Influence of Metal Particles on the Electric Field Distribution of Outlet Device in a 500 kV Transformer

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Abstract. Transformer is an important equipment serving in power system. In this paper, the influence of metal particles on the electric field of transformer outlet device is studed via numerical simulation. The results reveal that the metal particles can increase the maximum field strength between the oil gap of the outlet device and the maximum field strength increases with the increase of the particle radius. The local field strength greater than the allowable oil gap may cause local micro-discharge. Metal particles in the alternating current field oscillation and discharge may be the bubble can make the electric field distortion, accelerate the process of insulation cracking and may further lead to insulation breakdown. By altering the oil gap width of outlet device, its insulation endurance can be improved under the influence of metallic particles.

1. Introduction

As an indispensable equipment in power system, ultra-high voltage power transformer and its insulation reliability exerts a dominant influence on maintaining safe operation of the whole power grid, thereby ensuring the stability of energy transmission. Recently, there have been many accidents of AC 500 kV transformers caused by the flashover of outlet devices [1]. According to relevant reports, during the operation phase of the accident transformers, cases such as the exceeding of gas production rate, the existence of metal debris in the tank were prevailing. The failure of high capacity transformer may initiate a series of severe problem due to its vital importance in distributing energy as well as its difficulties in repairing. Therefore, it is necessary to carry out targeted investigations on this issue.

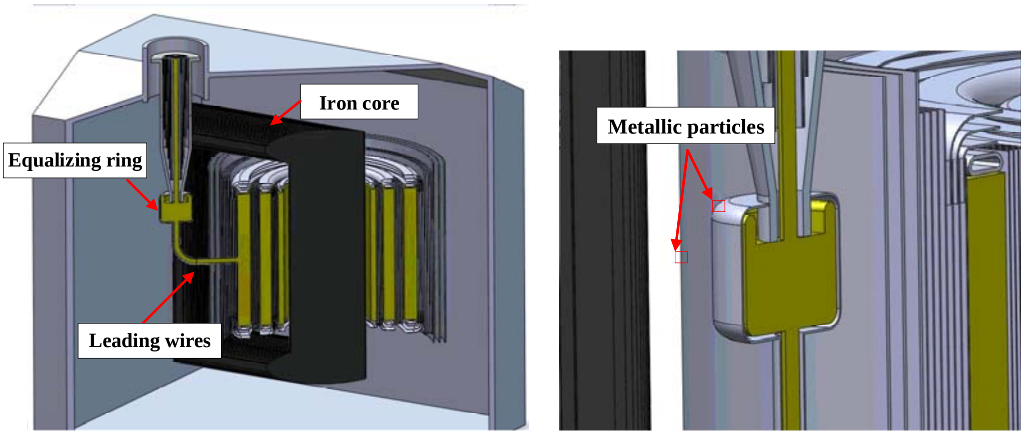
Previous reports have proposed many valuable clues regarding the influence of metal debris and particles on the outlet electric field of power transformer. Ref. [2] sampled and analyzed several particles in the oil of an operating transformer, determining the type and concentration of the metal particles in it. Ref. [3] proved by experiment that the metal particles in the oil is one of the main causes of transformer PD. Besides, some other reports concentrated on the influence of electrode shape, applied voltage and oil flow velocity on the characteristics of particle induced discharge, while the issue of electric field distortion caused by these particles still remains the subject of debate [4-6]. Moreover, the influence of particles on the electric field distribution for the transformer outlet devices still lakes insightful investigations [7-9].

To provide more insights into the influence of metal particles on the electric field of transformer outlet device via numerical approach, a three-dimensional numerical model calculating the electric field of AC 500 kV transformer outlet device is established in this work. Considering the accuracy of the simulation, we carry out the computations under different sectional sizes of meshes. Furthermore, the influence of particle size and position on the electric field of the outlet device are also taken into account. Results in this work are expected to serve as an auxiliary reference for transformer accidental analysis.

2. Model Description

2.1. Configuration

Referred to a 500 kV accidental transformer, a simulation model is established, whose schematic is shown in Fig.1. Note that the practical failure case was caused by the discharge between high-voltage equalizing ball and high-voltage core yoke. Therefore, the corresponding part is refined in the model. The tail of iron core and equalizing ball are surrounded by three layers of oiled paper insulation, with bushings considered as equivalent multi-layer capacitor bushings. The relative permittivity of insulation board, porcelain sleeve and transformer oil are set to be 4.5, 4 and 2.2, respectively.



(a) Transformer model (b) Particles` position

Figure 1. Schematic of the model.

(a) Bottom part (b) Top part

Figure 2. The metallic particles in the transformer tank.

When particles are large, the viscous drag is not as decisive as the gravity [10], thus these particles accumulate around the slowly flowing areas. This problem were found in the oil tank of above mentioned accidental transformer, as shown in Fig. 2. It was determined by measurement that some of the metal particles had the size between 0.5mm~2mm. Considering the relatively slow flowing velocity in the vicinity if outlet device, the metal particles may have an indispensable impact on the

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electric field characteristics. In this paper, metal particle models of different sizes are established at different layers of insulating oil gap, as shown in Fig. 1(b).

2.2. Dominant equations and boundary conditions
In this paper, the magnetic induced electric field, the displacement current and the internal resistive current within the insulating material are ignored due to their minor effects. The electric potential is determined by Poisson`s equation, as shown in equation (1)

$$\nabla^2 \varphi = 0 \tag{1}$$

Where φ represents the potential value. Without considering the space charge effect, the boundary condition is given by

$$\begin{cases} \varphi\big|_{\Gamma_1} = \varphi_0 \\ \dfrac{\partial \varphi}{\partial n}\Big|_{\Gamma_2} = 0 \end{cases} \tag{2}$$

Where $\varphi\big|_{\Gamma_1}$ represents Dirichlet boundary; $\frac{\partial \varphi}{\partial n}\Big|_{\Gamma_2}$ stands for Neumann boundary.

According to the IEC standard, 500 kV power equipment is required to withstand the maximum voltage of 550 kV system, 1175 kV (peak) impulse voltage, 1550/1675 kV (full wave / chopping) lightning impulse voltage and 680kV short-time induction or external voltage [11].

According to the empirical formula, the above voltages are all converted to 1min power frequency withstand voltage (effective value) less than 680 kV. The distribution of the electric field of the outlet device is simulated by using 680kV short-time power frequency test voltage and 550kV system voltage respectively.

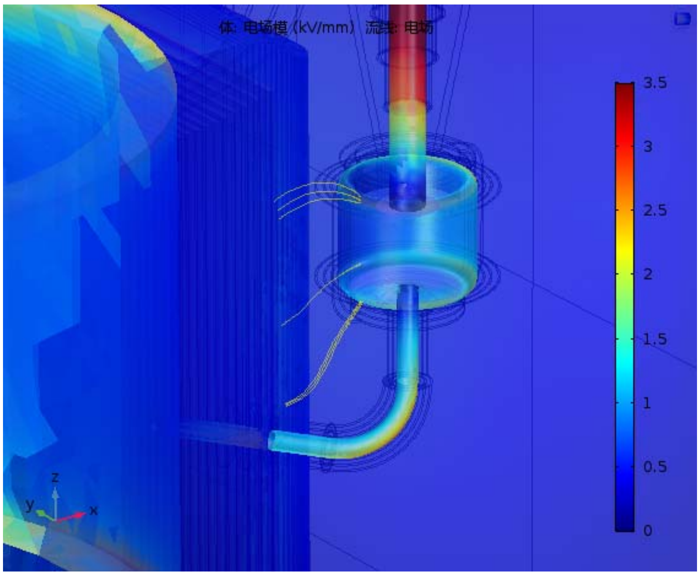
3. Results and Discussion

3.1. Simulation results
Figure 3 shows the electric field distribution of the outlet device without particles under short-time test voltage of 680 kV and operating voltage of 550 kV. According to the allowance electric field and insulation margin, as shown in equation (3, 4) [12]

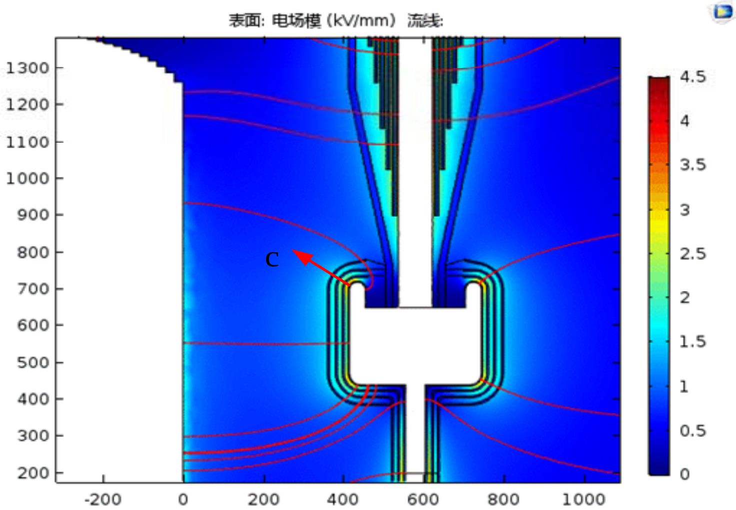
$$E_{\mathrm{al}}(d) = E_0 d^{-\tau} \tag{3}$$

$$\delta(d) = \frac{E_{\mathrm{al}}}{E_{\mathrm{AV}}} \tag{4}$$

Where: E_{al} is the allowance electric field, in kV / mm; d is the width of the oil gaps E_{AV} is the average electric field between oil gaps. Tab. 1 gives the maximum electric field intensity, allowable field intensity and insulation margin in each oil gap.



(a) Three-dimensional electric field distribution



(b) Electric field distribution for the middle intersection

Figure 3. Electric field distribution of outlet device.

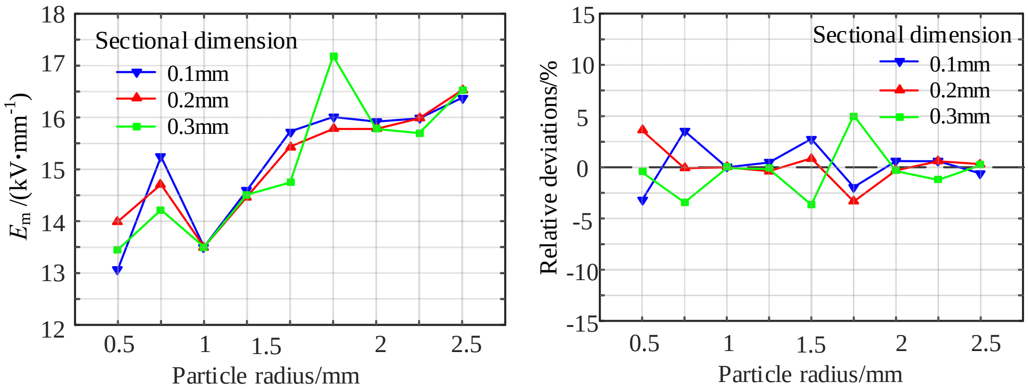
Inspecting Fig. 3 and Tab. 1, we can see that the equipotential lines at the bottom of the bushing are mainly concentrated in the vicinity of equalizing ring and insulating gaps near the curving areas of high voltage leading wires. The field strength gradually decreases from the inside to the outside. The maximum electric field value near the equalizing ring and leading wires locate at the first layer of oil gap near the side part of iron core and oil gap that is close to the curving area of leading wires, whose values are 4.64 kV/mm and 4.46 kV/mm, respectively.

Table 1. The maximum and the allowable electrical field of the insulating oil gap.

Layer	1^{st}	2^{nd}	3^{rd}	Long oil gap between the core and equalizing ring
Maximum electric field ($kV{\cdot}mm^{-1}$)	4.643	3.048	2.367	2.223
Average electric field/($kV{\cdot}mm^{-1}$)	3.694	2.588	2.047	0.976
Allowance electric field/(kV·mm-1)	9.171	8.573	7.894	2.532
Insulation margin	2.48	3.31	3.856	2.28

3.2. Influence of particles` size on the electric field characteristics

The influence of metallic particle size on the electric field of the outlet device is studied by taking the maximum operating voltage of the system as 550 kV and setting the metal particles attached to the oil gap at the first floor of the bend on the surface of the high voltage equalizing ring. Considering the quality of meshes and calculation accuracy, spherical metal particles with radius ranging from 0.5 to 2.5 mm are selected and the maximum field strength of the oil gap is calculated under different mesh sizes. The results are depicted in Fig. 4(a). Fig. 4(b) further illustrates the relative deviations of the simulation results under different mesh sizes.



(a) Maximum field strength in the oil gap (b) relative deviations compared with average value

Figure 4. The influence of maximum electrical field from different particle size and sectional dimension.

As shown in Fig. 4(b), when the radius of the metal particles are within 0.5 mm ~ 1 mm, the simulation results exhibits some deviations due to the similar size between meshes and particle radius. Increasing the radius of metal particles to about 1 mm ~ 2.5 mm, the simulation at 0.1 mm and 0.2 mm yield similar results, with the relative deviation no more than ± 5%, which is within the acceptable range for engineering. Therefore, those results can be considered as converged ones. Besides, as depicted in Fig. 4(a), the introduction of metallic particles enhances the maximum field strength near the oil gaps. Moreover, when increasing the radius of the particles, the maximum field strength around the oil gaps further increases, exceeding the relevant allowance value (9.17 kV/mm).

Based on above analysis, Fig. 5 further illustrates the insulation margin of the oil gap under the particle radius of 0.5 mm ~ 2.5 mm, taking 0.1 mm sectional mesh size as an example. Apparently, when the metallic particles are located at the surface of equalizing ring, the oil gap still retains a certain insulation margin, despite the fact that the local field strength of the oil gap is larger than the allowable value, which may initiate partial corona discharges.

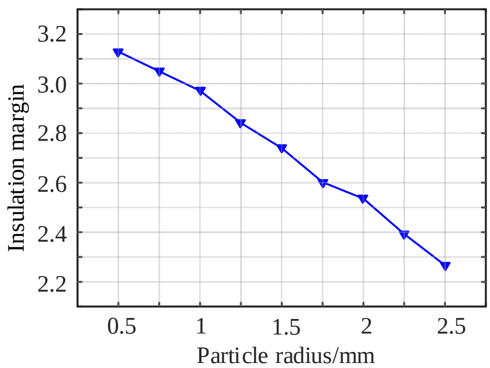


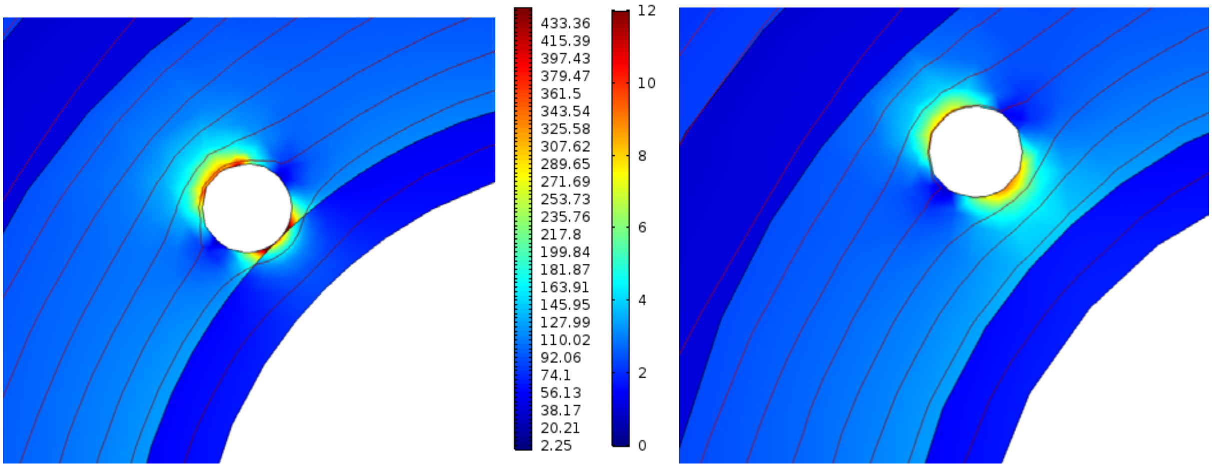
Figure 5. The influence of particle size on insulation margin in the first oil gap.

3.3. Influence of particles` locomotion on the electric field characteristics

In order to study the influence of the particles` locomotion on the electric field of the outlet device, a spherical metal particle with a radius of 2 mm is placed on the different sections of the oil layers in each layer, as shown in Fig. 1(b), to simulate and analyze the electric field of outlet device under those circumstances. Tab. 2 shows the maximum field strength when particles are located at different layers of oil gaps. It can be seen that when the particles are located in the bending zone of the equalizing ring, the electric field strength are the largest, even exceeding the allowance values. However, the maximum field strength is reduced beneath the allowable value (7.89kV / mm) when metallic particle is located at the third layer.

Table 2. The maximum electrical field of different Particles` positions

Particles` position (Layer number)	1st	2nd	3rd	Middle part of long oil gap
Maximum electric field /(kV·mm^{-1})	15.922	13.627	7.132	2.476



(a) On the surface (b) floating in the oil

Figure 6. The electric field distribution when the metallic particles in the first oil gap.

When particles are moving with oil flows, their lotus are influenced by electric field, which may induce oscillatory motions along the power lines, while amplitude of oscillation can reach 1 ~ 3 mm for particles with 0.5~2 mm radii [10]. Fig. 6 illustrates the distribution of electric field in the vicinity of the particles during the oscillation, calculated by the static simulation of particles in different positions of the oil gap. Obviously, during the oscillation phase, the metal particles squeezes the potential lines on both sides, resulting in an enhancement in the field strength, and the local field strength (15.92 kV / mm) when the particle is oscillated at the cardboard side is much larger than that hanging in oil gaps (11.886 kV / mm). Furthermore, it can be seen in Tab. 2 and Fig. 6 that when the particles oscillate in the first and second layer of oil gap, the reinforcement of local field strength caused by a single particle is sufficient to initiate the breakdown on its both side, causing the micro partial discharges.

3.4. *Influence of metallic particles on the electric field characteristics near the bubbles in the oil gap*

According to previous reports, partial discharge in the oil gaps of transformer is closely related to the bubbles. Experiments have also indicated that randomly distributed bubbles can be generated when partial discharges occur in the oil gap [12]. Note that the metal particles caused by the metallic particles may generate bubbles in the oil, therefore, the relevant case is studied here. In the simulation, two 2 mm radius ball-shaped bubbles are placed along the potential lines near the particle and 4 mm away perpendicular to the potential lines, respectively. Some key results are listed in Tab. 3. Know from Tab. 3, the influence of metal particles on the bubble electric field distribution along the power line direction is greater than the other case. When the metal particles are attached to the first and second oil layers, the field strength in the nearby bubbles exceed the breakdown field strength of air of 3 kV/mm. Therefore, it is presumable that when the metal particles cause corona discharge and generate bubbles nearby, chances are that it may cause breakdown of the bubbles, further reducing the insulating reliability of the oil gap and accelerating the progress of degradation.

Table 3. The maximum electric field of the bubble at different locations near the metallic particles.

Bubble position (Layer number)	Along power line direction 4mm(1st)	Vertical power line direction 4mm(1st)	Along power line direction 4mm(2nd)	Vertical power line direction 4mm(2nd)
No particles	3.464	3.772	2.438	2.504
Metal particles	9.026	3.990	5.608	2.554

3.5. Insulation optimization of outlet devices considering the influence of metal particles

The simulation of the metallic particles at different positions reveals that its influence on the insulation varies between different oil gap widths. To further investigate this issue, particles with the radius of 1 ~ 2.5 mm are simulated and analysed in different oil gap widths under the most severe condition (i.e. the metallic particles are located at the first layer of oil gap). Figure 7 shows the alteration of .insulation margin as a function of oil gap width. Apparently, when the radius of particle is less than 1.5 mm, the allowance electric field plays a major role in altering the insulation margin, and the insulation margin increases with gap width decreasing. Once the particle size exceeds 2 mm, a proper increase in oil gap width, although, reduces the allowance field strength, because of the increase in insulation distance, the insulation margin of oil gap actually increases slightly. Based on above, the oil gap width could be set at the size of 20~30 mm when having particles larger than 2 mm radius to optimize the use of insulation properties in the oil gaps.

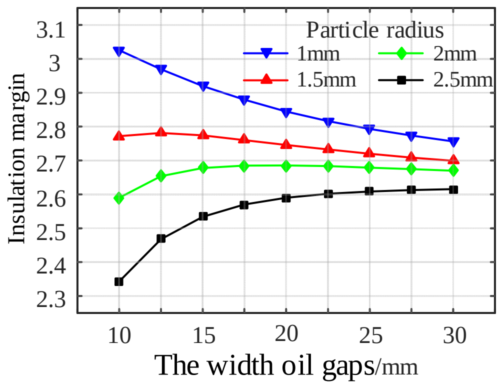


Figure 7. The influence of oil gap width on the insulation margin.

4. Conclusion

In this paper, the influence of metallic particles on the electric field distribution characteristics of outlet device in an AC 500 kV single-phase power transformer is studied via a 3D electrostatic simulation model. Some conclusive remarks are listed as follows:

• The maximum field strength in the transformer outlet device appears at the oil gap outside the equalizing ring near the iron core when no particle is induced, and the field strengths in each layer of oil gaps keep within the range of allowance.

• The metal particles can increase the maximum field strength of the oil gap, and the field strength further rises with the increase of the particle radius, causing micro-discharges.

• The oscillation of particles under the AC electric field can further promote the distortion of electric field by generating bubbles, initiating the subsequent partial discharges, thus accelerating the degradation and aging of insulation materials.

• By altering the oil gap width of outlet device, its insulation endurance can be improved under the influence of metallic particles. Oil gaps with gap width 20 ~ 30 mm are recommended to optimize the use of insulation properties when metallic particles with the radius of over 2 mm exist in the oil.

Acknowledgments

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