

Simulation Study on Electric Field Characteristics of Buffer Layer Ablation Defects in High-Voltage Cables

Xusen Liu

*College of Electrical Engineering, Xi'an Jiaotong University, Xi'an, China
liuxusen040902@stu.xjtu.edu.cn*

Abstract. Due to insufficient broadband material parameters and frequency-dependent electric field data, the evolution mechanism of the buffer layer ablation defects in high-voltage cables under non-power-frequency excitation remains insufficiently understood. This paper addresses this gap by combining 20 Hz–10 MHz broadband dielectric testing with frequency-domain electric-field simulation to analyze the electromagnetic response characteristics of buffer-layer ablation defects across different developmental stages. Dielectric measurements reveal significant differences in relative permittivity and conductivity between dry and moistened water-blocking powders, demonstrating that moisture ingress markedly alters the partial electrical properties of the buffer layer. Simulation results indicate that the defect-region electric field exhibits pronounced frequency sensitivity rather than monotonic variation; notably, the field strength in the powder region may exceed the air breakdown threshold within the 100–200 Hz range—a critical phenomenon that conventional power-frequency analysis fails to capture. Furthermore, the most significant variation in field strength occurs within the 20–500 Hz band, suggesting a strong influence on partial discharge excitation. These findings demonstrate that relying solely on 50 Hz power-frequency results is insufficient to explain partial discharge initiation under non-power-frequency test voltages such as DAC and oscillating wave, underscoring the necessity of incorporating frequency-dependent material properties into discharge mechanism analysis, simulation modeling, and field diagnostic methodology.

Keywords: High-voltage cable, Buffer layer ablation, Broadband dielectric properties, Frequency-domain simulation, Partial discharge

1. Introduction

With the advancement of the Energy Internet strategy and smart grid construction, high-voltage cross-linked polyethylene (XLPE) cables, due to their excellent electrical and mechanical characteristics, are gradually forming a power transmission mode dominated by cables and supplemented by overhead lines, becoming the core carrier of urban power transmission networks [1]. However, in recent years, buffer layer failures in high-voltage cables have shown a high-incidence trend. Statistics from the State Grid Corporation of China reveal that buffer layer ablation defects have become the leading cause of high-voltage cable body faults, accounting for over 80%,

with failures concentrated in the operational cycle after five years of service [2, 3]. Field dissection analyses reveal that ablation damage typically progresses through distinct stages: initial precipitation of strip-shaped high-resistance white powder or formation of discharge erosion marks at the trough positions corresponding to the corrugated aluminium sheath upon the buffer layer surface, subsequent development into through-holes penetrating the insulation shield, and, in severe cases, leading to main insulation breakdown and grid outage accidents.

Domestic universities and enterprises have carried out simulation or experimental research on the principles of cable buffer layer ablation problems, achieving considerable results. Existing research classifies ablation mechanisms into dry and moist categories based on environmental triggers and dominant physicochemical processes. In dry environments, cable bending or thermal cycling causes instability in the contact pressure distribution between the buffer layer and the corrugated aluminium sheath, concentrating radial conduction current in areas where the effective area of microscopic conductive pathways increases; sustained Joule heat accumulation eventually exceeds the thermal decomposition threshold (approximately 200°C) of polyester fibers and water-blocking powder, ultimately leading to material breakdown [4, 5]. In moist environments, water-blocking powder absorbs moisture and hydrolyzes, subsequently undergoing electrochemical corrosion reactions with the aluminum substrate to produce insulating deposits including aluminum hydroxide, alumina, and sodium salts [6-9]. These high-resistance powders not only block original conductive channels, but also induce current density concentration at geometric discontinuity edges, significantly accelerating the thermal damage process [10].

This paper investigates the electric field distribution characteristics and partial discharge causes of the buffer layer ablation defects in high-voltage cables, aiming to establish a multiscale electric field simulation analysis method that considers buffer layer moisture ingress, water-blocking powder precipitation, and defect stage evolution. This paper mainly revolves around the following contents: First, combining the structural composition of high-voltage XLPE cable buffer layers and fault dissection phenomena, it analyzes the relationships among buffer layer moisture ingress, white powder formation, interface contact degradation, and ablation defect development, and clarifies typical defect states including dry buffer layer, moistened buffer layer without powder production, Stage I, and Stage II; second, it establishes an electric field simulation model for the buffer layer ablation defects in high-voltage cables, comprehensively considering cable geometric structure, buffer layer material parameters, and other factors, and analyzes under different defect states electric potential, electric field strength, and current density distribution patterns; finally, simulation calculations are carried out under 50 Hz power-frequency conditions and within a broadband range, respectively, to study the effects of moisture ingress, powder precipitation, and defect expansion on partial field strength concentration; the results can provide reference for the mechanism interpretation, condition monitoring, fault prediction, and detection strategy optimization of buffer layer ablation defects in high-voltage cables.

2. Evolution of buffer layer ablation defects

Combining fault cable dissection phenomena and interface degradation characteristics after buffer layer moisture ingress, the development process of buffer layer ablation defects can be summarized into four stages [9]. The four stages correspond to different evolution states including high-resistance powder initial precipitation, defect propagation along the interface, damage penetration into the buffer layer interior, and insulation shield layer impairment.

Stage I: Microscopic Insulating Interlayer Formation. After the buffer layer becomes moistened, the interface between it and the corrugated aluminum sheath is easy to get electrochemical corrosion

under the combined effect of electric field and gravity, and white powder gradually precipitates at trough contact positions. The precipitates weaken the effective electrical contact between the buffer layer and the corrugated aluminium sheath, obstructing capacitive current discharge through contact points, thereby forming a microscopic insulating interlayer partially [11].

Stage II: Microscopic Insulating Interlayer Expansion. As the defect further develops, partial current gradually concentrates at limited contact points, causing current density and temperature rise to increase; at the same time, powder continues to precipitate and expand in the circumferential direction, covering more trough contact areas. At this point, the contact state between the buffer layer and the corrugated aluminium sheath further deteriorates, partial potential rises, the defect develops from partial formation toward interface expansion, and the defect region gradually acquires potential partial discharge conditions, which may induce floating discharge in severe cases [12].

Stage III: Through-Hole Channel Penetration. Under the combined action of sustained Joule heat and partial discharge, defects propagate further from the interface toward the buffer layer interior, and electrochemical corrosion continues to develop inward along degradation channels, promoting continuous generation and deposition of white powder at the degradation front, ultimately forming a damage channel penetrating from the interface toward the interior [13].

Stage IV: Insulation Shield Layer Damage. When white powder penetrates through the buffer layer and further develops to the insulation shield layer surface, due to the significant dielectric property difference between the two, the electric field near the interface will be significantly distorted and partial field strength concentration will form. At this time, the defect region is more likely to induce discharge developing toward the main insulation, ultimately resulting in insulation shield layer damage, which may further cause cable body failure in severe cases.

3. Model establishment and parameter settings

To quantitatively analyze the electric field distribution under different buffer layer states, this section takes the YJLW03 64/110 kV high-voltage XLPE cable as the research object, and establishes a frequency-domain electric field simulation model considering the corrugated aluminium sheath contact interface morphology. The model mainly includes structures such as copper conductor, conductor shield layer, insulation layer, insulation shield layer, buffer layer, degraded buffer layer, high-resistance powder, air gap, and corrugated aluminium sheath. According to differences in defect development stages, Stage I is analyzed using a two-dimensional partial cross-sectional model; Stage II adopts a three-dimensional model to describe its spatial distribution characteristics because the powder has already expanded extensively along the cable circumferential direction.

3.1. Geometric model and boundary conditions

The geometric model is simplified based on the actual cable structure. Copper conductor, conductor shielding layer, insulation layer, insulation shielding layer, buffer layer, and corrugated aluminium sheath are all processed as coaxial cylindrical layered structures. The inner surface of the corrugated aluminum sheath is characterized by periodic corrugated structure. For Stage I, defects mainly manifest as small amounts of powder precipitating at partial contact positions in corrugated troughs, with defects developing along partial cross-sections. Therefore, two-dimensional models can better reflect their partial field strength changes. For Stage II, powder coverage range obviously expands along the circumferential direction, and defects have three-dimensional spatial characteristics. Therefore, three-dimensional models are used for modeling.

In the simulation, rated phase voltage is applied to the line core and the voltage fluctuation coefficient should be considered. For 110 kV cables, the effective value of rated phase voltage is 64 kV. Considering 1.1 times voltage fluctuation coefficient, the AC voltage peak value applied to the line core is:

$$V = V_0 = \sqrt{2} \times 1.1 \times 64kV \approx 99.5kV \quad (1)$$

The corrugated aluminium sheath grounding boundary condition is:

$$V = 0 \quad (2)$$

Other outer boundaries of the model adopt electric insulation boundaries to ensure current mainly flows along cable radial and defect region discharge paths. The corresponding electric insulation boundary condition can be expressed as:

$$n \cdot J = 0 \quad (3)$$

3.2. Material parameter settings

The material parameters for each structural component in the model are shown in Table 1. In this study, the electric current field was adopted for the simulation instead of a pure electrostatic field. This is because the buffer layer and the precipitated powder are not ideal dielectrics; their electric response is jointly determined by conductivity and permittivity, especially under power-frequency and broadband conditions. Therefore, the electric current field model can better describe the coupling effect of conductive current and displacement current in the defect region. Among the model components, the copper conductor and corrugated aluminium sheath are treated as highly conductive materials. The XLPE insulation layer adopts typical parameters with low conductivity and a relative permittivity of 2.3, while the conductor shield layer and insulation shield layer are treated as semi-conductive materials. The healthy buffer layer and high-resistance powder adopt self-measured parameters obtained from broadband dielectric testing. In the 50 Hz power-frequency simulation, the equivalent conductivity and relative permittivity at the corresponding frequency are used. The degraded buffer layer is used to represent the buffer layer region whose electrical properties are significantly altered after moisture ingress, and its conductivity and relative permittivity are determined based on both literature data and measured parameters. Different geometric dimensions are adopted for different defect stages. In Stage I, the white powder is initially precipitated only in a limited partial contact region between the buffer layer and the corrugated aluminum sheath. The defect scale is small, and the electric field distortion is mainly concentrated in a partial radial cross-section. Therefore, a two-dimensional model is used to analyze the partial field distribution and reduce unnecessary computational complexity. In Stage II, the powder region further expands along the circumferential direction of the cable, and the defect no longer has a simple two-dimensional distribution. The electric field is affected by both radial and circumferential variations of the defect region. Thus, a three-dimensional model is established to more accurately describe the spatial distribution of the powder region and its influence on the electric field concentration.

Table 1. Geometric dimensions and material parameters of the model

Structure	Conductivity / ($S \cdot m^{-1}$)	Relative Permittivity	Outer Dia. / mm
Copper Conductor	5.998×10^7	1×10^4	30.3
Conductor Shield	1×10^{-3}	700	32.9
XLPE Insulation	1×10^{-15}	2.3	65.9
Insulation Shield	1×10^{-3}	700	67.9
Healthy Buffer	*	*	70
Degraded Buffer	1×10^{-5}	1000	70
High-R Powder	*	*	—
corrugated aluminium Sheath	2.75×10^7	1×10^4	78
Air Gap	1×10^{-16}	1.0	—

Note: "*" indicates that the material parameters are determined from broadband dielectric measurement results; power-frequency simulation uses equivalent parameters at the corresponding frequency.

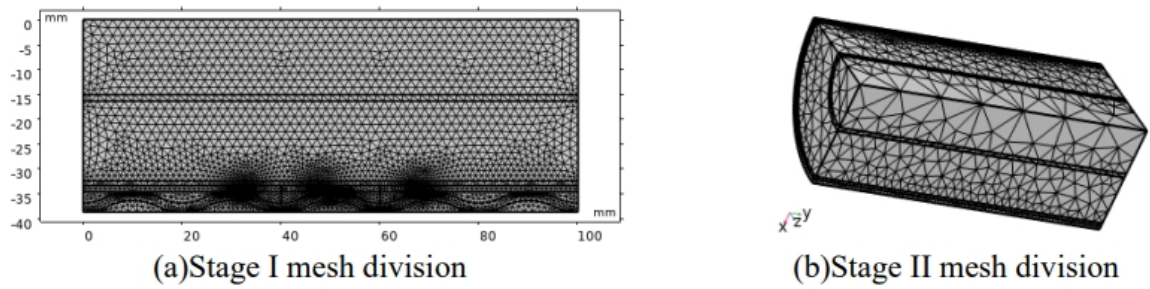


Figure 1. Stage I, II mesh division diagrams

3.3. Material parameter settings

Since both high-voltage cable buffer layers and white powder regions have certain conductive characteristics, electric field distribution in defect regions is not only determined by dielectric constant but also affected by conduction current, displacement current, and material frequency-dependent dielectric parameters. If only electrostatic field models are used, they can only describe potential distribution in ideal insulating media, difficult to reflect buffer layer semi-conductive characteristics and leakage current redistribution caused by high-resistance powder. Therefore, this thesis adopts frequency-domain current field models for calculating buffer layer ablation defect regions.

In frequency-domain current fields, the total current density within materials consists of conduction current density and displacement current density:

$$\mathbf{J} = \mathbf{J}_c + \mathbf{J}_d \quad (4)$$

where $\mathbf{J}$ is total current density, $\mathbf{J}_c$ is conduction current density, and $\mathbf{J}_d$ is the displacement current density. Conduction current density satisfies Ohm's law:

$$\mathbf{J}_c = \sigma \mathbf{E} \quad (5)$$

where σ is material conductivity and E is electric field strength. Frequency-domain displacement current density can be expressed as:

$$J_d = j\omega D = j\omega\varepsilon_0\varepsilon_r E \quad (6)$$

where $\omega = 2\pi f$ is angular frequency, f is applied voltage frequency, ε_0 is vacuum dielectric constant, ε_r is material relative dielectric constant, and D is electric displacement vector. Therefore, total current density in frequency-domain current fields can be written as:

$$J = (\sigma + j\omega\varepsilon_0\varepsilon_r)E \quad (7)$$

Electric field strength and potential satisfy:

$$E = -\nabla V \quad (8)$$

According to charge conservation conditions, without external current sources, the calculation domain satisfies:

$$\nabla \cdot J = 0 \quad (9)$$

Substituting the above equations, the frequency-domain current field governing equation is obtained:

$$\nabla \cdot [(\sigma + j\omega\varepsilon_0\varepsilon_r)\nabla V] = 0 \quad (10)$$

This equation indicates that potential distribution in defect regions is jointly determined by material conductivity, dielectric constant, and excitation frequency. When frequency is low or material conductivity is high, conduction current dominates in total current; when frequency increases, displacement current component gradually strengthens, and the material dielectric polarization characteristics have more obvious influence on the electric field distribution.

Through the above settings, current mainly redistributes along the cable radial direction and within defect regions. The model can reflect the influence of buffer layer-aluminum sheath contact state changes and white powder precipitation on partial potential, electric field strength, and current density. The potential distribution, electric field strength magnitude, and current density magnitude under different states are extracted as analysis objects, where the electric field strength and current density magnitudes are respectively:

$$|E| = \sqrt{E_x^2 + E_y^2 + E_z^2} \quad (11)$$

$$|J| = \sqrt{J_x^2 + J_y^2 + J_z^2} \quad (12)$$

For the two-dimensional model of Stage I, the z-direction component in the above equations can be neglected. By comparing the changes of $|E|$, $|J|$, and potential distribution under different defect stages, the influence of white powder precipitation and ablation damage development on buffer layer partial discharge risk can be further analyzed.

4. Simulation results analysis

After completing model establishment, this section first performs simulation analysis under 50 Hz power-frequency conditions for four typical states: dry buffer layer, moistened buffer layer without powder production, Stage I microscopic insulating interlayer formation, and Stage II microscopic insulating interlayer expansion. By comparing electric potential, electric field strength, and current density distributions, the influence patterns of moisture ingress and white powder precipitation on the electrical state of the buffer layer can be revealed.

4.1. Simulation analysis of dry buffer layer state

Under dry state, the buffer layer is in good contact with the corrugated aluminum sheath, and current can be discharged effectively through the buffer layer and corrugated aluminum sheath. Figure 3 gives the electric field distribution, current density distribution, and partial electric potential distribution under dry buffer layer conditions.

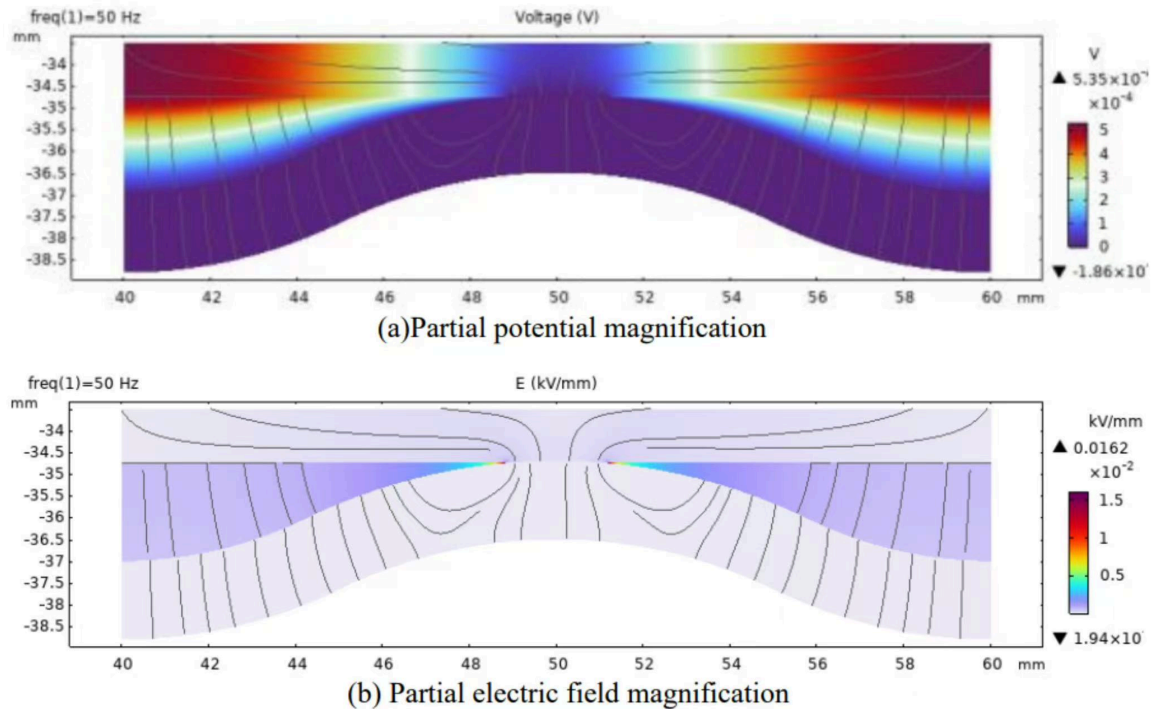


Figure 2. Dry buffer layer electric field distribution under conditions

Figure 2 indicates that the voltage drop is mainly concentrated within the XLPE insulation layer, the buffer layer region potential is close to ground potential, and the partial field strength level is low. Simulation results indicates that the average electric field strength of the dry buffer layer is only approximately 1.36×10^{-4} kV/mm, and the average current density is approximately 0.136 A/m². This indicates that when the buffer layer is in good contact with the corrugated aluminium sheath, current can be discharged effectively through the corrugated aluminium sheath, and no obvious potential elevation or partial field strength concentration has occurred within the buffer layer.

4.2. Simulation analysis of moistened buffer layer without powder production

When the buffer layer becomes moistened, but no obvious white powder precipitation has occurred, the water-blocking powder absorbs moisture and swells, altering the pore structure and partial conductive pathways of the buffer layer, and the contact state between the buffer layer and the corrugated aluminium sheath begins to degrade. Figure 3 gives the partial electric potential, electric field strength, and current density distributions under moistened conditions without powder production.

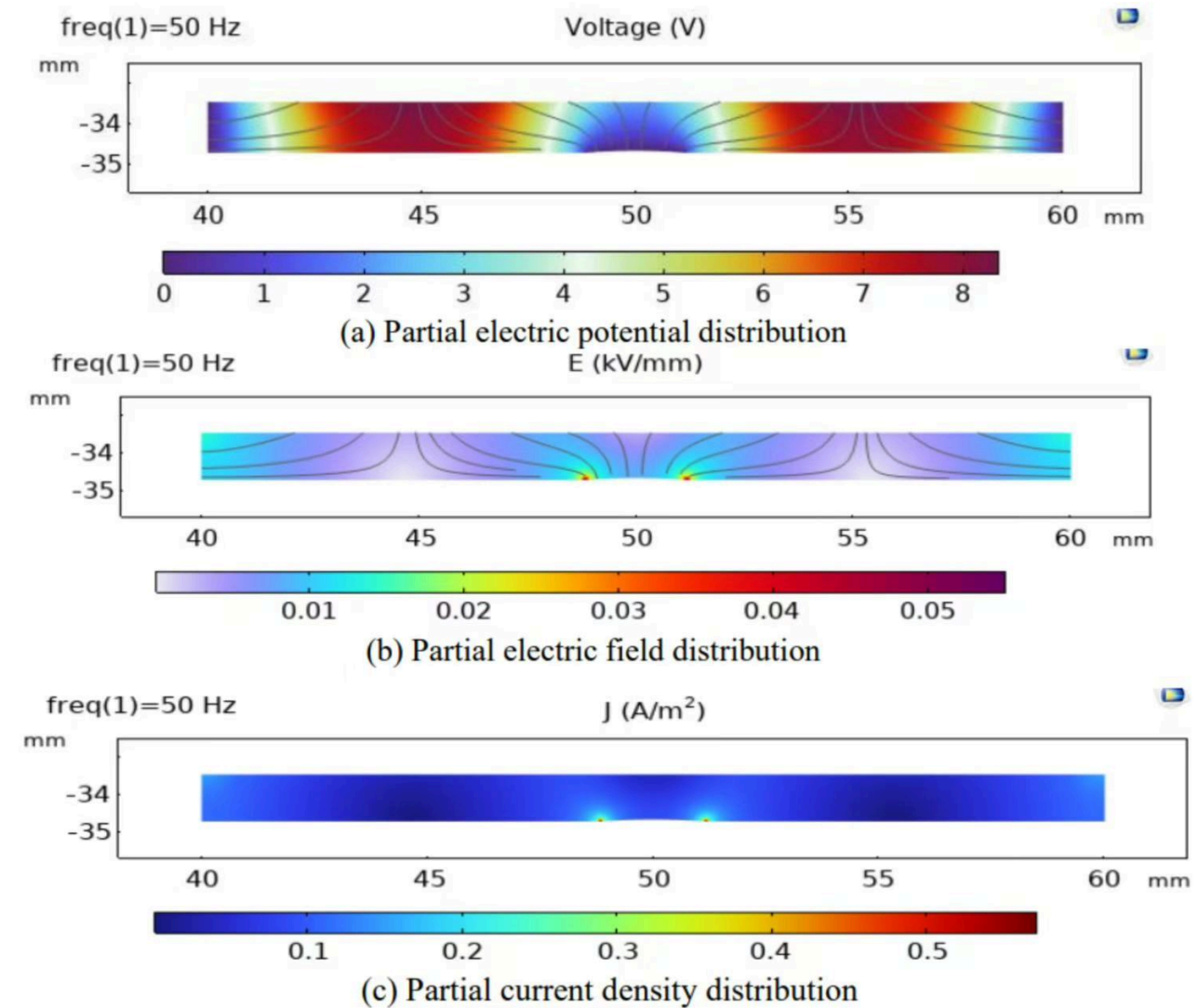


Figure 3. Electric field distribution under moistened buffer layer without powder production

Compared with the dry state, after the buffer layer becomes moistened, the average potential rises to approximately 5 V, the average electric field strength increases to approximately 0.006 kV/mm, which is approximately 44 times that of the dry state; the average current density decreases to approximately 0.067 A/m², a reduction of approximately 50.7% compared with the dry state. This indicates that moisture ingress weakens the discharge capability of the buffer layer for radial current, causing partial potential elevation and electric field distortion in the buffer layer region. Although no obvious powder defects have formed at this time, moisture ingress has already changed the electrical

boundary conditions of the buffer layer, providing a foundation for subsequent powder precipitation and ablation defect development.

4.3. Stage I power-frequency simulation analysis of buffer layer with moisture and powder production

Stage I corresponds to the microscopic insulating interlayer formation period. At this time, the boundary between the buffer layer and the corrugated aluminum sheath has begun to precipitate small amounts of white high-resistance powder, and the powder is mainly distributed at partial trough contact positions. Because the high-resistance powder weakens the effective electrical contact between the buffer layer and the corrugated aluminium sheath, the potential in the defect region is further elevated, and electric field concentration begins to appear in and around the powder.

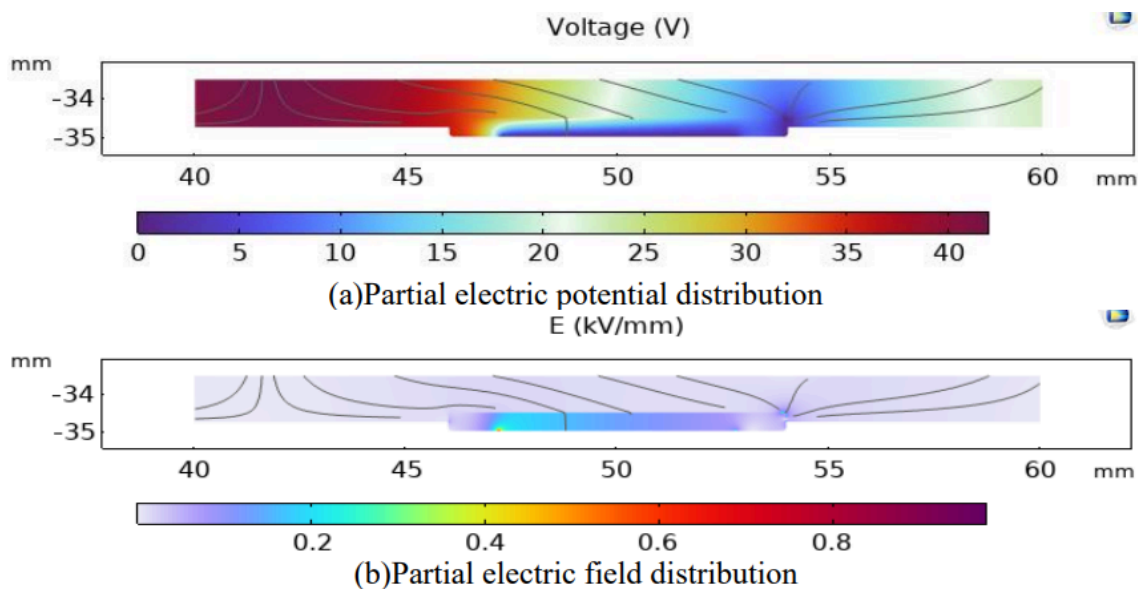


Figure 4. Power-frequency electric field distribution in Stage I defect region

Figure 4 indicates that the presence of white high-resistance powder significantly changes the partial electric field distribution. Under Stage I conditions, the moistened buffer layer average potential rises to approximately 7.65 V, the average electric field strength in the moistened buffer layer region is approximately 0.0065 kV/mm, while the average electric field strength in the high-resistance powder area reaches approximately 0.059 kV/mm, which is approximately 9 times that of the buffer layer body.

The above results indicate that under power-frequency conditions, although Stage I defects have not yet developed into large-area ablation, the powder region already exhibits obvious partial field strength concentration. The high-resistance powder blocks the original current discharge pathway, causing the electric field to concentrate at powder edges and the junction region with the buffer layer. This result shows that white powder precipitation is an important starting point for buffer layer electric field distortion and a key factor in the subsequent increase of partial discharge risk.

4.4. Stage II power-frequency simulation analysis of buffer layer with moisture and powder production

Stage II corresponds to the microscopic insulating interlayer expansion period. At this time, white powder has developed from partial precipitation to extensive expansion near the troughs of the corrugated aluminium sheath, the effective contact between the buffer layer and the corrugated aluminium sheath further deteriorates, and the defect region has more obvious three-dimensional spatial characteristics. Therefore, Stage II uses a three-dimensional model for simulation analysis, and its electric potential, electric field, and current density distributions are shown in Figure 6.

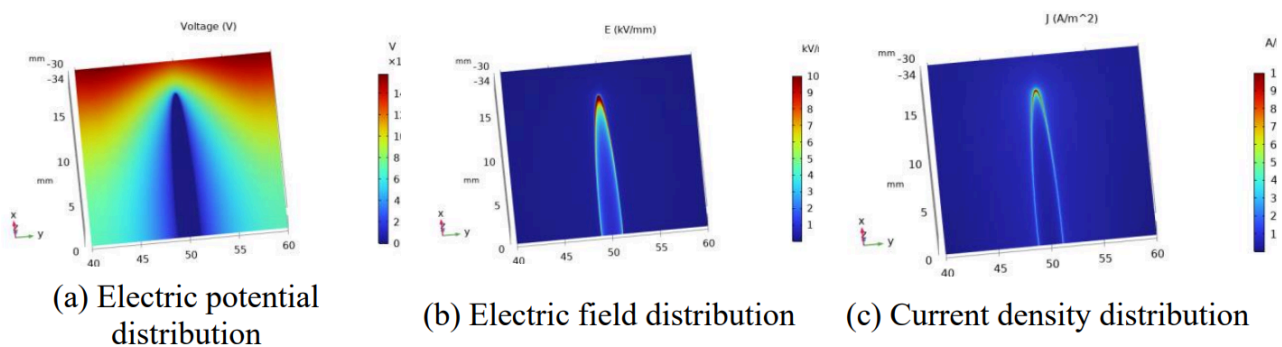


Figure 5. Power-frequency electric field distribution in Stage II defect region

As can be seen from Figure 5, under Stage II conditions the buffer layer average potential can reach approximately 700 V, which has significantly deviated from the good grounding state. The average electric field strength and average current density in the powder region are approximately 1.40 kV/mm and 0.49 A/m², respectively; the corresponding values for the degraded buffer layer region are approximately 0.125 kV/mm and 0.363 A/m². Compared with Stage I, the potential elevation, electric field distortion, and current concentration in the Stage II defect region are all significantly enhanced.

From the physical mechanism perspective, in Stage II the powder coverage range expands, causing the buffer layer and corrugated aluminium Sheath contact channels to further decrease, and the radial discharge pathways are blocked over a larger range. Partial current concentrates near the remaining contact points, causing powder tips and Degraded Buffer adjacent regions to form higher electric field strength. Although 50 Hz the partial field strength under power-frequency simulation is not sufficient to fully explain partial discharge phenomena under all special test voltages, it has clearly been reflected that defect expansion will significantly enhance partial electric field distortion, providing a foundation for subsequent broadband electric field simulation and partial discharge inception condition analysis.

To facilitate comparison of four Condition buffer layer electric field response differences, 50 Hz. The main simulation results under power-frequency conditions are organized in Table 2 shown.

Table 2. Under different buffer layer states 50 Hz power-frequency simulation results comparison

Condition	Main Structure Features	Average Potential	Average E-Field Strength	Result Characteristics
Dry Buffer Layer	buffer layer and corrugated aluminium Sheath contact well	Approaching 0 V	1.36×10^{-4} kV/mm	Radial current can be effectively discharged. No obvious field concentration observed.
Moistened, No Powder	Water-blocking powder absorbs moisture, Contact state begins to degrade	Approaching 5 V	Approaching 0.006 kV/mm	E-field approx.44x, Potential elevation appears
Moistened, Powder Stage I	precipitates at partial troughs High-R Powder	Approaching 7.65 V	Powder zone approx. 0.059 kV/mm	Powder zone field strength approx.9x
Moistened, Powder Stage II	Powder expands circumferentially, Contact severely degraded	Approaching 700 V	Powder zone approx. 1.40 kV/mm	Potential elevation and field distortion significantly enhanced

The comprehensive simulation results show, that in the process from dry to moistened, and then to powder precipitation and large-area expansion, the partial electric field strength exhibits a gradual enhancement trend. Under dry state, the buffer layer is in the good discharge state; After becoming moistened, the conductive pathway and interface contact state of the buffer layer change, causing potential elevation; Stage I, High-R Powder forms partial obstruction, making the powder region the electric field concentration position; in Stage II, powder further expands, the defect region develops from partial field strength concentration to obvious spatial electric field distortion. This pattern indicates, that the development of buffer layer ablation defects is essentially the result of contact interface degradation, discharge pathway destruction, and partial dielectric parameter mutation.

5. Broadband electric field simulation of buffer layer ablation defects

Based on the frequency-domain electric field simulation model established in Chapter 3, this section extends the material parameters from 50 Hz power frequency to the broadband range of 20 Hz–10 MHz, and performs broadband electric field simulations for Stage I and Stage II typical states with moisture-induced powder precipitation, respectively, analyzing the variation patterns of electric field strength in the defect region with frequency under each state.

5.1. Moistened buffer layer with powder precipitation: Stage I

Figure 7 gives the broadband field strength response in the defect region under Stage I conditions. As frequency increases, the electric field strength in the buffer layer and high-resistance powder region indicates an overall increasing trend, with more significant increase in the 10^5 – 10^6 Hz range; among them, the field strength in the high-resistance powder region is always significantly higher than that of the buffer layer body, exceeding it by approximately one order of magnitude overall. The results indicate that the partial field strength in the Stage I defect region has an obvious response to frequency changes, and analyzing its electric field distribution based solely on power-frequency conditions is difficult to fully reflect the partial electric field variation pattern under special test voltages. Broadband simulation shows that under high-frequency excitation conditions, the field strength concentration effect in the high-resistance powder region is more significant, and the partial discharge risk increases with rising frequency.

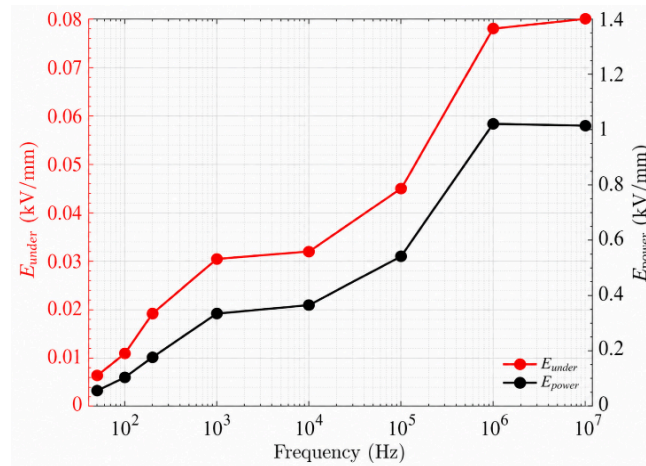


Figure 6. Broadband field strength response under Stage I conditions

5.2. Moistened buffer layer with powder precipitation: Stage II

Figure 7 shows the broadband electric-field response in the defect region under Stage II conditions. As the frequency increases, the field strength in both the buffer layer and the precipitated powder region generally increases at first and then declines, with a pronounced increase observed in the range of 20–10³ Hz. In particular, the field strength in the powder domain exceeds the typical air-gap breakdown field strength of 3 kV/mm within the 100–200 Hz range, indicating that the defect region is more likely to reach the field condition required for partial discharge inception in this frequency band. In addition, the current density in the buffer layer reaches 98,140 A/m² at 1 MHz, and remains higher than that in the powder domain after 200 Hz. This result suggests that, under high-frequency excitation, the buffer layer exhibits a much stronger partial current response, which is mainly related to enhanced capacitive and frequency-dependent conductive effects. Therefore, although high-frequency components may strengthen the partial electrical response of the defect region, they may also lead to more pronounced current concentration and dielectric loss in the buffer layer. This indicates that the selection of excitation frequency for defect detection should not only consider the ability to enhance the partial electric field, but also the possible influence of high-frequency current concentration.

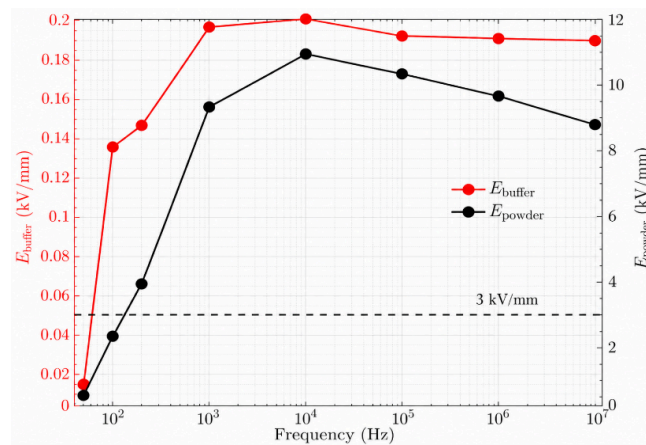


Figure 7. Broadband field strength response under Stage II conditions

Figure 8 shows Broadband response of field strength difference between Stages I and II. Results show, the field strength difference shows a trend of increasing at first and then decreasing, and 100~200 Hz and exceeds 3 kV/mm. This indicates that as powder develops from partial precipitation to large-area coverage and expands along the circumferential direction, the sensitivity of defects to frequency changes is further enhanced, Stage II shows a more significant partial field strength elevation effect than Stage I in the low-frequency range. This also indicates that, compared with power-frequency analysis, conducting broadband electric field simulation is more helpful in revealing the partial discharge formation conditions of buffer layer ablation defects under special test voltages.

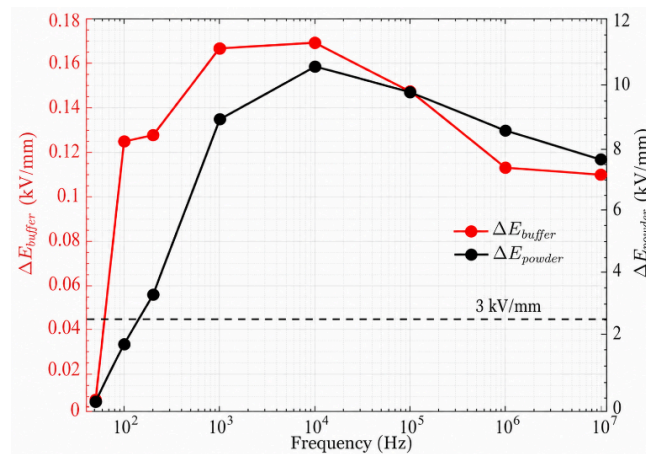


Figure 8. Broadband response of field strength difference between Stages I and II

6. Conclusion

This paper establishes a multiscale simulation model of electric field for high-voltage cables with buffer layer ablation defects. According to the buffer layer defect development process, the research objects are divided into typical states including dry buffer layer, moistened buffer layer without powder production, Stage I, and Stage II, and corresponding simulation models are established respectively. The 50 Hz power-frequency simulation results show that when the dry buffer layer and corrugated aluminium sheath are in good contact, the voltage drop is mainly concentrated in the main insulation layer, and the field strength in the buffer layer region is low; after the buffer layer becomes moistened, the radial discharge capability decreases, and partial potential begins to elevate; when the defect develops to Stage I and Stage II, the high-resistance powder region becomes the partial field strength concentration position, and the larger the powder coverage range, the more obvious the electric field distortion and the higher the partial discharge risk.

Secondly, this paper analyzes the effect of defect variation with frequency on electric field distribution. The broadband simulation results show that the electric field response of the buffer layer ablation defect region has obvious frequency dependence, and using only 50 Hz power-frequency results is difficult to fully explain the partial discharge phenomenon under special test voltages. Under Stage I conditions, the field strength in the high-resistance powder region increases overall with rising frequency, and is significantly higher than the surrounding buffer layer body; under Stage II conditions, as the powder region further expands, the electrical contact of the buffer layer with the corrugated aluminium sheath further deteriorates, the field strength variation in the defect region becomes more complex, and may reach higher levels within specific frequency bands. From this it can be seen that moisture ingress, powder precipitation, and defect morphology

expansion jointly determine the degree of partial electric field distortion in the buffer layer, and are important causes inducing partial discharge.

Comprehensive analysis shows that buffer layer partial discharge is not determined by one single factor, but is affected jointly by material moisture ingress, powder precipitation, interface contact degradation, and defect morphology development. The research results can provide a certain theoretical basis for the mechanism interpretation, partial discharge risk assessment, and fault prediction of buffer layer ablation defects.

References

- [1] Wu, K., Zhao, G., Li, B., et al. (2026). High-voltage cable buffer layer ablation mechanism, research progress on detection technology and solutions. *High Voltage Engineering*, 52(2), 789-800.
- [2] Chen, Y. (2019). *High voltage XLPE fault characteristics and mechanism of cable buffer layer*. South China University of Technology.
- [3] Hui, B. (2023). *High-voltage cable buffer layer ablation fault mechanism, research on defect detection and elimination methods*. South China University of Technology.
- [4] Liu, Y., & Chen, J. (2022). High voltage XLPE cable water-blocking buffer layer electrical–electro-thermal field analysis and simulated ablation test research. *Proceedings of the CSEE*, 42(4), 1260-1271.
- [5] Liu, H., Liu, R., Zhao, X., et al. (2021). Study on buffer layer ablation of high-voltage XLPE cable induced by radial current concentration. *Insulating Materials*, 54(8), 94-101.
- [6] Zheng, J., Su, X., Li, G., et al. (2022). Study on electrochemical corrosion characteristics and failure of high-voltage cable water-blocking buffer layer. *Insulating Materials*, 55(2), 91-96.
- [7] Su, C. Q. (2010). Failure analysis of three 230kV XLPE cables. In *2010 IEEE/PES Transmission and Distribution Conference and Exposition: Latin America (T&D-LA)* (pp. 22-25). IEEE.
- [8] Zhao, X. (2021). *Air gap discharge and electrochemical corrosion induced high-voltage XLPE research on cable buffer layer ablation fault mechanism* [Doctoral dissertation, Xi'an Jiaotong University].
- [9] Qiu, W., Zhang, Y., Xie, Y., et al. (2024). High voltage XLPE review of cable buffer layer defect research status. *Insulating Materials*, 57(4), 13-21.
- [10] Zhang, K., Gao, J., Wu, K., et al. (2026). Mechanism study of insulation shield damage caused by high-voltage cable buffer layer ablation. *Proceedings of the CSEE*, 46(1), 445-454.
- [11] Zhou, S., Liu, R., Jiang, L., et al. (2020). High voltage XLPE analysis of sheath ablation mechanism in insulated power cables. *High Voltage Apparatus*, 56(12), 171-176.
- [12] Ouyang, B., Li, W., Liu, Y., et al. (2021). High voltage XLPE water-blocking buffer layer ablation mechanism. *High Voltage Engineering*, 47(9), 3153-3162.
- [13] Duan, X., Liu, Y., Liu, S., et al. (2025). High voltage XLPE review of cable buffer layer ablation mechanism and detection methods. *Transactions of China Electrotechnical Society*, 40(5), 1541-1558.