International Conference on Lightning Protection
33rd International Conference on Lightning Protection
25 - 30 September 2016
Estoril, Portugal

Experimental Study of Lightning Strike Attachment Characteristics on Wind Turbine Generators

Mi Zhou, Jianguo Wang, Yadong Fan, Li Cai, and Haitao Huang
School of Electrical Engineering, Wuhan University
Wuhan, China
zhoumi927@whu.edu.cn, wjg@whu.edu.cn, ydfan@whu.edu.cn, caili@whu.edu.cn

***Abstract*—Experiments on lightning strike attachment characteristic of the wind turbine with 40-m-long blades, as simulated by a reduced-size model with a scaled ratio of 1:100, have been carried out. Obtained results show that, for all the concerned arrangements, the blade-tip receptor has the largest attachment probability than the other parts of wind turbine. In the case of simulated downward lightning test, the positive discharge tends to attach to the insulation parts of the blade and nacelle, whereas the negative ones tend to be intercepted by the blade-tip receptor and by the lightning rod. A contrary trend was found in the case of simulated upward lightning test. In the switching impulse voltage (250/2500 μs) test, more discharges attach to the insulation parts of blade than those in the lightning impulse ones (1.2/50 μs). Increase in the receptors will result in decreased attachment probability of the blade surface. The blades with a length of 40 m at least need four pairs of receptors in order not to be damaged by lightning.**

Keywords- attachment characteristic; blade; lightning; receptor; wind turbine generator.

I. Introduction

By the end of year 2014, the wind turbine generating capacity installed in the world was more than 369.6 GW [1]. With the rapid growth of wind farms and also with the increasing size of wind turbines, the damages of wind turbine generator due to lightning become more and more frequent. This damage is reported to be the most costly type of downtime event in wind turbine farm [2].

As illustrated in Fig. 1, the majority of modern wind turbine blades have been equipped with receptors on the surfaces to attract lightning discharges, and with the down conductors to conduct the lightning current towards the grounding system [3][4]. In general, single or multiple discrete receptors are installed on both sides of the blade [5]. Moreover, a lightning rod located on the nacelle is often an addition of the lightning protection for wind turbine generators, although the lightning rod cannot obtain enough height owing to the weight and wind pressure. Although these measures have undoubtedly decreased the incidence of fatal damage from direct lightning [6], they have not totally solved the problem. For example, available statistics reveal that between 4% and 8% of European wind turbines are damaged by lightning every year [7]. The extent of the lightning damages, especially winter-lightning damages to wind turbines in Japan is reported to be greater than that of European countries [8].

There is a growing need to investigate the performance of the lightning protection system of wind turbine. Several papers dealing with high voltage laboratory test of actual wind turbine blades (e.g., [8]–[14]) have studied the attachment manner of lightning and evaluated the damage mechanism. In these experiments, only a tip part of the actual wind turbine blade or some portions of wind turbine were used. Due, however, to the fact that the wind turbines are often in exposed locations and significantly taller than adjacent objects, almost any spot on the turbine, including blade, lightning rods, the nacelle, and the hub, is susceptible to direct lightning strikes [4].

One of the methods of determining effectiveness of lightning protection system is by performing scale model experiments in the high voltage laboratory. Plume [15], from many years of in-service experience, compared the laboratory test and natural lightning strike effect, and a conclusion that scale model tests of ground facilities can accurately predict initial natural lightning leader attachments to ground based structures had been obtained. Naka *et al.* [16] conducted model experiment to study the effects of the receptor shape and of the pollution on the blade surface. Yoh [17], using a 1:100 scale model, investigated a new lightning protection system for wind turbines with two ring-shaped electrodes. Radičević *et al.* [18] built a 1:40 scale wind turbine model to determine the influence of blade rotation on the lightning strike incidence. In all these studies, the experimental conditions, such as the receptor configurations, were relatively limited.

In this study, based on a reduced-size model with a scaled ratio of 1:100, experiments on lightning attachment characteristic of a 2-MW-class wind turbine with 40-m-long blades have been carried out. Impact of the number of discrete

This work was supported by National Natural Science Foundation of China (Grant number: 51207116).

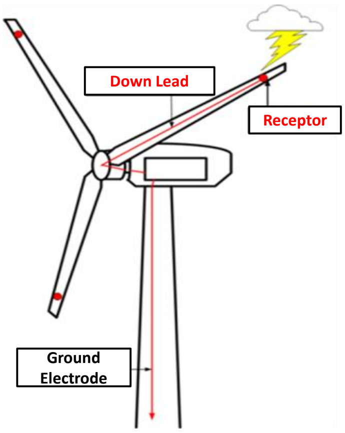


Figure 1. Schematic diagram of the lightning protection system of wind turbine generator

pairs, as well as the arrangement of the blade receptors on the lightning attachment characteristic is investigated.

II. TEST SETUP

As shown in Fig. 2, a reduced-size wind turbine model, with a scaled ratio of 1:100, was assembled to simulate an actual 2-MW wind turbine with a hub height of 80 m and a blade length of 40 m (thus the tower height of the model is 800 mm and the blade radius 400 mm). Three arrangements of lightning receptors, with respectively, two, three, and four pairs of receptors, as illustrated in Fig. 3, are taken into account. Table I gives the specific locations of the receptors. The blades of the model are manufactured from nonflammable resin and the hub is made from hollow tube. The receptors and down conductors of the model are of solid round copper wire 1.2 mm in diameter. Each receptor was bonded to the grounding system through the same copper conductor embedded in each blade.

All tests were carried out at the high voltage laboratory at Wuhan University, with a Marx generator rated at 2400 kV. Through adjusting the wave-shaping network, the Marx generator can generate an open-circuit waveform of 1.2/50 μs (lightning impulse type) and of 250/2500 μs (switching impulse type). The experiment test system is presented in Fig. 4. The scaled model was placed on a ground plane, and the hub was well grounded. Two still digital cameras from different directions were used simultaneously to record the arc discharge and the lightning attachment point on the wind turbine model.

To simulate downward lightning, a rod electrode is assumed to be a downward leader. The relative positions of the rod electrode and the scaled model were adjusted to simulate the coming leader from different directions. As shown in Fig. 5, the high-voltage electrode was located above the top of the wind turbine (position A) as well as the planes B, C, D, and E. The plane D is the horizontal plane passing through the center of the wind turbine model, and the intersection angles between OD1 and OB1, OC1, as well as OE1 are 60°, 30°, and −30°, respectively. For each horizontal place, there are seven high-voltage-electrode positions, with the inherent intersection angle increased in every 30°.

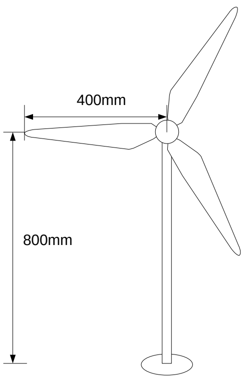
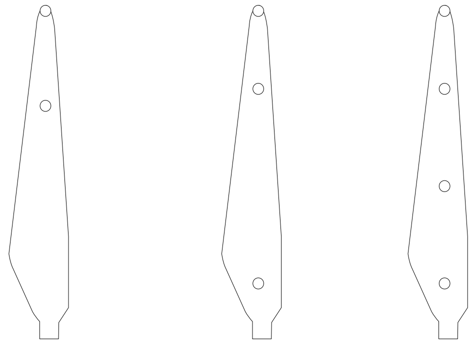


Figure 2. Structure size of the wind turbine model



(a) (b) (c)

Figure 3. Layout of blade receptors with (a) two, (b) three, and (c) four pairs of receptors.

TABLE I. BLADE RECEPTOR LAYOUT POSITION

	Distance to the blade tip (cm)		
	Receptor 2#	***Receptor 3#***	***Receptor 4#***
Two-pair receptor	1.3	—	—
Three-pair receptor	10	35	—
Four-pair receptor	10	22.5	35

Taking into account the rotation of the blade in the actual operation condition, four blade positions are considered here, as shown in Fig. 6. These positions are for static model (not rotating) which has four different angles of one blade relative to the ground plane (90°, 60°, 30°, and 0° with horizontal). Stationary tests are appropriate for leader attachment tests of wind turbine blades because a blade does not move very far during a leader approach from striking distance. For each test configuration, 10 positive discharges and 10 negative discharges were applied. The applied voltage level was slightly higher than the 50% sparkover voltage level.

III. RESULTS

A. *Downward Lightning Test*

1)Effect of polarity of applied voltage

In order to clarify the effect of polarity of applied voltage, the wind turbine model with two-pair receptors as shown in Fig. 3(a) was selected. The applied voltages were of switching

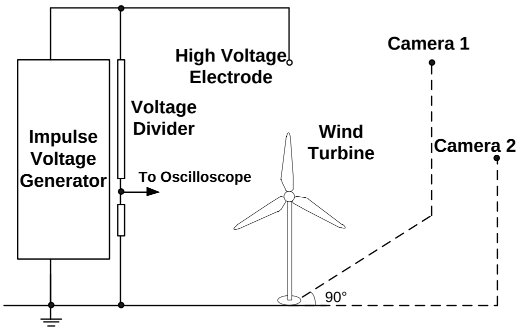


Figure 4. Experiment test system

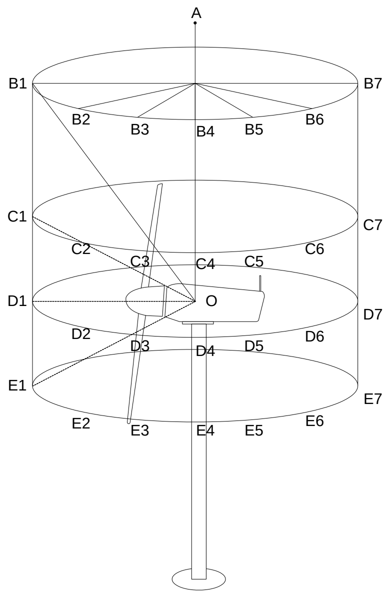


Figure 5. Position of the high voltage electrode

impulse type, and the air gap was adjusted to be 50 cm. Experimental results are summarized in Table II. As clearly shown in Table II, the positive discharge tends to attach to the insulation parts of the blade and nacelle, whereas the negative ones tend to be intercepted by the blade-tip receptor and by the lightning rod.

Moreover, the direction that a downward lightning leader approaches to is an important factor for the interception efficiency of the lightning protection system. If the lightning leaders come from the side direction, the receptors cannot always capture the lightning effectively. For example, when the high-voltage electrode was hung at position A or plane B, regardless of the polarity, all discharges terminated at the blade-tip receptor, indicating that when lightning leaders invade above the top region of wind turbine, they will be captured by the connecting leader initiated from the blade-tip receptor. However, when the high-voltage electrode was located at plane C, D, and E, the capturing ratio of lightning protection system was decreased to be, respectively, 87.9%, 66.2%, and 71.8% in the case of negative discharge. For the

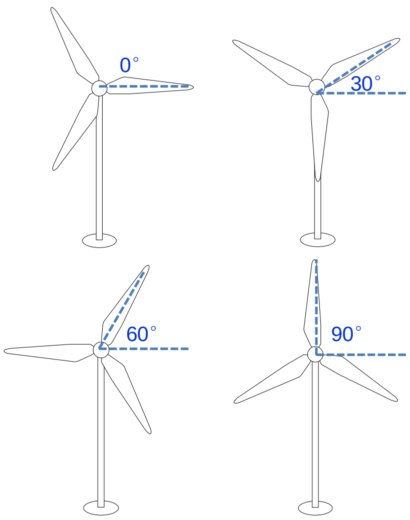


Figure 6. Wind blade rotating state

positive discharge, the corresponding ratio was decreased to be, respectively, 35.2%, 25.6%, and 28.6%.

2)Effect of waveshape of applied voltage

In an attempt to investigate the effect of waveshape of applied voltage, the wind turbine model with four-pair receptors as shown in Fig. 3(c) was selected. The polarities of applied voltages were fixed as negative, and the air gaps were also adjusted to be 50 cm. Obtained experimental results were summarized in Table III.

In the case of switching impulse test, the probability of attachment to the insulation parts of blade is larger and, hence, the capturing ratio of lightning protection system is significantly lower than that in lightning impulse test. However, if two adjacent receptors are close to each other, the lightning attachment probability of the region between them is very small. In the case of lightning impulse test, the lightning leader is more likely to attach the receptors.

The switching impulse voltage has a similar electric field to that of the natural downward leader development process. Longer front time can also provide sufficient time for the development of the upward stream.

3)Effect of receptor configurations

All the wind turbine models in Fig. 3 were used to study the effect of receptor configurations. With an air gap of 50 cm, the attachment probabilities of the blade surface (excluding the receptors, the nacelle, the lightning rod of nacelle, and the tower) are, respectively, 8.1%, 5.2%, and 0 for the blades with two, three, and four pairs of receptors, indicating that increase in the receptors will result in decreased attachment probability of the blade surface. The blades with a length of 40 m at least need four pairs of receptors. If the air gap was increased to be 70 cm, the attachment probabilities of the blade surface are 2.4%, 4.6%, and 0 for the blades with two, three, and four pairs of receptors, respectively, indicating that lightning

TABLE II. NUMBER OF DISCHARGES FOR VARIOUS ELECTRODE POSITIONS IN THE CASE OF NEGATIVE AND SWITCHING IMPULSE

Electrode Positions	**Polarity**	**Receptor**		**Blade**	**Nacelle**	**Lightning rod**	**Tower**	**Capturing ratio**
		1#	***2#***					
Position A	Negative	40	0	0	0	0	0	100%
	Positive	40	0	0	0	0	0	100%
Plane B	Negative	280	0	0	0	0	0	100%
	Positive	280	0	0	0	0	0	100%
Plane C	Negative	134	45	26	8	68	0	87.9%
	Positive	47	50	106	76	2	0	35.2%
Plane D	Negative	120	29	38	57	37	0	66.2%
	Positive	39	33	92	86	0	31	25.6%
Plane E	Negative	153	36	40	38	12	1	71.8%
	Positive	55	25	92	0	0	108	28.6%

TABLE III. NUMBER OF DISCHARGES FOR VARIOUS ELECTRODE POSITIONS IN THE CASE OF LIGHTNING IMPULSE AND OF SWITCHING IMPULSE

Electrode Positions	**Polarity**	**Receptor**				**Blade**	**Nacelle**	**Lightning rod**	**Tower**	**Capturing ratio**
		1#	***2#***	***3#***	***4#***					
Position A	Lightning Impulse	40	0	0	0	0	0	0	0	100%
	Switching Impulse	40	0	0	0	0	0	0	0	100%
Plane B	Lightning Impulse	280	0	0	0	0	0	0	0	100%
	Switching Impulse	280	0	0	0	0	0	0	0	100%
Plane C	Lightning Impulse	91	42	37	63	0	2	45	0	99.3%
	Switching Impulse	145	29	34	5	38	1	29	0	86.1%
Plane D	Lightning Impulse	59	50	28	67	6	56	14	0	77.9%
	Switching Impulse	15	35	28	85	62	46	4	2	60.3%
Plane E	Lightning Impulse	148	22	25	28	0	0	0	56	79.9%
	Switching Impulse	69	37	33	7	68	41	6	23	53.5%

attachment characteristic of wind turbine blade not only relate to the number of receptors, but also to the arrangement of receptors.

For all the arrangements, the blade-tip receptor has the largest attachment probability than the other parts of the wind turbine. As to the case of the 50-cm air gap, the attachment probabilities of the blade-tip receptor are 75.3%, 65.8%, and 70.9% for the blades with two, three, and four pairs of receptors, respectively, whereas for the case of the 70-cm air gap, the probabilities are 85.1%, 75.2%, and 77.9%, respectively. A large strike distance, or lager current amplitude, will result in a large attachment probability of the blade-tip receptors.

With respect to the 50-cm air gap, the total attachment probabilities of the nacelle, lightning rod of nacelle, and tower are, respectively, 15.7%, 11.8%, and 10.4% for the blades with two, three, and four pairs of receptors whereas those for the 70-cm air gap are, respectively, 12.6%, 10.3%, and 11.1%.

B. Upward Lightning Test

Regarding simulation of the upward lightning, the rod electrode shown in Fig. 4 was replaced by a steel, square plane with a width of 5 m. The results are summarized as follows:

As shown in Fig. 7, the rotating angle of the blade has a significant influence on the attachment characteristic. The lightning attachment points are concentrated on the blade-tip region with the blade's rotating angle of 0 °, 60 ° and 90 °. More than 30% of lightning attachment points are on the non-tip region with the blade's rotating angle of 30 °.

IV. SUMMARY

For all the arrangements, the blade-tip receptor has the largest attachment probability than the other parts of the wind turbine.

Concerning the effect of the polarity of applied voltage, in the case of simulated downward lightning test, the positive discharge tends to attach to the insulation parts of the blade and nacelle, whereas the negative ones tend to be intercepted by the blade-tip receptor and by the lightning rod.

In downward lightning model test, no direct correlations have been found between the rotation angles of the blade and the attachment characteristics, whereas in upward lightning model test, in the case that when the blade has an angles of 30 °, more than 30% of the discharge will attach the rest insulation part of blade tip, all the discharges attaching the blade tip in other angles.

The direction that a downward lightning leader approaches to is found here to be a very important factor for the interception efficiency of the lightning protection system of wind turbine generator. When the lightning leaders come from the side direction, the receptors cannot always capture the lightning effectively.

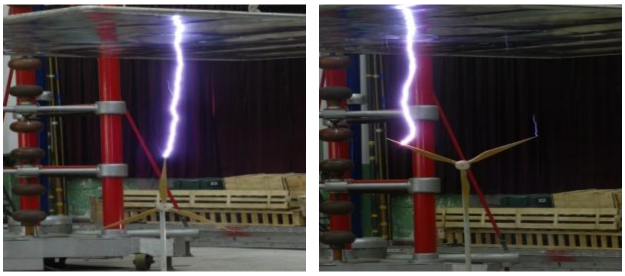


Figure 7. Representative photos taken by the cameras during the simulated upward lightning attachment test.

Due to the extended rise time to flashover of the switching impulse voltage that allows time for streamers and leaders to develop and progress from multiple locations internal and external to wind turbine blades, in the switching impulse voltage test, more discharges attach to the insulation parts of blade.

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