Processing of Upward Leader on the Wind Turbine Blade and Critical Length Inception Criterion

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***Abstract*—As a key physical process of the research about lightning protection of wind turbine blades, the inception mechanism and criterion of the upward leader need further investigation. A model of line charge with point charge at the head is used to simulate charge distribution of lightning downward leader. A curve about density of surface charges on blade is presented after considering the movement, diffusion and neutralization of the space charges nearby blade. Under the influence of space charge in both lightning downward leader channel and that on surface of blade, the potential nearby the blade is distorted obviously. Based on a simplified model of the development of upward leader, the paper proposes a critical length inception criterion for upward leader. The kernel of criterion is 'there exists a certain zone above the tip of blade where the background potential is larger than that in streamer, and if the length of this zone is longer than a background potential critical length, a stable upward leader will incept'. Lightning parameters and blade parameters such as amplitude of lightning current, lateral distance, length of blade and radium of receptor have no effect on the critical length. The critical length decreases with the increase of the relative density and humidity of air, and it increases with the increase of altitude. The feasibility of the proposed criterion is verified by the observation results of long air gap discharge for the vertical conductors under laboratory conditions.**

Keywords*- *Wind turbine; FEM; upward leader inception; critical length criterion; environmental impact factors.

I. Introduction

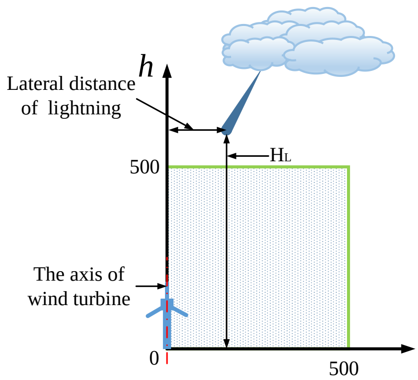
Renewable energy technology is central to global efforts to tackle the effects of climate change and embrace a move towards a cleaner, more sustainable energy society. However, the development of large-scale wind power generation meets challenges due to the limits from lightning protection [1].

Current researches on lightning protection of wind turbine blades are mainly about lightning risk assessment, blade lightning damage mechanism and so on. Yokoyama [2] from Japan summarized a large number lightning observations at the Nikaho wind park, and speculated the cause of damage of blades by lightning; Chinese Academy of Meteorological Sciences [3] analyzed the effect of the angle of the blades on the probability of lightning strike; Shanghai Jiaotong University [4] summarized experiment technologies on lightning attachment points of wind turbine blades. Long [5] used Self-consistent Leader Inception and Propagation Model to dynamically evaluate the upward connecting leader propagation under the influence of both stepped and dart leaders. Madsen [6] simulated downward initiated strikes by a leader with prospective peak current of 3kA approaching from various origins and directions, whereas upward strikes are simulated by a static field increasing slowly in amplitude. While, inception mechanism of lightning upward leader from the wind turbine blade, as a basic subject in the field of lightning protection, needs to be researched further.

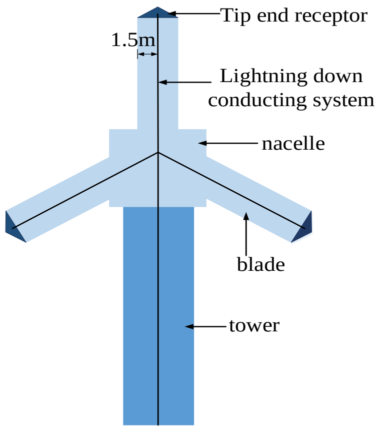
Based on the achievements from long gap discharge areas, this paper will study the inception mechanism of lightning upward leader from the wind turbine blades and propose a critical length criterion for the inception of upward leader. It will be a theoretical basis on studying the effect of lightning transient electromagnetic and making effective lightning protection measures.

II. ANALYSIS MODEL

Setting the bottom of wind turbine as the origin of coordinates, this paper establishes a coordinate system as shown in fig.1. The height of thundercloud is 2.5 km and the polarity is negative. The tower of wind turbines is made of reinforced concrete, and the height is 80m with a radius of 2m. Wind turbine blades are made of glass fiber reinforced plastics (GFRP), the length is 60m and 3m in width.



(a) The position between downward leader and wind turbine



(b) The structure schematic diagram of wind turbine

Figure 1. The schematic diagram of downward leader and wind turbine

A. Distribution of space charge at the tip of blade

A model of uniform linear charge combined with point charge at the head of leader is applied to simulate charge distribution of lightning downward leader. Background electric field is calculated with mirror image method.

In this paper, charged particles are divided into three categories [7], small ions n_+, large aerosol ions N_+ and aerosol neutrals N_a, according to their size and quantity of electric charges. Three convection/diffusion modules and an AC/DC module of COMSOL Multiphysics are used to solve the continuity equations for n_+, N_+ and N_a:

$$\frac{\partial n_+}{\partial t} = D\cdot\nabla^2 n_+ - \nabla\cdot\left(n_+\cdot\mu_{n+}\cdot\vec{E}\right) - k_{nN}\cdot n_+\cdot N_a \tag{1}$$

$$\frac{\partial N_+}{\partial t} = D\cdot\nabla^2 N_+ - \nabla\cdot\left(N_+\cdot\mu_{N+}\cdot\vec{E}\right) + k_{nN}\cdot n_+\cdot N_a \tag{2}$$

$$\frac{\partial N_a}{\partial t} = D\cdot\nabla^2 N_a - k_{nN}\cdot n_+\cdot N_a \tag{3}$$

Poisson's equation for electric field $\vec{E}$ and potential Φ is given by Equation (4):

$$\nabla\cdot\vec{E} = -\nabla^2\Phi = \frac{e\cdot(n_+ + N_+)}{\varepsilon_0} \tag{4}$$

Where μ_{n+} and μ_{N+} are the ionic mobility for small and aerosol ions respectively. k_{nN} is the small positive ion attachment coefficient to aerosol particles, D is the diffusion coefficient, e is the elementary charge and ε_0 is the dielectric permittivity. Initial concentration of n_+, N_+ and N_a is set to 0, 0 and 10^{11}m^{-3}[8], considering that before the inception of discharge there are no space charges near the tip of blade.

A large number of positive charges are gathered at the tip of blade under the influence of the background electric field, as shown in Fig.2. Surface charge density increases where the distance between a certain point on trailing edge and blade axis equals 1.5m due to smaller curvature radius.

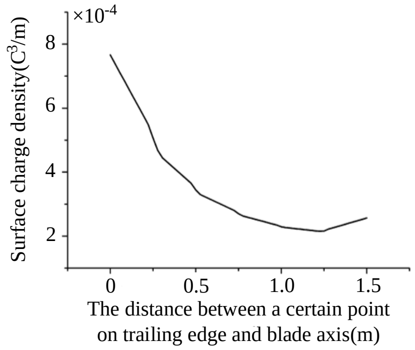
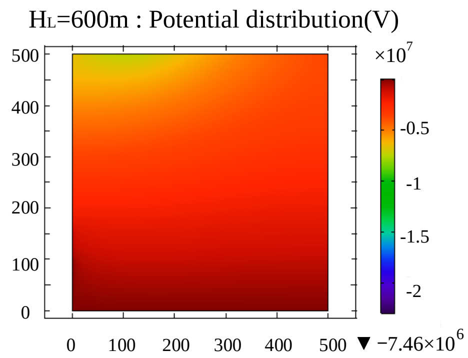


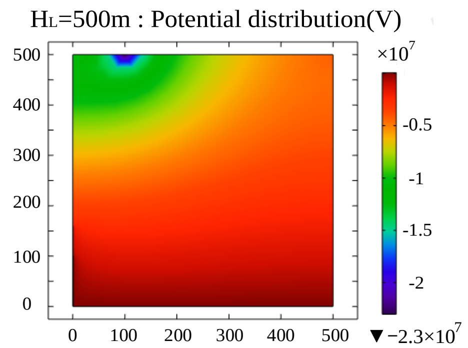
Figure 2. Distribution of charge density at the trailing edge of the blade

B. Background Potential Critical length inception criterion

According to the Poisson equation, the distribution of potential nearby blade is calculated by Equation (4). The Dirichlet boundary condition is adopted at the interface between air and ground, while Neumann boundary condition is adopted at air boundaries [9]. Potential distribution nearby wind turbine is calculated via COMSOL Multiphysics, as shown in Fig.3. Where H_L is the height of the head of downward leader.



(a) Potential distribution when H_L = 600m



(b) Potential distribution when H_L = 500m

Figure 3. Potential distribution of space

Compared with situation of H_L=600m, the potential of space increases obviously when H_L=500m, especially near downward leader's head. As shown in Fig.4, the background potential nearby the blades increases with the decrease of H_L.

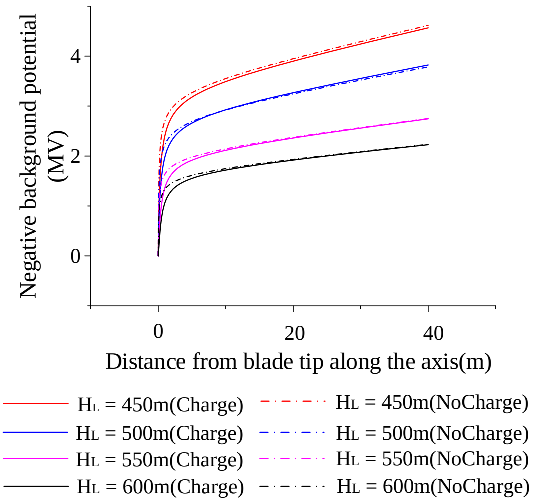


Figure 4. The potential distribution of space nearby the blades

Under the influence of space charge in lightning downward leader channel and that on surface of blade, the potential nearby the blade is distorted obviously, especially within 5m to the blade tip.

Compared with the situation without the movement of space charges, the potential near the tip of blade decreases obviously. The reason is that there are lots of positive charges collecting near the tip of blade, which weakens the background electric field.

In this paper, the wind turbine is installed at the altitude of 1200m, where the electric field intensity of streamer is -414 kV/m. The amplitude of lightning current is 30 kA, and lateral distance of lightning is 100m. The length of blade is 60m with a receptor at tip, whose radius is 0.05m.

Based on a simplified model of the development of upward leader [10-11], the relation between d_1 and H_L is obtained, where d_1 is the length of zone where background potential is larger than that in streamer, as shown in Fig.5. d_1 increases with the decrease of H_L, because background potential increases as the downward leader is closer to the ground.

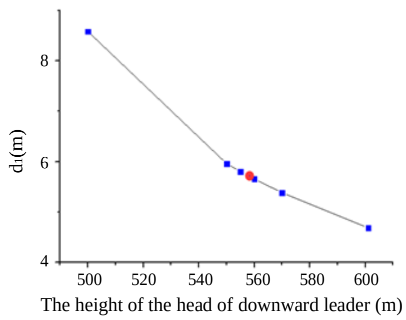


Figure 5. The change of d_1 with H_L

When d_1 is less than 5.75 m, the condition of stable propagation of an upward leader is not satisfied. On the contrary, when d_1 is more than 5.75 m, a stable upward leader is formed. So, in this paper $d_1 = 5.75m$ is defined as a background potential critical length for the inception of a stable upward leader, marked by a red dot in Fig. 5.

A background potential critical length inception criterion for upward leader is proposed, the kernel of which is 'there exists a certain zone where the background potential is larger than that in streamer, and if the length of this zone is longer than a critical length, a stable upward leader will incept'.

C. *The influence factors on critical length*

After repeating the simulation as followed in Sect. II "Analysis Model", we find that lightning parameters and blade parameters, such as amplitude of lightning current (*ALC*), lateral distance (*LD*), length of blade (*LB*) and radius of receptor (*RC*) have no effect on the background potential critical length, called l_{cri} for convenience, as shown in Tab.1.

Table 1. The critical length under different lightning and blade parameters

LD(m)	0	100	200	300	400
l_{cri}(m)	5.75	5.75	5.77	5.76	5.75
ALC(kA)	30	40	50	60	70
L_{cri}(m)	5.75	5.77	5.76	5.76	5.75
LB(m)	40	50	60	65	70
l_{cri}(m)	5.76	5.75	5.76	5.75	5.75
RC(m)	0.05	0.10	0.15	0.20	0.25
l_{cri}m)	5.75	5.75	5.76	5.76	5.75

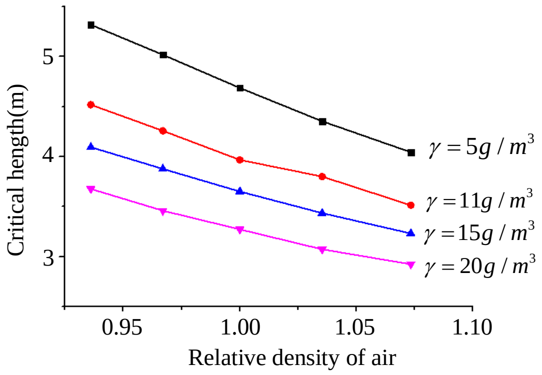
The electric field intensity of streamer is effected by many environmental factors such as pressure, temperature and humidity of air [12], as shown in Equation (5-6).

$$E_{str} = -425\delta^{1.5} - (4 + 5\delta)\gamma \tag{5}$$

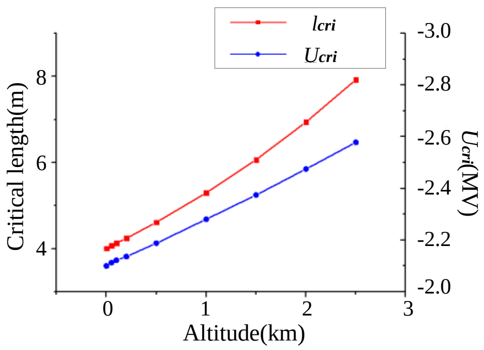
$$\delta = \frac{P}{P_0}\frac{T_0}{T} \tag{6}$$

Where E_{str} is the electric field intensity of streamer, δ is the relative density of air, γ is the humidity, P is pressure, T is temperature, P_0 and T_0 are pressure and temperature in standard atmospheric conditions.

After repeating the simulation under different environmental conditions as followed in Sect. II "Analysis Model", we find that the background potential critical length is influenced by environmental factors, especially relative density and humidity of air and altitude. The effect of environmental factors on l_{cri} is given in Fig.6. The critical length decreases if the relative density and humidity of air increases, and if attitude decreases.



(a) The change of l_{cri} with relative density and humidity of air



(b) The change of l_{cri} with altitude

Figure 6. The change of l_{cri} with environmental conditions

What's more, the Equations of l_{cri} and U_{cri}, the potential of l_{cri} are gotten by curve fitting, as shown in Equation (7)-(10):

$$l_{cri} = -6.72\delta - 0.075\gamma + 11.78 \quad (7)$$

$$U_{cri} = 2.86\delta^{2.5} + 0.03\gamma\delta^{1.5} - 0.03\gamma\delta - 5\delta^{1.5} - 0.05\gamma \quad (8)$$

$$l_{cri} = 1.53H + 3.92 \quad (9)$$

$$U_{cri} = -0.014H^3 + 0.12H^2 - 0.4H - 2.05 \quad (10)$$

Where δ is relative density, γ is humidity of air, H is the altitude of installation place of wind turbine.

III. EXPERIMENTS

A. *Experimental verification of the critical length inception criterion*

The effectiveness of the proposed criterion is validated referring to the observation results of long gap discharge experiment [13]. The gap between plate external electrode and the test specimen was 3m. The height of test specimen was 2m. Negative voltage polarity was applied to plate electrode, whose front time was 250µs and time to half value was 2500µs. Potential distributions at the axis of inverted rod to plane gaps just before the final jump with different radiuses of upper planes was shown in Fig. 7. The experiment site was Wuhan, capital city of Hubei Province, where average altitude was 23.3m, average relative humidity was 80%, and temperature was 25℃. According to Equation (9)-(10), l_{cri} and U_{cri} is calculated as followed:

$$l_{cri} = 1.53H + 3.92 = 1.53 \times 0.0233 + 3.92 = 3.96m$$

$$U_{cri} = -0.014H^3 + 0.12H^2 - 0.4H - 2.05 = -2064.3\text{kV}$$

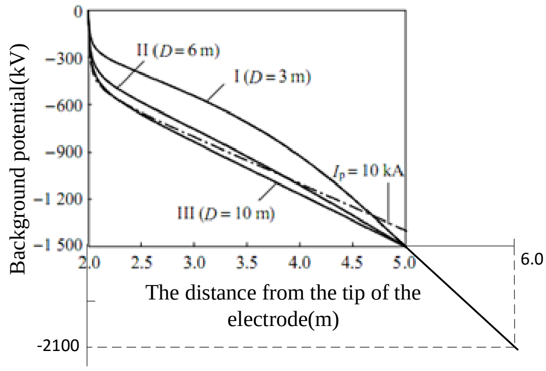


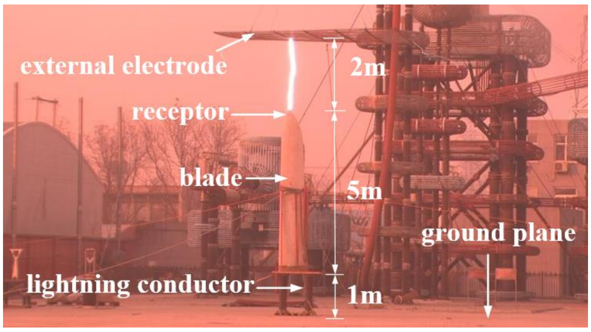
Figure 7. Potential distributions at the axis of inverted rod to plane gaps just before the final jump with different radiuses of upper planes [13]

On the basis of Fig.7, the potential of zone that is 5.96m away from the tip of the electrode is about -2100kV, after extending the horizontal axis to 5.96m. Background potential (U_1) is -2100kV, while potential in streamer (U_{cri}) is -2064.3kV, it is obvious that $|U_1| > |U_{cri}|$ and the length of zone where the background potential is larger than that in streamer is longer than a background potential critical length. The effectiveness of the proposed criterion is verify by such result.

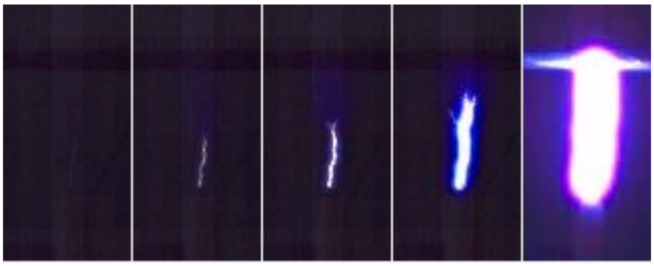
B. *Preliminary tentative experiments about long gap discharge experiment of blade*

Besides, lightning could strike on the blade surface even under the protection of the receptor. In order to obtain the distribution of attachment points and improve upward leader model proposed in this paper, a series of preliminary tentative experiments had been carried out.

Experiment platform was set up according to test setup suggested by IEC61400-24. External electrode, whose size was 5×5m, was suspended above the test specimen and at high potential when test was applied. Negative voltage polarity was applied to the electrode, whose front time was 250µs and time to half value was 2500µs. The air gap between the energized external electrode and the test specimen was 2m. To minimize the distortion on the electric field present in the gap, the test specimen was 1m far away from the ground plane and connected to ground with lightning conductor. The length of blade was 5m. The development process of lightning leader was caught by high-speed cameras (PHANTOM V1210), as shown in Fig. 8.



(a) Experiment platform



(b) The development process of leader

Figure 8. Experiment platform and the development process of leader

A series of tests had been done by using both positive and negative switching impulse. The blade tip sample is equipped with whole tip receptor and no side receptors. The whole tip receptor could intercept all lightning discharge when the angle between blade and horizontal plane was 90º (vertical) and 60º, which indicates that under these situation the blade is well protected. The further work is to figure out in which position the blade surface is vulnerable to the lightning stroke and what is the possibility of being hit.

IV. CONCLUSION

A background potential critical length inception criterion for upward leader is proposed. Lightning parameters and blade parameters have no effect on the critical length. The critical length decreases with the increase of the relative density and humidity of air, and it increases with the increase of altitude.

Based on criterion proposed in this paper, the study about distribution of lightning attachment points on blades will be carried out in the future. Nowadays, the position of receptors is not so reasonable that lightning is likely to strike the surface of the blade. So it is badly in need to figure out how the receptor attract the lightning stroke and use it to design the better LPS for blade. We could install receptors on blade more reasonable under the guidance of the study we will carried, and it will save enormous amounts of maintenance cost.

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