Simulation Study on Discharge Process of Negative Polarity in UHV Tower-line Air Gap

Yishi Yue1,a, Zhenyu Liao1*, Haiyue Wang2, Yanhui Zou1, Fuyong Huang1 and Cheng Wang1

1Electric Power Research Institute, State Grid Hunan Electric Power Company, Changsha, Hunan, 410007, China
2Equipment Department, State Grid Hunan Electric Power Company, Changsha, Hunan, 410007, China
ayueysl@hn.sgcc.com.cn
*Corresponding author’s e-mail: 380053129@qq.com

Abstract: Carrying out the research on the physical simulation model of the negative polarity discharge process in UHV 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 physical simulation model including initial corona initiation and streamer development, leader initiation, streamer-leader system development, and final jump is established. The model considers the characteristics of corona initial development, the randomness of the leader path, and the negative development of the negative leader. Finite element software was used to calculate the background potential distribution of the gap, and the experimental observations were used to verify the model established in this paper. Finally, the model was used to simulate the discharge process of the negative polarity in tower-line air gap under actual size of tower window structure. The results show that the simulation calculations agree well with the test results.

1. Introduction
Lightning strikes are the main cause of UHV transmission line trips. Statistics of recent lightning data show that the lightning currents that cause transmission line trips are mainly negative lightning. Long air gap is the main external insulation method for UHV transmission lines, and the choice of gap distance directly affects the lightning resistance level of the line[1-4]. Existing research on the discharge characteristics of long gaps with negative polarity are usually obtained by a large number of typical gaps or even true-type tests[5-9]. The test process consumes a lot of manpower and material resources, and the time cost is too large. Carrying out research on the physical simulation model of negative polarity discharge in long air gap can greatly reduce the test workload, optimize the insulation coordination of the actual project, and improve the economy and safety of the UHV transmission system.

In this paper, based on the physical mechanism of negative polarity discharge in UHV tower-line air gap, considering the dispersion and randomness of discharge, combined with the unique leader development mechanism of negative polarity discharge, the establishment includes initial corona initiation and development, secondary corona inception and leader inception, Simplified physical
simulation model of the process of continuous leading development and final jump, and the model was verified by the test results.

2. Physical Model of Negative Discharge in UHV 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 include initial corona inception and development, secondary corona and leader inception, leader development and final jump.

When the voltage applied to the excitation rod electrode reaches a certain value, the electric field on the surface of the wire electrode will exceed the critical field strength at the start of the corona, and the initial corona starts. According to the classical streamer theory, the initial corona must meet the number of space ions generated by the initial electron collapse enough to support the development of secondary electron collapse[10].

After the initial corona starts, it will be converted into a branched streamer and develop in the gap. During the development of the initial corona stream, free electrons flow into the electrode through the channel and the charge remains in the gap. At this time, the gas temperature $T$ in the area of the initial corona stream is about 300 K, which is the same as the ambient temperature. The current generated by free electron migration continuously converges on the common root of the streamer branch, and the energy provided by it raises the temperature of the gas near the root of the streamer branch until the streamer development stops. After the development of the streamer ceases, the thermal energy released by the vibrational kinetic energy relaxation process will continue to increase the temperature of the root of the streamer branch until the gas temperature reaches the critical temperature $T_{cr}$ (about 1500 K).

When the temperature rises to about 1500K, the negative ions in the streamer stem channel can be decomposed into neutral molecules and electrons in the form of thermal separation, which greatly reduces the internal electric field of the streamer stem, and the streamer stem transforms into a leader, that is, the leader beginning.

![Figure 1. Negative lightning discharge process](image)

After the start of the continuous leader, the discharge advances with a leader-streaming system. The streamer area is located in the head of the leader, providing electronics for the development of the leader. The streamer stem is heated to become a new leader segment, as if the leader channel is constantly moving forward. In the negative long-gap discharge, according to the experimental measurement results, the two electrodes produce leaders at the same time, and then the leaders develop towards each other. The development speed of the leaders of the two electrodes is approximately the same until the leader channel is formed through. This process can be approximated as the gap length is modified by the same length according to the one-sided leader development length.

The leader channel usually develops along an irregular path under the action of an electric field, and its channel radius is on the order of hundreds of microns to tens of millimeters. The potential distortion method is used to calculate the space charge of the leader head. The head development speed of leader can be obtained by increased space charge According to the figure 1, the lead development speeds of the two electrodes with long gaps of negative polarity are approximately the same, so the lead development process can be calculated.
Whether the continuous development of the leader is related to the rate of change of the impulse voltage. When the rate of voltage rise is very low, the leader will appear in the Restrike process. The Restrike process consists of three physical processes: a leader dissipation or de-dissociation process (step1), a leader halo initiation and a leader channel conductivity re-restoration process (step2), and a leader-flow focus on a new development process (step3). When the ionization activity in the streamer area in front of the leader head is gradually weakened, the electrons generated by ionization are gradually reduced. These electrons are mainly adsorbed by oxygen-neutral molecules when passing through the streamer branch and the leader channel, and the electrons that finally enter the rod electrode gradually decrease to zero. The current gradually decreases to zero.

However, the presence of an applied voltage gradually increases the voltage applied to the leader. When the voltage of the leader head increases to a certain level, the electric field near the head ionizes the air and satisfies the initial conditions of the corona. After the corona starts, a large number of electrons are generated, re-injected into the leader channel, and the energy is transferred to the neutral gas molecules in the channel through collision electrons, so the temperature of the leader channel will rise again, and its conductivity will increase. development of.

The leader jump process is the last physical process before the long gap discharge breakdown. The formation of the leader is not a necessary condition for gap breakdown, because the leader may be extinguished naturally during the development process under different external voltage excitations. The speed of the leader development and the pre-discharge current will increase significantly only when the length of the leader exceeds a certain percentage of the gap. At this time, the gap breakdown is inevitable and the final breakdown.

3. Simulation model verification

The experiment is designed as a gantry suspension ±800 kV DC simulation tower, and the air gap distance between the voltage equalizing ring on the simulation conductor side and the tower crossarm and the column can be changed within the range of 4~10m. The UHV DC test base can measure and store real-time atmospheric parameters such as air pressure, temperature, humidity, wind force, and wind direction at the test site, which is convenient for meteorological correction of test data. During the superimposed test, the tower pole is grounded, and a DC voltage and an operating impulse voltage are applied to the simulated wire. The test voltage waveform is DC superimposed with 20/2500µs and 80/2500µs operating shock waves of negative polarity. Use the lifting method to obtain 50% breakdown voltage.

Using COMSOL Multiphysics multi-physics finite element calculation software to calculate the initial electric field of the tower window discharge, using the principle of potential superposition, the initial background electric field and the modified gap electric field of the opposite development are simulated separately, and the tower window 3D model is based on the actual tower structure, considering the size gap of the discharge channel relative to the tower window structure, a two-dimensional model can be used to achieve the approximate modeling of the tower window structure.
According to the principle of electric field superposition, the normalized COMSOL calculated potential distribution can easily obtain the potential distribution of any excitation voltage under the same gap structure. The obtained test data and calculation data are shown in Figure 3–6.

**Figure 2.** Tower window structure and potential distribution diagram (central section)

**Figure 3.** 50% critical breakdown voltage of different gap lengths for negative polarity tower models (20/2500μs)

**Figure 4.** The error value of the simulation calculation and test measurement of different gap lengths under the negative pole tower window model (20/2500μs)

**Figure 5.** 50% critical breakdown voltage of different gap lengths for negative polarity tower models (80/2500μs)

**Figure 6.** The error value of the simulation calculation and test measurement of different gap lengths under the negative pole tower window model (80/2500μs)
From the comparison between the calculation results and the test results, it can be seen that under different wavefront times, the simulation calculation results are in good agreement with the test results, indicating that the long-gap development model of two-way development can effectively simulate the development of negative long-gap development. It is proved that the simulation model is feasible to study the discharge characteristics of negative electrode in tower window.

4. Conclusion
In this paper, based on the physical process of negative polarity long air gap discharge, a physical simulation model including initial corona initiation and development, secondary corona and leader initiation, continuous leader development and final jump process is established. The model takes corona into account. The initial dispersion, the randomness of the lead path and the opposite development of the negative lead have verified the rationality and effectiveness of the model through the test results.

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