Experimental Study on Lightning Attachment Manner to Wind Turbine Blades with Lightning Protection System

Zixin Guo, Qingmin Li, *Member, IEEE*, Yufei Ma, Hanwen Ren, Zhiyang Fang, Chun Chen and Wah Hoon Siew, *Member, IEEE*

***Abstract*—Different types of lightning protection systems (LPS) have been developed for wind turbines to protect the blades from lightning strikes. However, severe damages caused by lightning strikes still happen frequently, which creates huge costs. Experiments using a 5m blade specimen with tip receptors from 1.5 MW wind turbine blades under 3 m air gap were conducted to investigate the lightning attachment manner to the wind turbine blade with LPS in different situations. Factors including polarity of the lightning strikes, orientation of the blade and the lateral distances between the wind turbine blade and the lightning downward leader were taken into account. It was found that the types of the discharge path under positive and negative lightning strikes are quite different, and the positive discharges are much more dangerous to wind turbine blade than the negative ones. The lateral distance between the downward leader and the wind turbine blade is a key factor that influences the interception efficiency. Three types of receptor interception failure were discovered. Multiple upward leaders may incept from the blade body as to intercept the downward leader. However, the protection range of the tip receptor is quite limited, and the connection of the tip receptor and the blade body is the most vulnerable position hit by the lightning strikes. The results present useful reference to optimal design of the wind turbine blade LPS.**

***Index Terms*—Lightning protection; Wind turbine blade; Lightning protection system; Lightning attachment; Multi-upward leaders**

I. Introduction

WIND power generation is one of the most important renewable energy systems. In China, more than 100 000 wind turbines (>169 GW) have been installed by the end of 2016. Although wind turbines are equipped with lightning protection system (LPS) designed to provide sufficient protection, the damage caused by lightning strikes remains one of the biggest threats to the wind turbines. It leads to important costs, including maintenance cost and economic loss due to out of operation or the replacement of the damaged blades. Now there is a trend that more wind farms are built in mountainous areas where severe lightning accident is more likely to happen.

Most manufacturers install discrete receptors along the blade surface connecting to the ground by a down conductor as recommended by IEC standard 61400-24 [1]. As shown in Fig. 1, two types of receptors are widely used. One is the tip receptor installed at the tip of the blade, and the other one is the side receptor installed on both sides of the surface along the blade. A down conductor is installed adjacent to the web of the beams along the wind turbine blade. The distance between the receptors is about 5 to 10 m. Field observation indicates that approximately 90% of the lightning strikes hit on the area within 5 m of blade tip while remaining 10% hit on the blade surface 5 m to 10m from the tip [2]. It is also interesting to note that many lightning strikes that cause damage hit on the interval of the two receptors [3-5].

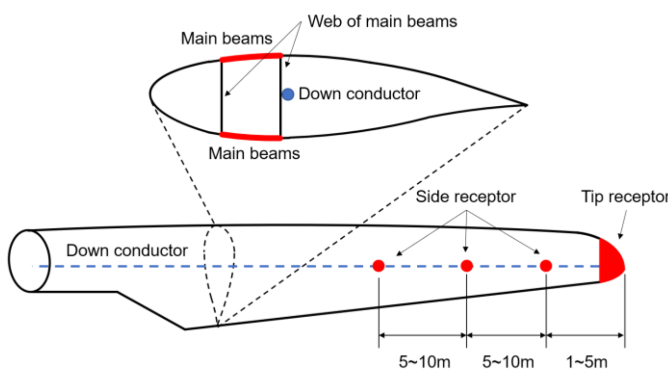

Fig. 1. Lightning protection system of wind turbine blade.

Long air gap experiments were conducted to simulate the behavior of the lightning strikes on the blades with different kinds of receptors [6-11]. These previous studies focused on the comparison of different kinds of receptors, such as tip receptor, side receptor, metal mesh, diverters and so on, which aimed to find out the best one or the combination of them. Experiments were conducted using blade tips with/without receptor, and the performance of both side and tip receptors were tested [6]. The protection efficiency of the tip receptor is much higher than that of the side receptor. The influence of the size of the side receptor was

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also studied [7]. The performance of different kinds of receptors was tested under different orientations and attack angles [8]. The inception of the upward leaders from three different kinds of receptors was captured by high speed camera [9]. The influence of the pollution depends on the types of the receptors installed [11]. Nowadays, most manufacturers design the LPS of blade following the studies and operation experience available. However, the wind turbine blades are still often hit by lightning strikes. The question why the LPS of the wind turbine blade fails to intercept the lightning downward leader is not yet to be answered.

Simulation work has been done towards the mechanism of upward leader inception from wind turbines [12]. The conditions for an upward leader to incept from different receptors were judged, and the protection area of the receptors were analyzed [13]. However, the blade surface near the receptor is still sometimes hit by lightning strikes even if the protection areas of the two receptors overlap with each other by theoretical calculation. The process of the interception failure needs to be reproduced first by experiments, and the analytical model can be then improved.

Multiple factors contribute to the performance of the wind turbine blade LPS. First of all, the wind turbine blade is in rotation, with a speed of 6-20 r/min. For a 45m blade, the line speed of the blade tip is about 28.3-94.2 m/s, which is only 0.01%-0.05% of the speed of downward leader (1.8×10^5 - 2.6×10^5 m/s [14]). Therefore, during the attachment process, the wind turbine is assumed to be static. Field observation shows that the numbers of lightning strikes to the wind turbine blade in the orientation of 90°, 60° and 30° are about the same [15]. However, the behavior of the receptor changes under different blade orientations.

Lightning strike is a random phenomenon, which may develop from any directions above the wind turbine blade. Similar to the transmission line, the lateral distance (LD) between the lightning strike and the wind turbine blade affects the interception behavior of the lightning protection system. As shown in Fig. 2, the lateral distance is represented by two dimensions: axial direction lateral distance (ADLD) and radial direction lateral distance (RDLD). The ADLD, which refers to the concept of lateral distance for transmission lines, may cause shielding failure, which means that the lightning strike may hit on the blade surface instead of the receptor [8]. The attack angle of the blade and the RDLD will affect the path of the upward leader from the receptor, and may cause creeping discharges [1,6,16].

In this paper, experiments are conducted to investigate how the receptor behaves under the lightning strikes and how the LPS fails to intercept them. Various experimental configurations, including positive and negative polarity lightning strikes, different blade orientations, and different lateral distances, are taken into consideration. The prominent polarity effect of the discharges and the asymmetrical influence of the lateral distance are analyzed. Summary of the receptor interception failure patterns under positive discharge is presented. The results can be referred for the optimal design of the wind turbine blade LPS.

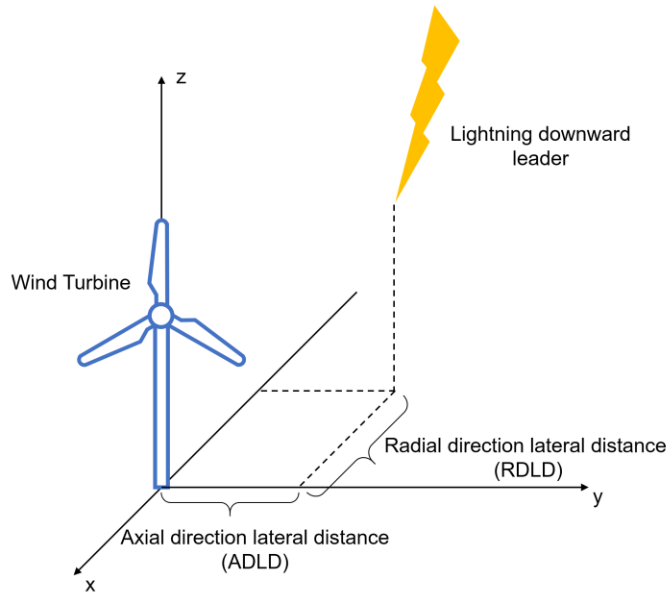


Fig. 2. The lateral distance represented by two dimensions: axial direction lateral distance (ADLD) and radial direction lateral distance (RDLD).

II. Experiments

A. Specimen

A 5 m glass fiber reinforced polymer (GFRP) wind turbine blade tip is used with the consideration of both operational feasibility and comparability. The specimen is cut from 1.5 MW WT blade SINOMA45.2B with an aluminum tip receptor and 70 mm^2 copper down conductor inside the blade chamber connected to the ground as shown in Fig. 3.

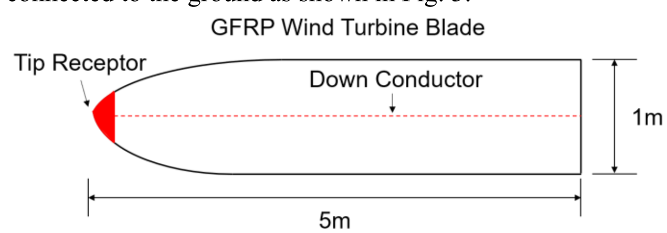


Fig. 3. The 5m GFRP wind turbine blade specimen with an aluminum tip receptor and $70mm^2$ copper down conductor inside blade chamber.

B. Method

The experimental setup is shown in Fig. 4. The experiments are conducted in North China Electric Power Research Institute (NCEPRI). A rod electrode is employed as the downward leader. The vertical distance between the tip of the blade specimen and the bottom of the rod electrode is 3 m. The blade specimen is elevated above the ground on a 1m non-conductive support. For the test voltage waveform, the 250/2500 μs standard switching impulse (positive and negative) is adopted in order to produce the background electric field similar to real lightning strikes. The impulse is obtained by the 5.4 MV high voltage impulse generator in NCEPRI. The breakdown probability is approximately 100% for the applied voltage, which is determined as follows: the 50% breakdown voltage is achieved in the first stance, and then the voltage increases to a level that the breakdown probability reaches nearly 100%. There are three kinds of typical blade orientations: 30°, 60° and 90° with horizontal. In this paper, 90° and 30° are used for the experiments. A digital camera is used to capture the discharge behavior by long-exposure, and a high-speed camera Phantom V1210 is used to capture the attachment process. The frame rate is 240601 fps (4.156 μs/frame), and the resolution is 128×128 pixel.

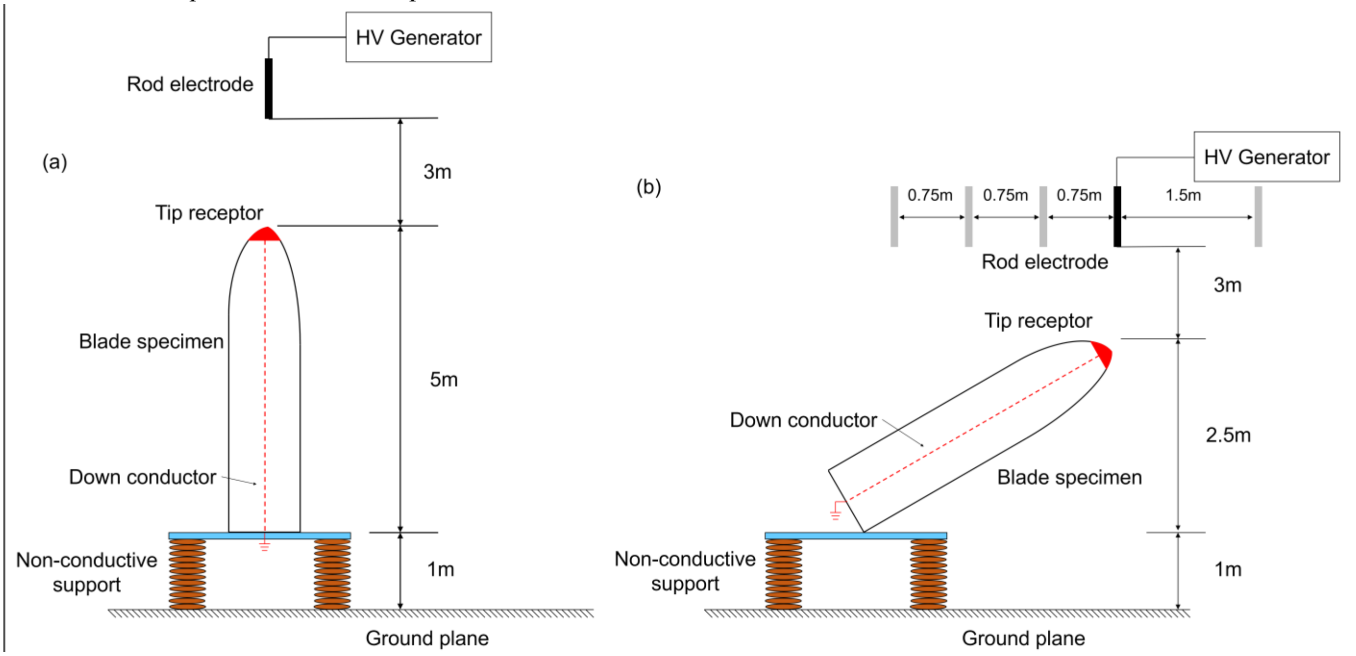


Fig. 4. (a) Experimental setup for blade orientation 90° with horizontal. (b) Experimental setup for blade orientation 30° with horizontal.

The lateral distance between the rod electrode and the tip of the blade specimen is adjustable in order to simulate the lightning strikes coming from different directions. In this paper, only ADLD is considered (hereinafter referred to as "lateral distance (LD)"). For the sake of convenience, the ratio between the horizontal distance from the downward leader tip to the bottom of the blade and the length of the blade is proposed to classify the different lateral distances (See Fig. 5):

$$R = \frac{L_{tip-bottom}}{L_{blade}} \tag{1}$$

where $L_{\text{tip-bottom}}$ is the horizontal distance between the downward leader and the foot point of vertical line from the blade tip to the blade bottom, L_{blade} is the horizontal distance from the blade tip to the blade bottom (foot point), as shown in Fig. 4(b) and Fig. 5.

Lateral distance can be classified into 3 groups:

- R >1, the downward leader comes from the direction far from the wind turbine blade. Lateral distance is -1.5 m.
- R =1, the downward leader comes from above the tip of the wind turbine blade. Lateral distance is 0 m.
- R <1, the downward leader comes from the direction close to the wind turbine blade. Lateral distances are 0.75m, 1.5 m and 2.25 m.

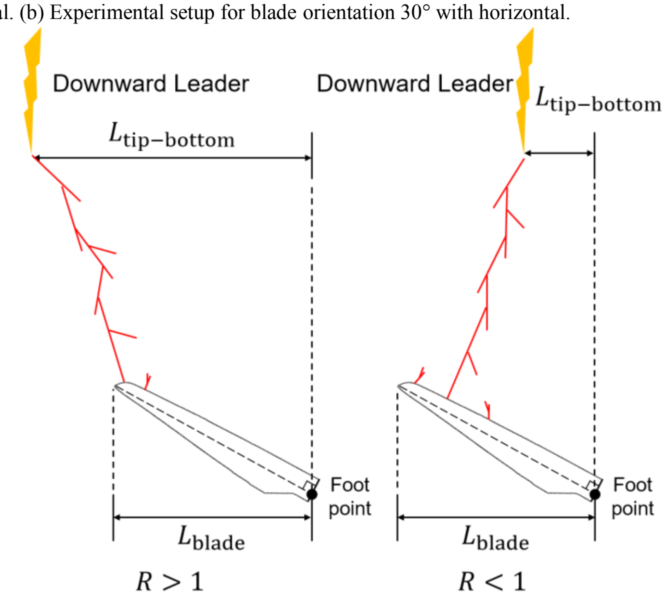


Fig. 5. The ratio between the horizontal distance from downward leader tip to the bottom of blade and the length of blade classifies different lateral distances. R >1: LD=-1.5m; R =1: LD=0m; R <1: LD=0.75m, 1.5m and 2.25m.

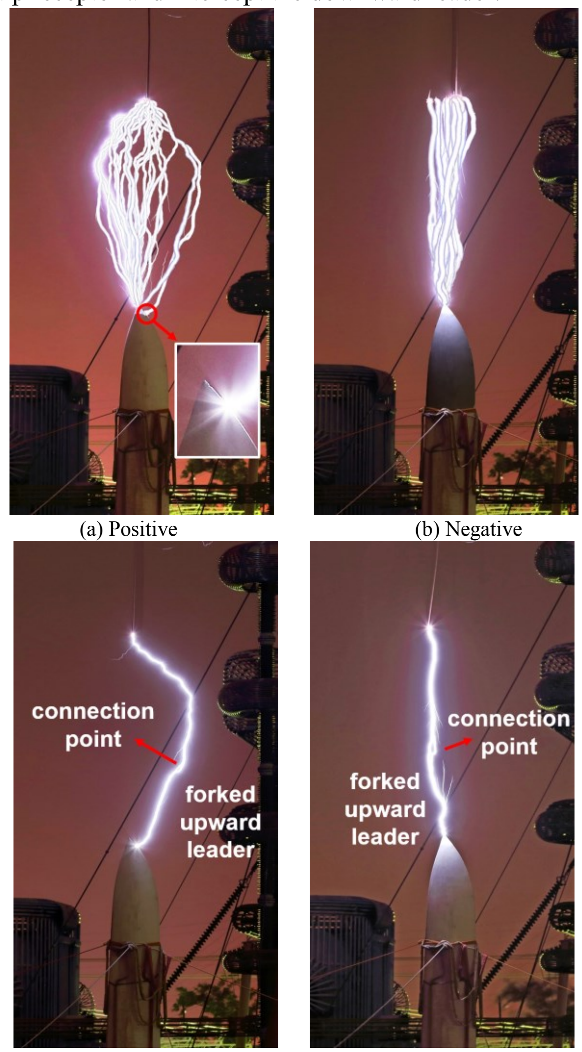
III. RESULTS

Experiments are conducted with both positive and negative standard switching impulses under different orientations and lateral distances. The results show very prominent polarity effect. In Section A, a comparison is made in terms of the voltage polarity. In Section B, the performance of the receptor with positive impulse is analyzed. Section C describes an interesting phenomenon observed in the experiments of Section B with positive impulses. In Section D, three types of the receptor interception failures are observed by the experiments with positive impulses under the orientation of 30° with horizontal (LD=2.25 m). In Section E, the discharges inside the blade chamber are observed with positive impulses under the orientation of 30° with horizontal.

A. The relationship between impulse polarity and the characteristics of discharge path

Both positive and negative standard switching impulses are conducted for the orientation of 90° and 30° with horizontal.

For the orientation of 90°, each polarity impulse is conducted for 20 times (see Table I). All the discharges (both positive and negative) hit on the tip receptor and the upward leaders are observed. However, there is significant difference between the positive and negative discharges. On the one hand, the paths of the positive discharges are scattered and convergent at the tip receptor, as shown in Fig. 6(a), and the negative discharges just develop straightly downward to the tip receptor, as shown in Fig. 6(b). Positive discharges are much more scattering than the negative ones. Under positive impulse, the downward leader propagates randomly within about one third of the length of the air gap, and then expends towards the tip receptor. On the other hand, all the discharges hit on the tip of the receptor except one positive discharge that hits on the boundary of the tip receptor and the body of the blade, which may cause damage to the wind turbine blade under natural lightning strikes, as shown in Fig. 6(a). In that case, the upward leader can incept not only from the tip of the receptor but also from the boundary. Results from electric field simulation show that although the downward leader does not develop directly toward the tip receptor, and the blade body is in sharp shape, the tip of the tip receptor is at the position of maximum electric field gradient. It is discussed in section IV why no upward leader incepts from the tip of the receptor which is supposed to be the easiest position. For the tip receptor, it is much easier to intercept negative discharges than the positive ones. The position of the connection points is at about 40% of the gap from the blade tip, as shown in Fig. 6(c) and (d). Under 90° with horizontal, no matter what direction the leader propagates downward, upward leader will incept from the tip receptor and intercept the downward leader.



(a) Positive (b) Negative

(c) Connection point (positive) (d) Connection point (negative)

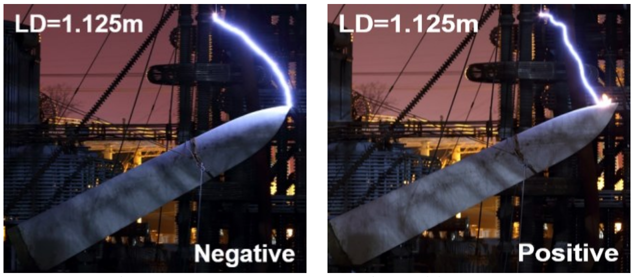
Fig. 6. (a) The paths of 20 positive discharges. (b) The paths of 20 negative discharges. (c) The position of positive discharge connection point is at about 40% of the gap. (d) The position of negative discharge connection points is at about 40% of the gap.

TABLE I
DISCHARGE MANNER FOR ORIENTATION OF 90° WITH HORIZONTAL

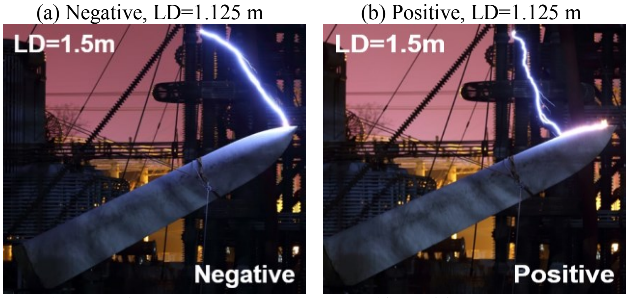
Polarity	Instantaneous breakdown voltage (kV)*	Striking attachment point						Total
		Tip receptor				Blade surface		
		Tip		Side				
		Times	%	Times	%	Times	%	Times
negative	1700.65	20	100%	0	0%	0	0%	20
positive	1164.70	19	95%	1	5%	0	0%	20

* The instantaneous breakdown voltage is the average voltage measured by oscilloscope of all the discharges under the same condition (polarity and lateral distance). The peak value of the applied voltage is 2000kV for negative, 1500kV for positive.

For the orientation of 30° with horizontal level, the difference between the positive and negative discharges is more obvious, as shown in Fig. 7. The vertical distance is 1.5 m and the lateral distances are 1.125 m and 1.5 m. All the negative discharges hit on the receptor. The striking attachment point of negative discharges is located at the tip of the receptor (LD=1.125 m), or at the side of the receptor (LD=1.5 m). However, all the experiments with positive discharges show creeping discharges on the blade surface. It is worth noting that the applied voltage is much higher than 50% of the breakdown voltage. The reason why there are only creeping discharges other than upward leaders from the tip receptor is that the tip receptor cannot attract the positive downward leader efficiently and the downward leader does not propagate towards to the tip receptor directly. The length of the creeping discharges increases when the lateral distance increases from 1.125 m to 1.5 m. From the results of cases with 30° and 90° orientations, the receptor interception efficiency for negative discharges is much higher than that for the positive ones, which are therefore much more destructive. It is concluded that the negative discharge is insensitive to the lateral distance to some extent.



(a) Negative, LD=1.125 m (b) Positive, LD=1.125 m



(c) Negative, LD=1.5 m (d) Positive, LD=1.5 m

Fig. 7. (a) For LD=1.125m, the negative discharge hits on the tip of receptor. (b) For LD=1.125m, the positive discharge hits on blade surface and cause creeping discharge. (c) For LD=1.5m, the negative discharge hits on the side of receptor. (d) For LD=1.5m, the positive discharge hits on blade surface and causes longer creeping discharge.

B. The relationship between lateral distance and attachment manner

Both positive and negative experiments are conducted with different lateral distances. As shown in Section A, all the negative discharges are intercepted by the tip receptor under different lateral distances. However, the consequences of experiments with positive discharges are quite different. Although the energy of the positive impulses used in the experiments is much smaller than that of real lightning strikes, it still causes damages as shown in Fig. 14 in Section D. Hence, positive lightning strikes are more dangerous to the wind turbine blades. Hence, the experiments using positive impulses under the orientation of 30° with horizontal are conducted to study the relationship between the lateral distance and the attachment manner. Lightning strikes from different directions are simulated under five level of lateral distances, and experiments with same lateral distance are repeated for 20 times (except one case for 17 times) as shown in Table II. The striking attachment points are classified into four types as shown in Table III and Fig. 8. It is worth noting that, part of the tip receptor is inside the blade.

- Type I, the striking attachment point is located at the far tip of the receptor, in which case the receptor protects the blade from the lightning strikes.
- Type II, the striking attachment point is located at the receptor side, from the tip to the boundary of the receptor and the blade body (≈15 cm from the receptor tip), due to the increase of the lateral distance.
- Type III, the striking attachment point is located at the blade body very close to the tip receptor, from the boundary of the receptor and the blade body to the edge of the receptor inside the blade (≈15 cm), in which case both creeping discharges and penetrating discharges into the blade may happen, which may eventually cause blade damage.
- Type IV, the striking attachment point is located at the blade body far from the edge of the receptor inside the blade, in which case the blade will be penetrated by the discharges.

TABLE II
DISCHARGE MANNER FOR ORIENTATION OF 30° WITH HORIZONTAL

Lateral distance (m)	R	Instantaneous breakdown voltage (kV)*	Breakdown time (μs)	Striking attachment point: Tip receptor interception success		Tip receptor interception failure		Total
-1.5	>1	1481.49	166.67	15	75%	5	25%	20
0	=1	1423.95	150.61	19	95%	1	5%	20
0.75	<1	1248.55	101.01	15	75%	5	25%	20
1.5	<1	1268.06	113.95	6	35%	11	65%	17
2.25	<1	1466.10	162.23	2	10%	18	90%	20

* The instantaneous breakdown voltage is the average voltage measured by oscilloscope of all the discharges under the same condition (polarity and lateral distance). The peak value of the applied voltage is 1600kV.

TABLE III
FOUR TYPES OF STRIKING ATTACHMENT POINT

Tip receptor	Type I	Receptor tip
	Type II	Receptor side
Blade body	Type III	Blade surface close to tip receptor
	Type IV	Blade surface far from tip receptor

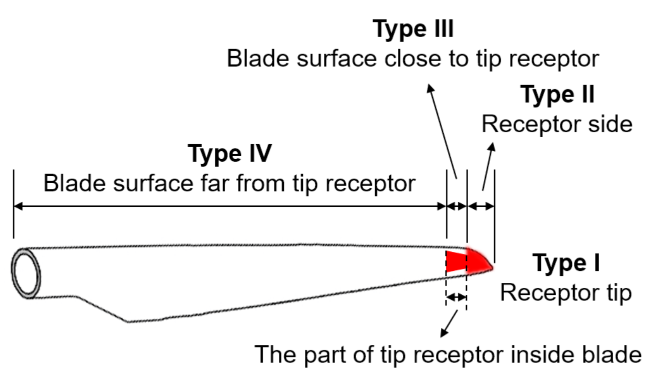


Fig. 8. Four types of striking attachment point.

The attachment manner changes under different lateral distances, as shown in Fig. 9 and Fig. 10. The interception efficiency of the tip receptor reaches maximum when the lateral distance is 0 m (approximately 95%). With the increase of the lateral distance under conditions of both R >1 and R <1, the efficiency decreases with different gradients and shows significant asymmetry. For R <1 condition, the interception efficiency decreases much faster than that of R >1, which means that the protection area of the tip receptor depends on both the lateral distance and the direction where the downward leader comes from.

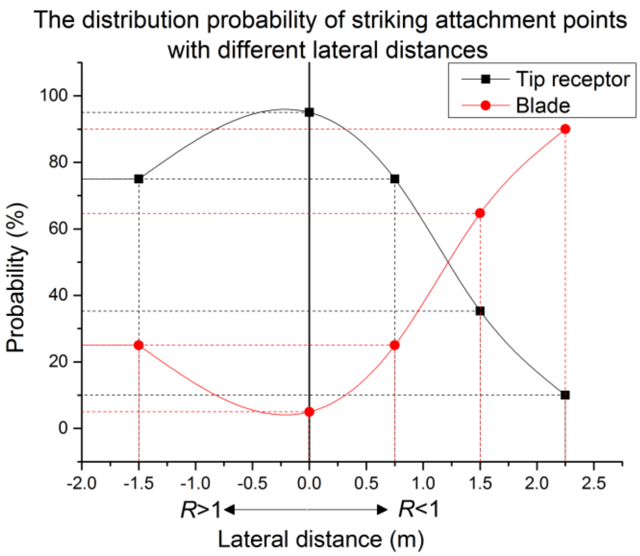


Fig. 9. The attachment manner changes with different lateral distances.

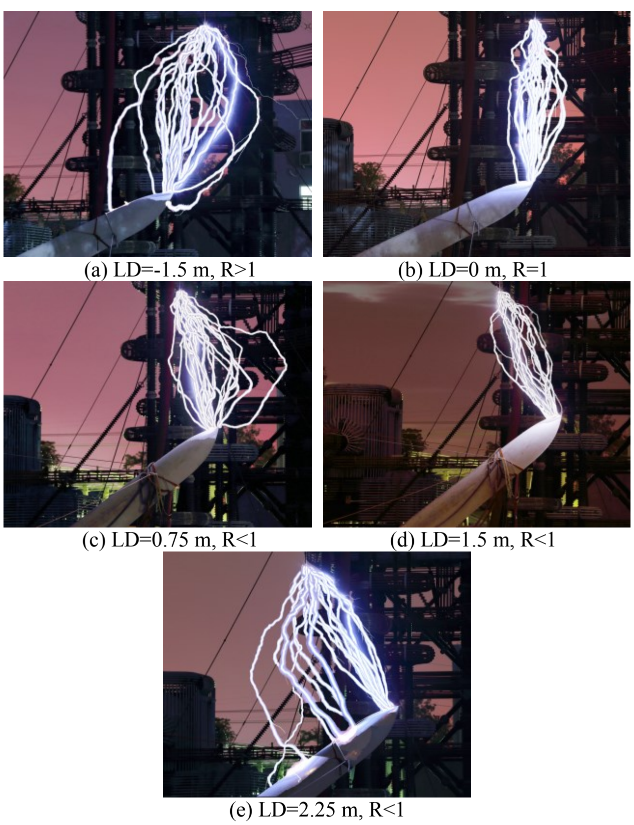


Fig. 10. (a) The paths of 20 discharges for LD=-1.5m, R >1. (b) The paths of 20 discharges for LD=0m, R =1. (c) The paths of 20 discharges for LD=0.75m, R <1. (d) The paths of 17 discharges for LD=1.5m, R <1. (e) The paths of 20 discharges for LD=2.25m, R <1.

With the increase of lateral distance, the distribution of the striking attachment points shows a tendency that the striking attachment point moves away from the tip receptor, as shown in Fig. 11. When lateral distance is 0m, most discharges hit on the receptor tip and side. With the increase of LD, more discharges hit on the blade surface near the boundary of the receptor and the blade body, which causes creeping discharges instead of hitting on the receptor directly. When the lateral distance is large enough, the receptor fails to attract most of the downward leaders and the discharges hit on the surface of the blade body.

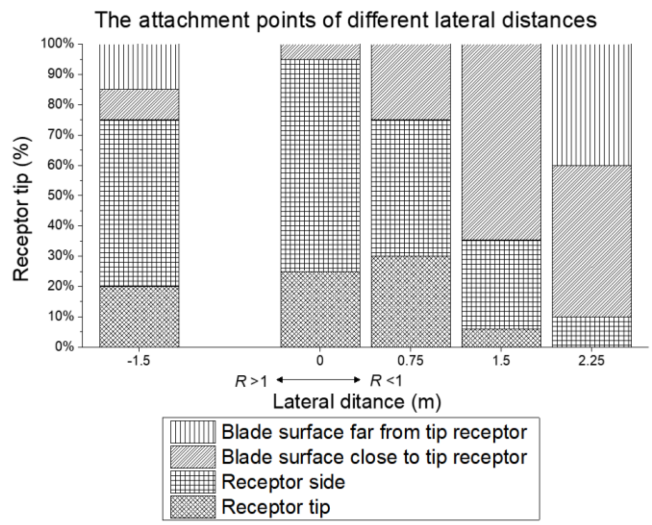


Fig. 11. The striking attachment points under different lateral distances.

C. Multiple upward leaders incept in "group" form

Multi-upward leaders are observed during the attachment process in Section B with positive impulses. As shown in Fig. 12, the upward leaders prefer to incept near each other. The upward leaders are observed at different location on the blade specimen, including the receptor and the blade surface, and one of the upward leaders finally connects to downward leader. In addition, there is only one cluster of upward leaders, which means that no upward leader incepts from other places. For example, as showed in Fig. 12(c) and (f), the discharge hits on the blade body and at least two upward leaders close to each other incept to connect the downward leader, but there is no upward leader incepts from the tip receptor or any other position of the blade. In Fig. 12(b) and (e), the striking attachment point is close to the tip receptor, but no upward leader incepts from the receptor. In Fig. 12(b), upward leaders incept from the channel of creeping discharge developed from the boundary of the receptor and the blade surface, which is regarded as receptor interception failure according to III. Section D. In Fig. 12(e), one upward leader incepts from the creeping discharge channel and one may incept from the edge of the receptor inside the blade and get out of the blade surface from the pinhole.

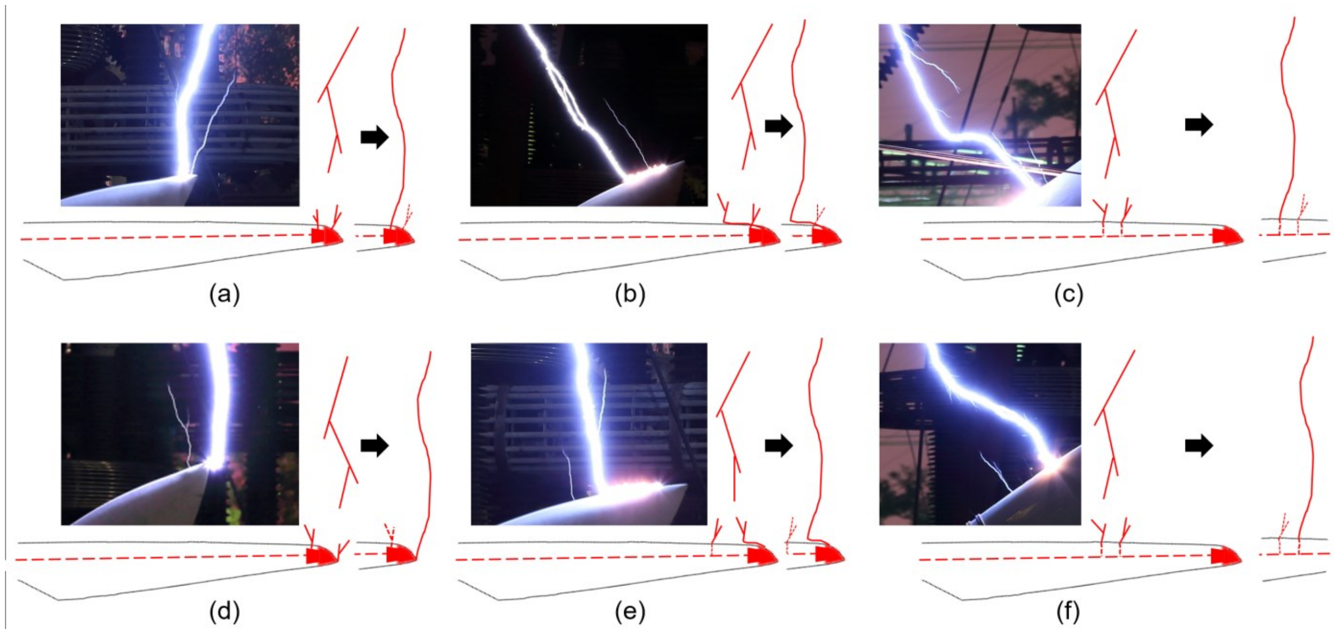


Fig. 12. Multiple upward leaders incept from the wind turbine blade and intercept downward leader.

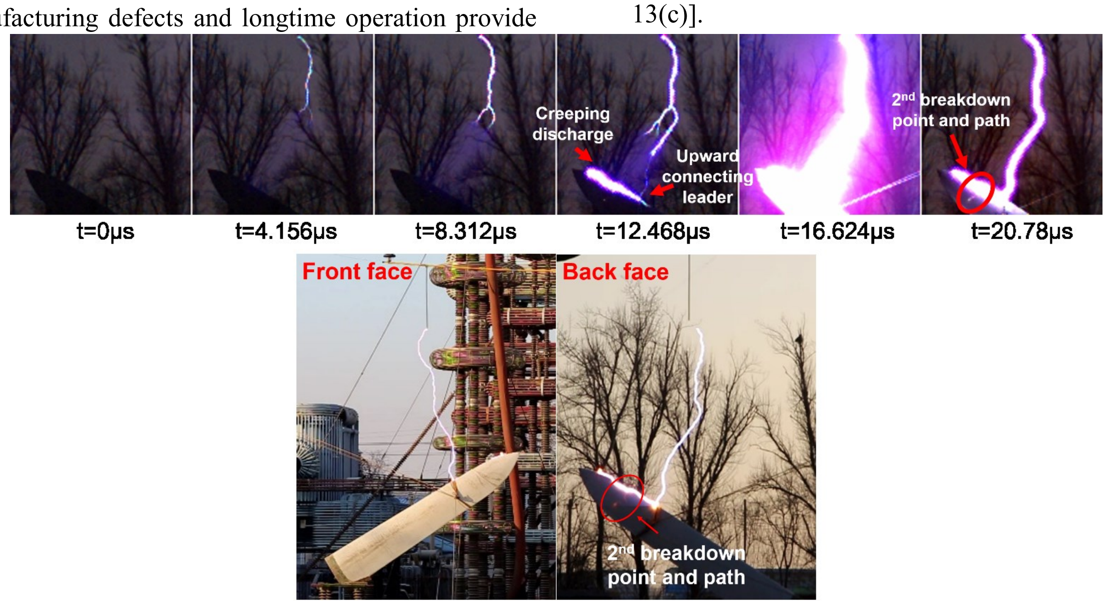
Preliminary numerical simulation is done based on unstable leader inception physical model [17-19]. The time-dependent background electric field near the blade specimen and the charge in corona zone are calculated to evaluate whether the unstable leader will incept. The results for the orientation of 90° with horizontal match the experimental results. However, for orientation of 30° with horizontal, the results show that the upward leader will first incept from the tip receptor no matter what the lateral distance is, which is not in accord with the experimental results.

What's more, the position where the upward leader incepts from the wind turbine blade remains unknown. The tiny pinholes on the blade could be the reason why upward leaders were observed to develop from the blade surface and intercept the downward leaders. The tiny pinholes on the blade surface due to manufacturing defects and longtime operation provide the channel for the upward leaders to incept from the down conductor as to get out of the blade chamber.

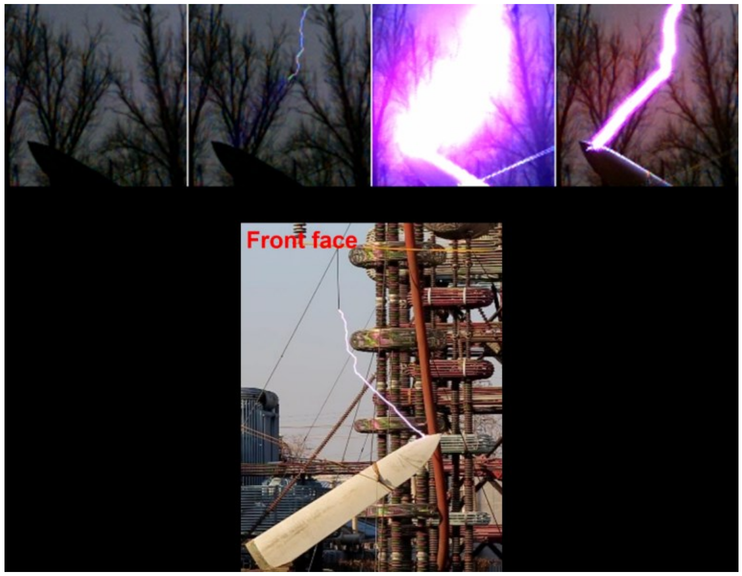
D. Three types of receptor interception failure

To figure out how the receptor fails to intercept lightning strikes is the first step to optimize the design of LPS. The experiments with positive impulses under orientation of 30° with horizontal setup (LD=2.25 m) are conducted. In the experiments, three types of typical interception failure are observed for positive standard switching impulses as follows:

- Creeping discharge from the receptor along the leading/trailing edge (Fig. 13(a));
- Discharge hitting on the blade leading/trailing edge (Fig. 13(b));
- Discharge hitting on the blade surface directly (Fig. 13(c)].



(a) Creeping discharge from receptor along the leading/trailing edge



(b) Discharge hitting on blade leading/trailing edge

(c) Discharge hitting on blade surface directly

Fig. 13. Three types of receptor interception failure. High speed camera captured from back face and camera captured from both front and back face

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More than half of the cases in the experiments, the receptor interception failure is creeping discharges from the receptor along the leading/trailing edge. Similar phenomena can be found in [8,10]. In general, about 4 μs (1 frame) before the connection of the upward and downward leaders, creeping discharge develops on the leading/trailing edge from the boundary of the receptor and the blade to downward leader, as shown in Fig. 13(a) when t=12.468 μs. Then upward leader incepts from the discharge channel and connects to the downward leader. The length of the creeping discharge channel varies from 29 cm to 159 cm. In the case showed in Fig. 13(a), the creeping discharge channel is longer (more than 1.5m), and there is a second breakdown point at the half of the channel. The light inside the blade chamber indicates that there are two conductive paths of the discharge. One is along the creeping discharge channel to the receptor to the down conductor, and finally to the ground. The other one is along the creeping discharge channel, through the blade chamber to the down conductor, and to the ground. Both the creeping discharge and second breakdown point will cause damage to the blade.

From the experimental results, the leading/trailing edge of the blade is the second most vulnerable position under the discharges, as shown in Fig. 13(b). The discharges can hit on the blade leading/trailing edge very close to the tip receptor (44 cm from the blade tip). Although the energy of the impulse is not so large, it really causes damage to the blade. As shown in Fig. 14, two small holes were made on the leading edge by the discharge. After the hole formed, all the discharges propagate to this point. The surface diameter of the hole is about 1cm. There will be some pinholes on the edge of the blade after 3~5 years operation, which increases the risk for the edge of the blade to be hit. The two pieces of the blade are glued together at the leading and trailing edge, and the manufacturing defects, such as air bubble inside the junction, will also make it vulnerable to be hit. In another case, the upward leader incepts from the edge of blade close to the inside part of the receptor

(≈25 cm from blade tip) and connects to the downward leader. However, after being connected, the discharge creeps (about 10cm) to the outside part of the receptor instead shown in Fig. 15. In addition, part of tip receptor is inside blade and surrounded by GFRP. For this case, the position where the upward leader incepts is quite near the internal edge of the tip receptor which distorts the electric field nearby. The upward leader may incept firstly from the inside part of the receptor and get out from the tiny holes in the blade surface. After being connected, another path may be found for the discharge, creeping to the outside part of the receptor, then to the ground. The shape of the tip receptor shows sensible influence on the interception performance of the receptor. Side receptor also has a metal base inside the blade, and field observation shows that there are some damages on the blade surface near the side receptor. Hence, the shape of the receptor should be redesigned.

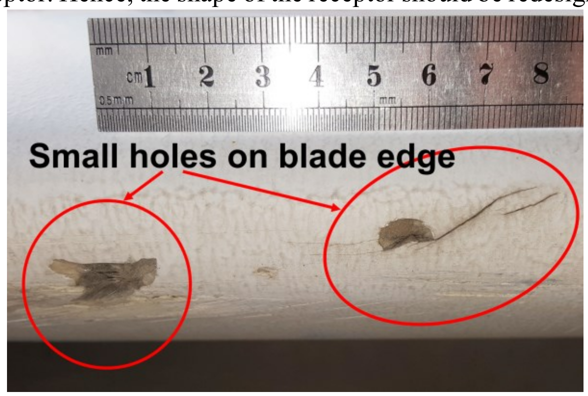

Fig. 14. Small holes are made on the leading edge in the experiments and the surface diameter of the hole is about 1cm.

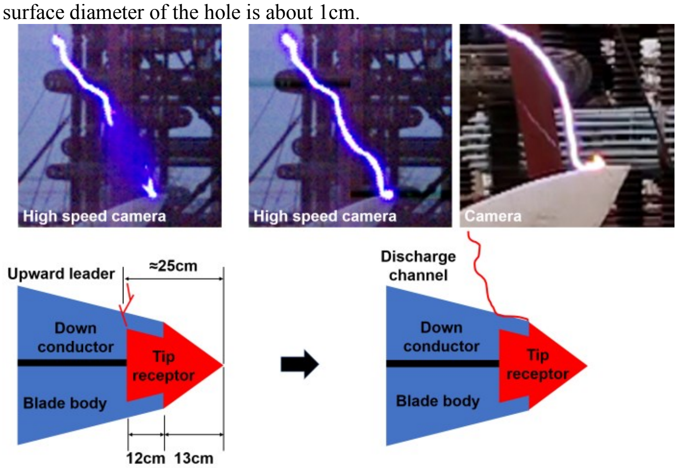

Fig. 15. The shape of receptor may cause lightning strike creeping discharges along the blade edge.

The discharge can bypass the edge of the blade and hit on the blade surface directly. As shown in Fig. 13(c), upward leaders incept from both the edge and the surface of the blade, and the discharge finally hits on the surface. According to frames with t=8.312 μs and t=16.624 μs, although the upward leader that incepts from the leading edge connects the downward leader, the discharge continues to go downward to the upward leader that incepts from the blade surface, and finally hit on the blade surface. Small cracks are made on the blade surface, and it is expected that for natural lightning strikes, much severer damages will be made. The upward leader may incept from the down conductor inside the blade chamber and penetrate through the weak points of the blade, such as tiny pinholes and other defects. The existence of the down conductor may lead to this phenomenon. Therefore, the down conductor could be placed at a better position. External down improves the performance of the blade LPS [20-21] and works not only as a path of lightning current, but also as a receptor along the whole blade, which can be treated as a super diverter. In addition, external down conductor has quite insignificant influence on the aerodynamic performance [21]. However, it remains a question that whether it will affect the aerodynamic performance of the blade after being hit by the lightning strike. Besides, carbon fiber reinforced plastic (CFRP), which is conductive, is the next generation material for the beam of blade for offshore wind turbines. For a CFRP blade, it is necessary to equip external down conductors to protect the main beam.

From the experimental results, it is found that before the upward leader incepts and eventually connects, the space between the downward leader tip and the striking attachment point is occupied by the leader corona which is the diffused corona region at the tip of the leader [22]. The leader corona dramatically influences the point where an upward leader may incept. It is worth noting that, the tip receptor does not produce streamer as efficiently as to develop into upward leader to attract the downward leader. For the wind turbine blade LPS, the design of the receptor should be improved to make it more effective to incept upward leader.

E. Discharge inside blade chamber

When the positive discharge hits on the blade surface far from the receptor (LD=2.25 m, R <1), there are some light inside the blade which means that the discharge gets inside the blade and hits on the down conductor, as shown in Fig. 16. The direction of the discharge propagates inside the blade can be random and even to the very tip of the blade, as shown in Fig. 16(c). It is also reported that, the discharge may get inside the blade from the attachment point on the blade surface, then propagate and finally hit on the base of the receptor [7]. There is no damage caused by the light inside on the surface. However, the manufacturing defects can be observed from this phenomenon, which means that the blade body is not uniform. The light indicates that the discharge path goes through the defected part of the blade body. This lack of uniformity increases the chances of blade surface being hit by lightning strikes. According to the field observation from wind farm, there is a case that the lightning strike hits on the blade surface at 10 m from the blade tip and causes blade rupture at 1 m from the blade tip. This phenomenon does not happen when lightning strike hits on the blade surface close to the receptor, in which condition the discharge creeps to the edge of tip receptor. Future experiments will aim to study the behavior of discharge inside the blade.

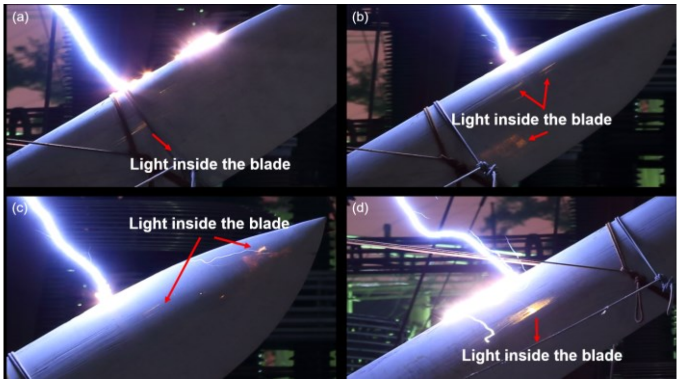

Fig. 16. Discharges get inside the blade when hitting on the blade surface (LD=2.25m, R <1).

IV. Discussion

The experimental results show strong polarity effect that positive lightning strikes are more difficult to be intercepted by the receptor. The influence of the surroundings can be ignored, and the results are not disturbed by nearby objects. studies about sharp-tipped and blunt-tipped lightning rod give some potential reasons [23,24], but the case discussed is for negative lightning strikes. The distribution of space charge plays an important role in the polarity effect. The space charge caused by corona disturbs the electric field near the receptor, which influences the inception of the upward leader. For negative discharges, when the downward leader propagates, there will be corona from the tip receptor. The electrons are quickly absorbed by the receptor, and the heavy positive ions move to the rod electrode very slowly. The local electrical field E_{nearby} is enhanced compared with that without space charge, which makes the streamer corona more easily transform into a leader, as shown in Fig. 17(a). For positive discharges, the positive ions caused by corona will assemble around the receptor and the local electrical field E_{nearby} decreases dramatically. The positive space charge works like a shield and prevent the leader incept from the tip of the blade. What's more, the corona can be generated earlier under positive discharge, which enhances the shielding effect, as shown in Fig. 17(b).

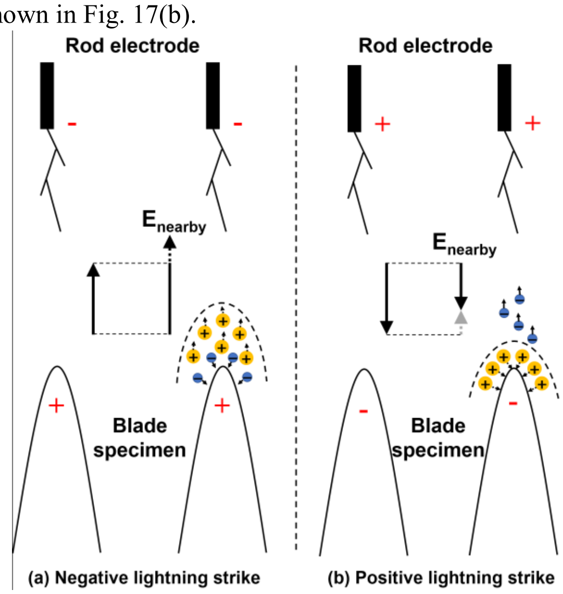

Fig. 17. Polarity effect of lightning strikes.

The blade orientation plays an important role in the shielding effect. When the blade is in 90° with horizontal, the effect is insignificant, and most discharges hit on the receptor at the tip of the blade. When the blade is at 30° with horizontal, the interception efficiency of the receptor decreases dramatically. Although it is difficult for the streamer to transform into leader at the receptor because of the space charge, creeping discharge may develop along the blade surface from the receptor, as shown in Fig. 18. Once the creeping discharge channel is long enough, it will be exposed into a much stronger electrical field and the upward leader will incept from it and connect to the downward leader. The positive downward leader may not propagate directly to the receptor, which causes creeping discharges from the boundary of the receptor and the blade. However, the development of a creeping discharge is not due to a low level of applied voltage. The cases in which the discharges directly hit on the blade surface prove that, the applied voltage is strong enough to break down the whole air gap.

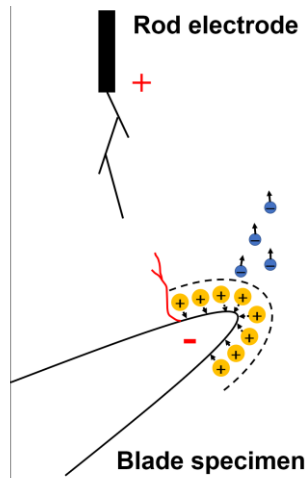

Fig. 18. Shielding effect for blade orientation 30° with horizontal.

V. Conclusion

Experiments of lightning attachment are conducted to study the lightning attachment manner to the wind turbine blades with LPS under different blade orientations and lateral distances.

Although the occurrence of positive lightning strikes is one ninth of negative ones in nature, positive lightning strikes have much higher peak current and are more scattering than the negative ones, which can possibly lead to interception failure of the receptor. Therefore, more attention should be paid to the protection from positive lightning strikes when design and test LPS of the wind turbine blade.

The lateral distance between the lightning downward leader and the wind turbine blade is one of the key factors of receptor's interception efficiency. The protection area of the receptor shows significant asymmetry when lateral distance is different, and the discharges can be intercepted more efficiently when R >1 than R <1.

There are three types of receptor interception failure found in the experiments: creeping discharge from the receptor along the leading/trailing edge, discharge hitting on the blade leading/trailing edge and discharge hitting on the blade surface directly.

The boundary of the receptor and the blade body is the most vulnerable position if hit by lightning strikes. Creeping discharges may happen on the blade surface from the tip receptor, which can cause damage. It is difficult to repair this area because tip receptor could not be replaced. Therefore, the design of tip receptor should take the boundary damage into consideration.

The existence of the receptor affects the electric field nearby and the upward leader may incept from it in the first stance. However, the shielding effect is not significant enough to protect the wind turbine blade from being hit by lightning strikes and the blade surface will also be hit. More study needs to be done to find the minimum number of the receptors needed and the optimal positions of them.

Multiple upward leaders may incept from the wind turbine blade during attachment process. The upward leaders are "in group" which means that upward leaders are close to each other, and no upward leader incepts from the tip receptor when the discharges hit on the blade body.

Lightning strikes hitting on the surface of the wind turbine blade may go inside the blade chamber and propagate randomly, which can cause damage not only near the positions where the discharge hits on but also far from the striking attachment point. The insulation strength of the down conductor sheath should be reinforced in order to prevent the expansion of the damaged area.

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