Lightning Faults Analysis and Protection Measures for UHV DC Transmission Line

Shanqiang Gu¹, Jian Li¹ and Jian Wang²

ABSTRACT

In recent years China is rapidly developing the UHV DC transmission project, and however the lightning has become the biggest threaten to the safe and stable operation of UHV DC transmission lines. In order to master the fault reasons and characteristics, and thus to find the solutions, this paper conducted the detailed statistical and correlation analysis on the actually happening 19 lightning faults of the three major ±800 kV UHV DC transmission lines. With the analysis results of the lightning faults, this paper had a detailed discussion on the technical parameters of ±800 kV UHV DC line arrester, and gave an introduction of the designed and developed arrester equipment.

Keywords: Lightning protection, UHV DC, transmission line, lightning current, shielding failure, line arrester.

INTRODUCTION

In recent years China is rapidly developing the UHV DC transmission project, and has successfully constructed ten ±800 kV DC transmission lines by the end of November 2017 China. And the total line length has exceeded 17000 kilometers, and the total transmission capacity is 736 GW which is more than 3 times of installed capacity of the Three Gorges Hydropower Station. Relying on its advantages in longer distance, higher capacity, and less power loss, UHV DC transmission systems have become an important measure for cross-region and cross-border power transmission, and been playing a vital role in the global energy internet [1 - 3]. However many faults have taken place since these UHV DC transmission lines were put into operation, and most of them were caused by lightning strikes. The lightning has become the biggest threaten to the safe and stable operation of UHV DC transmission lines in China. And how to solve the lightning faults of UHV DC lines is a very important subject for China power grid.

Most UHV DC transmission lines are with big tower height, and pass through the areas with high thunderstorm days, high soil resistivity and complex terrain, which causes the high

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lightning shielding failure probability. Some work have been conducted to study the lightning protection of DC transmission lines [4 - 8], while most of them focused on the simulation or experiment of lightning performance of the line towers. Since the lightning activities along the whole line are very complex, the lightning faults are also very different. By now there are less references to conduct the detailed analysis on the actually happening lightning faults of UHV DC transmission lines. And the corresponding lightning protection measures are also very lack.

In order to master the fault reasons and characteristics, and thus to find the solutions, we conducted the detailed statistical and correlation analysis on the 19 lightning faults. With the analysis results of the lightning faults, we discussed the suitable lightning protection measures for the UHV DC transmission lines, and gave the specific parameters and characteristics in this paper.

LIGHTNING FAULTS ANALYSIS

Statistical Distribution

According to the operating data of State Grid Corporation of China (SGCC), the three major ±800 kV UHV DC transmission lines from southwest to east of China, named FuFeng, JinSu, and BinJin, have met 25 line faults since 2010, among which 19 ones are caused by lightning strikes, and the lightning fault ratio reached 76%. Table 1 gives the amount of lightning faults of each line and each year. From Table 1 we can see that among the 19 lightning faults BinJin Line owned most, 9 ones, and the year of 2016 owned most, 5 ones. There is some dispersivity on their temporal distributions. Although FuFeng and JinSu lines are in the same line corridor, their lightning fault amounts have a big difference.

<table>
<thead>
<tr>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>FuFeng</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>JinSu</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>BinJin</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>9</td>
</tr>
<tr>
<td>Total</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>5</td>
<td>2</td>
<td>19</td>
</tr>
</tbody>
</table>

For the DC transmission system the control and protection strategy against the line fault is different from the AC transmission system. Generally once meeting the line’s lightning flashover the system will restart so as to clear the fault. If it fails, repeat the restart once more. And in some cases, the system will repeat the restart for the third time with the half system operating voltage. If it still fails, the system will be blocked. So in principle the restart success rate will be high for the DC transmission line, but in fact it was not as high as expected because of the impact of the lightning subsequent flashes. For the above 19 lightning there are 14 ones with the successful restart and the restart success rate is averagely 73.7%, which is less than the reclosing success rate of 500 kV AC transmission lines in China according to the operating experience [9, 10].
Correlation with the Lightning Density

Generally the characteristics of lightning activities around the line corridor have an important impact on the lightning fault occurrence probabilities for the overhead transmission line. So one of the reasons of high lightning fault rate for the three major UHV DC lines is that they pass through the relatively higher lightning activities in China, and Figure 1 shows the lightning zone distribution of their whole line corridors, which was drawn according to the data detected by Lightning Detection Network of China Power Grid (CPLDN) from 2010 to 2017 [11]. From Figure 1 we can see that lightning activities of BinJin line are stronger than those of FuFeng and JinSu, which is consistent with their fault amounts. The 19 faults locate in different lightning zone, i.e. 3 in B1, 1 in B2, 10 in C1, and 5 in C2. Relatively the proportion in C (C1 & C2) is higher.

In order to study furtherly the correlation between the fault and the lightning density, we conducted the statistics of the annual lightning densities of its corresponding line corridor for each fault, as shown in Table, where the statistics width is 20 km on each side of the line. Table 2 also gives the annual lightning densities of its corresponding line section (40 km × 40 km around the line) for each fault. From Table II we can see the lightning densities of the whole line corridor in the fault year are mainly between 2 (km$^2$·year)$^{-1}$ and 5 (km$^2$·year)$^{-1}$, and those of the line section are distributed from 1 (km$^2$·year)$^{-1}$ to 11 (km$^2$·year)$^{-1}$. If calculating the average values for the two conditions of lightning densities we get 3.86 (km$^2$·year)$^{-1}$ and 4.45 (km$^2$·year)$^{-1}$ respectively for the former and latter. That means that a single lightning fault does not show significant correlation with the lightning densities of the whole line corridor or line section.

Table II. The Annual Lightning Densities of its corresponding Line corridor and Line section for each Fault.

<table>
<thead>
<tr>
<th>Fault No.</th>
<th>Fault Year/Month</th>
<th>Lightning Density ((km$^2$·year)$^{-1}$)</th>
<th>FuFeng Line</th>
<th>JinSu Line</th>
<th>BinJin Line</th>
<th>Line Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2010/08</td>
<td>3.99</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>7.58</td>
</tr>
<tr>
<td>2</td>
<td>2012/04.</td>
<td>3.94</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>2.74</td>
</tr>
<tr>
<td>3</td>
<td>2012/08</td>
<td>/</td>
<td>3.82</td>
<td>/</td>
<td>/</td>
<td>4.79</td>
</tr>
<tr>
<td>4</td>
<td>2013/05</td>
<td>5.36</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>2.75</td>
</tr>
<tr>
<td>5</td>
<td>2013/06</td>
<td>/</td>
<td>5.69</td>
<td>/</td>
<td>/</td>
<td>4.17</td>
</tr>
<tr>
<td>6</td>
<td>2013/08</td>
<td>/</td>
<td>5.69</td>
<td>/</td>
<td>/</td>
<td>10.27</td>
</tr>
</tbody>
</table>
Correlation with the Lightning Current

The lightning current causing each fault was inquired from the CPLDN, as given as Table III, where it failed to get the certain current for the No. 16 fault for some reasons. Table 3 shows the absolute values of these lightning currents are distributed between 15 kA and 70 kA. For the ±800 kV DC lines their withstand level of back flashover is usually beyond 200 kA, and that of shielding failure is tens of kA. Combining the fault analysis reports from the line operation department, we can determine all the faults are caused by lightning shielding failures. According to the cumulative probability distribution of lightning current amplitude in China [10] as well as recommended by IEEE we can calculate the cumulative probability from 15 kA to 70 kA to be 78.6%, while the cumulative probability above 200 kA is about 0.6%. That means the occurrence probability for the lightning currents which are easy to cause the line’s shielding failure fault is very high. And basically the lightning back flashover will not appear from the perspective of lightning current probability. So the lightning faults of UHV DC lines have strong correlation with the lightning current distribution.

Table III. Lightning Current Causing Each Fault.

<table>
<thead>
<tr>
<th>Fault No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current (kA)</td>
<td>-15</td>
<td>5</td>
<td>8</td>
<td>26.4</td>
<td>-43</td>
<td>8</td>
<td>3</td>
<td>1</td>
<td>-37</td>
<td>-48.9</td>
</tr>
<tr>
<td>Fault No.</td>
<td>11</td>
<td>12</td>
<td>13</td>
<td>14</td>
<td>15</td>
<td>16</td>
<td>17</td>
<td>18</td>
<td>19</td>
<td>/</td>
</tr>
<tr>
<td>Current (kA)</td>
<td>-52</td>
<td>-54</td>
<td>20.2</td>
<td>-32</td>
<td>-37</td>
<td>-25</td>
<td>6</td>
<td>2</td>
<td>50.5</td>
<td>/</td>
</tr>
</tbody>
</table>

Correlation with the Tower Spans

Besides of the lightning activities the faults also have correlations with other influence factors such as line’s geomorphological conditions, ground line protection angles, and insulation configurations. In our fault analysis, we found the lightning fault occurrence probability also has very strong correlation with the tower spans. Figure 2 gives the two spans between the fault tower and its adjacent two towers. From Figure 2 we can see that almost all the fault towers have at least one span beyond 500 m. In fact the bigger tower span will cause the increase of line sag and thus decrease the protection effect of ground wire. On the other
hand the towers with bigger spans are usually locating in the undulating terrain, which also
decrease the lightning shielding effect of ground.

![Figure 2. The Two Spans between the Fault Tower and its Adjacent Two Towers.](image)

**LIGHTNING PROTECTION MEASURES**

From the above analysis results of lightning faults, we can find the main protection
measures should be focused on the lightning shielding failure protection, especially for those
towers in bad terrain. For the conventional lightning protection measures applied on the AC
transmission lines, such as reducing the protection angle of the ground wire and the
grounding resistance of tower, and installing the tower head lightning rods, and we can find
their protection effects are very limited for the above protected object. And the practical
operating experience also shows that those measures have not gotten good application effects.
In fact the line arrester is known as the most effective means for lightning protection of the
transmission lines at present. Now the ±500 kV DC line arresters have been developed and
applied widely [12].

Considering the electrical and structural parameters of the already operational ±800 kV
UHV DC lines, we have developed ±800 kV DC line arresters in recent years. The designed
structure configuration the arrester is shown as Figure 3. It consists of the arrester body,
conductor electrode, and low-voltage electrode. The arrester body adopts the five-section
series suspension structure. Each section of arrester body includes the polymer housing,
insulating cylinder, valve disc core, and metal flanges. The whole length of the arrester
reaches 9.2 m.

![Figure 3. Structure Configuration of ±800 kV DC line arrester.](image)

The main technical parameters are given as follows. For the whole arrester, rated voltage
is 960 kV; 50% discharge voltage under 1.2/50 μs lightning impulse (peak value) ≤ 2700 kV;
switching impulse withstand voltage (peak value) is 980 kV; DC wet withstand voltage is 900 kV; rated short circuit current effective value is 50 kA; small current short circuit current effective value is 800 A. For the arrester body, DC reference voltage under 1 mA ≥ 960 kV; nominal discharge current (peak value) is 30 kA; residual voltage under 8/20 µs 30 kA nominal discharge current (peak value) ≤ 1900 kV; 2 ms rectangular impulse withstand current is 2000 A; leakage current under 0.75 reference voltage ≤ 50 mA; withstand current under 4/10 µs high current impulse (peak value) is 100 kA; specific creepage distance ≥25 mm/kV.

According to the above parameters, the lightning impulse co-ordination factor between the arrester and air gaps of insulators or tower window is about 1.93, and the discharge voltages of the arrester under lightning impulse with different discharge time are at least 37% less than the corresponding discharge voltages of the tower air gaps. The developed arrester has very good action and protection characteristics. Now the arresters have begun to be applied on actual ±800 kV UHV DC lines, as shown in Figure 4, which achieved good lightning protection results.

CONCLUSION

This paper presents and discusses the detailed statistical and correlation analysis on the 19 lightning faults of FuFeng, JinSu, and BinJin ±800 kV UHV DC transmission lines in China. The results show that the faults have different temporal and spatial distributions. They have no significant correlation with the lightning densities of the whole line corridor or line section, but strong correlation with the lightning current distribution. The lightning fault occurrence probability also has very strong correlation with the tower spans. This paper also presents the main technical parameters of developed ±800 kV UHV DC lines arresters, and they have very good action and protection characteristics. Now the arresters have begun to be applied on actual lines, which would solve the lightning fault problems for UHV DC lines in the future.

REFERENCES