Study on the Characteristics of UHV Negative Lightning Discharge in Tower-line Air Gap

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Abstract: Research on the characteristics of UHV negative lightning discharge process in tower-line air gap is of great significance to the lightning protection of UHV transmission lines. Based on the physical mechanism of negative discharge in long air gap, a simulation model of UHV negative lightning discharge is established. According to the UHV negative discharge model, the relationship between the development speed of the leader, lightning current wave front time, gap length and breakdown voltage in the physical process of lightning development is studied and analyzed. The analysis results discuss the influence of the development speed of the positive and negative polarity leader on the simulation calculation, and the relationship between wavefront time, gap length and breakdown voltage is obtained through fitting.

1. Introduction

UHV DC transmission technology has the characteristics of large transmission capacity, long transmission distance, and low power loss. At the same time, due to its high tower height and various terrain and climatic conditions along the line corridor, it is susceptible to lightning strikes causing line trips[1-3]. According to the natural lightning observation results, the number of negative ground lightnings accounts for more than 90% of the total number of ground lightnings[4]. Considering the actual UHV size model, the main discharge process in UHV negative lightning is negative discharge in long air gap. At present, the research on the characteristics of negative discharge in long air gap is usually obtained through experimental methods. The test process requires a lot of time and economic costs. The research on gap discharge simulation is of great significance[5-9].

Based on the physical mechanism of negative discharge in long air gap, this paper considers the actual UHV tower window structure, establishes a physical simulation model of UHV negative lightning discharge, and uses the test results to verify the model. The discharge characteristics of UHV negative lightning strikes are analyzed from the perspectives of the development speed of the positive and negative polarity leader and the wavefront time. The fitting relationship between the wavefront time, gap length and breakdown voltage is proposed.
2. Simulation Model of UHV Negative Lightning Discharge in Tower-line Air Gap
The main discharge process in UHV negative lightning in tower-line air gap is negative discharge in long air gap, which includes initial corona inception and development, secondary corona and leader inception, leader development and final transition.

After the initial corona inception, it will be transformed into a branched stream and develop in the gap. When the number of ions produced by the streamer head is less than the initial corona self-sustaining condition, the stream will stop developing. After the development of the streamer stops, the temperature of the roots of the streamer branches will continue to increase, and the streamer stems will turn into a leader when the critical temperature is reached. After the leader is initiated, the discharge advances in a leader-streamer system. In the negative long-gap discharge, the positive and negative electrodes produce a leader almost at the same time, and then the leader develops towards each other until they penetrate to form a leader channel. When the voltage rise rate is very low, the leader will undergo the restrike process. Due to the existence of the applied voltage, the voltage applied to the leader gradually increases. When the leader head voltage increases to a certain level, the leader-streamer system re-development. Finally, when the length of the leader exceeds a certain proportion of the gap, the development speed of the leader and the pre-discharge current will both increase significantly, and the gap will eventually break down[10-15].

According to the simplified model established above, the simulation calculation of the negative discharge process in tower-line air gap is carried out, and the calculated and experimental data obtained are shown in the Figure 1-2.

![Figure 1](image1.png)
Figure 1. Breakdown voltage of different gap lengths for tower window negative discharge models (20/2500μs)

![Figure 2](image2.png)
Figure 2. Breakdown voltage of different gap lengths for tower window negative discharge models (80/2500μs)
It can be seen from the comparison of the calculation results and the test results that the simulation calculation results are in good agreement with the test results under different wavefront times, indicating that the long-gap development model of bidirectional development can effectively simulate the development of negative discharge process in long air gap. Prove the feasibility of using the simulation model to study the characteristics of UHV negative lightning discharge.

3. Research on the Characteristics of UHV Negative Lightning Discharge in Tower-line Air Gap

In the negative discharge process in tower-line air gap, the positive and negative polarity leader develop in opposite directions. In actual observations, it appears as an approximately synchronous development process. Due to the less actual development process sample, the development speed of the positive and negative polarity leader may still have difference. In consideration of the actual UHV tower structure, the relationship between the development speed of the negative leader and the breakdown voltage under the standard lightning current of 1.2/50μs in the six-split conductor with a sub-conductor spacing of 450mm is analyzed.

![Figure 3: Breakdown voltage under the different development speed of negative polarity leader](image)

Figure 3. Breakdown voltage under the different development speed of negative polarity leader

As shown in Figure 3, the faster the negative polarity leader develops, the higher the calculated breakdown voltage. At the same time, under the same gap length, when the difference between the development speed of the negative leader and the development speed of the positive leader is small, the breakdown voltage curve does not change significantly. For the curve of breakdown voltage varying with gap length, the development speed of the leader has little effect on the overall trend of the curve.

Considering the only observation samples at present, the same development speed of positive and negative polarity leader are selected as the calculation method to simulate the UHV tower window model. Under the actual possible size of UHV, the length of the gap between the tower window and the wire is generally 6 to 14 meters. The common lightning current waveform is selected as the excitation, and the simulation calculation results of the breakdown voltage under the tower window model are analyzed. as the Figure 4 shows.
Figure 4. breakdown voltage under different wavefront time

Under different wavefront times, the breakdown voltage increases as the gap length increases. Under the same gap length, the longer the wavefront time, the lower the breakdown voltage. The least square method is used to fit the breakdown voltage and the gap length, and the basic fitting formula is: \( U_{50} = a \times d^{b} \). Under calculating the wavefront time, the fitting relationship between the breakdown voltage and the gap length is shown in Table 1.

| wavefront time | fitting formula |
|----------------|-----------------|
| 0.4μs          | \( U_{50} = 835.82 \times d^{0.639} \) |
| 1.2μs          | \( U_{50} = 671.53 \times d^{0.698} \) |
| 2.0μs          | \( U_{50} = 623.91 \times d^{0.716} \) |
| 2.6μs          | \( U_{50} = 593.57 \times d^{0.730} \) |
| 3.0μs          | \( U_{50} = 584.25 \times d^{0.731} \) |

Combining the fitting relations listed in the Table 1, the coefficient \( a \) and the coefficient \( b \) both change with the wavefront time, and the least square method is used to fit the wavefront time and the coefficient again, and the breakdown voltage and the wavefront can be obtained fitting relationship between time and gap length:

\[
U_{50} = 705.254 \times T_r^{-0.180} \times d^{(0.736 - 0.151 \log T_r^{-0.908})}
\]  

(1)

4. Conclusion

In this paper, a simulation model of the UHV negative discharge process in tower-line air gap is established, and the characteristics of the negative discharge in tower-line air gap are studied through the simulation model, and the following conclusions are obtained:

- In the process of tower-line discharge with negative polarity, the development speed of the positive and negative polarity leader has little effect on the change trend of the breakdown voltage curve. Under the same gap length, the faster the development speed of the negative polarity leader, the smaller the breakdown voltage. At the same time, when the development speed of the positive and negative polarity leaders is not much different, the breakdown voltage changes little.

- When the positive and negative polarity leaders develop at the same speed, there is a corresponding relationship between the wavefront time, gap length and breakdown voltage. Under the same wavefront time, the longer the gap length, the greater the breakdown voltage; under the same gap
length, the longer the wavefront time, the lower the breakdown voltage. The relationship between wavefront time, gap length and breakdown voltage is obtained by fitting.

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