

Article

Research on Safety Distance Calculation and Altitude Correction Methods for On-Site Withstand Voltage Tests of UHV AC Equipment

Wenlong Liao ¹, Yueping Yang ¹, Xiaoxu Ma ², Yu Tian ² and Yujian Ding ^{2,*}¹ State Grid Sichuan Electric Power Research Institute, Chengdu 610041, China² School of Electrical Engineering, Beijing Jiaotong University, Beijing 100044, China

* Correspondence: hv_cepri@126.com

Featured Application

The proposed method can be applied to on-site withstand voltage testing of UHV AC equipment under varying altitude conditions. It provides a quantitative basis for determining minimum safety distances and optimizing test configuration and isolation strategies, thereby improving testing safety and the reliability of insulation performance assessment, particularly in high-altitude and complex environmental conditions.

Abstract

On-site withstand voltage testing is essential for evaluating insulation performance and detecting defects in UHV AC equipment; however, existing safety distance criteria are mainly based on empirical experience or extrapolated from low-altitude and lower-voltage conditions, limiting their applicability. To address this issue, a systematic framework for safety distance calculation and altitude correction is developed. The selection principles and circuit configuration of the test system are analyzed to clarify the constraints between power capacity and tuning under high-voltage, large-capacity conditions. Based on air-gap discharge characteristics, a minimum safety distance model is established for the 1000 kV main transformer with respect to grounded structures and personnel. Meteorological factors and proximity effects are further incorporated to propose correction methods and on-site zoning strategies. Results indicate that a baseline safety distance of approximately 10 m is appropriate at altitudes up to 1000 m, and the model captures the nonlinear degradation of insulation strength in long air gaps at higher altitudes. A case study at 3620 m yields a minimum safety distance of 16.4 m, providing a quantitative basis for safe UHV AC on-site testing under varying altitude conditions.



Academic Editors: Alexander Barkalov, Larysa Titarenko and Kazimierz Krzywicki

Received: 15 April 2026

Revised: 27 May 2026

Accepted: 27 May 2026

Published: 2 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.

Keywords: UHV AC; on-site withstand voltage test; safety distance; air gap discharge

1. Introduction

With the continuous growth of electricity demand and the uneven spatial distribution of energy resources, the development of safe and efficient long-distance bulk power transmission systems has become increasingly important [1]. Ultra-high voltage (UHV) transmission technology has been widely adopted due to its advantages of large capacity and low transmission loss [2]. On-site withstand voltage testing is essential for verifying insulation performance of UHV AC equipment prior to commissioning [3]. Among various test parameters, the rational design of air-gap safety distance is critical for ensuring test

reliability and the safety of personnel and equipment [4–6]. Safety distance is jointly determined by multiple factors, including electrical clearance, personnel isolation, and electric field distortion margins [7].

Current practices primarily follow national standard recommendations combined with voltage level, altitude, and environmental conditions, using correction factors and empirical margins [8]. Existing standards are mainly based on normal atmospheric conditions below 1000 m altitude. However, under high-altitude conditions, reduced air density decreases breakdown field strength and alters discharge characteristics [9–12]. As altitude increases, the increased mean free path of electrons makes air gaps more susceptible to discharge, reducing insulation margins. Direct extrapolation of standard conditions thus leads to either overly conservative designs or insufficient safety margins. This issue becomes particularly prominent above 4000 m, affecting test accuracy and operational safety. Moreover, current standards provide no explicit correction factors for high-altitude AC withstand voltage testing, resulting in a lack of unified design guidance [13].

In engineering practice, the typical workflow of altitude correction using empirical coefficients followed by field simulation exhibits notable limitations: empirical formulas cannot capture nonlinear discharge characteristics and safety margins lack standardized determination criteria [8]. Consequently, the current standard system remains insufficient for guiding safety distance design at high altitudes [14]. In practice, excessive reliance on empirical margins leads to larger spatial requirements and reduced site utilization efficiency, while overly conservative margins may even increase operational risk under constrained plateau conditions [15]. Therefore, a minimum safety clearance model and an associated correction framework tailored for high-altitude UHV testing is necessary.

To address these challenges, this study develops a minimum safety distance model based on air-gap discharge characteristics for typical energized components relative to grounded structures and personnel. A correction framework considering meteorological conditions, proximity effects, and local electric field characteristics is proposed, together with an on-site zoning strategy. Distinct from existing standards that rely on single altitude correction factors or empirical margins, the core contribution is a quantifiable, multi-factor coupled framework. Specifically, three innovations are presented: first, the test amplification factor K_{test} , taken as 2.4; second, the proximity effect is introduced as an independent correction factor K_{prox} , taken as 1.08, to quantify the influence of adjacent grounded structures; third, a four-step calculation strategy—“baseline distance–altitude correction–proximity correction–safety margin”—is established and validated using field data from Aba and Ganzi substations, yielding a recommended minimum safety distance of 16.4 m. Together, these contributions address the inadequacy of current standards for long air gaps at high altitudes and provide a quantitative design basis for on-site UHV AC testing.

2. Withstand Voltage Tests and Requirements for Ultra-High Voltage Transformers

On-site withstand voltage tests are the most direct and effective method for assessing the insulation strength of transformers. Depending on the nature of the applied voltage and the test subject, transformer withstand voltage tests are primarily categorized into power-frequency AC withstand voltage tests, impulse withstand voltage tests (lightning impulse and switching impulse), and on-site partial discharge tests, each with distinct test objectives, voltage requirements, waveform parameters and safety distance requirements.

2.1. Power-Frequency AC Withstand Voltage Test

The core of the power-frequency AC withstand voltage test lies in simulating the power-frequency voltage that the equipment is subjected to during actual operation, thereby verifying the performance of its main insulation and longitudinal insulation. Figure 1 shows a schematic diagram of the power-frequency AC withstand voltage test. In on-site testing of ultra-high-voltage transformers, to prevent voltage waveform distortion or the masking of partial discharge signals, the test frequency must generally strictly adhere to the provisions of standards such as GB/T 1094.3–2023 [16], being controlled within the range of 45 Hz to 65 Hz and as close as possible to the 50 Hz power frequency.

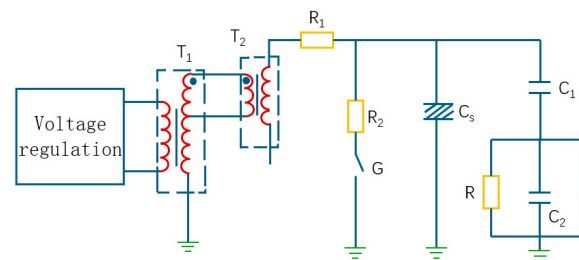


Figure 1. Schematic diagram of a power-frequency AC withstand voltage test.

Furthermore, given the intense electromagnetic radiation and the risk of air gap breakdown associated with ultra-high voltage levels of 1000 kV and above, an isolation zone must be established on site that extends far beyond that required for conventional 220 kV equipment (typically greater than 5 m). Test personnel must strictly recalculate safety distances in accordance with the on-site supervision regulations for ultra-high-voltage systems to ensure the absolute safety of personnel and surrounding live equipment. The derived test voltage of 953 kV (peak value 1348 kV) serves as the key input parameter for the subsequent safety distance calculation.

2.2. Impulse Withstand Voltage Test

On-site impulse tests for transformers comprise two categories: lightning impulse tests and switching impulse tests. These are key tests for assessing the transformer's insulation's ability to withstand lightning overvoltage and switching overvoltage. Compared to laboratory conditions, on-site testing is subject to multiple factors such as site conditions, environmental climate and nearby live equipment, resulting in significantly increased technical difficulty and safety risks [17]. Among these, the accurate setting of the test voltage amplitude is a prerequisite for ensuring the effectiveness of the assessment, whilst the establishment of safety distances constitutes the baseline for safeguarding personal and equipment safety. In accordance with IEC 60076–3:2018 [18] and in conjunction with the relevant provisions of GB/T 1094.3–2023 [16] and DL/T 1947–2018 [11], the main technical parameters for the test are determined as shown in the Table 1.

Table 1. Comparison of key technical parameters for impulse withstand voltage testing.

Item	Lightning Impulse Test	Switching Impulse Test
Rise time (T1)	$1.2 \mu\text{s} \pm 30\%$	$250 \mu\text{s} \pm 20\%$
Half-peak duration (T2)	$50 \mu\text{s} \pm 20\%$	$2500 \mu\text{s} \pm 60\%$
Number of applications	15 applications each for positive and negative polarity	10 cycles each for positive and negative polarity
Amplitude Control Deviation	90–110% of rated value	90–110% of rated value
Interval Time	≥ 1 min (to ensure insulation recovery)	≥ 1 min (to ensure insulation recovery)
Main Waveform Scheme	Standard full-wave	Oscillatory switching impulse (higher sensitivity)

The high-voltage and high-energy impulses impose stringent requirements on the on-site grounding system. Before and after each impulse test, the condition of the equipment and the safety clearances shall be re-verified in accordance with DL/T 1947-2018.

2.3. On-Site Partial Discharge Testing

Partial discharge testing is a highly sensitive method for detecting minute ageing and hidden defects in insulation systems. Ultra-high-voltage main transformers predominantly employ single-phase split-core autotransformers with neutral-point voltage regulation without excitation. Structurally, they consist of two parts: the main transformer (hereinafter referred to as the “main transformer”) and the voltage-regulating compensation transformer (hereinafter referred to as the “voltage-regulating compensation transformer”), with the internal connection of their windings shown in Figure 2. In the figure, A—1X denotes the high-voltage winding of the main transformer; Am—1X denotes the medium-voltage winding of the main transformer; 1a—1x denotes the low-voltage winding of the main transformer; 2X—X denotes the voltage-regulating winding; 2a—2x denotes the voltage-regulating excitation winding; 3X—X denotes the compensation excitation winding; and 2x—x denotes the compensation winding. CV denotes the control voltage; LV denotes the low-voltage winding; LT denotes the line terminal; LE denotes the earth terminal; EV denotes the excitation voltage; and TV denotes the test voltage.

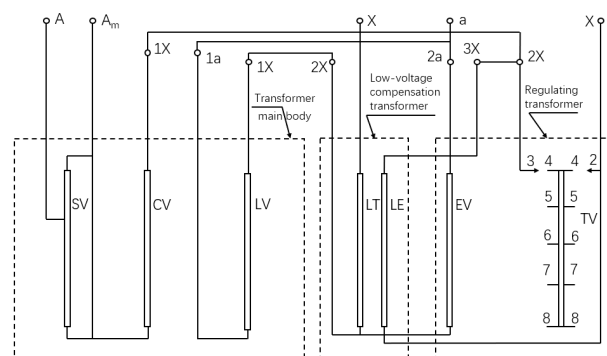


Figure 2. Wiring diagram of a 1000 kV transformer winding.

To prevent irreversible damage to complex insulation structures caused by voltage surges, partial discharge testing of the main transformer must strictly comply with the requirements of technical standards such as DL/T 1947–2018. The pre-applied voltage, measurement voltage steps and voltage application procedure for on-site partial discharge testing are shown in Figure 3. The horizontal axis represents the applied voltage duration, and the vertical axis represents the voltage magnitude.

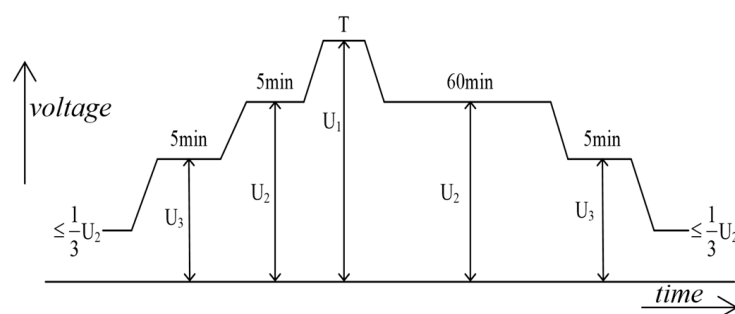


Figure 3. Schematic diagram of the voltage application procedure for partial discharge testing of the main body.

The stringent partial discharge limit directly motivates the introduction of the test amplification factor K_{test} in Section 3.3, as excessive background corona would mask the true internal PD signals.

With regard to discharge level assessment, 1000 kV ultra-high-voltage transformers must comply with extremely stringent standards; in accordance with the GB/T 24846–2018 [10] standard, the partial discharge levels at the high-, medium- and low-voltage terminals are limited to 100 pC, 200 pC and 300 pC, respectively. Should test data exceed these limits, serious safety hazards such as defects in the high-voltage bushing's equalizing sphere or loosened internal fasteners are likely to occur. As interference from high-frequency power sources and external corona discharges in the field environment can easily lead to data distortion, actual testing must adhere to the single-point earthing principle and incorporate anti-corona equalizing rings.

3. Analysis of the Selection of Test Safety Distances

3.1. General Requirements for Test Distances

In high-voltage testing technology, the interaction of electric fields between the test specimen and surrounding live parts or earth electrodes (proximity effect) significantly influences its discharge characteristics. Therefore, the arrangement of the test specimen must comprehensively consider factors such as the distance between the specimen and other live or earthed devices, the height above ground (which should simulate actual operating conditions), and the routing and fixing methods of the high-voltage leads. These parameters are generally specified by the relevant technical committees based on the specific equipment type and test objectives.

To eliminate the interference of the proximity effect on test results, the clear distance between the test specimen and external components must be controlled to be no less than 1.5 times the shortest discharge path of the specimen itself; at this distance, the proximity effect can be considered negligible. However, under special test conditions—such as wet tests, artificial pollution tests, or other scenarios where the voltage distribution on the test specimen and the surrounding electric field are unaffected by external objects—this distance should be appropriately reduced, provided that no destructive discharge occurs to external components during the test. For tests at higher voltage levels, particularly where the peak value of the AC or positive-polarity impulse voltage exceeds 750 kV, stricter criteria must be applied to suppress the proximity effect. In such cases, provided that the distance between the live electrode and the adjacent object is not less than its distance to earth, the influence of the adjacent object may be considered negligible [19]. For the convenience of engineering applications, reference may be made to the relationship curve between the maximum test voltage and the minimum permissible distance between the high-voltage electrode and the earth electrode or external live body, as shown in Figure 4. This curve is derived from extensive test data and electric field analysis, and illustrates the non-linear growth trend of distance requirements at high voltages. For special structures or test requirements where a clear distance smaller than the values shown in the figure is required, verification must be carried out based on experimental results or through precise electric field calculations to ensure sufficient insulation margin. In Figure 4 the fitted equation for AC in the range $1 \text{ m} \leq d \leq 10 \text{ m}$ is $U_{\text{peak}} = 560 d^{0.75}$.

Furthermore, during dry tests, the test specimen itself should be kept dry and clean, and the test should be conducted under the ambient atmospheric conditions of the test area to ensure the standardization and repeatability of the test.

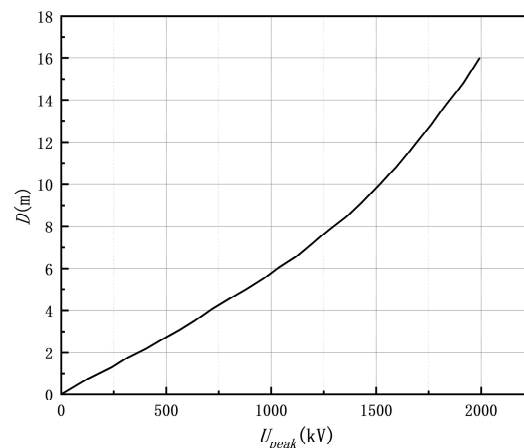


Figure 4. Maximum test voltage versus minimum clear distance for AC or positive switching impulse with a rod-plate gap. (Standard reference atmosphere is 101.3 kPa, 20 °C, 11 g/m³ according to IEC 60060-1:2010 [20]. Data sources are IEC 60060-1:2010 Annex D.1 and GB/T 16927.1–2011 [21].)

3.2. Requirements for Safety Clearances in Impulse Withstand Voltage Tests

The rod-to-plate gap, as a typical physical model of a highly non-uniform electric field, determines the minimum clearances required within the test chamber based on the magnitude of the discharge voltage. The discharge curves for lightning impulse tests and operational impulse tests are shown in Figure 5.

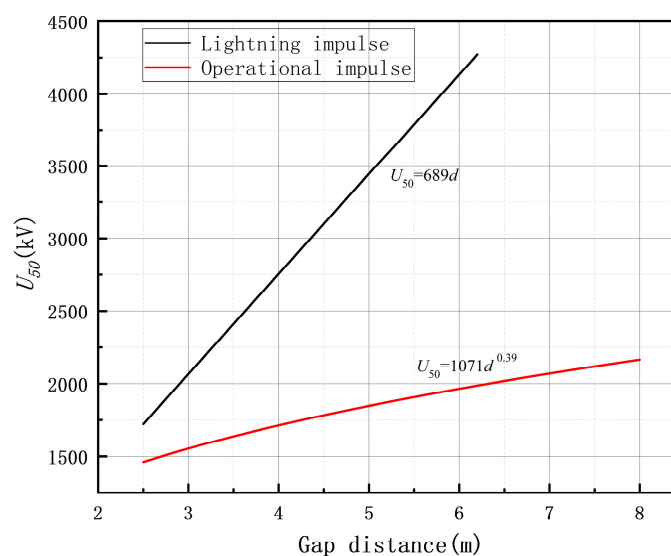


Figure 5. Discharge curves for lightning impulse and switching impulse under standard atmospheric conditions (conductor–structure gap; standard reference atmosphere is 101.3 kPa, 20 °C, 11 g/m³ according to IEC 60060-1:2010 [20].).

To ensure that power transformers do not experience external flashover when subjected to various types of overvoltage intrusion, the design of their external insulation air gaps must be strictly based on the characteristics of air discharge. In accordance with the provisions of the national standard GB/T 1094.3–2023 [16], the test safety distance must take into account the discharge characteristics under both lightning impulse and switching impulse waveforms. For operating conditions where the rated lightning impulse level does not exceed 850 kV, the standard explicitly states that the straight-line distance clearance between the line terminal and ground should primarily refer to the rod-to-plate electrode clearance configuration model in IEC 60071-1:2023 [22].

When the system voltage level increases and the lightning impulse withstand voltage reaches or exceeds 850 kV, the design basis for air gaps shifts from the basic rod-to-plate gap model to the conductor-to-support gap model to reflect the electric field distribution at the ends of high-voltage bushings and connection points in actual engineering applications [3]. In operational impulse tests, however, due to the longer rise time of the wavefront, the insulation strength of the air gap exhibits a distinct saturation effect. The specific minimum air gap requirements for different equipment voltage levels and their corresponding impulse voltage ratings are detailed in the Table 2.

Table 2. Impulse withstand voltage ratings and minimum air gap requirements for equipment at different voltage levels.

Maximum Voltage of the Equipment U_m (kV)	Rated Lightning Impulse Withstand Voltage (kV, Peak)	Rated Operational Impulse Withstand Voltage (kV, Peak)	Minimum Air Clearance: To Earth (mm)	Minimum Air Clearance: Between Phases (mm)
12	75	-	125	125
40.5	200	-	220	220
72.5	325	-	320	320
126	480	-	450	450
252	850	750	1600	1800
252	950	850	1800	2000
363	1050	850	2300	2600
363	1175	950	2600	3100
550	1425	1050	3400	4100
550	1550	1175	4000	4900

The standard contains specific provisions regarding insulation requirements for neutral terminals, with the safety clearance adjusted according to the level of the neutral point's lightning impulse withstand voltage.

Further tests on the discharge characteristics of long air gaps under low atmospheric pressure have shown that, when the operating altitude of main equipment such as transformers exceeds 1000 m, the reduction in air density causes a significant decline in insulation performance. For typical structures (such as rod-to-rod gaps and rod-to-plate gaps) at equivalent gap distances, the $U_{50\%}$ discharge voltage exhibits a marked reduction; therefore, it is essential to introduce corresponding atmospheric parameter correction models to adjust the discharge voltage. Given that atmospheric pressure is a composite reflection of atmospheric parameters such as air density, ambient temperature and humidity, non-linear formulas incorporating atmospheric characteristic indices are currently the primary method used to model the discharge voltage correction process in high-altitude regions.

To establish the correction relationship for air-gap discharge voltage under high-altitude conditions, the altitude correction factor K_a is introduced, defined as the ratio of the discharge voltage under test conditions to that under standard atmospheric conditions:

$$K_a = \frac{U_H}{U_0} \quad (1)$$

where U_H is the discharge voltage at altitude H and U_0 is the discharge voltage under standard atmospheric conditions.

According to gas discharge theory and similarity laws, the discharge voltage of an air gap mainly depends on air density, and the two follow a power-law relationship:

$$K_a \propto (\delta)^n \quad (2)$$

n is the atmospheric characteristic exponent representing the influence of air pressure on external insulation discharge voltage and δ is the air density.

Within the troposphere ($H < 11$ km), according to the International Standard Atmosphere (ISA) model, the variation in air density with altitude can be expressed as:

$$\delta = \left(1 - \frac{H}{45.1}\right)^{5.36} \quad (3)$$

In summary, based on further derivation with respect to altitude, the atmospheric parameter correction factor can be further expressed as a function of altitude H [23]:

$$K_a = \left(1 - \frac{H}{45.1}\right)^{5.36n} \quad (4)$$

By calculating the average atmospheric characteristic index under different voltage waveforms, such as power frequency, lightning impulse and switching impulse, a fundamental theoretical correction factor can be provided for the verification of air gaps in on-site withstand voltage and partial discharge tests.

In engineering practice, there is a significant difference in magnitude between the design clearance of the equipment's external insulation and the temporary safety operating distance required for on-site testing. Taking a 1000 kV ultra-high-voltage substation as an example, the comparison table of design air clearances and on-site testing safety distances is shown in the Table 3.

Table 3. Comparison table of design air clearances and on-site testing safety distances for 1000 kV ultra-high-voltage equipment.

Dimension/Altitude	Altitude ≤ 1000 m (Standard Environment)	Altitude 3700 m (High-Altitude Environment)
Power-frequency design clear air gap (A1)	4.2 m	5.3 m
Operational surge design clear air gap (A2)	7.5 m	9.5 m
Safety distance verified by on-site testing	10 m	15.3 m
Test magnification factor (K_{test})	Approx. 2.4 times	2.4 (based on the ratio at low altitudes)
Proximity effect correction factor (K_{prox})	-	1.08

As can be seen from the table above, when extrapolating this test scenario to ultra-high-altitude regions of 3700 m, simple theoretical atmospheric pressure corrections are insufficient to ensure test safety. Electric field distortions caused by adjacent grounding bodies in the on-site layout may result in a reduction of approximately 8% in the breakdown voltage.

Furthermore, when conducting on-site withstand voltage and partial discharge tests for UHV systems, corona discharge interference—which is highly prone to occurring at the high-voltage end—can be suppressed by installing appropriately sized corona-free rings or anti-corona hoods. The overall outer diameter of the 1000 kV side equalizing ring typically needs to be 2600 mm or greater. The massive equalizing hood reshapes the local electric field distribution and significantly affects the clearance factor within the insulation breakdown voltage correction system, thereby directly influencing the assessment of the overall external insulation clearance breakdown voltage and the final determination of the test safety distance.

3.3. Safety Distance Requirements for Power-Frequency and Partial Discharge Withstand Tests

In UHV AC on-site withstand voltage tests, long-duration power-frequency withstand tests are typically conducted in conjunction with partial discharge tests, i.e., long-duration induced withstand tests combined with partial discharge tests, the discharge characteristic curve of which is shown in Figure 6.

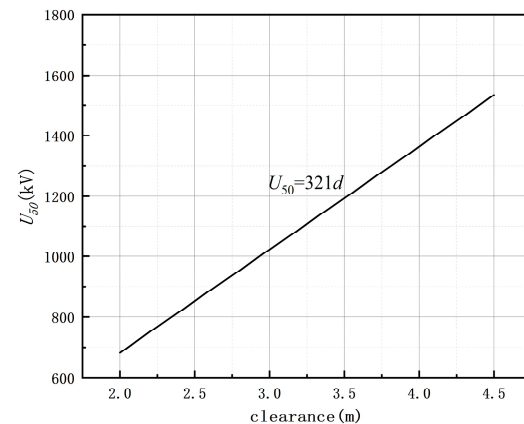


Figure 6. Discharge characteristic curve for short-duration power-frequency tests. Under standard atmospheric conditions (conductor–structure gap; data were obtained from experiments conducted at the UHV DC Test Base in Changping, Beijing, at an altitude of 55 m, which is approximately equivalent to standard atmospheric conditions).

In order to accurately define the safe test distance for field tests under standard atmospheric conditions at low altitudes (≤ 1000 m), rigorous simulations must be conducted based on specific voltage application procedures. According to the voltage application standards for partial discharge testing of UHV main transformers, the maximum test voltage (rms) U_{test} is typically set at 1.5 times the maximum operating phase voltage of the equipment, calculated as follows:

$$U_{test} = \frac{1.5U_m}{\sqrt{3}} = \frac{1.5 \times 1100}{\sqrt{3}} \approx 953(\text{kV}) \quad (5)$$

Since ionization and breakdown in air gaps primarily depend on the peak electric field strength of the applied voltage, this rms value must be converted to the peak test voltage U_{peak} :

$$U_{peak} = 953 \times \sqrt{2} \approx 1348(\text{kV}) \quad (6)$$

Referring to the power-frequency discharge characteristic curve for rod-to-plate gaps, long-duration alternating electric fields cause space charge to migrate and accumulate extensively within an extremely non-uniform electric field. Under standard atmospheric conditions (low altitude ≤ 1000 m), to withstand a power-frequency voltage with a peak of 1348 kV, the purely theoretical minimum electrical clearance (i.e., the critical distance for breakdown discharge) is approximately 4.2 m [24].

However, in field tests for partial discharges in ultra-high-voltage equipment, the design threshold for safety distances is far higher than the simple “breakdown prevention” critical value. The core limiting factors lie in the suppression of corona discharge and the attenuation of proximity effects. Given the extremely stringent standards for partial discharge in 1000 kV transformers (with a requirement of ≤ 100 pC for partial discharge at the high-voltage end), if the air gap is maintained at only the theoretical clearance of 4.2 m, the surface of the high-voltage end and surrounding earth electrodes would very easily reach the threshold for air ionization, thereby triggering intense corona discharge. These high-frequency pulse currents generated by external air ionization will enter the

measurement circuit via spatial electromagnetic coupling and conduction, completely masking the true, faint partial discharge signals within the transformer and causing the test to fail.

Therefore, in practical engineering applications, the on-site test safety distance D_{safe} must be calculated by applying a test amplification factor K_{test} —which incorporates margins for corona suppression and spatial electric field distortion—to the theoretical air clearance. Based on engineering statistics and electric field simulation experience, the test amplification factor for UHV testing at low altitudes is typically set at around 2.4. The value of 2.4 is not an empirical assumption, but an engineering-equivalent amplification factor derived from standard-based comparisons. According to GB/T 24842, under standard atmospheric conditions, the theoretical minimum air clearance corresponding to a 1000 kV power-frequency voltage is approximately 4.2 m. In contrast, based on DL/T 1275–2013 [25], an air clearance of about 10 m is typically required in on-site testing to ensure operational reliability. The ratio of these values yields the coefficient (approximately 2.4). This coefficient characterizes the equivalent scaling between ideal discharge conditions and practical test configurations and has been widely adopted in the engineering design of clearances for UHV equipment during on-site testing.

Accordingly, the required test safety distance for low-altitude regions is calculated as follows:

$$D_{\text{safe}} = D_{\text{gap}} K_{\text{test}} \approx 4.2 \times 2.4 \approx 10.08(\text{m}) \quad (7)$$

It should be noted that the above safety distance calculation primarily addresses air-gap breakdown and corona suppression. However, surface discharge along insulating components, such as transformer bushings and grading rings, is another critical factor. Under high-altitude low-pressure conditions, the surface flashover voltage degrades more severely than the breakdown voltage of pure air gaps, due to enhanced surface charge accumulation and desorption of adsorbed gases, which further distort the local electric field. In the context of UHV AC on-site testing, surface discharge can introduce high-frequency interference that compromises partial discharge measurements. Therefore, in practical engineering, additional measures are taken, including optimizing the shape and surface finish of grading rings and increasing creepage distances. For the 1000 kV main transformer studied herein, field experience at low altitudes (≤ 1000 m) confirms that the 10 m safety distance, together with properly designed anti-corona rings, is adequate to suppress surface discharge as well.

In summary, to ensure that no destructive discharges occur during testing, whilst guaranteeing that the spatial electric field strength at the ends of high-voltage bushings relative to ground and surrounding structures remains well below the threshold field strength for air ionization and, to maintain an acceptable level of partial discharge background noise, when conducting 953 kV power frequency and partial discharge tests on 1000 kV main transformers in low-altitude areas (≤ 1000 m), the minimum required test safety distance shall be strictly defined as 10 m.

4. Special Requirements for High-Altitude Areas

In UHV AC on-site withstand voltage tests, the reduction in air gap insulation strength caused by high-altitude environments presents a core challenge for safety distance design. From a microscopic physical perspective, the reduced atmospheric pressure at high altitudes increases the mean free path between air molecules, thereby increasing the kinetic energy gained by electrons as they accelerate in an electric field. This makes them more prone to collision ionization, consequently lowering the breakdown voltage of the air [26]. According to the provisions of GB/T 16927.1-2011 [21], in atmospheric condition corrections, the effect

of altitude is primarily reflected through the relative air density δ , with the correction factor being:

$$k_1 = \delta^m \quad (8)$$

which depends on the combined effect of atmospheric pressure p and temperature t .

For long air gaps at ultra-high voltage levels, the altitude correction is not a simple linear proportion; a dimensionless parameter g must be introduced to characterize the pre-discharge behavior during the discharge process, with g determining the range of values for the correction exponent m . The formula for calculating parameter g is:

$$g = \frac{U_{50}}{500L\delta k} \quad (9)$$

where U_{50} is the peak voltage at which the probability of a destructive discharge occurring in the gap under actual atmospheric conditions is 50%; L is the shortest discharge path length of the test specimen (i.e., the air gap distance); and k is a correction parameter determined based on the voltage type (AC, DC, positive/negative polarity impulse) and the absolute atmospheric humidity.

Under UHV test conditions, due to the extremely high voltage levels and large gap distances, the rate at which breakdown voltage increases with distance slows down. This non-linear characteristic means that in regions above 3000 m altitude, traditional correction methods for altitudes below 1000 m often carry a risk of inaccuracy due to a lack of experimental support at extreme altitudes. Therefore, for high-altitude regions, this paper adopts the m -parameter method of IEC 60071-2:2023 [27] and verifies U_{50} through an iterative procedure. This method primarily considers the influence of altitude on breakdown voltage, assuming that the effects of temperature and humidity approximately cancel each other out.

Taking the Aba UHV substation at an altitude of 3620 m as an example, the controlled test conditions for on-site testing were long-duration induction withstand voltage tests with partial discharge monitoring on the 1000 kV main transformer, with a control voltage as high as 953 kV. In low-altitude regions (≤ 1000 m), the minimum safety distance required for this test voltage is 10 m. The m -parameter method stipulates that the breakdown voltage of air gaps must be corrected according to the following formula:

$$U_t = \frac{U_0}{K_a} \quad (10)$$

where U_t is the voltage value under test conditions, in kV; U_0 is the voltage value under standard atmospheric conditions, in kV; and K_a is the altitude correction factor. When the withstand voltage of external insulation is corrected from standard atmospheric conditions to altitudes below 2000 m, the formula for calculating the atmospheric correction factor K_a is:

$$K_a = e^{m \frac{H-1000}{8150}} \quad (11)$$

where K_a is the altitude correction factor, used to reinforce the external insulation of electrical equipment in areas with an altitude exceeding 1000 m; H is the altitude of the substation or line location, in meters; and m is a correction factor related to the voltage type and gap structure. Under lightning impulse voltage and power-frequency voltage conditions, $m = 1$.

For power-frequency withstand voltage tests, the exponent m is typically taken as 1. When applying altitude correction for the Aba substation at an elevation of 3620 m, the altitude is conventionally rounded up to 3700 m for conservative design, resulting in an altitude correction factor K_a of 1.38.

By combining the baseline clearance at plain areas with the altitude correction factor, the minimum required air clearance for the high-altitude site can be expressed as:

$$D_0 = K_a D_{safe} \quad (12)$$

Finally, using a baseline value of 10 m for plain areas, the minimum required air clearance under high-altitude conditions is calculated to be 13.8 m.

To further verify the applicability of the proposed altitude correction method in practical engineering, a field test at the Ganzi UHV substation located at an altitude of approximately 3500 m was selected as a representative case for analysis. Specifically, the Ganzi substation is situated at an elevation of about 3500 m, and the recorded atmospheric pressure during the transformer partial discharge test was approximately 65–66 kPa. During the test, the actual air gap between the busbar on the steel structure above the transformer and the grading shield of the 1000 kV bushing was approximately 13.2–13.9 m, with an average value of about 13.5 m. Under this gap condition, intermittent corona discharge was observed on the high-voltage-side grading shield. According to the standard altitude correction method, the calculated minimum air clearance is approximately 13.8 m. However, in preliminary voltage-raising tests, when the gap was increased to this calculated value, noticeable corona discharge and initial leader development were already observed, indicating that the theoretical calculation exhibits certain deviations under extreme low-pressure conditions.

Further analysis suggests that, under high-altitude environments, space charge effects become significantly enhanced, leading to distortion of the electric field distribution and consequently reducing corona inception and breakdown voltages. In addition, the influence of nearby grounded structures in the field layout cannot be neglected. According to experimental observations, the proximity effect can reduce the breakdown voltage by approximately 8%, which is consistent with reported results in the literature.

Based on this, the theoretical result is further corrected by introducing both the proximity effect correction and the engineering safety margin. The air clearance can be expressed as:

$$D = D_0(1 + K_1)(1 + K_2) \quad (13)$$

where K_1 is the proximity effect correction factor, taken as 0.08, and K_2 is the safety margin factor, taken as 0.10. The corrected air clearance is calculated as:

$$D = 13.8 \times 1.08 \times 1.1 \approx 16.4 \text{ (m)} \quad (14)$$

The corrected result is in good agreement with the safe clearance observed in field tests without obvious discharge, with the error within an acceptable range. The comparison indicates that the standard-based altitude correction method alone may underestimate the required clearance under complex high-altitude conditions. By incorporating proximity effects and safety margins, the calculated results are more consistent with engineering measurements, thereby validating the rationality and engineering applicability of the proposed correction approach.

5. Conclusions

This study addresses the difficulty in reasonably determining safety distances for on-site withstand voltage testing of UHV AC equipment under high-altitude conditions. A systematic investigation is conducted with respect to test circuit design, discharge interference control, and altitude-dependent safety distance correction, and the following conclusions are obtained:

(1) By introducing a test amplification scaling factor, a suppression mechanism for high-frequency corona interference induced by high-voltage bushing terminals and nearby grounded structures is established. A baseline safety operating distance of 10 m is identified for regions at altitudes of 1000 m and below.

(2) Considering the coupled effects of altitude-dependent atmospheric parameters such as air pressure and air density, a safety distance calculation model applicable to high-altitude conditions is developed. The applicability of the model is demonstrated for altitudes up to approximately 3700 m, based on field validation at the Aba and Ganzi substations.

(3) Based on actual pressurized observations at high-altitude sites, when determining the final safety distance for extreme high-altitude regions, it is essential to account for proximity effects and a safety margin of approximately 10% in addition to the altitude correction. Taking the Aba Ultra-High Voltage Substation as an example, calculations indicate that the minimum safe operating distance required for on-site testing should be 16.4 m to completely avoid the risk of discharge and ensure the authenticity and validity of the test data.

Author Contributions: Conceptualization, W.L. and Y.D.; Data curation, X.M., Y.T. and Y.D.; Formal analysis, Y.Y. and X.M.; Investigation, W.L. and Y.Y.; Methodology, Y.Y., X.M. and Y.T.; Resources, W.L. and Y.Y.; Software, Y.Y. and Y.T.; Supervision, W.L., Y.Y. and Y.D.; Validation, X.M., Y.T. and Y.D.; Visualization, W.L. and Y.T.; Writing—original draft, Y.T.; Writing—review and editing, X.M. and Y.D. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the State Grid Sichuan Electric Power Company Scientific and Technological Project (Grant No. 52199723003M), entitled “Research on Key Technologies for High-Altitude UHV On-Site Testing and Integrated Equipment Development.”

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

Conflicts of Interest: Wenlong Liao and Yueping Yang was employed by State Grid Sichuan Electric Power Research Institute. 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.

References

1. He, W.; Wei, H.; Zhang, Y.; Liu, Y.; Liu, Y.; Wan, B.; Zhou, Y.; Wang, Y.; Gan, Z. The characteristics of negative corona discharge and radio interference at different altitudes based on coaxial wire-cylinder gap. *Plasma Sci. Technol.* **2024**, *26*, 025501. [\[CrossRef\]](#)
2. Geng, J.; Lv, F.; Ding, Y.; Zhao, Y.; Li, P.; Wang, P. Influences of surface tips of a shield ball on the discharge characteristics of a long sphere-plane airgap under positive switching impulses. *IET Sci. Meas. Technol.* **2018**, *12*, 902–906.
3. Ortega, P.; Waters, R.; Haddad, A.; Hameed, R.; Davies, A. Impulse breakdown voltages of air gaps: A new approach to atmospheric correction factors applicable to inter-national standards. *IEEE Trans. Dielectr. Electr. Insul.* **2007**, *14*, 1498–1508.
4. Geng, J.; Qin, Y.; Lv, F.; Yao, X.; Ding, Y. Electric field distribution and switching impulse discharge under shield ball surface scratch defect in an UHVDC hall. *Energies* **2018**, *11*, 1408. [\[CrossRef\]](#)
5. Geng, J.; Chen, Y.X.; Lv, F.; Wang, P.; Ding, Y. Photo electric properties during streamer-to-leader transition in a long positive sphere-plane gap. *Phys. Plasmas* **2020**, *27*, 083509.
6. Fang, Y.Q.; Wang, L.N.; Li, R. Switching Impulse Flashover Characteristics of Live Working Air Gaps in High Altitude Areas and Discharge Voltage Correction. *J. Electr. Eng.* **2020**, *35*, 2681–2688.
7. Phillips, T.A.; Robertson, L.M.; Rohlf, A.F.; Thompson, R.L. Influence of air density on electrical strength of transmission line insulation. *IEEE Trans. Power Appar. Syst.* **1967**, *29*, 948–961. [\[CrossRef\]](#)
8. Harada, T.; Aoshima, Y.; Ishida, Y.; Ichihara, Y.; Anjo, K.; Nimura, N. Influence of air density on flashover voltage of air gaps and insulators. *IEEE Trans. Power Appar. Syst.* **1970**, *29*, 1192–1202. [\[CrossRef\]](#)
9. DL/T 596-2021; National Energy Administration. Preventive Test Code for Electric Power Equipment. China Electric Power Press: Beijing, China, 2021.

10. GB/T 24846-2018; State Administration for Market Regulation Standardization Administration of the P.R.C. Preventive Test Standards of 1000kV AC Electrical Equipments. Standards Press of China: Beijing, China, 2018.
11. DL/T 1947-2018; National Energy Administration. Supervision Code for Special Tests During On-Site Handover of AC UHV Electrical Equipment. China Electric Power Press: Beijing, China, 2018.
12. DL/T 408-2023; National Energy Administration. Safety Code of Electric Power Industry—Electric Part of Power Plants and Transformer Substations. China Electric Power Press: Beijing, China, 2023.
13. He, Y.; Chen, J.B.; Shao, M.F.; Li, H. Research on the Present Situation and Development of On-site Acceptance Test Technical Standard for UHV AC Equipment. *China. Stand.* **2019**, *21*, 135–138+168.
14. Aihara, Y.; Watanabe, Y.; Kishizima, I. Analysis of new phenomenon regarding effects of humidity on flashover characteristics for long air gaps. *IEEE Trans. Power Appar. Syst.* **1983**, *102*, 3778–3782. [[CrossRef](#)]
15. Ramirez, M.; Moreno, M.; Pigini, A.; Rizzi, G.; Garbagnati, E. Air density influence on the strength of external insulation under positive impulse: Experimental investigation up to an altitude of 3000 m a. s. l. *IEEE Trans. Power Deliv.* **1990**, *5*, 730–737. [[CrossRef](#)]
16. GB/T 1094.3-2023; Power Transformers—Part 3: Insulation Levels, Dielectric Tests and External Clearances in Air. Standardization Administration of China: Beijing, China, 2023.
17. Xiao, J.; Zhen, G.; Wang, B.; Li, Y. Security Distance of Distribution Network: Definition and Method. *Proc. CSEE* **2017**, *37*, 2840–2851.
18. IEC 60076-3:2018; Power transformers—Part 3: Insulation Levels, Dielectric Tests and External Clearances in Air. International Electrotechnical Commission: Geneva, Switzerland, 2018.
19. Chen, W.; Zeng, R.; He, H. Research Progress of Long Air Gap Discharges. *High-Volt. Technol.* **2013**, *39*, 1281–1295.
20. IEC 60060-1:2010; High-Voltage Test Techniques—Part 1: General Definitions and Test Requirements. International Electrotechnical Commission: Geneva, Switzerland, 2010.
21. GB/T 16927.1-2011; High-Voltage Test Techniques—Part 1: General Definitions and Test Requirements. Standardization Administration of China: Beijing, China, 2011.
22. IEC 60071-1:2023; Insulation Coordination—Part 1: Definitions, Principles and Rules. International Electrotechnical Commission: Geneva, Switzerland, 2023.
23. GB/T 45846-2025; State Administration for Market Regulation Standardization Administration of the P.R.C. Standard At-mosphere. Standards Press of China: Beijing, China, 2025.
24. GB/T 24842-2018; Overvoltage and Insulation Coordination for 1000 kV UHV AC Transmission Project. Standardization Administration of China: Beijing, China, 2018.
25. DL/T 1275-2013; Guide for Insulation Coordination in High-Voltage Systems. National Energy Administration of China: Beijing, China, 2013.
26. Calva, P.A.; Espino, F.P. Correction Factors for Positive DC Voltages. *IEEE Trans. Dielectr. Electr. Insul.* **1998**, *5*, 541–544. [[CrossRef](#)]
27. IEC 60071-2:2023; Insulation Co-Ordination—Part 2: Application Guidelines. International Electrotechnical Commission: Geneva, Switzerland, 2023.

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.