

Electric Field Distribution Characteristics and Insulation Assessment for Typical Capacitive Core Defects of Oil-Immersed Bushings

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ABSTRACT: Oil-immersed transformer bushings are critical power system components, whose internal defects can cause electric-field distortion and insulation breakdown. In this study, a three-dimensional finite element model of a transformer bushing is established via COMSOL Multiphysics using actual structural parameters. The baseline electric field and voltage distributions under defect-free conditions are analyzed, and systematic simulations and quantitative evaluations are conducted to explore electric-field distortion and corresponding insulation risks under four typical defects: capacitor core metal particle contamination, insulating oil gas bubbles, capacitor final screen grounding loss, and capacitor screen damage. The results demonstrate that all defects break the inherent electric-field uniformity and induce local field intensification. Metal particle contamination and capacitor screen damage pose the greatest risks of distortion and insulation breakdown, while grounding loss causes the most extensive overall electric-field disturbance. This study clarifies the defect-induced electric-field response mechanisms, providing theoretical support for fault early identification, risk warning, and optimized operation of oil-immersed transformer bushings.

1. INTRODUCTION

As a critical component of power equipment, transformer bushings play an essential role in power transmission and equipment insulation, thereby ensuring the stable operation of power transformers [1–5]. Transformer bushings operate in complex environments and are subjected to combined effects of electrical, thermal, and magnetic stresses, which pose significant challenges to their insulation performance. To ensure efficient and safe operation, bushings must possess excellent insulation properties, thermal stability, and strong resistance to electromagnetic interference [6]. In practice, oil-immersed bushings commonly face insulation-related risks throughout their lifecycle, from manufacturing to operation and maintenance. During the manufacturing process, defects such as metal-particle contamination, capacitor screen damage, residual insulating impurities, and inadequate sealing may occur. During operation and maintenance, issues such as oil leakage, moisture ingress, and insulating oil degradation are frequently observed, which can significantly degrade the insulation performance of the bushing. If not detected and mitigated promptly, they can easily trigger operational accidents in the power grid, resulting in severe economic losses. Therefore, analyzing the real-time operating conditions and insulation status of transformer bushings is of great significance for ensuring the reliable operation of transformers and maintaining the security of power systems [7].

In the field of electro-thermal simulation and mechanism analysis of typical defects, researchers have developed multidimensional simulation models tailored to the distinct operating conditions of power and oil-gas casings, thereby revealing the evolution mechanisms of various defects. Si's team established a scaled-down model of the valve-side bushing of an ultra-high-voltage (UHV) converter transformer and performed electric-field simulations for typical defects, such as poor grounding of the terminal screen and capacitor screen wrinkling. The results indicate that terminal-screen grounding defects can cause local electric-field distortion exceeding 300%, with the distorted region mainly concentrated within 10 mm of the terminal screen, thereby clarifying the fundamental mechanism underlying the partial discharges induced by such defects [8]. Gao's team focused on the temperature field distribution characteristics. Through finite element simulations, they found that the hotspot temperature in the valve-side bushing of a UHV converter transformer was primarily concentrated at the junction between the current-carrying conductor and the flange. Under rated load conditions, the hotspot temperature can reach 78°C — approximately 22°C higher than that of the bushing body, providing quantitative evidence for the early warning of current-carrying connection defects [9]. In addition, Zhang et al. innovatively incorporated environmental variables into the simulation model. Their results confirmed that wind significantly affects temperature characteristics of the partial-discharge defects in 1100 kV Gas-Insulated Switchgear (GIS) outlet bushings. When the wind speed increases from 0.5 m/s to 3 m/s, the temperature increase at the defect location decreases

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by approximately 40%, providing environmental correction parameters for the infrared thermographic diagnosis of outdoor bushing defects [10].

Simulation studies in the oil and gas and nuclear power sectors have primarily focused on the thermo-mechanical coupling effects of structural defects. Jing's team developed a coupled simulation model to characterize cement sheath defects in well casings under alternating thermal loads in underground gas storage reservoirs. Their results showed that void defects in the cement sheath may increase the thermal stress concentration factor of the casing by approximately 1.8 times and that the frequency of alternating thermal loads is positively correlated with the amplitude of thermal stress [11]. Zhou et al. quantified the influence of wellbore temperature on the collapse resistance of casings with defects. The simulation results indicate that, at a wellbore temperature of 120°C, a corrosion defect with a depth of 2 mm can reduce the casing collapse strength by 27%, representing an additional decrease of 8 percentage points compared to that under ambient conditions [12]. Focusing on nuclear power applications, Xu et al. investigated the wear-induced subsidence mechanism of thermal sleeves in nuclear power plants through numerical simulations. Their findings revealed that for every 0.5 mm increase in wear depth, the probability of control rod sticking increases by approximately 15%, providing theoretical support for wear prevention and reliability improvement of nuclear power plant casing structures [13].

Fundamental investigations into the properties of insulating material and the physics of discharge processes have been a primary focus for researchers in recent years. A classical theoretical framework for the relationship between temperature fields and insulation aging was established. Youssef et al. developed a steady-state temperature distribution model for high-voltage bushings, marking the first time that the contributions of winding losses (65%) and dielectric losses (35%) to the temperature rise were quantified. This model remains the core theoretical foundation for modern bushing thermal design [14]. Saha et al. conducted long-term monitoring experiments and proposed the “10°C half-life rule” for oil-paper insulation. Using Fourier transform infrared spectroscopy (FTIR), they demonstrated a strong linear correlation (coefficient = 0.94) between the intensity of the carbonyl ($C=O$) absorption band and the degree of insulation aging, offering a chemical characterization method for assessing the aging status of insulation materials [15].

Finite-element simulation and nanocomposite insulating materials have become important approaches for investigating oil-gap discharge in transformers and electrothermal coupling in converter transformer bushing insulation. Li et al. established a numerical model for transformer oil-gap discharge based on field-induced ionization mechanisms, showing that the generation and migration of free charge carriers produce pre-breakdown current, while Joule heating induces low-density regions and streamer development. Their work explains, from a microscopic perspective, the coupled effects of space charge, electric-field distortion, and temperature rise during breakdown in liquid dielectrics [16]. For solid bushing insulation, Yadav et al. conducted electrothermal finite-element analysis of a ± 800 kV converter transformer bushing and demonstrated

that nano-hexagonal boron nitride modified impregnated paper can improve thermal dissipation and, to some extent, reduce electric-field stress concentration [17]. Du et al. further proposed an Epoxy Resin/Graphene Oxide (EP/GO) nanocomposite approach for improving the internal electric-field distribution of DC bushing insulation by regulating the temperature coefficient of electrical conductivity. Their results showed that an appropriate GO filler content can reduce the temperature sensitivity of conductivity and lead to more uniform radial and axial electric-field distributions [18].

At present, systematic research on the electric-field distribution characteristics within bushings under different defect conditions and the factors influencing them is limited. Based on this, the main contributions of this study are as follows.

Section 2 establishes a three-dimensional model of oil-immersed bushings. Section 3 analyzes the electric-field distribution characteristics of oil-immersed bushings under normal operating conditions. Section 4 focuses on four typical defective operating conditions and investigates the electric-field distribution characteristics of oil-immersed bushings in defective states. Section 5 presents a quantitative analysis of the above four typical defects and the corresponding insulation risk assessment.

2. ELECTRIC FIELD DISTRIBUTION CHARACTERISTICS IN OIL-IMMERSED TRANSFORMER BUSHINGS

2.1. Electric Field Distribution in Oil-Immersed Transformer Bushings

The core insulation system of oil-immersed bushings is primarily composed of cellulose paper and mineral insulating oil, supplemented with oil-impregnated fiber-reinforced composite structures. The electric-field distribution within the bushing is jointly governed by the dielectric properties of the insulation materials and the structural design, exhibiting inherently nonuniform characteristics. Under a DC electric field, the dielectric constants of cellulose paper and mineral insulating oil differ significantly, approximately 3.5–4.0 for cellulose paper and 2.2–2.4 for mineral oil, resulting in electric-field distortion at the interfaces between the two media and generating field-strength gradients. In addition, structural variations along the axial and radial directions further exacerbate field nonuniformity. Radially, the electric field strength was the highest at the conductor surface and gradually decreased outward. Axially, owing to insulation aging and nonuniform impurity distribution, the electric-field strength distribution exhibits localized fluctuations.

Nonuniform electric-field distribution and localized field-strength distortions are the primary triggers of insulation failure in bushings. Regions of local field-strength concentration can exceed the dielectric withstand threshold of insulation materials, initiating partial discharges. During such discharges, electrons collide with insulating molecules, breaking the macromolecular chains of cellulose paper and generating reactive species, such as ozone and nitrogen oxides. These processes accelerate the oxidative aging of mineral insulating oil, leading to the formation of acids, esters, and sludge. The resulting degra-

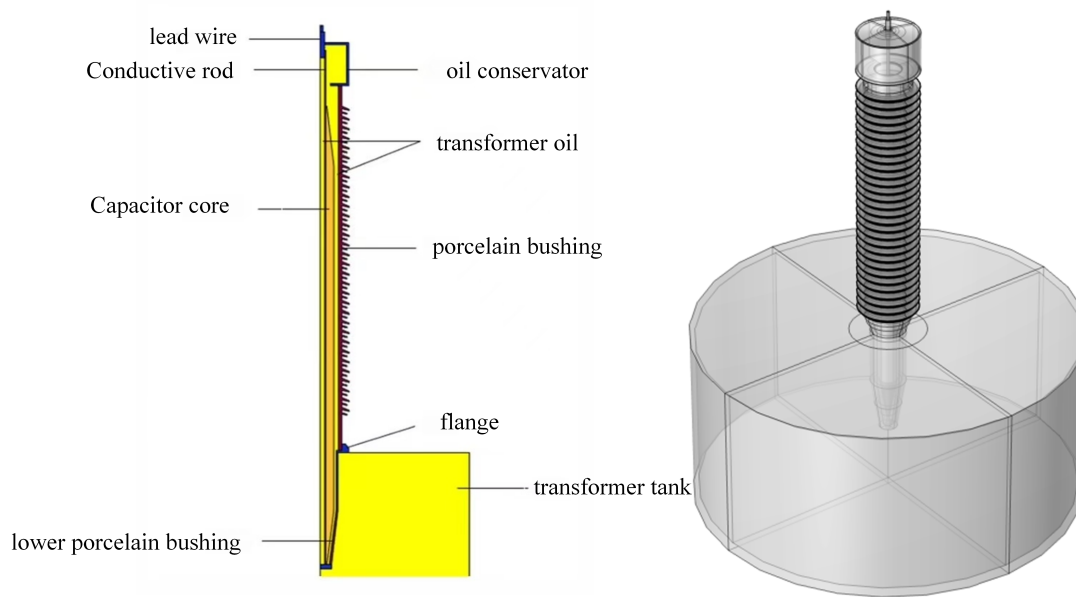


FIGURE 1. Structural diagram of the oil-immersed bushing and its finite-element model.

dation products further reduce the dielectric performance of the insulation, exacerbate space charge accumulation, and intensify electric-field distortion, forming a vicious cycle: electric-field distortion $\rightarrow$ partial discharge $\rightarrow$ insulation aging $\rightarrow$ space-charge accumulation $\rightarrow$ further field distortion. Under prolonged stress, the dielectric strength of the insulation continuously decreases, ultimately leading to electrical breakdown, bushing failure, and operational shutdown, thereby threatening the overall safety of the converter stations. Therefore, when the electric-field distribution characteristics within bushings are analyzed, the patterns of electric-field strength distortion under various defect conditions are critical.

2.2. Three-Dimensional Model of Oil-Immersed Bushing

The structure and finite element model of the oil-immersed bushing are shown in Fig. 1. The bushing is primarily composed of a capacitor core, transformer oil, upper and lower porcelain bushings, grounding flange, conductive rod, and other fixed accessories. The insulation performance of an oil-immersed bushing depends on its internal capacitive core, which improves the electric-field distribution and enhances insulation effectiveness. The capacitive core was constructed by alternately winding oil-impregnated paper and aluminum foils around a conductive rod, forming an oil-paper composite insulation structure that can be regarded as a concentric cylindrical capacitor. The external insulation of the oil-paper bushing is provided by the upper and lower porcelain housings, with the upper housings designed with sheds to enhance their external insulation performance.

The material parameters used for the oil-immersed bushing are listed in Table 1. Graded aluminum foils were incorporated in the winding process to improve the uniformity of the electric field within the capacitive core. These foils were coaxially arranged around the conductive rod and insulation paper, with the dimensions of each foil layer detailed in Table 2.

3. CHARACTERISTICS OF ELECTRIC FIELD DISTRIBUTION IN OIL-IMMERSED BUSHINGS UNDER DEFECT-FREE CONDITIONS

3.1. Overall Characteristics of Electric Field and Voltage Distribution

To study the electric field and voltage distributions in the oil-immersed bushings, an AC voltage of 110 kV was applied to the conductive rod, as shown in Fig. 2, and the electric field and voltage distributions at the capacitive core are shown in Fig. 3.

As shown in Fig. 2 and Fig. 3, the overall electric field in the oil-immersed bushing exhibits significant axial symmetry. This characteristic stems from the concentric cylindrical structure of the capacitive core and uniform distribution of the insulating medium. The voltages exhibited a uniform attenuation trend along the radial direction of the bushing. This is consistent with the voltage division design principle of capacitive screens, indicating that capacitive screens can effectively homogenize the electric field.

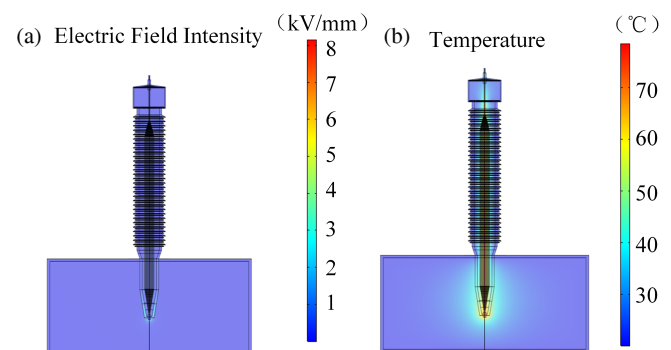
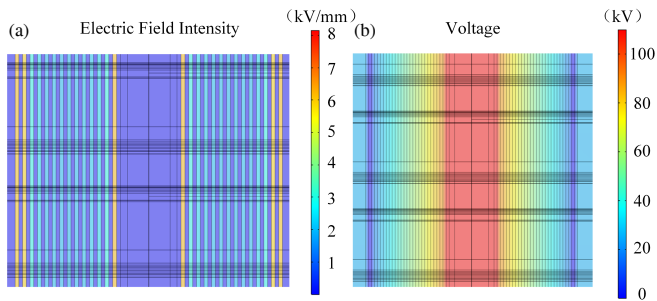


FIGURE 2. Overall electric field and voltage distribution of the oil-immersed bushing. (a) Electric-field distribution. (b) Voltage distribution.

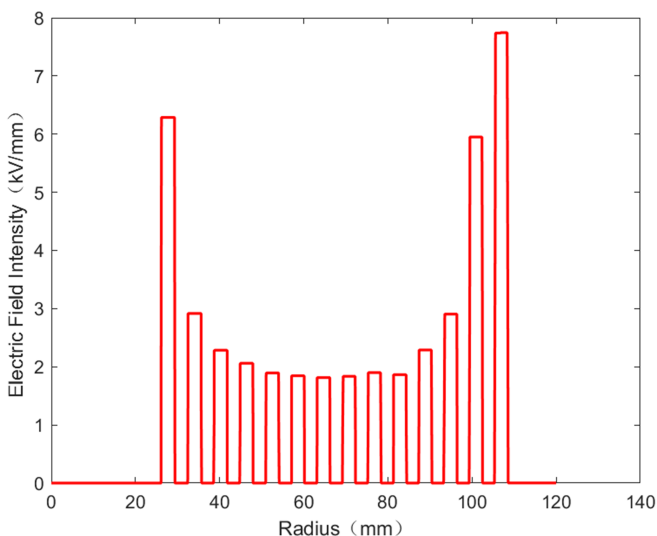
TABLE 1. Physical properties of materials in the oil-immersed bushing model.

Material	Relative permittivity	Conductivity ($\text{S}\cdot\text{m}^{-1}$)	Thermal conductivity $\text{W}/(\text{m}\cdot\text{K})$
Copper	1.0	6.0×10^7	400
Oil-Impregnated Paper	2.13	5.0×10^{-12}	0.2
Aluminum foil	8.09	3.774×10^7	238
Porcelain bushing	4.2	1.0×10^{-13}	3.5
Stell	1	4.032×10^6	150
Aluminum alloy	4000	4.0×10^7	150
Transformer oil	5.0×10^{-12}	2.13	0.2

**FIGURE 3.** Electric-field and voltage distribution of the capacitor core of the oil-immersed bushing. (a) Electric-field distribution. (b) Voltage distribution.

3.2. Laws of Internal Electric Field and Voltage Distribution in Oil-Immersed Bushings

Figure 4 shows the radial electric-field intensity distribution in the defect-free bushing. The radial electric field of the capacitive core exhibited a multi-peak gradient distribution but overall showed a gradient change along the radial direction. It can be seen from the figure that the maximum electric-field intensity $E_{\max} \approx 8 \text{ kV/mm}$, and the average electric-field intensity in the middle region $E_{\text{avg}} \approx 2.5 \text{ kV/mm}$. Although some peak values

**FIGURE 4.** Radial electric-field intensity distribution in the defect-free bushing.**TABLE 2.** Dimensions of aluminum foil layers in the oil-immersed bushing model.

Number of layers	Radius/mm	Length/mm	Thickness/mm
1	106	3490	3
2	99	3547	3
3	93	3609	3
4	87	3668	3
5	81	3726	3
6	75	3787	3
7	69	3849	3
8	63	3911	3
9	57	3974	3
10	51	4035	3
11	45	4097	3
12	39	4158	3
13	32	4220	3
14	26	4286	3

can be found in the electric field under defect-free conditions, a controllable gradient uniformity is achieved through voltage division by the capacitive screens, and no extremely concentrated electric-field intensity is observed.

Figure 5 shows the axial electric-field intensity distribution of the defect-free bushing. At the same radius, the magnitude of the electric-field intensity remained constant regardless of the changes in the axial position. This characteristic provides an important prerequisite for conducting multi-axial position analysis of metal particles and air bubble defects in oil. This ensures that the axial position does not interfere with the research results on the laws of electric-field distortion induced by defects, and thus allows the study to focus on the impact of the defects themselves on the electric-field distribution.

Figure 6 shows the radial voltage distribution in the defect-free bushing. As shown in the figure, the voltage exhibits stepwise linear attenuation along the radial direction: the central conductive rod region is at a high potential; as it moves radially outward, the potential drops significantly in a stepwise manner each time it passes a capacitive screen and finally drops to 0 V at the outermost grounded capacitor screen.

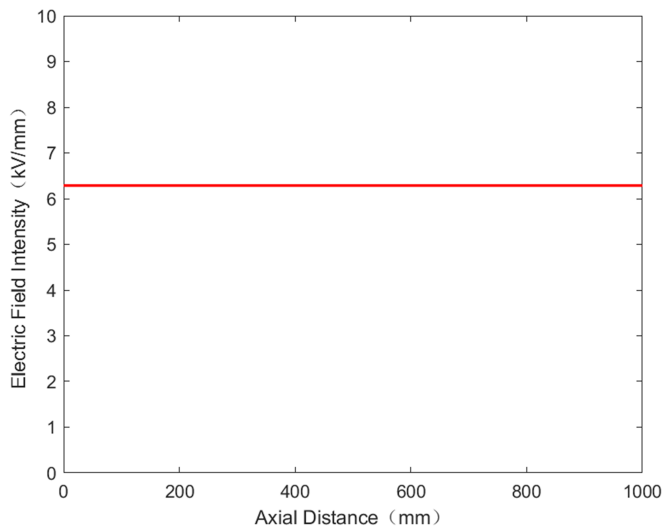


FIGURE 5. Axial electric-field intensity distribution of the defect-free bushing.

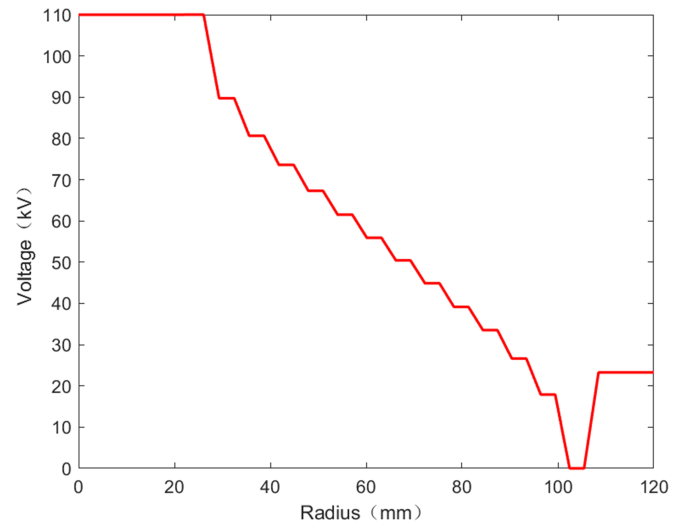


FIGURE 6. Radial voltage distribution of the defect-free bushing.

TABLE 3. Laws of the internal electric-field distribution of the bushing under the defect-free condition.

Indicator	Characteristic
Electric field intensity	$E_{\max,0} = 8 \text{ kV/mm}$
Electric field uniformity	Multi-peak gradient distribution
Voltage attenuation gradient	Stepwise linear attenuation from 110 kV to a gradient of 0 V

It can be seen from the above analysis that under defect-free conditions, the oil-immersed bushing utilizes the voltage division effect of its capacitive screens to achieve a uniform electric-field distribution gradient and stepwise voltage attenuation. It effectively controls the electric-field intensity at critical locations, prevents excessive local electric-field concentration, and thus ensures the stability and reliability of the overall insulation performance of the bushing. The laws governing the internal electric-field distribution are summarized in Table 3.

4. ELECTRIC FIELD DISTRIBUTION CHARACTERISTICS OF THE OIL-IMMERSED BUSHING WITH TYPICAL DEFECTS

Generally, there are four common types of defects in oil-immersed transformer bushings: metal particle contamination in the capacitive core, air bubbles in the oil, lack of end-screen grounding, and damage to the capacitive screen. In light of this, studies were conducted under the above four types of typical defects to clarify differences in the internal electric-field characteristics of the bushing under different defects and their influence mechanisms. This is of great significance for the early identification of defects, early warning of insulation risks, and optimization of the operation and maintenance of oil-immersed transformer bushings.

4.1. Electric Field Distribution in the Capacitive Core with the Metal Particle Doping Defect

Some copper particles were selected to reproduce the characteristics of metal debris generated by wear and detachment on the surface of conductive rods during actual operation and maintenance. The defect location is limited to the area near the innermost layer of the capacitor core for the following reasons. On the one hand, this area is adjacent to the copper conductive rod and serves as a typical location where debris detached from the conductive rod migrates and accumulates — condition that matches the potential real-world distribution of such metal particles. On the other hand, the electric-field intensity distribution remains consistent at different axial positions with the same radius. By fixing the radial and axial positions of the metal particles, the interference caused by inherent differences in electric-field intensity can be effectively eliminated. This enables the research to concentrate on how the distance between metal particles and capacitive screens affects electric-field distortion within the same high electric-field-intensity area, avoids the contingency of conclusions caused by experiments at a single location, and ensures the comprehensiveness and reliability of subsequent electric-field characteristic analysis results. Nine metal particles with a radius of 1.5 mm are placed at different axial positions of the capacitor core, at distances of 0.5 mm, 1 mm, and 1.5 mm from the capacitive screens, respectively, as shown in Fig. 7.

An AC voltage of 110 kV is applied to the conductive rod. The distortion effects of these metal particles on the electric field are shown in Fig. 8, Fig. 9, and Fig. 10.

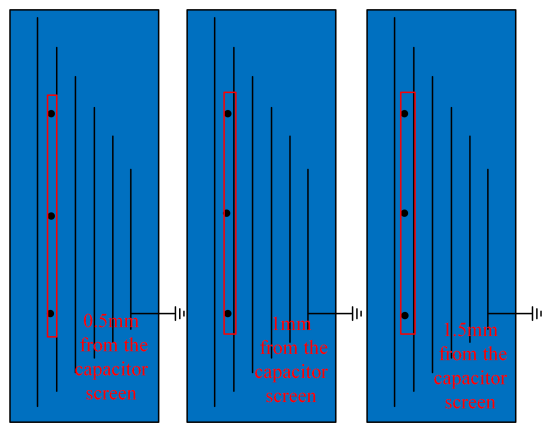


FIGURE 7. Locations of metal particles in the capacitor core.

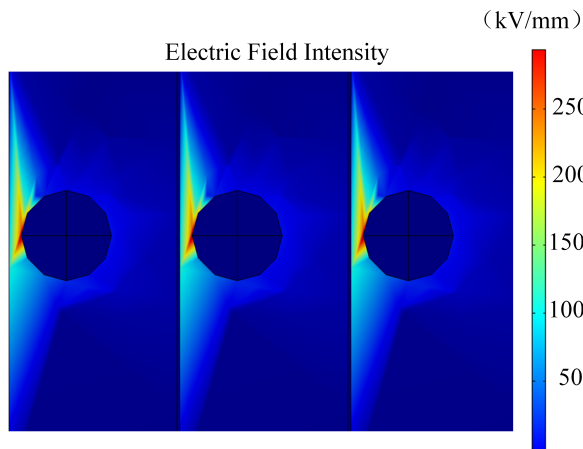


FIGURE 8. Electric-field distortion caused by metal particles at a distance of 0.5 mm from the capacitor screen at different axial positions.

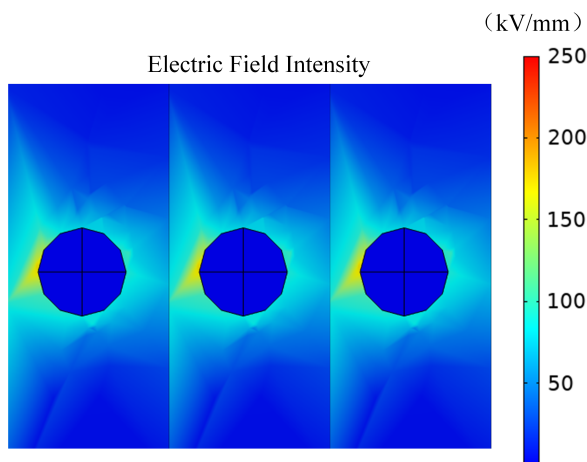


FIGURE 9. Electric-field distortion caused by metal particles at a distance of 1 mm from the capacitor screen at different axial positions.

As shown in Figs. 8–10, when metal particles exist in the capacitive core, the local electric-field distortion varies significantly with the distance between the particles and the capacitor screen. The radial distribution of the electric-field intensity inside the capacitive core doped with metal particles is shown in Fig. 11.

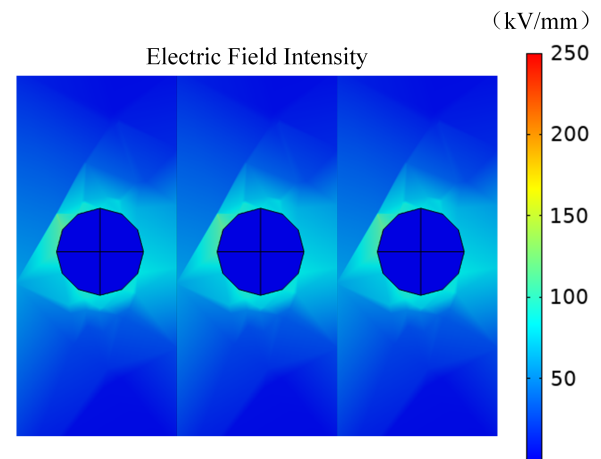


FIGURE 10. Electric-field distortion caused by metal particles at a distance of 1.5 mm from the capacitor screen at different axial positions.

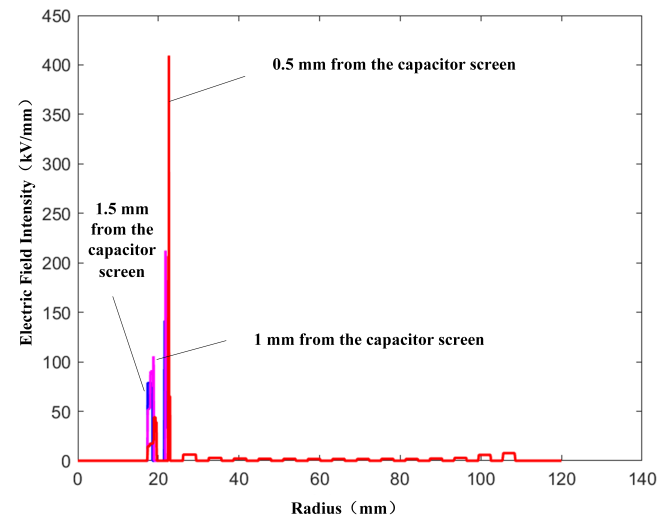


FIGURE 11. Electric-field intensity distribution inside the bushing with metal particles doped at distances of 0.5 mm, 1 mm, and 1.5 mm from the capacitor screen.

When the metal particles are far from the capacitive screen, the electric-field distortion is locally spherical, and the region of high electric-field intensity is confined to the vicinity of the metal particle surface. When the metal particles are close to the capacitive screen, the electric field extends in a long and narrow shape. The equipotential surfaces of the capacitor screen forcibly redirect the electric field, causing the electric-field lines to form a long, narrow high electric-field-intensity band between the particles and the capacitive screen. The distortion range significantly expands along the direction of the capacitor screen, impairing the original uniform voltage division area of the capacitor screen.

4.2. Electric-Field Distribution under the Defect of Air Bubbles in the Oil

Nine air bubbles with radii of 1 mm, 1.25 mm, and 1.5 mm were placed at different axial positions in the same radial direction near the innermost layer of the capacitor core, as shown in

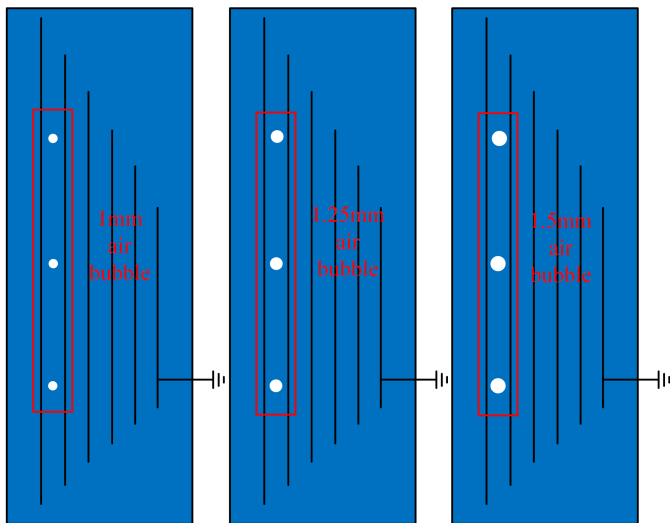


FIGURE 12. Schematic diagram of air bubble distribution with different radii.

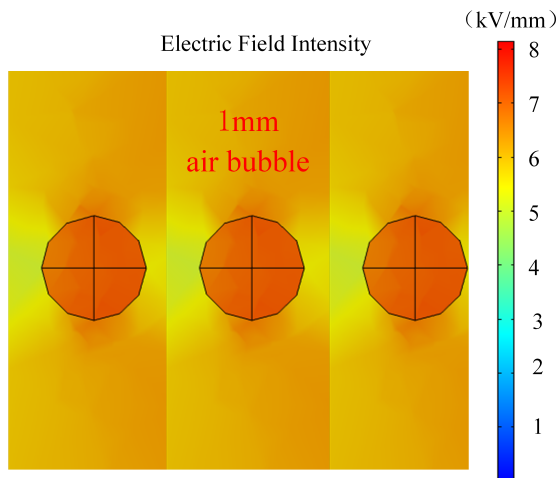


FIGURE 13. Electric-field distortion caused by 1 mm air bubble impurities at different axial positions.

Fig. 12. These bubbles were used to study the impact of air bubbles of different sizes on the electric field inside the bushing.

An AC voltage of 110 kV was applied to the conductive rods. The electric-field intensities inside and in the surrounding areas of the 1 mm, 1.25 mm, and 1.5 mm air bubbles are shown in Figs. 13–15, respectively. By comparing the electric-field intensity distributions in the figures, it can be seen that the inside and surrounding areas of the 1 mm air bubble are dominated by the red color spectrum corresponding to a high electric-field intensity, exhibiting distinct high electric-field-intensity characteristics. The red color in the inside and surrounding areas of the 1.25 mm air bubble is lighter, showing a relatively lower electric-field intensity than the 1 mm air bubble. The areas corresponding to the 1.5 mm air bubble are mostly distributed in the orange-yellow color spectrum (representing a relatively low electric-field intensity), and the degree of electric-field intensity concentration decreases significantly. Based on this, the

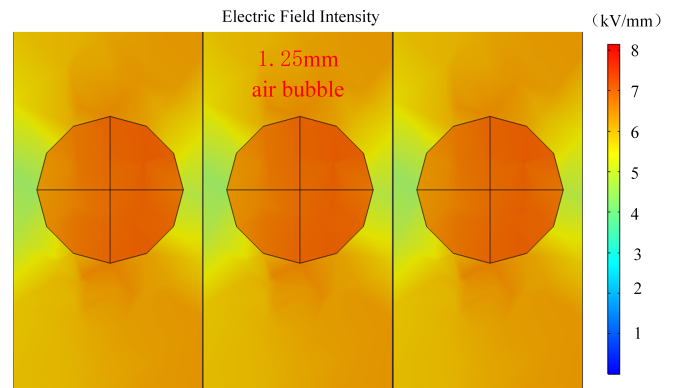


FIGURE 14. Electric-field distortion caused by 1.25 mm air bubble impurities at different axial positions.

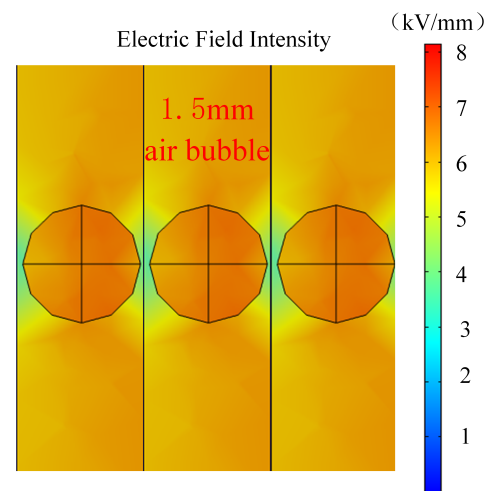


FIGURE 15. Electric-field distortion caused by 1.5 mm air bubble impurities at different axial positions.

following conclusion can be drawn: under the 110 kV voltage condition, there is a significant negative correlation between the air bubble size and local electric-field intensity; specifically, the smaller the geometric size of the air bubble, the higher the degree of electric-field intensity concentration inside and in the surrounding areas.

The radial electric-field intensity distribution inside the bushing doped with air bubbles is shown in Fig. 16.

As shown in Fig. 16, an obvious electric-field concentration phenomenon occurred inside the air bubbles. This is completely different from the tip, where the external electric-field concentration within the air bubbles is much lower than that in transformer oil, leading to a significant increase in the electric-field intensity inside the bubbles. A comparison of the electric-field intensity contour maps shows that the smaller the air bubble size, the more pronounced the electric field concentration effect. The electric-field concentration of the air bubbles with radii of 1 mm and 1.25 mm is higher than that of the 1.5 mm. This is because smaller bubbles have a larger interface curvature, and the electric-field refraction enhances the focusing effect.

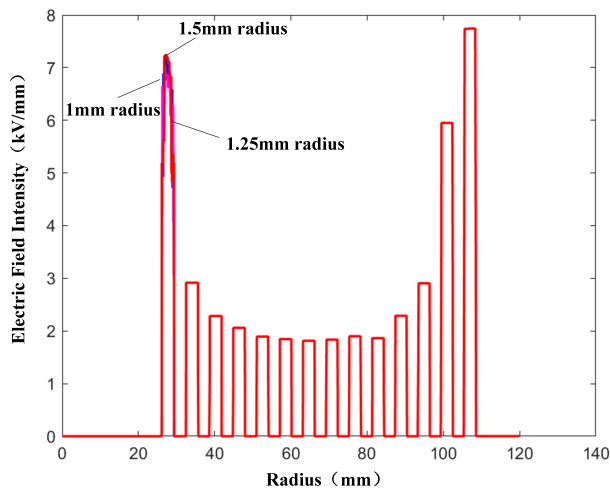


FIGURE 16. Electric-field intensity distribution inside the bushing with air bubble impurities of different sizes.

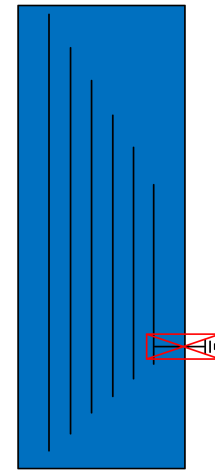


FIGURE 17. Schematic diagram of the defect of capacitive end screen grounding disconnection.

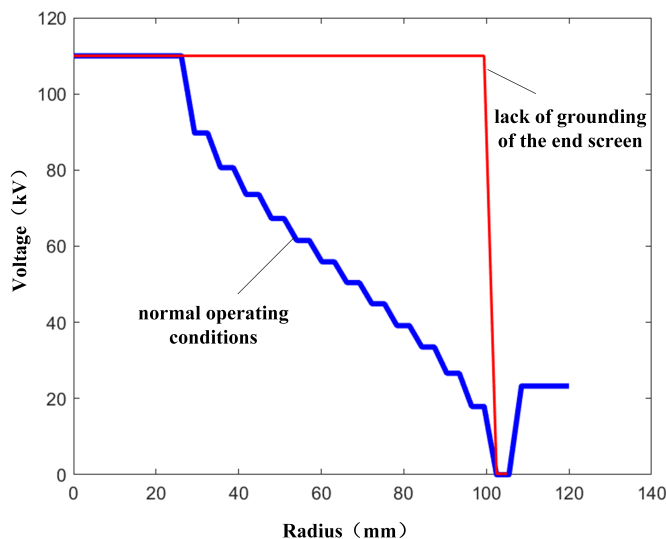


FIGURE 18. Potential distribution under the defect of grounding disconnection.

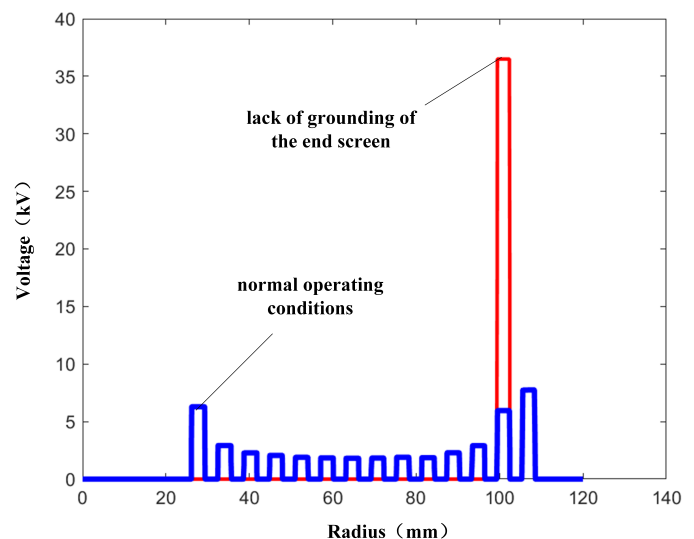


FIGURE 19. Electric-field intensity distribution under the defect of grounding disconnection.

4.3. Electric Field Distribution under the Defect of Capacitor End Screen Grounding Disconnection

Under normal conditions, the capacitive end screen grounding serves two main functions: (1) it provides a voltage discharge path that clamps the potential of the outermost capacitive screen to ground, ensuring that the capacitor screens, from the inside to the outside, form a “high potential-low potential” series voltage division structure; (2) it determines the voltage division ratio of each capacitive screen, and end screen grounding constitutes the closed-loop condition for the series capacitor voltage division mechanism. A schematic of the ground screen loss-of-ground defect is shown in Fig. 17.

Under the same operating conditions, a simulation of the defect of capacitive end screen grounding disconnection was conducted, and the results are shown in Fig. 18. Owing to the capacitor end-screen grounding disconnection, the voltage that should be originally distributed across all capacitor screens is

concentrated on one or two capacitive screens adjacent to the end screen, and the potential drops sharply from 110 kV to 0 V. Capacitive screens possess a concentric cylindrical structure: the closer a capacitor screen is to the outer layer, the larger its coupling capacitance with adjacent screens, and the smaller its capacitive reactance. Owing to potential stagnation, the capacitive reactance of the inner capacitive screens is equivalent to infinity, so they contribute negligibly to voltage division. Consequently, one or two capacitive screens adjacent to the end screen were forced to withstand a 110 kV voltage drop.

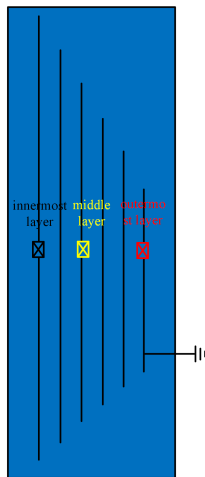
Figure 19 shows a comparison of the electric-field intensity distributions for a capacitor end screen lacking grounding and one without defects. The potential dropped from 110 kV to 1 V over an extremely narrow range, resulting in an extremely large potential gradient. The electric-field intensity accumulated and rose to 36 kV/mm in this region, whereas the electric-field intensity in other regions was almost 0 V.

TABLE 4. Quantitative table of electric-field distortion under metal particle defects.

Analysis Dimension	Defect-Free	0.5 mm from the capacitive screen	1 mm from the capacitive screen	1.5 mm from the capacitive screen
maximum electric field intensity (kV/mm)	8	≈ 400	≈ 220	≈ 150
electric field distortion coefficient K	—	≈ 50	≈ 27.5	≈ 18.75

4.4. Electric-Field Distribution under the Defect of Capacitive End Screen Damage

Capacitor screens in oil-immersed bushings serve for electric-field homogenization and voltage division, can optimize the electric-field distribution within the insulation structure, and fundamentally improve the insulation reliability of the equipment. Capacitor screen damage generally refers to the tearing and carbonization of insulation paper or the deformation and breakage of aluminum foil. Both types of damage compromise the integrity of the capacitive screen. To investigate the impact of capacitive screen damage at different positions on electric-field distortion, this study selected damage occurring at the innermost, middle, and outermost layers as the research objects. A schematic of the capacitive screen damage positions is shown in Fig. 20.

**FIGURE 20.** Schematic diagram of the defect of capacitor screen damage.

An AC voltage of 110 kV was applied to the conductive rod, and the electric-field distortion caused by the defect in the capacitive screen damage is shown in Fig. 21.

Figure 22 demonstrates the electric-field intensity distribution under the condition of a defect in the capacitor screen damage. The closer the capacitor screen damage is to the outermost layer, the greater the proportion of potential difference it withstands in the voltage division structure, and the more significant the electric-field distortion is caused by the damage.

When the innermost and middle-layer capacitive screens are damaged, the electric-field intensity in the correspond-

ing regions increases; moreover, the visual magnitudes of the electric-field intensity increase are relatively similar for both layers. However, the original baseline electric-field intensity in the middle layer was relatively low, and the actual increase in electric-field intensity after damage was smaller than that in the innermost layer. The outermost layer is located at the end segment of the potential difference, and the proportion of the potential difference between adjacent capacitor screens is the largest. After damage, the originally dispersed high potentials concentrated in the damaged area, resulting in a relative increase in the electric-field intensity far higher than that in the inner and middle layers.

5. DISCUSSION

5.1. Quantitative Analysis of Electric Field Distortion inside the Bushing

The degree of electric-field distortion was quantified by considering the maximum electric-field intensity inside the bushing under the defect-free state, denoted as $E_{\max,0}$. The electric-field distortion coefficient K is shown in (1):

$$K = \frac{E_{\max, \text{defects}}}{E_{\max, 0}} \quad (1)$$

It can be seen from Equation (1) that the greater the impact of a defect is on the degree of electric-field distortion, the larger the electric field distortion coefficient K becomes.

Table 4 presents a quantitative summary of the electric-field distortion coefficient for metal particle defects. The degree of influence that metal particles exert on the electric field exhibits a strong correlation with their distance from the capacitive screen. For metal particles located 0.5 mm away from the capacitive screen, the maximum electric-field intensity is 50 times that in the defect-free state, and the electric-field distortion coefficient surges to 50, far exceeding 18.75 times observed at a distance of 1.5 mm from the capacitive screen. It indicates that the equipotential surface constraint of the capacitive screen significantly amplifies the electric-field distortion effect of the metal particles.

The quantitative analysis of the electric-field distortion caused by air bubble defects in oil is presented in Table 5. After the introduction of air bubbles, sharp peaks in the electric-field intensity appeared in the regions corresponding to the radii of the bubbles. The maximum electric-field

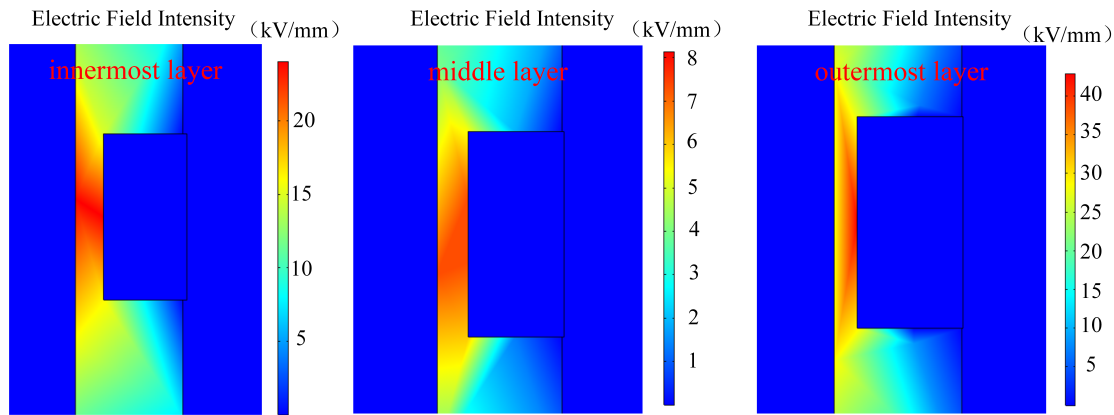


FIGURE 21. Electric-field intensity distribution under the defect of capacitor screen damage.

TABLE 5. Quantitative table of electric-field distortion with air bubble defects in oil.

Analysis Dimension	Defect-Free	1 mm air bubble	1.25 mm air bubble	1.5 mm air bubble
maximum electric field intensity (kV/mm)	8	≈ 7.24	≈ 7.20	≈ 7.03
electric field distortion coefficient K	—	≈ 0.905	0.9	0.879

TABLE 6. Quantitative table of electric-field distortion with end screen grounding disconnection defects.

Analysis Dimension	Defect-Free	Grounding Loss State
maximum electric field intensity (kV/mm)	8	≈ 36
electric field distortion coefficient K	—	≈ 4.5

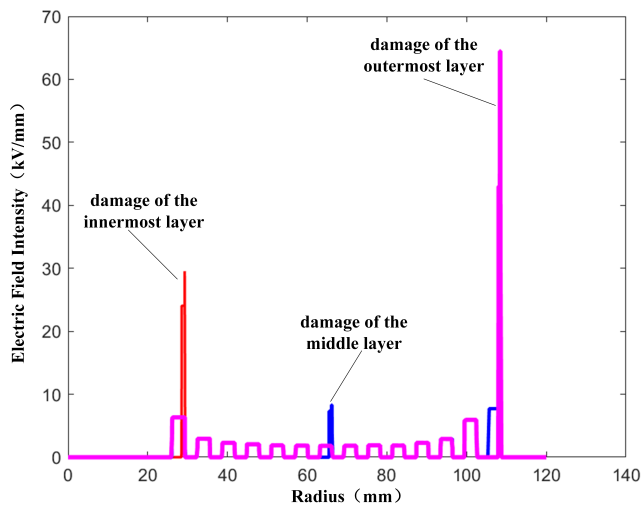


FIGURE 22. Electric-field intensity distribution under the defect of capacitive screen damage.

intensities inside air bubbles with radii of 1 mm, 1.25 mm, and 1.5 mm all exceed 7 kV/mm; all three are higher than the electric-field intensity at their respective locations in the defect-free state, but none exceeds the maximum electric-field intensity in the defect-free state.

The quantitative analysis of the grounding disconnection defect of the capacitive end screen is shown in Table 6. When the grounding of the capacitor end screen is disconnected, the

electric-field intensity is 4.5 times that in the defect-free state, and the electric-field uniformity is disrupted.

The quantitative analysis of the capacitor screen damage defects is presented in Table 7. When the outermost-layer capacitive screen is damaged, the maximum electric-field intensity increases to 8.125 times that of the defect-free state, and the electric-field distortion coefficient is 8.125. For the middle-layer capacitor screen, the electric-field intensity at the damaged location is higher than that at the corresponding location in the defect-free state, but does not exceed the maximum electric-field intensity in the defect-free state. When the innermost layer capacitor screen is damaged, the maximum electric-field intensity increases to 3.75 times that of the defect-free state, and the electric-field distortion coefficient is 3.75. The electric-field distributions of the capacitor screens with three different degrees of damage all change from a uniform gradient to localized extreme concentration.

5.2. Insulation Risk Assessment

For oil-paper composite insulation, the partial discharge inception electric-field intensity $E_{pd,oip} = 8 \sim 20$ kV/mm, and the breakdown electric-field intensity $E_{bd,oip} = 40 \sim 80$ kV/mm. For mineral insulating oil, the partial discharge inception electric-field intensity is $E_{pd,oil} = 10 \sim 25$ kV/mm, and the breakdown electric-field intensity is $E_{bd,oil} = 20 \sim 40$ kV/mm. In the defect-free state, the maximum electric-field intensity of the bushing is $E_{max,0} = 8$ kV/mm; the reference

TABLE 7. Quantitative table of electric-field distortion under capacitor screen damage defects.

Analysis Dimension	Defect-Free	Damage of the Innermost Layer	Damage of the Middle Layer	Damage of the Outermost Layer
maximum electric field intensity (kV/mm)	8	≈ 30	≈ 8	≈ 65
electric field distortion coefficient K	—	≈ 3.75	≈ 1	≈ 8.125

TABLE 8. Insulation risk assessment criteria based on electric-field distortion coefficient.

Risk Level	Range of K	Quantitative Determination Basis
Low	$K \leq 1.25$	does not reach the discharge threshold of any medium
Medium	$1.25 < K \leq 2.5$	does not exceed the upper limit of the inception electric field intensity of oil-paper insulation
High	$2.5 < K \leq 5$	does not break through the maximum of the lower limits of the breakdown electric field intensity
Extremely High	$K > 5$	exceeds the withstand limit of the medium

distortion coefficient is $K_0 = 1$, which serves as the core reference benchmark for insulation risk assessment.

To ensure the safety and universality of the assessment criteria, the principle of conservative value selection was adopted: the critical threshold for partial discharge was set to the minimum of the upper limits of the inception electric-field intensities of the two media (20 kV/mm); the critical breakdown threshold was set to the maximum of the lower limits of the breakdown electric-field intensities of the two media (40 kV/mm); and the critical distortion coefficient was calculated by combining these thresholds with the reference electric-field intensity.

Critical distortion coefficient for partial discharge $K_{pd} = \frac{20}{8} = 2.5$; Critical distortion coefficient for breakdown $K_{bd} = \frac{40}{8} = 5$; Critical distortion coefficient for safety margin is the one corresponding to the lower limit of the inception electric-field intensity of insulating oil, that is, $K = \frac{10}{8} = 1.25$, which serves as the boundary between low risk and medium risk. The assessment criteria are presented in Table 8.

When the distance between the metal particle and capacitor screen was 0.5 mm, the maximum electric-field intensity in the defect region $E_{\max} \approx 400$ kV/mm, and the electric-field distortion coefficient $K \approx 50$; when the distance between the particle and capacitor screen was 1 mm, $E_{\max} \approx 220$ kV/mm, and the electric-field distortion coefficient $K \approx 27.5$; when the distance between the metal particle and capacitor screen was 1.5 mm, the maximum electric-field intensity in the defect region $E_{\max} \approx 150$ kV/mm, and the electric-field distortion coefficient $K \approx 18.75$. Therefore, regardless of the relative position (whether near or far) between the metal particle contamination defect in the capacitive core and the capacitor screen, the risk is extremely high. Moreover, when the particle is close to

the capacitor screen, the risk level is significantly higher than that when it is far from it.

For bubble defects in the oil with radii of 1 mm, 1.25 mm, and 1.5 mm, the electric-field distortion coefficient K is less than 1 in all cases, below the critical threshold for low risk in the assessment criteria. Therefore, the bubble defects in the oil were classified as low risk.

The electric-field distortion coefficient of the capacitor screen damage defects varied significantly depending on the damage location. When the innermost layer capacitor screen was damaged, $E_{\max} \approx 30$ kV/mm, and the electric-field distortion coefficient $K \approx 3.75$; when the middle-layer capacitor screen was damaged, $E_{\max} \approx 8$ kV/mm, and the electric-field distortion coefficient $K \approx 1$; when the outermost layer capacitor screen was damaged, $E_{\max} \approx 65$ kV/mm, and the electric-field distortion coefficient $K \approx 8.125$. For the risk assessment of damage at different locations, damage to the middle-layer capacitive screen was determined to be low risk, whereas damage to the innermost and outermost layer capacitive screens was classified as high risk.

Based on the above assessment results, the insulation risk levels and core parameters of the four typical defects are listed in Table 9.

Based on the above assessment results, a quantitative basis is provided for the operation and maintenance disposal of oil-immersed bushing defects: for extremely high-risk defects (metal particles) and high-risk defects (damage to the innermost and outermost capacitor screens and absence of capacitor final screen grounding), emergency shutdown and maintenance shall be implemented; low-risk defects (bubbles in oil and damage to the middle capacitor screen) can be incorporated into the regular operation and maintenance system to achieve differentiated risk management and control.

TABLE 9. Insulation risk assessment criteria based on electric-field distortion coefficient.

Defect Type	Distortion Coefficient	Insulation Risk Level
Metal particle 0.5 mm away from the capacitor screen	50	Extremely High Risk
Metal particle 1mm away from the capacitor screen	27.5	Extremely High Risk
Metal particle 1.5 mm away from the capacitor screen	18.75	Extremely High Risk
1 mm air bubble	0.905	Low Risk
1.25 mm air bubble	0.9	Low Risk
1.5 mm air bubble	0.879	Low Risk
Absence of Final Screen Grounding	4.5	High Risk
Damage to the Innermost Layer	3.75	High Risk
Damage to the Middle Layer	1	Low Risk
Damage to the Outermost Layer	8.125	High Risk

5.3. In-Depth Discussion of the Physical Mechanisms of Defect-Induced Electric-Field Distortion

5.3.1. Physical Mechanism of Electric-Field Distortion Induced by Metal-Particle Defects

Metal particles, acting as conductive bodies, undergo electrostatic induction in an electric field. When suspended within the oil-paper insulation medium, free charges accumulate on their surfaces until the particles effectively become equipotential bodies. The capacitor screen itself is a strictly equipotential surface. As a metal particle approaches the capacitor screen, a microscopic gap is formed between them. The induced opposite charges on the particle and the bound charges on the capacitor screen generate a strong image-charge attraction force. Meanwhile, the extremely narrow gap forces the electric-field lines emitted from the particle surface to terminate almost perpendicularly on the capacitor screen, thereby forming a narrow “electric-field tunnel.” This geometric constraint significantly compresses the distribution space of the equipotential lines, causing the average potential gradient within the gap to increase sharply under the same potential difference.

5.3.2. Physical Mechanism of Electric-Field Distortion Induced by Metal-Particle Defects

Bubbles have a distinctly different dielectric constant from transformer oil and oil-impregnated paper. In an electrostatic field, the boundary condition dictates that the normal component of the electric displacement vector is continuous, as expressed by the formula $\varepsilon_1 E_{1n} = \varepsilon_2 E_{2n}$. Therefore, when electric-field lines pass vertically through the interface from a medium with a high dielectric constant into one with a low dielectric constant, the normal component of the electric-field intensity inside the bubbles rises sharply. This is the fundamental reason for the increased field strength within bubbles.

Small-sized bubbles have greater curvature, and their surfaces deviate further from a plane microscopically. When electric-field lines traverse highly curved interfaces, the refrac-

tion and focusing effect is intensified. Consequently, the density of electric-field lines passing through the bubble is much higher than that on its two sides, producing a higher peak value of local electric-field intensity inside the bubble. This explains the counter-intuitive phenomenon that bubble size is negatively correlated with the degree of electric-field concentration.

5.3.3. Physical Mechanism of Electric-Field Distortion Induced by Defect of Absent Capacitor Final Screen Grounding

The capacitor core is essentially a series capacitor chain arranged from the inside out. Under normal operating conditions, the outermost final screen is solidly grounded, providing a zero-potential reference point for the entire series branch. Consequently, the electric potential decreases in a uniform stepped manner from the conductive rod to the final screen along each capacitor screen.

When the final screen loses its low-impedance grounding path, the potential of the outermost capacitor screen is no longer clamped to zero. Instead, it is charged to a certain floating potential by the stray capacitance of the inner layers. To sustain the total voltage drop of the system from 110 kV to 0 V, the potential difference is concentrated across the inter-screen gaps adjacent to the final screen. Nearly all the voltage is thereby applied to the rearmost capacitor unit, destroying the uniform distribution of the electric field.

5.3.4. Physical Mechanism of Electric-Field Distortion Induced by Capacitor Screen Damage

Capacitor screens are artificially configured ideal equipotential surfaces whose primary function is to homogenize the electric-field distribution. When intact, the concentric cylindrical capacitor screens guide electric-field lines to align regularly along the radial direction and form a uniform potential gradient.

However, if a capacitor screen is damaged, the boundary conditions of the equipotential surface within the damaged area will experience an abrupt geometric discontinuity. The originally smooth and continuous equipotential surface forms sharp

protrusions or depressions at the damaged edges. In line with the fundamental principles of electrostatic fields, electric-field lines are always perpendicular to the surface of a conductor. At the tips and corners of damaged edges, a large number of electric-field lines are forced to converge and pass densely perpendicular to the boundary. Consequently, the density of electric-field lines in this region is far higher than that in intact areas. This field line squeezing effect induces extremely high local electric-field intensity near the damage site.

Further analysis indicates that outer capacitor screens withstand most of the potential difference transmitted from inner layers, and the potential difference between an outer screen and its adjacent screen is the largest. Therefore, the boundary geometric discontinuity triggered by damage to outer screens arises under the maximum local potential difference. The resultant field line squeezing effect is the most severe, bringing about the maximum rise in electric-field intensity, which reaches 65 kV/mm.

In comparison, despite the relatively high baseline electric-field intensity of inner capacitor screens, the potential difference between inner screens and their neighbors is small. As a result, the absolute magnitude of electric-field distortion after damage is relatively limited. This discrepancy reveals a key law: the insulation risk induced by defects depends not only on the geometric morphology and material properties of the defects, but also strongly on their topological position in the overall electrical stress distribution of the system.

5.3.5. Key Points on Defect Prevention and Mitigation Measures

In view of the physical mechanisms and insulation risks of the above four typical defects, targeted preventive measures can be implemented from three dimensions: design, manufacturing, and operation and maintenance. For metal particle defects, manufacturing cleanliness and insulating oil filtration shall be strictly controlled. Operational intervention can be realized through particle detection and circulating filtration of oil. For gas bubble defects in oil, the processes of vacuum oil filling and drying degassing shall be optimized. It is also necessary to regularly monitor dissolved gas and ensure sound sealing performance of the equipment. For the absence of capacitor final screen grounding, reliable anti-loosening grounding terminals shall be adopted in design, and circuit continuity must undergo mandatory inspection before product delivery. During routine operation and maintenance, regular tests of grounding resistance and infrared temperature measurement shall be performed. As for capacitor screen damage, the winding tension and insulating paper wrapping process shall be well controlled in the manufacturing stage. In operation, the component condition can be assessed via dielectric spectroscopy or dielectric loss detection. Timely replacement or major overhaul shall be arranged for high-risk damage. In addition, it is suggested to establish an early warning threshold system based on the electric-field distortion coefficient to carry out differentiated disposal of defects at different risk levels. Multi-physics field simulation or digital twin technology can be adopted for regular verification, so as to systematically reduce the insulation risks induced by defects.

6. CONCLUSION

To address the problems of electric-field distortion and the difficulty in quantitatively evaluating insulation risks induced by typical defects in the capacitor core of oil-immersed transformer bushings, this study establishes a three-dimensional simulation model based on COMSOL Multiphysics. It systematically analyzes the electric-field distribution characteristics under defect-free conditions and four typical defects, namely metal particle doping, bubbles in oil, absence of final screen grounding, and capacitor screen damage. Based on this, insulation risk classification and assessment were performed. The main conclusions of this study are as follows.

1) The benchmark characteristics of the electric-field distribution of the bushing in the defect-free state are clarified. In the defect-free state, the internal electric field of the bushing exhibits a segmented uniform distribution, and the capacitive screen realizes stepped and stable attenuation of the potential along the axial direction through effective voltage division. The maximum electric-field intensity in key areas is stably maintained at 8 kV/mm, which does not exceed the partial discharge inception electric-field intensity of the oil-paper insulation material. This verifies the rationality of the bushing structural design and provides a reliable reference benchmark for comparing defective states.

2) The laws and differences in the electric-field distortion caused by the four types of typical defects are revealed. When metal particles are doped in the capacitor core, an extreme electric-field concentration is induced at the particle tips, and the maximum electric-field intensity increases by more than 50% compared with the defect-free state, with the distortion range concentrated around the particles. For bubbles in oil, the difference in dielectric constant causes refraction of electric-field lines. The maximum electric-field intensity induced by bubbles with three different radii is all higher than 7 kV/mm, and the bubble size is negatively correlated with the distortion degree. The absence of capacitor final screen grounding damages the overall voltage division mechanism, resulting in an overall disorder of electric-field distribution. The electric-field intensity near the final screen surges to 35 kV/mm, and this defect has the widest distortion impact range. Capacitor screen damage leads to complete failure of the electric-field homogenization function, and the maximum electric-field intensity in the defective area soars to 65 kV/mm, far exceeding the breakdown threshold of oil-paper insulation, making it the most harmful defect type.

3) A quantitative analysis of the degree of electric-field distortion caused by the four types of defects is conducted, and insulation risk level assessment criteria are proposed and applied. This provides a basis for formulating a regular operation and maintenance system for transformer bushings and realizing differentiated risk management and control.

4) The four typical defects have fundamentally different electric-field distortion mechanisms. As floating conductors, metal particles form extremely narrow high-field regions via the tip effect and capacitive coupling with capacitor screens. Gas bubbles in oil induce electric-field refraction at material interfaces due to their low dielectric constant, and smaller bub-

bles produce more prominent distortion. The absence of capacitor final screen grounding breaks the series voltage division network, resulting in floating potential and voltage concentration. Capacitor screen damage causes the field line squeezing effect owing to geometric discontinuity of equipotential surfaces; damage to outer screens yields the most drastic distortion because of the maximum potential difference across adjacent layers. The above mechanisms reveal the intrinsic correlation among defect type, defect location, and insulation risk from a causal perspective, and provide a theoretical basis for differentiated operation and maintenance.

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