

Article

Research on Breakdown Voltage During Live-Line Work on Equipotential Bands at Different Altitudes

Yong Peng ¹, Rui-Xun Qiao ^{1,*}, Xing-Lie Lei ¹, Kai Liu ¹, Zhong-Hua Qiu ², Bin Xiao ¹ and Ya-Di Zhang ³¹ China Electric Power Research Institute, Wuhan 430074, China² State Grid Sichuan Extra High Voltage Company, Chengdu 610041, China³ State Grid Corporation of China Southwest Branch, Chengdu 610041, China

* Correspondence: qiaoruxun@epri.sgcc.com.cn

Abstract

High-altitude, low-pressure environments significantly reduce the insulation strength of air gaps, posing severe risks to live-line working on Ultra High Voltage and Extra High Voltage (UHV/EHV) transmission lines. To address this challenge and ensure operational safety, this paper proposes a predictive gap discharge voltage calculation model based on the dynamic coupling of time-varying electric fields and space charge. Unlike existing approaches that rely on static, geometry-dependent empirical corrections, the proposed model achieves high predictive capability by intrinsically mapping air relative density and absolute humidity to dynamically modify key microscopic discharge parameters, including the effective ionization coefficient, attachment coefficient, and streamer internal electric field strength. This physical framework enables the successful simulation of the complete progression from streamer inception to leader development and final breakdown, thereby calculating the 50% breakdown voltage under varying altitudes and gap distances. To rigorously validate the proposed model, breakdown tests were conducted using simplified sphere–plane gaps and full-scale simulated gaps between a human worker and a tower window at altitudes of 23 m and 2100 m. Additionally, third-party experimental datasets were utilized for comprehensive comparative analysis. The results demonstrate that the model's predictive values align excellently with multi-source experimental data, establishing its high accuracy and practical engineering value for complex electrode configurations under diverse high-altitude conditions.

Keywords: altitude; breakdown voltage; discharge characteristics; physical model

Academic Editor: Federico Barrero

Received: 6 June 2026

Revised: 25 June 2026

Accepted: 26 June 2026

Published: 30 June 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

In recent years, China has rapidly advanced the construction of EHV/UHV projects, gradually establishing a backbone network that supports long-distance, high-capacity power transmission [1,2]. EHV/UHV transmission lines serve as vital corridors for power transmission in China. Ensuring their reliable operation significantly enhances the efficiency of energy resource allocation, strengthens grid security and power supply reliability, and provides stable, efficient electricity support for economic and social development [3,4]. The shutdown and maintenance of EHV/UHV transmission lines will result in reduced cross-regional transmission capacity, hinder the integration of clean energy, and increase grid operational risks, directly impacting the stable functioning of the economy and society as well as the safety and stability of the power system [5,6]. Transformer station serve as the hubs of the power grid, performing critical functions such as voltage conversion,

power flow regulation, and system stabilization. Their operational reliability directly impacts the overall safety of the grid. Failures can trigger operational risks and result in substantial economic losses [7,8]. Therefore, conducting efficient and reliable live-line work can minimize planned outages, which is crucial for maintaining the continuous and stable operation of the EHV/UHV backbone network [9]. In addition to conventional live-line maintenance, recent years have witnessed an increasing adoption of unmanned aerial vehicles (UAVs) and advanced robotic systems for transmission-line inspection and condition assessment. These technologies, supported by novel energy harvesting solutions [10], play a vital role in reducing maintenance costs and improving overall operational safety. However, despite these significant technological advancements in monitoring and inspection, conventional equipotential live-line work remains inherently indispensable for complex physical repairs and direct equipment maintenance.

In live-line work, safety distances serve as the core technical basis for ensuring personnel safety and stable equipment operation [11]. During live-line working at the same potential, personnel are positioned at a high potential. This creates a typical human-ground gap with an extremely complex electric field distribution between the worker and grounded components or equipment at different potentials. The breakdown voltage of this gap serves as the fundamental basis for establishing safety distances [12]. However, the low atmospheric pressure and low air density conditions in high-altitude environments significantly weaken the insulating strength of air gaps, resulting in a marked decrease in breakdown voltage for the same gap distance compared to lowland areas [13]. Directly applying safety distances designed for lowland conditions poses significant safety risks to live-line workers in high-altitude areas [14,15]. Therefore, conducting systematic research on the breakdown characteristics of typical operational clearances in substations under different altitude conditions holds significant practical importance.

Currently, scholars both domestically and internationally have conducted extensive research on high-altitude air gap discharges. Studies have primarily focused on empirical correction formulas for gap breakdown voltage versus altitude and investigations into the mechanisms underlying the microscopic physical processes of discharge [16,17], providing crucial theoretical foundations and experimental references for the work presented herein.

Through field tests in different high altitude areas, Wang and others systematically obtained key engineering parameters such as minimum safety distance and combined clearance for typical operating conditions of 220 kV transmission lines, which provided important data support for the formulation of relevant technical standards [18]. Fang and colleagues conducted switching impulse voltage discharge tests on 750 kV double-circuit lines with common towers at altitudes ranging from 2000 m to 4300 m. They analyzed the effects of altitude and operational posture on discharge characteristics and proposed an improved discharge voltage correction method suitable for high-altitude environments [19]. Lü conducted a feasibility study on live-line operations for 110 kV transmission lines in the 4000–5000 m high-altitude regions of Naqu, Tibet Autonomous Region. Considering factors such as environmental conditions and safety distances, they calculated and analyzed the safety distances for live-line operations and the associated hazard rates. The study validated the feasibility of live-line work in this region by completing safety distance verification for tower equipment [20]. In the aspect of mechanism research, Wang et al., by studying the discharge process of typical electrode structures in different altitude areas, carried out fine measurement and mechanism analysis on the key characteristic parameters such as the dispersion of streamer initiation time, the amount of injected charge and the development speed [21].

Based on the aforementioned research foundation, this paper proposes a calculation model for live-line work gap discharge voltage that accounts for altitude effects. By

comparing and validating this model against typical operating conditions and experimental data from existing studies conducted at different altitudes, it can further provide reference and basis for establishing technical standards and safety distances for live-line work in regions with varying elevations.

The paper is organized as follows:

Section 1 introduces the research background, the necessity of live-line work in high-altitude environments, and the scientific novelty of the proposed model.

Section 2 details the theoretical development of the dynamic physical calculation model for gap discharge voltage, incorporating altitude-dependent meteorological parameters.

Section 3 presents the systematic validation of the proposed model through comprehensive comparisons with simplified and full-scale equipotential live-line work tests at altitudes of 23 m and 2100 m.

Section 4 further investigates and discusses the gap breakdown characteristics across a broader altitude gradient (23 m, 2000 m, and 3000 m) using multi-source test data.

Section 5 summarizes the main conclusions of this study and outlines future research prospects.

2. Calculation Model for Gap Discharge Voltage During Live-Line Work on Power Transmission Lines

Developing a physical model of gap discharge characteristics applicable to more common practical operating conditions is an effective approach to address the limitations of laboratory testing environments, which cannot cover all altitude ranges and gap distances for live-line work under equal potential conditions. Ensure that factors such as altitude and gap distance not covered in the tests are taken into account to obtain more comprehensive gap discharge data. During intervals of live-line work in the same potential gap, corona discharge phenomena frequently occur on the backs or feet of workers, exhibiting a structure similar to that of a spherical electrode and a rod electrode. Under different operating conditions, there exists a unique critical corona radius. If the electrode curvature radius is smaller than the critical corona radius, the corona initiation voltage during discharge will be lower than the continuous leader initiation voltage [22]. The critical electric corona radius formula for rod electrodes and spherical electrodes is as follows [23,24]:

$$R_c = 0.38(1 - e^{-0.2d}) \quad (1)$$

During the construction of the discharge test setup for live-line work in equipotential zones, the curvature radius at the back of the live working personnel is less than the critical corona radius. During the test, a charge accumulation process occurs between the onset of the streamer and the initiation of leader. Consequently, a computational model accounting for time-varying electric fields and space-charge coupling was established to calculate the 50% discharge voltage at different altitudes. Figure 1 illustrates the computational flowchart.

This model solves for breakdown time and breakdown voltage while accounting for altitude effects. A hybrid numerical framework combining COMSOL Multiphysics 6.3 and MATLAB R2023b is adopted. COMSOL is utilized exclusively to compute the 3D electrostatic background field (Laplacian field) under a unit voltage for specific electrode configurations. The normalized axial electric field and potential profiles are then exported to MATLAB, which executes the entire transient simulation loop. Within MATLAB, the model calculates physical quantities such as the ionization boundary and internal electric field strength within the streamer based on atmospheric pressure at different altitudes combined with Dalton's law of partial pressures.

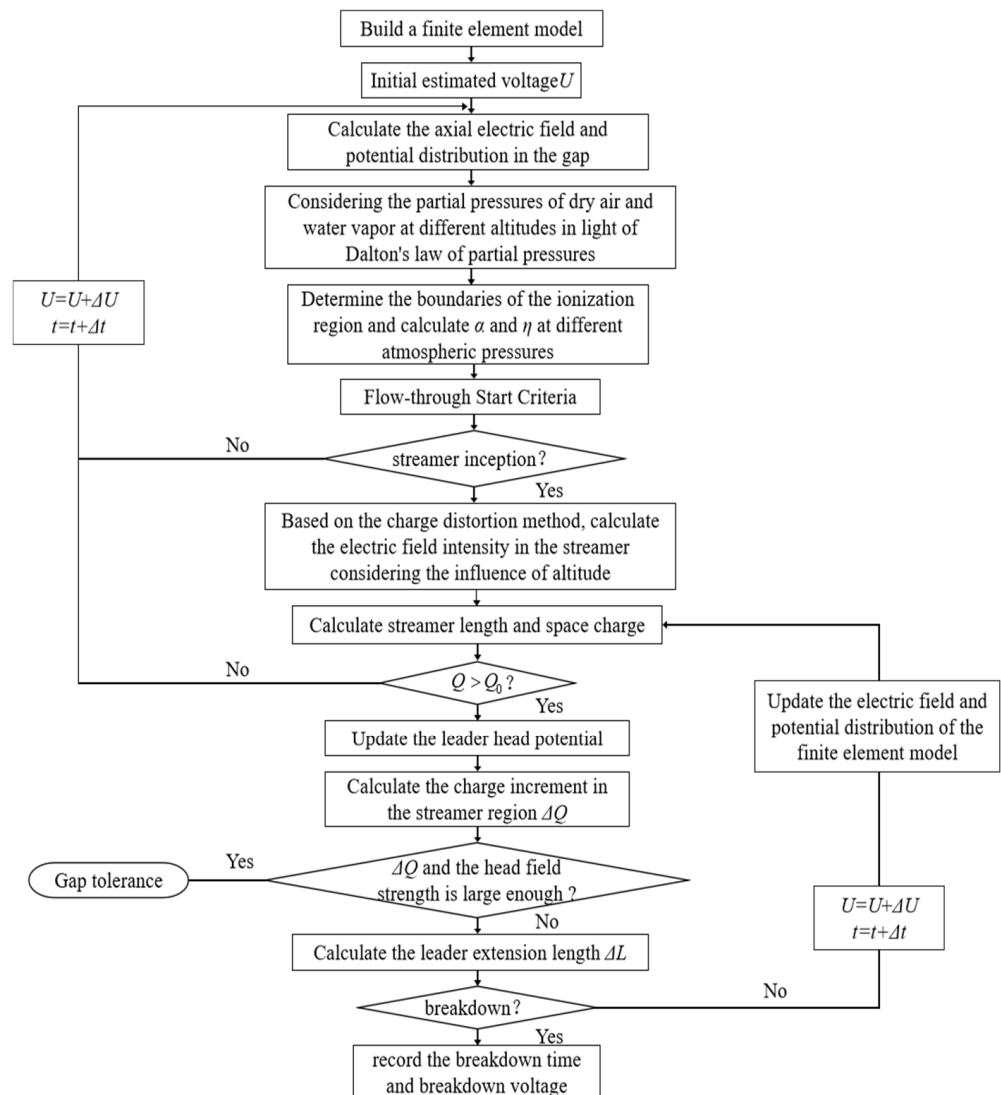


Figure 1. Flow chart for Calculating Gap Breakdown Voltage.

Under test conditions, the development of current flow within the live-line work gap at the same potential determines the initiation of the leader [25]. This model employs a streamer initiation criterion based on the critical charge method, calculating the electron multiplication factor through the effective ionization coefficient. Streamer initiation occurs [26] when the equivalent number of electrons accumulated by electron avalanches N_e satisfies Equation (2).

$$\int_0^{z_{cr}} [\alpha(E) - \eta(E)] dz \geq \ln(N_{stab}) \quad (2)$$

In the equation, z_{cr} represents the ionization boundary, α denotes the ionization coefficient, η signifies the recombination coefficient, and N_{stab} indicates the critical number of electrons required for the flow to initiate, which is taken as 10^8 in the model [27]. The ionization coefficient α and the recombination coefficient η also vary under different atmospheric conditions at different altitudes.

The relative density and humidity of air vary with altitude, causing changes in the ionization coefficient α and recombination coefficient η of the gap corona voltage. Dalton's law of partial pressures describes atmospheric pressure p as the sum of the partial pressure p_d of dry air and the partial pressure p_w of water vapor, as shown in Equation (3).

$$p = p_d + p_w \quad (3)$$

Therefore, the ionization coefficient and recombination coefficient η for live-line work gaps at different altitudes can be derived from Equations (4) and (5).

$$\begin{cases} \alpha = \frac{p_d}{p} \alpha_d + \frac{p_w}{p} \alpha_w \\ \frac{\alpha_d}{p} = 4.7786e^{-221 \frac{p}{E}} \\ \frac{\alpha_w}{p} = 0.001 \left(\frac{E}{p} \right)^2 - 0.06 \frac{E}{p} + 1 \end{cases} \quad (4)$$

$$\begin{cases} \eta = \frac{p_d}{p} \eta_d + \frac{p_w}{p} \eta_w \\ \frac{\eta_d}{p} = 0.87 \times 10^{-5} \left(\frac{E}{p} \right)^2 - 0.54 \times 10^{-3} \left(\frac{E}{p} \right) + 0.01298 \\ \frac{\eta_w}{p} = -3.67 \times 10^{-5} \left(\frac{E}{p} \right)^2 + 0.026 \left(\frac{E}{p} \right) - 0.2732 \quad \frac{E}{p} < 38.5 \\ \frac{\eta_w}{p} = -2.5 \times 10^{-5} \left(\frac{E}{p} \right)^2 - 2.5 \times 10^{-4} \left(\frac{E}{p} \right) + 0.235 \quad 38.5 \leq \frac{E}{p} \leq 60 \end{cases} \quad (5)$$

This model employs the charge distortion method [28] to solve for the streamer. It assumes that the internal electric field strength E_s within the streamer remains relatively stable under standard atmospheric pressure. The background potential distribution within the gap during streamer development is denoted as $U_n(x)$, while the spatial potential distribution after streamer generation is denoted as $U_e(x)$. Thus $U(x)$ satisfies Equation (6).

$$U(x) = U(0) - E_s \cdot l_s \quad (6)$$

In the equation, $U_0(x)$ represents the potential of the high-voltage electrode, and l_s denotes the length of the streamer propagating axially along the gap. At different altitudes, the internal electric field strength E_s within the streamer is influenced by the relative air density δ and absolute humidity H . The corresponding E_s is calculated as per Equation (7) [29].

$$E_s = 497\delta \left(1 + \frac{H - 11}{100} \right) \quad (7)$$

The spatial positive charge Q^+ generated during the streamer stage can be calculated using Equation (8) [30].

$$Q^+ = K_Q \int_0^{l_s} [U_e(x) - U_n(x)] dx \quad (8)$$

In the formula, K_Q represents the spatial charge potential distortion coefficient, which is set to $3.5 \times 10^{-11} \text{C}/(\text{V} \cdot \text{m})$.

Based on the thermal dissociation criterion [31], it is considered that the leader initiates when the internal charge Q_{sc} within the streamer reaches the critical charge $Q_{crit} = 1 \mu\text{C}$ required for leader initiation, as shown in Equation (9).

$$Q_{sc}(t) = \int q_s dt \geq Q_{crit} \quad (9)$$

After the initiation of the leader, the charge increment ΔQ of the streamer discharge can be determined by the rise in the background potential within the gap during time interval Δt , as shown in Figure 2. The variation in the leading development length ΔL within Δt can be obtained through Equation (10) with ΔQ .

$$\Delta L = \frac{\Delta Q}{q_L} \quad (10)$$

In the formula, q_L represents the charge per unit length of the leader, taken as $50 \mu\text{C}/\text{m}$ [32].

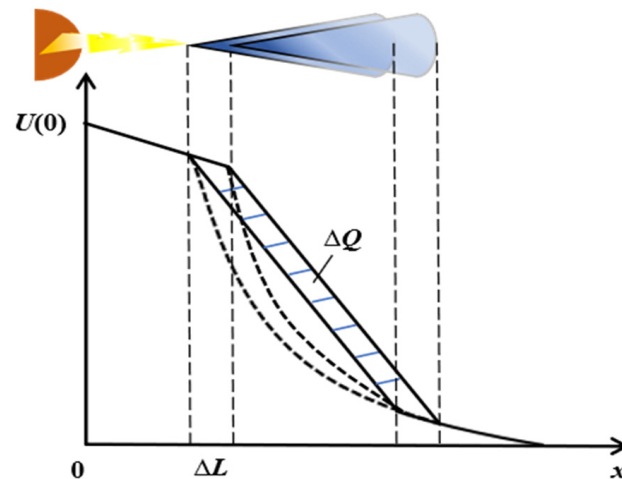


Figure 2. Schematic Diagram of Streamer-Leader Discharge Development.

During the calculation process, when the leader length in the gap satisfies either a remaining gap distance less than the final breakdown distance or an average electric field strength in the remaining gap exceeding the critical breakdown field strength, the gap is deemed to have broken down. To determine the 50% breakdown voltage, the proposed model employs a deterministic iterative approach rather than stochastic probability modeling. By applying a bisection search method with a voltage step resolution of 1 kV, the peak value of the applied impulse voltage is systematically adjusted. For each peak voltage, a complete simulation of the dynamic discharge process is executed. The absolute minimum peak voltage that satisfies the aforementioned breakdown criteria is recorded as the critical breakdown threshold. Since the physical model evaluates the intrinsic discharge threshold under specific mean atmospheric parameters without introducing random statistical perturbations, this deterministic critical voltage is directly defined as the theoretical 50% discharge voltage for comparison with the experimental statistical results.

Building upon this model, this paper focuses on investigating the gap distances for live-line work at different altitudes. This research can provide an accurate data foundation for subsequent studies on the specific requirements for safe operations on transmission lines of various voltage levels under different altitude conditions.

3. Model Validation

To verify the feasibility and accuracy of the proposed calculation model for breakdown voltage in equipotential live-line work gap, this paper conducts a systematic comparison and evaluation using experimental data from multiple sources. The model was applied to a simplified electrode configuration and compared with existing standard experimental data to verify the accuracy of the model's calculations.

To address real operating conditions, full scale tests were conducted to supplement the simplified electrode model and better reflect actual operational scenarios. At the same time, the computational accuracy of the model presented in this paper was verified by comparing it with data from these tests. Finally, by comparing the model with typical experimental data published in relevant academic research both domestically and internationally, we will test its generalizability and reliability through a broader range of experiments. Through the above comparison and validation process, we aim to comprehensively and objectively demonstrate the theoretical validity and engineering practicality of this model, as well as its improvements and advantages over existing methods.

This study established a test platform for live-line work on transmission lines under positive-polarity switching impulse conditions. To simulate the typical working conditions of

live-line workers on transmission lines of 100 kV and below, the test was designed to replicate equipotential live-line work. To verify the applicability of the model presented in this paper to both simplified electrode model tests and full scale model tests, the experiments utilized a sphere–plate gap configuration and a simulated human back-to-simulated tower window gap configuration to simulate live-line work conditions in an equipotential zone.

In the simplified electrode test, the test site was located at an elevation of 23 m, with ambient temperatures ranging from 30.1 to 32.9 °C and relative humidity ranging from 44.2% to 60.0%. The radius of curvature of the spherical electrode used in the test was 0.45 m. During the full scale test, the test site was located at an elevation of 2100 m, with ambient temperatures ranging from 29.1 °C to 31.5 °C and relative humidity ranging from 28.6% to 43.7%. For the simulation of live-line workers, a mannequin that closely matches the shape and structure of a real human body is used. The mannequin is 0.5 m wide and 1.8 m tall when standing, and is dressed in a full set of shielding clothing. Its limbs can be freely bent, and during testing, the position of the spherical electrode and the mannequin can be adjusted to reflect various working conditions, thereby accurately simulating the operational status of workers on-site. The test busbar has a diameter of 170 mm and a total length of 5 m. It is supported by post insulators in conjunction with insulator bases. During the equipotential live-line work test, the distance between the worker and the simulated tower window was adjusted by moving the worker’s position, with electrode distances set to 1.00 m, 2.00 m, and 3.00 m. The switching impulse voltages were generated by different equipment depending on the test site. Specifically, for the tests conducted at an altitude of 23 m, a 5400 kV/527 kJ impulse voltage generator was utilized. For the high-altitude tests at 2100 m, a 7200 kV/720 kJ impulse voltage generator was employed to provide the necessary testing capacity. The applied switching impulse voltage was measured using a voltage divider connected to a high-precision oscilloscope, which features a 1 GHz bandwidth and a maximum sampling rate of 5 GSa/s.

3.1. Comprehensive Validation Results of Gap Discharge Voltages

To comprehensively validate the accuracy of the proposed model across different altitudes and electrode configurations, geometric models for both the simplified sphere–plane and the full-scale dummy-to-tower window configurations were constructed in COMSOL based on the experimental setups. The exact environmental parameters corresponding to each specific test site were inputted into the dynamic simulation script. The validation encompasses both our own equipotential live-line work tests (at 23 m and 2100 m) and third-party standard experimental data [33]. To provide a clear and synthetic comparison, all experimental and simulated 50% breakdown voltages, along with their relative calculation errors, have been integrated and summarized in Table 1.

Table 1. Synthetic Comparison of Experimental and Simulated Gap Discharge Voltages.

Altitude	Electrode Configuration	Gap Distance	Experimental U_{50}/kV	Simulated U_{50}/kV	Relative Error
23 m	Sphere–Plane ($R = 0.45 \text{ m}$)	1.00 m	984	1002	1.83%
		2.00 m	1218	1260	3.45%
		3.00 m	1589	1607	1.13%
2100 m	Full-Scale (Human–Tower)	2.00 m	671	705	5.07%
		3.00 m	850	899	5.76%
		3.50 m	978	1016	3.89%
2100 m	Sphere–Plane ($R = 0.30 \text{ m}$)	2.00 m	783	814	3.96%
		3.00 m	875	892	1.94%
2100 m	Sphere–Plane ($R = 0.45 \text{ m}$)	2.00 m	1069	1127	5.43%
		3.00 m	1275	1355	6.27%

In the simplified electrode test, the COMSOL geometric model is shown in Figure 3, the axial electric field across the gap is presented in Figure 4, and the comparison of the simulated and experimental results is illustrated in Figure 5.

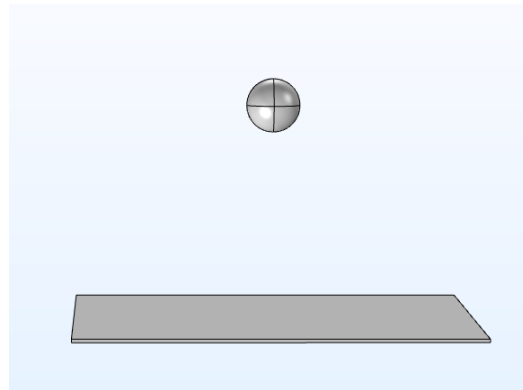


Figure 3. Sphere–Plane Gap Discharge Simulation Model.

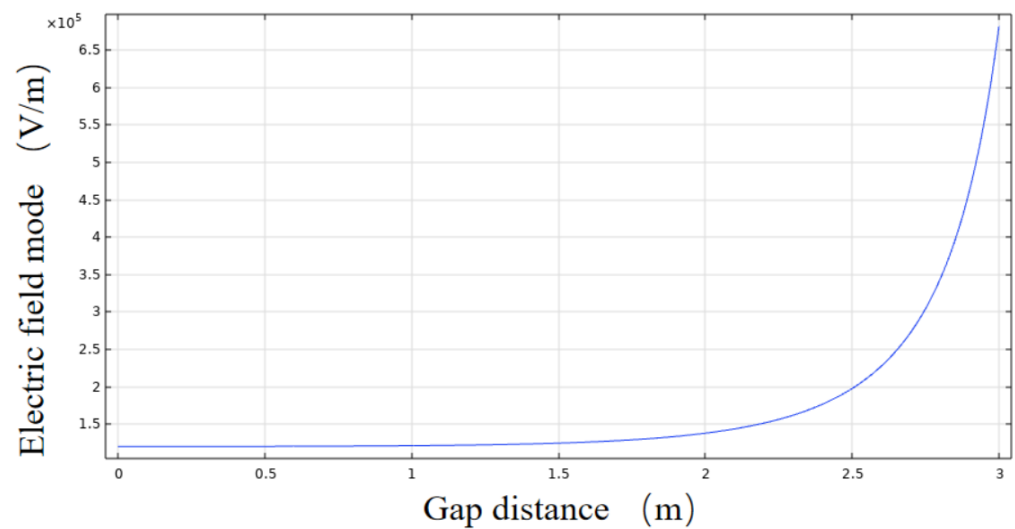


Figure 4. Axial Electric Field Distribution in Sphere–Plane Gap.

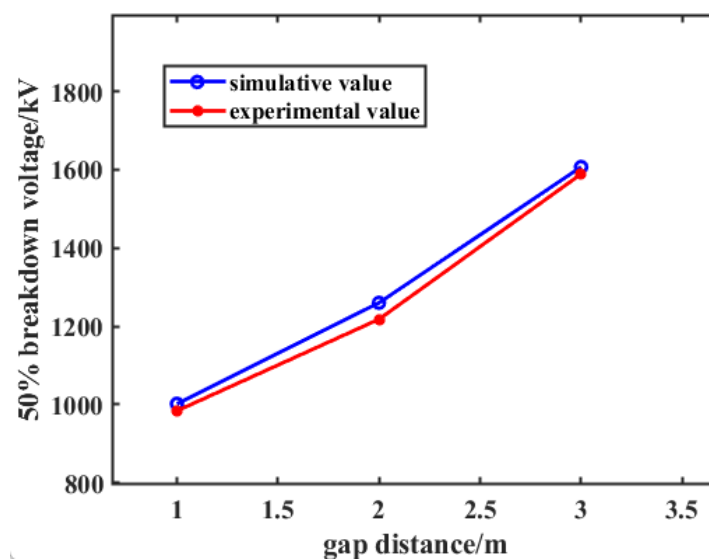


Figure 5. Comparison Curve of Simulation Results and Test Data.

In the full-scale model test, the COMSOL geometric model is shown in Figure 6, the axial electric field across the gap is presented in Figure 7, and the comparison of the simulated and experimental results is illustrated in Figure 8.

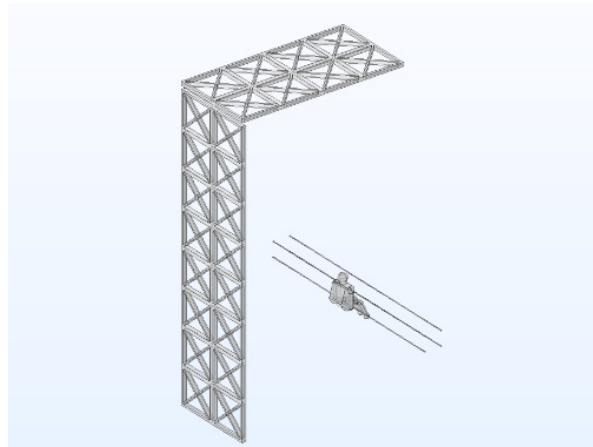


Figure 6. Prototype Discharge Simulation Model.

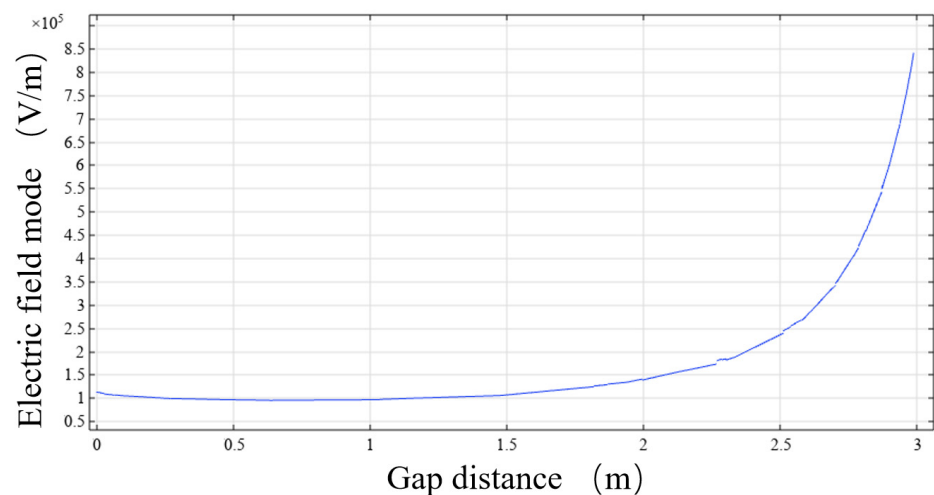


Figure 7. Simulated Axial Electric Field Distribution in Human Back-to-Tower Window Gap.

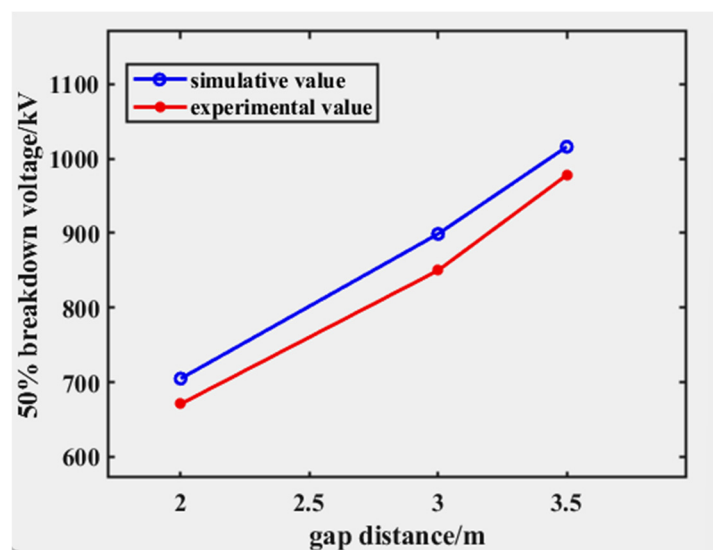


Figure 8. Comparison Curve of Simulation Results and Test Data.

Research [33] obtained the breakdown voltage values for the sphere–plate gap through simplified electrode testing. During the test, the ambient temperature was maintained between 24.6 and 31.0 °C, the atmospheric pressure was 0.0798 MPa, the relative humidity ranged from 29.3% to 40.0%, and the altitude was 2100 m. In equipotential live-line work conditions, to simulate the back of a live-line worker, spherical electrodes with radius of curvature of 0.3 m and 0.45 m were used, and the distance between the spherical electrodes and the simulated tower window was set to 2.0 m and 3.0 m. Figures 9 and 10 show a comparison between the breakdown voltage calculated using the model presented in this paper and the experimental results, respectively.

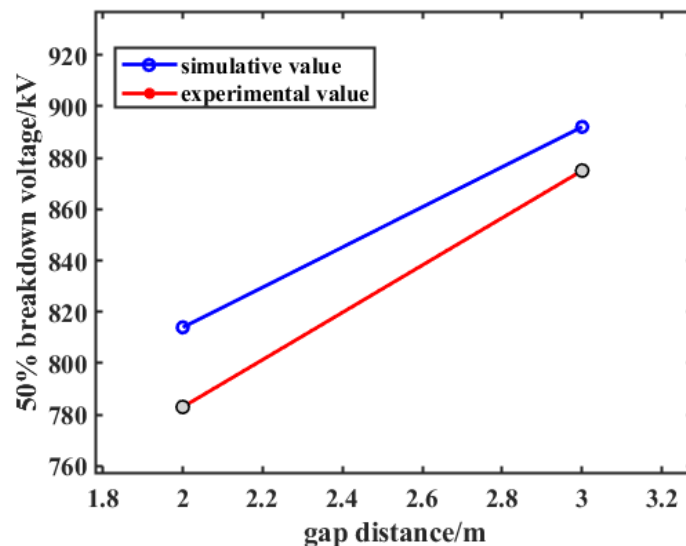


Figure 9. Comparison Chart of Simulated Values vs. Experimental Results (Curvature radius 0.3 m).

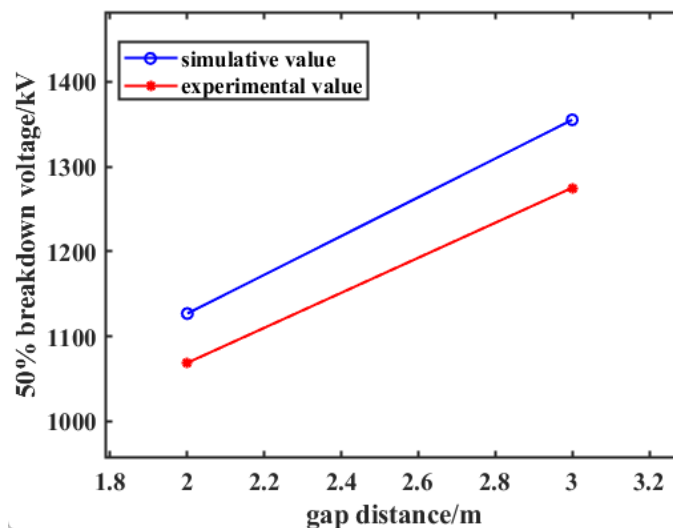


Figure 10. Comparison Chart of Simulated Values vs. Experimental Results (Curvature radius 0.45 m).

Through systematic experimental comparisons, the proposed model demonstrates stable predictive capabilities across multiple benchmark datasets and altitude scenarios. To objectively evaluate the model's computational accuracy, a quantitative assessment was conducted using the Mean Relative Error (MRE) and Maximum Deviation metrics. As summarized in Table 2, the deviations between the simulation results and the experimental data were calculated for all tested configurations.

Table 2. Quantitative Error Assessment of Simulated Breakdown Voltages.

Dataset Configuration	Altitude	Mean Relative Error	Maximum Deviation
Simplified Sphere–Plane Gap	23 m	2.14%	3.45%
Full-Scale Prototype Gap	2100 m	4.91%	5.76%

3.2. Discussion

The comparison of the test results reveals the fundamental influence of electrode geometry on the discharge process. In simplified electrode model test, the electric field distribution is relatively regular, and the model predictions show a high degree of consistency with the experimental results. This validates the accuracy of the model's core physical field calculations and the streamer initiation criteria derived from them. The degree of electric field concentration is related to the radius of curvature of the spherical electrode, which determines the discharge initiation point and initial intensity.

Real live-line work scenarios do not involve idealized sphere–plate configurations. The introduction of full scale model tests is intended to evaluate the model's applicability under complex, irregular electric fields. The dummy and the tower window form a system that generates multiple local electric field distortions. The systematic deviation of the simulation value is slightly higher than the experimental value, which is due to the idealized treatment of extreme nonlinear physical processes such as the streamer-leader conversion process and the dynamic shielding effect of space charge on the electric field in the model, while the actual discharge development has more randomness.

The environmental parameters involved in the experiment affect the macroscopic breakdown characteristics by changing the microscopic physical state of the discharge medium. The decrease in pressure will lead to the decrease in air density. The microscopic mechanism is that the number density of gas molecules decreases, which makes the average free path of electrons increase. Under the same electric field strength, electrons are more likely to accumulate enough energy to trigger ionization between two collisions, which makes the development of electron avalanche and the initiation of streamer easier.

In this paper, the micro-physical mechanism is integrated into the calculation process of macro-breakdown voltage, and the parameters such as effective ionization coefficient and critical breakdown field strength are corrected by air density to obtain more accurate simulation results. In the simplified sphere–plane gap models, the MRE is strictly maintained below 3.0%. For the full-scale equipotential live-line work gaps, which feature highly complex and irregular electric field distributions, the simulation yields a slightly higher deviation due to the idealized macroscopic treatment of space charge shielding. Nevertheless, the Maximum Deviation under these extreme full-scale conditions remains bounded at approximately 5.8%. These quantitative metrics objectively confirm that the model meets the strict accuracy thresholds required for high-altitude live-line safety clearance design.

It is worth noting that while the number of tested gap distances in the validation datasets is numerically limited, these specific data points are highly representative. Conducting full-scale equipotential live-line tests at extreme high altitudes presents significant logistical and safety challenges, making dense experimental data collection highly impractical. Therefore, the tested gap distances were specifically targeted to correspond to the critical safety clearance boundaries dictated by practical engineering standards for various voltage levels. The model's ability to accurately predict breakdown voltages at these critical conditions demonstrates its reliability for engineering design, highlighting its value in interpolating safety parameters where extensive physical testing is prohibitive.

4. Breakdown Characteristics at Different Altitudes

The breakdown voltage calculation model for equipotential live-line work gaps, as proposed in this study, has been systematically compared with experimental data from multiple sources. This comparison verifies its accuracy and reliability under conventional environmental conditions. To further expand the model's engineering applicability, this paper conducts a comparative analysis of experimental data on the breakdown characteristics of equipotential live-line work gaps at different altitudes. Reference [19] reports experiments on the operational impulse discharge characteristics of a full-scale equipotential live-line work geometric model, with gap lengths ranging from 3 m to 8 m, conducted at altitudes of 23 m, 2000 m, and 3000 m. To accommodate the requirements of full-scale human-tower model tests across varying altitudes, different impulse voltage generators were utilized. The tests at the altitude of 23 m were conducted using a 5400 kV/527 kJ impulse voltage generator. For the extreme high-altitude scenarios at both 2000 m and 3000 m, a 3600 kV/360 kJ impulse voltage generator was utilized. Specifically, the 23 m altitude test was performed at the Wuhan UHV Outdoor High-Voltage Test Site of the China Electric Power Research Institute; the 2000 m altitude test was conducted at the Ping'an Transmission and Distribution Line Training Base of Qinghai Provincial Electric Power Company; and the 3000 m altitude test was carried out at the outdoor test site of the Haixi 750 kV Switching Station in Qinghai. The test data from these equipotential live-line work tests under different altitude conditions, as reported in Reference [19], are referenced in this paper and presented in Table 3.

Table 3. Test Results of Gap Discharge Voltage under Different Altitude Conditions.

Altitude	d/m	U_{50}/kV
23 m	4.02	1466
	5.00	1663
	5.96	1845
2000 m	3.50	1187
	4.00	1380
	5.00	1580
3000 m	4.20	1221
	5.20	1398
	6.20	1617

By comparing and validating the model's computational results against experimental data collected at various altitudes, we systematically evaluate the model's accuracy and stability under different atmospheric pressure conditions, thereby providing theoretical support and practical guidance for planning safe working distances during live-line work on transmission lines in high-altitude regions.

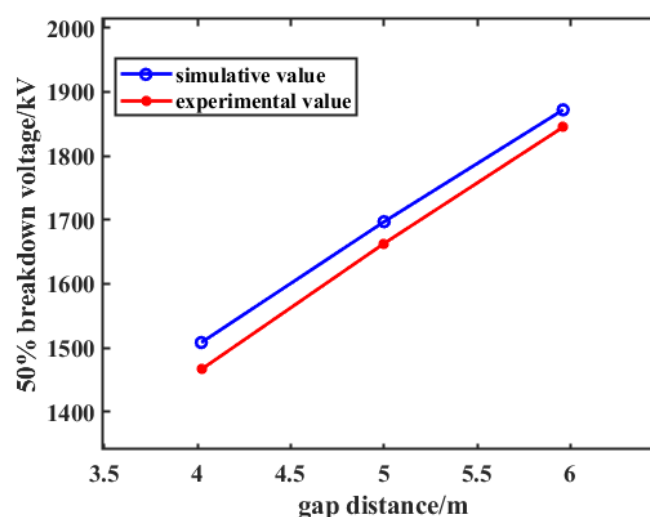
4.1. Breakdown Voltage Variations Across Altitude Gradients

To systematically evaluate the breakdown characteristics across a wide altitude gradient, dynamic simulations were executed for the full-scale equipotential live-line work gap at altitudes of 23 m, 2000 m, and 3000 m. The specific environmental parameters of each test site were rigorously applied as boundary conditions. The consolidated comparison of all experimental and simulated 50% breakdown voltages is systematically presented in Table 4.

Table 4. Synthetic Comparison of Experimental and Simulated Gap Discharge Voltages.

Altitude	Atmospheric Pressure	Gap Distance	Experimental U_{50}/kV	Simulated U_{50}/kV	Relative Error
23 m	101.0 kPa	4.02 m	1466	1508	2.86%
		5.00 m	1663	1697	2.04%
		5.96 m	1845	1872	1.46%
2000 m	79.0 kPa	3.50 m	1187	1235	4.04%
		4.00 m	1380	1415	2.54%
		5.00 m	1580	1649	4.37%
3000 m	71.6 kPa	4.20 m	1221	1248	2.21%
		5.20 m	1398	1413	1.07%
		6.20 m	1617	1624	0.43%

In Reference [19], identical simulated towers and simulated conductors were constructed at the Wuhan UHV outdoor test site, located at an elevation of 23 m. During testing, the simulated towers and conductors were suspended from the test site's tower windows, with the simulated towers securely grounded using flexible copper strips. The simulated conductors were suspended at a height of more than 20 m above the ground. During the equipotential test, a copper wire was used to connect the dummy and the conductor to ensure they were at the same potential. By moving the dummy's position, live-line work gap of varying lengths could be created. The distance between the simulated conductor and the crossarm was maintained greater than the distance between the dummy and the side of the tower to ensure that the discharge developed along the path from the dummy to the side of the tower. The average atmospheric pressure and average relative humidity at the test site were 101.0 kPa and 12.68 g/m³, respectively. A surge voltage generator was used to produce a standard positive-polarity switching impulse voltage of 250/2500 μs , which was applied to the test specimen via high-voltage leads. The 50% breakdown voltage of the live-line work gap was calculated using the voltage ramping method. The comparison of the experimental values with the simulation results is shown in Figure 11.

**Figure 11.** Comparison Chart of Simulated Values vs. Experimental Results (Altitude 23 m).

Switching impulse tests were conducted at the Qinghai Ping'an Power Transmission and Distribution Training Base, located at an altitude of 2000 m. The average atmospheric pressure and average relative humidity at the test site were 79.0 kPa and 5.38 g/m³,

respectively. The 50% breakdown voltage and standard deviation were obtained for different gap distances. The comparison of the experimental values with the simulation results is shown in Figure 12.

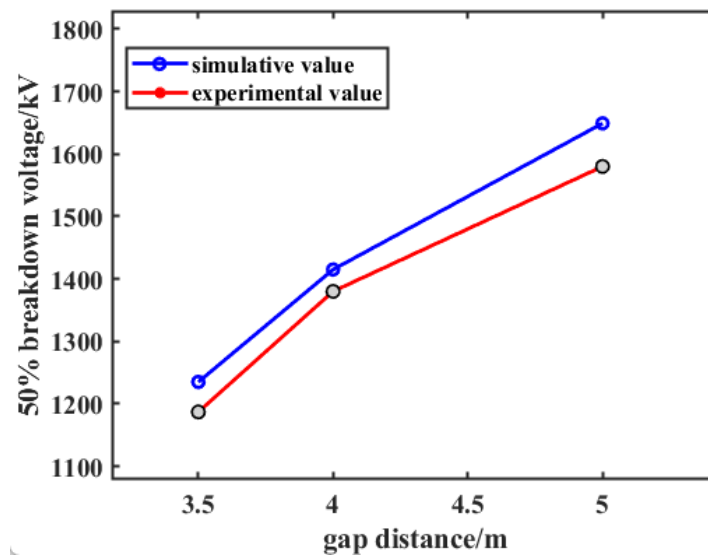


Figure 12. Comparison Chart of Simulated Values vs. Experimental Results (Altitude 2000 m).

Switching impulse tests were conducted at the outdoor test site of the 750 kV substation in Haixi, Qinghai, located at an altitude of 3000 m. The average atmospheric pressure and average relative humidity at the test site were 71.6 kPa and 5.73 g/m³. The 50% breakdown voltage was measured for different gap distances. The comparison of the test data with the simulation results is shown in Figure 13.

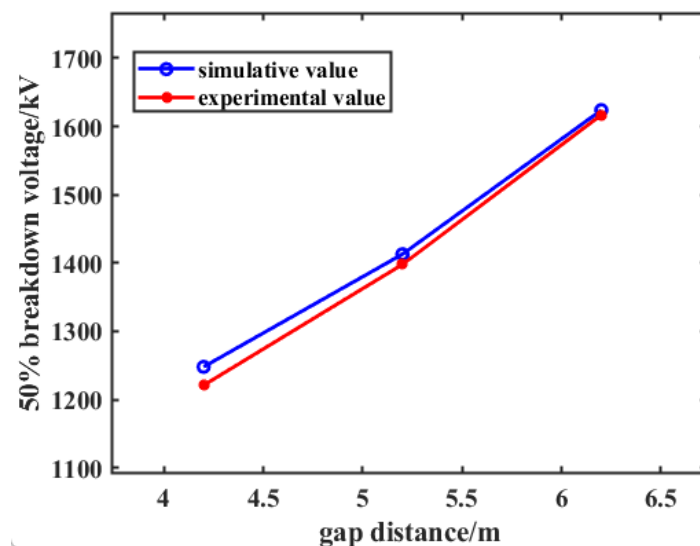


Figure 13. Comparison Chart of Simulated Values vs. Experimental Results (Altitude 3000 m).

To further verify the generalization capability of the proposed model across a wide altitude gradient, a quantitative statistical error analysis was conducted for the multi-altitude datasets described in this section. The Mean Relative Error and Maximum Deviation for each altitude condition were calculated and are systematically summarized in Table 5. The quantitative results demonstrate that the model maintains excellent predictive consistency across all altitude gradients.

Table 5. Statistical Error Assessment of Simulated Breakdown Voltages across Altitude Gradients.

Altitude	Test Gap Range	Mean Relative Error	Maximum Deviation
23 m	4.02–5.96 m	2.12%	2.86%
2000 m	3.50–5.00 m	3.65%	4.37%
3000 m	4.20–6.20 m	1.24%	2.21%

4.2. Discussion

In this paper, by comparing experimental and simulation results of the switching impulse breakdown characteristics of equipotential live-line work gaps at three typical altitudes, 23 m, 2000 m, and 3000 m, the applicability of the proposed computational model under different atmospheric pressure conditions is systematically verified. The experimental data clearly reveal the general trend that the breakdown voltage of the gap decreases with increasing altitude. Starting from the influence of environmental parameters on the microscopic properties of air, this study delves into their role throughout the entire discharge development process and ultimately examines the mechanisms that determine the macroscopic breakdown voltage.

Changes in environmental parameters caused by variations in altitude are primarily reflected in changes in atmospheric pressure P and temperature T , which together determine the relative density δ of the air. Relative density is the parameter that links the macroscopic environment to the microscopic discharge process.

Under the altitude gradient studied in this paper, atmospheric pressure decreases significantly, and this decrease in pressure is the primary factor causing a reduction in the relative density of air δ . The decrease in relative density alters the microscopic physical properties of air as an insulating medium. The number density of gas molecules n decreases, resulting in fewer gas molecules per unit volume. The mean free path of electrons λ increases; that is, the average distance an electron travels under the influence of an electric field before undergoing two collisions with gas molecules becomes longer. Due to the increase in λ , the kinetic energy accumulated by electrons between collisions is more likely to exceed the ionization energy of the gas, resulting in an increase in the effective ionization coefficient and a higher probability of electron collision ionization. Meanwhile, the influence of temperature is not limited to indirectly affecting collision frequency through changes in density; temperature itself also affects the average kinetic energy and excitation cross-section of gas molecules, thereby modulating the ionization and attachment processes.

Furthermore, the mechanism by which absolute humidity H exerts its influence is independent of atmospheric pressure and temperature. Water molecules are highly electronegative and strongly adsorb free electrons, forming slow-moving negative ions. This process consumes the seed electrons upon which discharge development depends, thereby inhibiting the progression of ionization. Changes in these microscopic parameters ultimately determine the macroscopic breakdown characteristics of the gap by governing the entire discharge process from initiation to breakdown. The initiation of streamer discharge requires that the ionization intensity within the critical volume be satisfied. According to empirical formulas, the field strength required for streamer initiation E_s is approximately proportional to the relative density of air δ . Therefore, as altitude increases and δ decreases, the applied electric field strength required for streamer initiation correspondingly decreases. Under the same gap distance and applied voltage waveform, the electric field in the gap is more likely to reach the streamer initiation threshold in a low-pressure environment, making discharge easier to trigger. Once discharge initiates, its propagation speed and stability are similarly governed by microscopic parameters. The electric field strength required to maintain ionization and forward propagation at the streamer tip is also related to air

density. Low-density air facilitates the maintenance and extension of the streamer channel, potentially accelerating its propagation speed and increasing the number of branches. The formation of the leader channel depends on sufficient Joule heating at the streamer root. Under low-pressure conditions, due to low gas density and reduced heat dissipation, heat accumulates more readily at the root of the streamer. This may lower the energy threshold required for the streamer to transition into a leader, thereby promoting the early formation of the leader. Once the leader is formed, its high conductivity will strongly distort the electric field ahead of it, greatly accelerating the final breakdown process.

Changes in altitude contribute to a decrease in gap insulation strength by both lowering the discharge initiation threshold and promoting discharge development; macroscopically, this manifests as a reduction in breakdown voltage. The computational results of the model in this paper agree well with experimental data from different altitudes. The fundamental reason for this is that the model corrects key discharge parameters, such as the critical breakdown electric field strength and the ionization coefficient, by introducing the relative air density δ , thereby intrinsically reflecting the changes in the aforementioned microscopic physical processes in the calculations. While the simulated values show consistent trends, slight numerical discrepancies may stem from the model's idealized treatment of highly nonlinear factors such as the dynamic distribution of space charge and the complex surface states of electrodes; these factors introduce additional statistical dispersion and uncertainty in real-world experiments. The accuracy of the model's predictions provides a theoretical tool with good extrapolation capability for calculating safety clearance distances for live-line operations at high altitudes and with complex electrode configurations, thereby reducing experimental costs.

The quantitative results demonstrate that the model maintains excellent predictive consistency across all altitude gradients. At an altitude of 23 m, the MRE is 2.12% with a Maximum Deviation of 2.86%. As the altitude increases to 2000 m and 3000 m, the model's MRE remains bounded at 3.65% and 1.24%, respectively. This highly bounded error profile proves that by directly integrating the relative air density δ and absolute humidity H into the microscopic discharge parameter corrections, the model effectively captures the macroscopic altitude effects, confirming its high reliability for engineering clearance design in diverse geographical regions.

5. Conclusions

This paper proposes a computational model that accounts for time-varying electric fields and space charge coupling to calculate the 50% switching impulse discharge voltage for equipotential live-line work gap at different altitude. To comprehensively verify the accuracy and general applicability of the model in practical engineering applications, the research team conducted breakdown tests of equipotential live-line work gap at elevations of 23 m and 2100 m, and systematically compared the test data from the simplified electrode model with that from the full scale model. At the same time, this paper references published experimental data from regions at different altitudes for comparison and conducts multi-source data validation. The main conclusions are as follows:

- (1) In the simplified electrode model, the electric field distribution is relatively regular. The simulation results obtained from the model in this paper show excellent agreement with experimental data, thereby validating the effectiveness of the model's core physical field calculations and the streamer injection and leader development criteria. However, in full scale model tests that more closely mimic real-world operating conditions, the simulation results show significant discrepancies from the experimental data due to the complex electric field distribution and the presence of multiple local distortions. This reflects the model's idealized treatment of extreme nonlinear

physical phenomena, such as the complex shielding effects of space charge and the random nature of the streamer-to-leader transition during actual discharge processes. Nevertheless, the model accurately predicts the trend in breakdown voltage under both configurations, demonstrating its continued applicability and engineering value for complex electrode configurations.

- (2) Both experimental and simulation data consistently show that, for a given gap distance, the breakdown voltage decreases significantly with increasing altitude. Increased altitude leads to a decrease in atmospheric pressure and a reduction in the relative density of air. This results in an increase in the mean free path of electrons and an increase in the effective ionization coefficient, thereby lowering the threshold electric field strength required for the initiation and development of streamer injection and promoting the transition of streamer injection to a leader. These changes in the microscopic processes ultimately manifest macroscopically as a significant decrease in breakdown voltage with increasing altitude for the same gap distance.
- (3) A comparison of experimental data for different spherical electrode radius reveals that, at the same altitude and gap distance, increasing the electrode radius of curvature significantly raises the breakdown voltage. This is because a larger radius of curvature reduces the concentration of the electric field on the electrode surface, thereby increasing the corona initiation voltage and the streamer initiation voltage. This clearly indicates that when establishing safety procedures for live-line work in high-altitude regions, the shape of the worker's shielding suit and the equivalent radius of curvature of protruding body parts must be incorporated as key design factors, rather than relying solely on the idealized electrode assumption.
- (4) The proposed dynamic physical model presents significant advantages and broad future research prospects. Its primary advantage lies in the ability to accurately predict breakdown characteristics without relying on static, geometry-dependent empirical correction factors. By intrinsically coupling micro-physical discharge processes with macroscopic meteorological parameters, this model significantly reduces the reliance on costly, logistically prohibitive, and dangerous full-scale field tests in extreme high-altitude environments. Looking forward, future research will focus on extending the current computational framework to account for more complex, coupled environmental factors, such as the impact of severe salt spray and varying ambient humidity on corona initiation and discharge development. Additionally, integrating this specialized numerical physical model with advanced artificial intelligence frameworks, such as Large Language Models, presents a highly promising pathway to establish an intelligent, multi-agent predictive maintenance system for power grid equipment. This integration will further enhance the long-term operational safety, defect hazard analysis, and reliability of UHV/EHV transmission corridors.

Author Contributions: Conceptualization: Y.P. and R.-X.Q.; Methodology: Y.P., X.-L.L. and K.L.; Formal analysis and investigation: K.L., Z.-H.Q. and B.X.; Writing—original draft preparation: X.-L.L., Z.-H.Q. and Y.-D.Z.; Writing—review and editing: Y.P. and R.-X.Q.; Funding acquisition: Z.-H.Q. and B.X.; Resources: K.L., Z.-H.Q. and Y.-D.Z.; Supervision: Y.P. All authors have read and agreed to the published version of the manuscript.

Funding: The authors declare that this study received funding from State Grid Electric Power Technology Co., Ltd. under Grant Agreement No [5500-202455164A-1-1-ZN].

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: Authors Yong Peng, Rui-Xun Qiao, Xing-Lie Lei, Kai Liu and Bin Xiao were employed by the company China Electric Power Research Institute. Author Zhong-Hua Qiu was employed by the State Grid Sichuan Extra High Voltage Company. Author Ya-Di Zhang was employed by the company State Grid Corporation of China Southwest Branch. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. The funder was not involved in the study design, data collection, analysis, interpretation of data, the writing of this article, or the decision to submit it for publication.

Abbreviations

The following abbreviations are used in this manuscript:

EHV Extra High Voltage
UHV Ultra High Voltage

References

- Ren, S.; Bao, R.; Gao, Z. Arrival of distant power: The impact of ultra-high voltage transmission projects on energy structure in China. *Energy* **2025**, *316*, 134527.
- Han, X.; Sun, X.; Chen, H.; Qiu, N.; Lv, D.; Wang, N.; Wang, X.; Zhang, J. Review on the Development of UHV AC Transmission Engineering Technology in China. *Proc. CSEE* **2020**, *40*, 4371–4386+4719.
- Zhou, Y.; Chen, J.; Zhang, L.; Zhang, Y.; Teng, C.; Huang, X. Development Opportunities for UHV Power Transmission Technology under the Background of “Dual Carbon” Goals and “New Infrastructure” Initiative. *High Volt. Eng.* **2021**, *47*, 2396–2408.
- Lei, X.; Sun, X.; Wang, W.; Liu, L.; Li, X.; Pang, G. A Characterization Method for Coupling Relation in Multi-Infeed HVDC System. *Electr. Power* **2021**, *54*, 66–73. [[CrossRef](#)]
- Zhang, K.; Zhang, C.; Zhou, Z.; Liu, Z.; Deng, Y.; Gu, C.; Zhou, S.; Sun, D.; Liu, H.; Yu, X. An Ensemble Learning Model for Aging Assessment of Silicone Rubber Considering Multifunctional Group Comprehensive Analysis. *Polymers* **2025**, *17*, 2988.
- Gao, C.; Luo, K.; Li, L.; Guo, J.-R.; Lu, M.; Xu, Z.-Y. Sample Analysis of Failed Large Tonnage Porcelain Insulators on UHV DC Overhead Transmission Lines. *J. Electr. Eng. Technol.* **2024**, *20*, 1–13.
- Liu, Z.; Fan, S.; Cai, S.; Huang, R.; He, G. Optimal dispatch method for virtual capacity expansion of distribution transformer station area considering economic cost. *IET Conf. Proc.* **2025**, *2024*, 197–203.
- Santos, G.R.; Zancul, E.; Manassero, G.; Spinola, M. From conventional to smart substations: A classification model. *Electr. Power Syst. Res.* **2024**, *226*, 109887.
- Zhang, Q.; Wang, L.; Fang, Y.; Liu, K.; Gao, J. Simulation Analysis Method of Discharge Characteristics for the Gap between Equipotential Operator and Tower Frame. *Trans. China Electrotech. Soc.* **2019**, *34*, 2415–2423.
- Citroni, R.; Di Paolo, F.; Livreri, P. A Novel Energy Harvester for Powering Small UAVs: Performance Analysis, Model Validation and Flight Results. *Sensors* **2019**, *19*, 1771.
- Fang, Y.; Wang, L.; Li, R.; Liu, K.; Song, B. Switching Impulse Discharge Characteristics and Discharge Voltage Correction for Live Working in High Altitude Areas. *Trans. China Electrotech. Soc.* **2020**, *35*, 2681–2688.
- Gao, J.; Wang, L.; Li, G.; Fang, Y.; Song, B.; Xiao, B.; Liu, K. Discharge of Air Gaps During Ground Potential Live-Line Work on Transmission Lines. *Electr. Power Syst. Res.* **2020**, *187*, 106519.
- Yang, B.; Ding, Y.; Ma, X.; Lu, Z.; Yao, X.; Su, Y. Altitude Correction of Switching Impulse Breakdown Voltage for Rod-Plane Long-Gap Based on OT-IRM Algorithm. *IEEE Trans. Power Deliv.* **2025**, *40*, 548–557.
- Fang, Y.; Wang, L.; Li, R.; Song, B.; Gao, J.; Liu, K. Simulation Calculation on Discharge Characteristics of Live Working Gap on EHV/UHV Transmission Lines. *Power Syst. Technol.* **2020**, *44*, 4435–4444.
- Fang, Y.; Mao, S.; Yang, B.; Fang, J.; Zeng, H.; Tian, S. Development Characteristics of Leader Discharge Channel in Sphere-Plate Gap at Different Altitudes. *High Volt. Eng.* **2025**, *51*, 3089–3099.
- Liliana, A.; Oscar, D.; Yury, S. Experimental investigation of air breakdown voltage at different altitude conditions. *IET Conf. Proc.* **2025**, *2023*, 243–247.
- Ning, W.; Chen, Y.; Zhang, Y.; Zhang, G.; Shen, S.; Huang, X.; Jia, S. Effects of temperature and humidity on short-uniform air gap breakdown at elevated altitude. *J. Phys. D Appl. Phys.* **2026**, *59*, 015204.
- Wang, B.; Yue, S.; Wu, Y.; Ding, Y.; Zhang, Z.; Hou, T.; Han, J. Study on the safety distance technology of live working on 220 kV transmission lines in high altitude areas. *Power Syst. Prot. Control* **2017**, *45*, 158–162.
- Fang, Y. Research on Discharge Model of EHV/UHV Transmission Lines Live Working Gap in High Altitude Environment. Ph.D. Thesis, Wuhan University, Wuhan, China, 2019. [[CrossRef](#)]

20. Lv, X.; Wu, J.; Zhu, L.; Ma, X. Feasibility analysis of live working for 110 kV transmission line in high altitude area of Naqu. *Zhejiang Electr. Power* **2019**, *38*, 67–71.
21. Wang, P.; Xiao, Z.; Wang, X.; Chen, Y.; Ding, Y.; Geng, J. Discharge inception time delay characteristics under positive switching impulse at high altitude. *High Volt. Eng.* **2022**, *48*, 857–864.
22. Feng, Q.; Huang, L.; Liu, D.; Wu, J.; Qi, H.; Dang, Z. Negative corona discharge characteristics of needle-plate and rod-plate electrode structures at different temperatures. *High Volt. Eng.* **2021**, *47*, 1847–1856.
23. Waters, R.T. Positive discharges in long air gap discharges at Les Rnardières–1975 results and conclusions. *Electra* **1977**, *53*, 31–153.
24. Cheng, Z.; Li, X.; Wu, W.; Tian, Z.; Ge, C.; Ye, Q. Spatial distribution of corona currents and port measurement methods. *J. Phys. D Appl. Phys.* **2026**, *59*, 015004.
25. Lv, F.; Liu, X.; Wang, Q.; Wang, P.; Geng, J.; Ding, Y.; Chen, Y. Random development characteristics of streamer discharge path under positive switching impulse voltage. *J. North China Electr. Power Univ. (Nat. Sci. Ed.)* **2023**, *50*, 9–18.
26. Abdel-Salam, M.; Al-Abdul-Latif, U. Simulation of energized Franklin rods for lightning protection. *IEEE Trans. Ind. Appl.* **2002**, *33*, 651–659.
27. Ruan, J.; Tang, L.; Qiu, Z.; Huang, D.; Liao, Y.; Huang, C. Breakdown voltage calculation of short air gaps with sphere-plane-sphere electrodes based on streamer inception criterion. *High Volt. Appar.* **2017**, *53*, 38–44. [[CrossRef](#)]
28. Bondiou, A.; Gallimberti, I. Theoretical modelling of the development of the positive spark in long gaps. *J. Phys. D Appl. Phys.* **1994**, *27*, 1252–1266.
29. Lei, Y.; Cai, G.; Pan, C. Electric field intensity and critical length of initial streamer region in lightning striking wind turbine blades under atmospheric conditions. *Trans. China Electrotech. Soc.* **2019**, *34*, 4392–4399.
30. Gu, S.; Xie, S.; Xiang, N.; He, J.; Yan, B.; Li, T. Three-dimensional physical simulation of streamer-leader propagation in long air gap under positive polarity. *High Volt. Eng.* **2014**, *40*, 2903–2910.
31. Gallimberti, I. The mechanism of the long spark formation. *J. Phys. Colloq.* **1979**, *40*, C7-193–C7-250.
32. Arevalo, L.; Wu, D.; Jacobson, B. A consistent approach to estimate the breakdown voltage of high voltage electrodes under positive switching impulses. *J. Appl. Phys.* **2013**, *114*, 083301–083308.
33. Fang, Y.; Mao, S.; Yang, B.; Gao, J.; Zhang, X. Development characteristics of streamer inception in sphere-plane gap under positive switching impulse at high altitude. *Trans. China Electrotech. Soc.* **2024**, *39*, 6175–6186.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.