terminal voltage; i_{2q} is tail current. $U_{2q}=2U_{1q}$; $U_{1q}=U_{1f}$; $i_{1f}=U_{1f}/Z_1$; $i_{2q}=i_{1q}+i_{1f}=0$.

Fig. 2 Wave refraction and reflection when the end of the line is open circuit

3.1.2 Load short circuit can generate 2 times of overcurrent. When the load is short circuited, using the Peterson's law, the electromotive force of the power supply is $2U_q$, which is twice the incident voltage wave. The internal resistance of the power supply is a resistance with a value equal to Z_1, and the load is a resistance with a value equal to Z_2, and the voltage on Z_2 is the refracted voltage U. The sum of the ratio of the refracted wave current to the refracted wave voltage and the internal resistance Z_1 of the power supply is equal to twice the incident wave current. It can be seen that when the circuit is in a short circuit state, the current at point A is twice the incident wave current. The physical process and its equivalent circuit are shown in Fig. 3.



Note: $U=U_q+U_f$; $U_q=Z_1 i_q$; $U_f=-Z_1 i_f$; $U=Z_2 i$; $i_q=i+i_f$; $2i_q=\frac{U}{Z_1}+i$.

Fig. 3 Refraction and reflection of traveling waves at node A and their equivalent circuits

3.1.3 Risk of carbon brush reflection. Due to the flashing of wind turbine blades, lightning current passes through the carbon brush installed on the hub and is connected to the grounding wire of the tower. Overvoltage caused by poor or damaged carbon brush contact can cause lightning current flashover discharge, leading to damage to the wind turbine equipment. The situation of carbon brush short circuit is relatively rare.

3.2 Strong magnetic field radiation When lightning strikes the wind turbine, its lightning current is introduced underground from the wind turbine blades through copper rings, carbon brushes, and PE wires. Taking a 1.5 MW of wind turbine as an example, the diameter of the tower is about 4 m. If the SCADA system at the bottom of the tower is 4 m away from the grounding wire of the wind turbine and the damage threshold is 2.4 Gs[8], the maximum lightning current that can withstand the flashing of the blade lightning arrester should be ≤4.8 kA. When the wind turbine is struck by a 193.4 kA of lightning, the magnetic field strength at a distance of 6 m from the PE line can reach 64.5 Gs, greatly exceeding the damage value of the wind turbine SCADA system, and the SCADA system will inevitably be damaged.

4 Impact of lightning induced strong electromagnetic field on surrounding wind turbines

4.1 Calculation of lightning induced magnetic field According to the analysis of spatial and temporal vectors of electromagnetic waves, it can be concluded that lightning protection measures mainly focus on electromagnetic fields generated by the original current within a distance of $\lambda/4$. The magnetic field generated by lightning current is calculated using the Biot – Savart theorem[9] and the equation (3).

$$\gamma H=\frac{1}{2\pi R} \tag{3}$$

where $\gamma=1$ (in m. k. s. a system of unit); H is magnetic field intensity (A/m); I is current (A); R is distance from measurement point to current source point (m).

In lightning protection engineering technology, the Gaussian unit system is often used because $B=\mu_0 H$. For convenience, the equation (3) can be transformed into the equation (4).

$$B=\frac{\mu_0 I}{2\pi R} \tag{4}$$

where B is magnetic induction intensity (T, 1 T$=10^4$ Gs); $\mu_0=4\pi\times10^{-7}$; I is current (A); R is distance from measurement point to current source point (m)[10].

For specific areas protected by regional lightning protection design[11], the gradient distribution of magnetic field strength can be directly calculated using the equation (3). By selecting a value for I in the equation (3) and assigning values to R separately, the gradient distribution of magnetic field intensity of wind turbine and wind farm at the lightning strike point can be calculated. The lightning current uses the maximum negative flash current value $I=193.4$ kA retrieved in the Dianbai wind farm area by the 3D lightning monitoring system of the Institute of Electrical Engineering, Chinese Academy of Sciences. Based on a distance of 500 m from the interception point wind turbine radius, the gradient distribution of the magnetic field intensity is calculated in two steps.

Setting the damage value of electronic device $B=2.4$ Gs into the equation (5), the value of R (radius range) is calculated[12]:

$$R_{2.4\mathrm{Gs}}=\frac{\mu_0 I}{2\pi B}=161.2\ \mathrm{m} \tag{5}$$

The calculation results indicate that the radius of 2.4 Gs of magnetic field intensity is 161.2 m when the lightning current is 193.4 kA.

4.2 Impact of lightning induced strong electromagnetic field on surrounding wind turbines According to the time vector relationship of the electromagnetic field, it can be seen that when the electromagnetic field is transmitted in the direction of propagation, their time vector phase relationship is horizontal in the electric field and vertical in the magnetic field with a spatial difference of 90° between the two (Fig. 4).

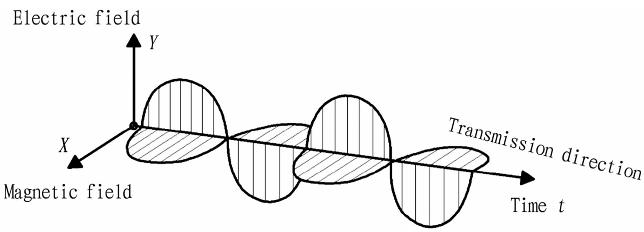


Fig. 4 Time vector relationship between electric and magnetic fields

Therefore, the magnetic field generated by the wind turbine current at the lightning strike point will propagate outward parallel to the ground with the lightning strike point as the center (horizontal gradient below the height of the wind turbine lightning rod). The 690 V power supply line arranged vertically on the ground inside the surrounding wind turbine and the control line connected to the engine room and tower base are parallel to the direction of the magnetic field generated by the wind turbine at the lightning strike point, which will have a serious impact[13]. The amplitude relationship between electric field and magnetic field is represented by the following equation[14]:

$$\eta=\frac{E_0}{H_0}=\frac{\omega\mu}{k}=\sqrt{\frac{\mu}{\varepsilon}} \tag{6}$$

H_0 is amplitude of the magnetic field; E_0 is amplitude of the electric field. In free space, the wave resistance (vacuum) impedance is:

$$\eta_0=\sqrt{\frac{\mu_0}{\varepsilon_0}}=120\pi=377\ \Omega \tag{7}$$

When electromagnetic waves propagate in the air, the impedance value of free space waves can be approximated as 377 Ω. The electric field strength at a certain distance from the wind turbine of the lightning strike point can be calculated using the above formula.

4.3 Spatial gradient of magnetic field intensity from wind turbine *R* at interception point Assuming lightning current $I=193.4$ kA, the straight-line distance R between any point in the protection zone and the interception point is divided into 5 gradients every 100 m, and R is set into the equation (4) to calculate B[15]. $R_1=100$ m, $R_2=200$ m, $R_3=300$ m, $R_4=400$ m, and $R_5=500$ m are into the equation (4), and the results are as below: $B_1=3.87$ Gs, $B_2=1.93$ Gs, $B_3=1.29$ Gs, $B_4=0.97$ Gs, and $B_5=0.77$ Gs. The gradient distribution is shown as Fig. 5.

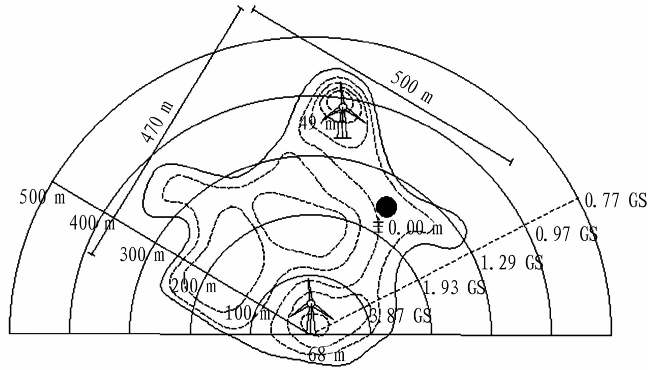


Fig. 5 Horizontal gradient of magnetic field space from wind turbine R at interception point

The calculation results indicate that SCADA of wind turbine at the lightning strike point may be damaged[16], and it needs to be reinforced. When the amplitude of the lightning current is 193.4 kA, it has a serious impact on other wind turbines with a distance ≤ 161.2 m from the wind turbine at lightning strike point. The line overvoltage caused by the excessive magnetic field strength of the wind turbine at the lightning strike point will be transmitted to other wind turbines at the speed of light through the physical medium (steel wire for optical fibers, 690 V line, grounding connection line, *etc.*) connected to the wind turbine at the lightning strike point, causing SCADA damage.

5 Summary

5.1 Low flashover probability of wind turbine blade lightning arrester For ground objects, the main form of lightning damage is direct lightning strikes. The probability of the wind turbine using a blade lightning arrester to receive overhead lightning strikes is 0.006 3%, and the theoretical probability of receiving side lightning strikes is 0. Therefore, the wind turbine blade lightning arrester cannot effectively prevent direct lightning strikes. The method of using wind turbine blade lightning arresters does not meet the requirements of national lightning protection technical specifications. It is obvious that new theories and technical methods are needed for wind turbine lightning protection.

5.2 Posing a serious threat to the safe operation of wind turbines The calculation of the electromagnetic field intensity generated by lightning strikes on the wind turbine indicates that a lightning current greater than 4.8 kA may cause damage to the SCADA system at the bottom of the wind turbine tower. The radiation electromagnetic field generated by lightning currents may cause damage to the SCADA system of the wind turbine within 161.2 m from the lightning strike point, and cause serious interference to the SCADA system of the wind turbine within 200 – 500 m. Strong electromagnetic field of lightning strike may cause the high-voltage switch of overhead power lines to trip, and the overvoltage flashover and melting of underground metal optical cables.

5.3 Technical roadmap for achieving lightning safety of wind turbines It can be imagined that a new type of lightning rod can be installed on the top of the wind turbine nacelle, which can generate a longer upward lead than traditional lightning rods and attenuate the current at the lightning point, achieving effective lightning interception[17]. It will greatly improve the lightning safety of wind farms by installing lightning pulse high-energy absorbers on the power lines of wind turbine power generation systems.

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novative thinking, and strengthen their understanding of social situations. Combining with local characteristics, distinctive teaching resources should be developed, and sports teaching models suitable for rural areas should be created. Combine with local customs and traditional sports culture, school-based courses could be developed. In practice, they should continuously accumulate situational materials and adapt to teaching in different situations. Through various means, their own professional development could be achieved. Utilizing their own knowledge and skills, it could revitalize the sports industry of rural mass, and promote the construction of rural spiritual civilization.

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