Study on Lightning Protection Methods for Wind Turbine Blades

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Lightning protection measures for wind turbines are becoming important as the use of wind turbines is increasing rapidly along with its capacity and height. In order to understand the manner of lightning attachment to wind turbine blades, experiments with various types of blade samples were conducted. Experimental studies revealed following issues. Regarding a non-conductive blade sample, the 50% flashover voltage of polluted blade sample was reduced by 10% as compared to a non-pulled blade sample. Creeping discharges on the polluted blade samples occurred more frequently, and penetrated through the surface, damaging the blade sample. The blade sample with a receptor system showed lower protection performance than the blade covered with a conducting cap.

Keywords: lightning protection, wind turbine blade, creeping discharge, receptor

1. Introduction

In recent years, lightning damages to wind-power plants are increasing as the number and size of installed wind turbines becoming rapidly larger. Especially lightning damages to wind turbine blades are quite serious since the cost for replacements is remarkably high and long repair time is necessary(1)(2). The extent of the lightning damages, particularly winter-lightning damages to wind turbines in Japan is reported to be greater than that of European countries, where wind turbine generators are most widely used. The coast of Sea of Japan is considered one of the most suitable areas for wind power generation, however, winter lightning occurs frequently(3). As compared to the summer lightning, the current duration of winter lightning is often very long, and it tends to strike tall structures intensively. Since the energy of winter lightning is remarkably large, it causes a considerable damage(1)(2)(3).

Modern wind turbines are composed of hollow blades made of composite material, such as glass fiber reinforced plastic (GFRP). In Europe and other many countries, various types of lightning protection systems which consist of lightning attachment points and down-conductors for allowing lightning current to flow to the earth safely are used. These lightning protection systems are assumed to intercept lightning discharge just like a lightning rod on buildings. However, these methods are developed independently by each wind turbine manufacturer, and the effect of lightning protection with these approaches has not been properly evaluated. Wind turbines with the blades which equip a lightning protection system are also widely used in Japan, but such blades are damaged by lightning many times. These conventional measures may be not adequate for winter lightning in Japan.

On the other hand, the blades made of GFRP without any extra lightning protection system are also used in Japan. The reason of this is based on the fact that lightning attachment probability to the blades made of all non-conductive materials is expected to be low. In addition, irrelevant lightning protection system may increase the lightning attachment to the blade and induce the trouble in electronic circuit, etc... However, in recent years the lightning damages on such non-conductive blades have also increased. Generally, insulation strength of a non-conductive material decreases if the surface of the material is polluted by the adhesion of a salt deposit. This is a significant problem at the electric transmission facilities around the coastal areas. As the wind turbines are commonly constructed near the seaside or the offshore where a good wind condition is expected, the effect of pollution should be taken into consideration when a lightning damage on non-conductive blades is investigated(4).

In this paper, experimental results related to the manner of lightning attachment to scaled wind turbine blades are shown. The mechanism of the occurrence of lightning damage on wind turbine blades and some approaches of blade lightning protection technique are investigated.
2. Lightning Discharge Experiments

The experiments were carried out by using a 12 MV Impulse Generator at Shiobara testing yard of CRIEPI. Figure 1(a) and (b) show the equivalent circuits for experiments with lightning impulse voltages and switching impulse voltages, and Fig. 2(a) and (b) show the lightning impulse waveform of 2/50 $\mu$s and the switching impulse waveform of 250/2500 $\mu$s, respectively. The discharge manner was observed by two digital cameras from different directions simultaneously. An Automatic lightning discharge progressing-feature observation system (ALPS) was also used to detect a transient luminescence. The ALPS consisted of a liquid crystal triggering camera with a fiber-coupled pin-photodiode array and it was used to observe the discharge manner with a sampling time of 0.1 $\mu$s.

3. Experiments on Non-conductive Blade Sample

3.1 Experimental Conditions

Figure 3 shows the experimental setup with a non-conductive blade sample. The 3 m blade sample was cut from an actual 12 m long wind turbine blade made of GFRP. The blade sample was fixed vertically with a wooden foundation, and a gap length between an electrode and the tip of the blade sample was set to 4 m. In order to investigate an influence of pollution on a blade, an artificial pollution test was also conducted. The polluted blade samples were prepared by spraying the water mixed with salt and powdered clay. The degree of pollution was set for the equivalent salt deposit density (ESDD) value of 0.1 mg/cm$^2$, which corresponds to the high polluted condition near the coast of Sea of Japan. The 50% flashover voltages (FOV) of polluted and non-polluted blade samples were measured with positive switching impulse voltages by the up-and-down method. For a comparison, the measurement of 50%FOV of 3 m metallic pipe was also conducted.

3.2 Experimental Results

Figure 4 shows the typical discharge manner on the non-polluted, non-conductive blade samples. Since the blade sample was made of dielectric materials, electrode-to-ground discharge was observed frequently as shown in Fig. 4(a). Creeping discharges along the edge of the lower half of the blade sample were also observed several times as shown in Fig. 4(b). In this experiment, no damage was found on the blade sample.

On the other hand, the discharge manner was quite different under the polluted condition. Electrode-to-ground discharge did not occur any more, and creeping discharges along the whole face of the blade sample were always observed as shown in Fig. 5. Figure 6 shows the result of 50%FOV measurements. The value of 50%FOV of the polluted blade sample was about 10% lower than the non-polluted blade sample. In the experiment, until the twenty fourth discharge test, no apparent damage was observed.

However, at the twenty fifth discharge test, the discharge penetrated the blade sample as shown in Fig. 7(a). The damaged spot of the front and back side of the blade sample are shown in Fig. 7(b) and (c), respectively. The penetration was sometimes observed in the subsequent experiments. The damaged spot of these discharges was just near the first
Next, the experiment under the condition of the negative switching voltage and 3 m-length gap was conducted on the same polluted blade sample. During the experiment, creeping discharge occurred 10 times and later the discharge hit the edge of the blade tip. Figure 8 shows the damaged area caused by the discharge. As compared to the penetration damage, larger part of the edge was damaged and fragmented glass fiber was clearly seen as the resin was melted away.

4. Experiments on Blade Sample with a Receptor

The effect of a small metal receptor on the face of the blade tip was investigated. A copper receptor, 25 mm in diameter was fitted on the face of a 3 m blade sample. The same type of blade sample as the previous ones was used in this experiment. The receptor attached point was located at 250 mm from the tip and 130 mm each from the both edges. A down conductor from the back side of the receptor, running through the inside of the blade sample, was connected to the ground. As wind turbine blades are revolving in practice, experiments were performed with four typical arrangements of the blade sample such as vertical, oblique 45°, horizontal 1 and horizontal 2 as shown in Fig. 9(a)–(d), respectively. Positive and negative lightning impulse voltages were applied to each setup.

4.1 Vertical Arrangement

The discharge propagated along the surface of the blade tip and attached to the receptor all the time. When the discharge struck the edge of the blade tip on the way to receptor, it damaged the tip portion as shown in Fig. 10. The Fig. 10(a) shows the front view of the blade during discharge, (b) shows the view from right side, and (c) shows the damaged area of the blade.

4.2 Oblique (45°) Arrangement

In this arrangement, even after discharge experiments were performed 20 times, no damage was found. In all the cases, the discharge propagated along the surface of the blade and attached to the receptor, except for 2 cases with negative polarity that the discharge passed through the air and attached to the receptor directly. Figure 11 shows these discharge manners.

4.3 Horizontal Arrangement 1: Trailing Edge Facing Electrode

The first discharge penetrated through the back side (the side with no receptor) trailing edge around the middle part of the blade sample as shown in Fig. 12, and attached to the down conductor which was laid down on the inside part of the blade. Similar discharge phenomena were observed for subsequent two discharge.

4.4 Horizontal Arrangement 2: Leading Edge Facing Electrode

Figure 13 shows the discharge manner which caused damage on the back side of the leading edge. Figure 14 shows the discharge progressing-feature captured by
Fig. 9. Experimental setup for the blade sample with a receptor

Table 2. Results of the vertical arrangement experiments

<table>
<thead>
<tr>
<th>Polarity</th>
<th>Discharge No.</th>
<th>Discharge manner</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive</td>
<td>1 – 3</td>
<td>Blade surface → Receptor</td>
</tr>
<tr>
<td></td>
<td>4, 5</td>
<td>Blade surface → Receptor</td>
</tr>
<tr>
<td>Negative</td>
<td>6</td>
<td>Damaged the tip of the blade</td>
</tr>
<tr>
<td></td>
<td>7, 8</td>
<td>Magnified the damage of No.6</td>
</tr>
<tr>
<td>Positive</td>
<td>10 – 12</td>
<td>Blade surface → Receptor</td>
</tr>
</tbody>
</table>

Table 3. Results of the oblique arrangement experiments

<table>
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<th>Polarity</th>
<th>Discharge No.</th>
<th>Discharge manner</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive</td>
<td>1 – 3</td>
<td>Blade surface → Receptor</td>
</tr>
<tr>
<td></td>
<td>4 – 11</td>
<td>Blade surface → Receptor</td>
</tr>
<tr>
<td>Negative</td>
<td>12, 13</td>
<td>Struck the receptor directly</td>
</tr>
<tr>
<td>Positive</td>
<td>14 – 20</td>
<td>Blade surface → Receptor</td>
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Table 4. Results of the horizontal arrangement 1 experiments

<table>
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<tr>
<th>Polarity</th>
<th>Discharge No.</th>
<th>Discharge manner</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive</td>
<td>1</td>
<td>Penetrated the back side trailing edge</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Penetrated the back side trailing edge</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Magnified the damage of No.2</td>
</tr>
</tbody>
</table>

ALPS corresponding to the discharge shown in Fig. 13(a). In Fig. 14, white and gray dots indicate the luminescence of the discharge, and the value at the bottom of each frame indicate the elapsed time after triggered. The movement of the bright dots corresponds to the progressing feature of discharge every 0.1 μs. These figures show that after the discharge penetrated the blade edge, it progressed in the downward direction and attached to the down conductor.
Lightning Discharge on Wind Turbine Blade

5. Experiments on Blade Sample Covered with Conducting Cap

As a blade lightning protection method other than a receptor system, a metallic-cap with a down conductor can be employed at the blade tip. In order to investigate the effect of this kind of protection measure, following experiments were conducted. The top 260 mm length of the blade sample was completely covered with copper tape, and connected to the down conductor. The blade sample was arranged obliquely (45°) as shown in Fig. 15. The positive and negative switching impulse voltages were applied. In the case with positive polarity, the leading edge was arranged upward, and in the case with negative polarity, the trailing edge was upward. The gap length between electrode and the blade sample was different for the polarity due to the limitation of the impulse voltage generation.

In many cases, discharge struck the conducting cap directly as shown in Fig. 16(a) and lightning current transmitted to ground through the down conductor safely. However, in positive discharge cases, discharge attached to the blade edge just below the conducting cap area and progressed upward to the conducting cap 2 times, and when it occurred again, it caused considerable damage to the surface of the blade sample. Figure 16(b) shows this discharge manner striking the blade edge, and Fig. 17 shows the damaged area. After the discharge, damaged area was burned with flame during several seconds. In the case of the negative polarity, all discharge were attached to the conducting cap successfully. The reason of this result was assumed partly because the gap length was shorter compared to the positive case. But taking into consideration this, we can guess that this type of blade sample

<table>
<thead>
<tr>
<th>Polarity</th>
<th>Discharge No</th>
<th>Discharge manner</th>
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<tbody>
<tr>
<td>Positive</td>
<td>1, 2</td>
<td>Struck the conducting cap directly</td>
</tr>
<tr>
<td></td>
<td>3, 4</td>
<td>Blade edge → Receptor</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Damaged below the conducting cap</td>
</tr>
<tr>
<td></td>
<td>6 ~ 8</td>
<td>Struck the conducting cap directly</td>
</tr>
<tr>
<td></td>
<td>9, 10</td>
<td>Damaged below the conducting cap</td>
</tr>
<tr>
<td>Negative</td>
<td>11 ~ 20</td>
<td>Struck the conducting cap directly</td>
</tr>
</tbody>
</table>

Table 6. Results of the copper covered blade sample experiments

Fig. 13. Discharge manner to the horizontally arranged blade sample

Fig. 14. Discharge progressing feature observed by ALPS

Fig. 15. Experimental setup for the blade sample covered with conducting cap

Fig. 16. Discharge manner to the blade sample covered with conducting cap

Fig. 17. Damaged area
has relatively higher protection performance than the blade sample with a small receptor. Further investigation considering the azimuth angle of the blade and the direction of the lightning strike are needed.

6. Conclusion

In order to investigate the mechanism of the occurrence of the lightning damage to the wind turbine blades and the effect of the various types of the blade protection system, lightning attachment experiments using 3 m scaled blade samples were conducted. Following results were obtained.

(1) Regarding non-conductive blade, creeping discharge occurred more frequently in the polluted condition, and sometimes penetrative destruction was also observed. In addition, the edge of the blade was also struck and damaged.

(2) The effectiveness of the receptor lightning protection method was not found to be adequate. The vertically arranged blade sample was damaged at the tip, and in the case of horizontally arranged blade samples, discharge penetrated the edge of the middle part of the blade samples. Obliquely arranged blade sample was not damaged, but since the discharge progressed on the surface of the blade sample to the receptor, it has high probability to strike the edge of the blade and cause damage.

(3) The blade sample covered with conducting cap at the top of the blade showed relatively high protection efficiency. If the improvement such as coating material and planar dimension of coating area is achieved, it will be expected to work much better.

It should be noted that actual wind turbine blades are several ten times longer than the samples used in the experiments, and the energy of the lightning discharge is expected to reach to thousand times larger than the experimental studies. Therefore in practice, wind turbine blades will be exposed to much severer circumstance.

Further investigation related to various lightning protection methods is also planned and we aspire to propose the appropriate blade lightning protection method in Japan.

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References


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