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AC Flashover Characteristic at the Triple Junction of the Oil-Pressboard Insulation

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ABSTRACT Oil-pressboard insulation in transformers is prone to surface tracking or creeping discharge during operation. The oil-pressboard interface is believed to be one of the weakest points in the insulation system. In this paper, AC flashover characteristic at the triple junction of the oil-pressboard interface under a slightly inhomogeneous electric field has been studied. The results showed that the creeping discharge always started at the triple junction, then developed along the pressboard (PB) surface, and finally reached the opposite electrode. The reason was that the triple junction was subjected to the maximum electric field strength. The field strength corresponding to the breakdown of the pure oil gap (POG) was decreased with the increment in the gap distance between electrodes due to the volume effect. As a comparison, the field strength corresponding to the breakdown for PB only changed slightly with the gap distance. Besides, the breakdown electric field of both POG and PB hardly changed when the electrode diameter increased. The above results could be applied to the inverse calculation and estimation of the flashover voltage levels under longer gap distances with any electrode diameter. Moreover, the relative position of the oil gap and PB could influence the flashover voltage levels. The breakdown voltage with PB directly contacting the ground electrode was 10% higher than that with PB directly contacting the high voltage electrode. This could be explained by the different charge behavior. The obtained results could provide a reference for the insulation margin design in ultra-high-voltage transformers.

INDEX TERMS Oil-pressboard insulation, triple junction, ac surface flashover, breakdown strength.

I. INTRODUCTION

Oil-impregnated pressboard (PB) was commonly used to partition the large oil gaps to enhance the overall dielectric strength of the composite insulation system in transformers. However, it is also believed that the oil-PB interface becomes the electric weak link of the composite insulation system [1]. According to the CIGRE report, insulation failures within the winding coil, on-load tap, and connecting device comprise most of the malfunction in transformers [2], [3]. In these weak areas, the insulation of oil-immersed transformers requires compatibility with the formation of the oil path for cooling and has a complicated structure with static shields and L-shaped PB barriers. A high creepage electric field is produced on the surface of the solid insulation. Therefore, insulation failure mainly results from surface tracking or creeping discharge along PB [4]. Although design experiences tend to successfully limit the tangential stress on PB surface to be 1-2kV/mm maximum, creepage discharges could still be observed to develop for long distances under low stress. And an eventual flashover may follow to make a total breakdown leading to a catastrophic transformer failure [5].

In recent years, it is commonly recognized that the discharges tend to creep along the oil-PB interface rather than propagating in the oil gap and lead to flashovers with irrecoverable damages left on PB surface [6]. Based on this consensus, much attention has been paid to the surface flashover characteristics of the oil-PB interface. Several

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influence factors of oil-PB surface flashover have been studied under AC stress. Dai *et al.* [5] and Zhao *et al.* [7] found that moisture content contributed to the gas bubble formation to lower the breakdown strength of oil-PB. Studies from Okubo *et al.* [8] and Kamata *et al.* [9] showed that the increase in perpendicular electric field strength introduced by back-side electrodes reduced the flashover voltage to some extent. Dang *et al.* found that the PB thickness had an influence on the shape of flashover trees using needle-plate electrodes [10]. Cheng *et al.* built a relationship between the formation and propagation of the carbonized tree and partial discharges (PD). Experimental results showed that the white mark was the outside appearance of the carbonized trees inside PB [11]. A work from Jadidian *et al.* revealed that the oil-PB interface significantly changed the propagation mechanism of the discharge streamer due to the difference between the permittivity of oil and PB [12]. Wang *et al.* attributed the promotion effect of PB surface on creeping discharges to the bubble residence and the accumulation of surface charges [1]. In the past couple of years, the development of DC transmission system has gained significant momentum. The oil-paper insulation system in the valve side of the converter transformers subjects to AC and DC voltage components simultaneously. Hence the surface flashover characteristic of oil-PB interface under DC component and superimposed AC-DC voltage became a hot topic. Ebisawa *et al.* found that the creepage strength under DC voltage was affected adversely by the surface distance [13]. A work from Jin *et al.* revealed that higher temperatures could accelerate the discharge process on PB surface thereby decreasing flashover voltage levels [14]. Zhou *et al.* pointed out that the flashover values increased with the increment in the DC component [15]. A study from Qi *et al.* indicated that the surface charge accumulation due to the DC component might cause the non-uniformity of the electric field distribution in the vicinity of oil-PB interface [16].

From the above, hitherto the literature has shown abundant knowledge about the surface flashover of oil-PB interface and covered most aspects. However, with the advancement in voltage levels of transformers, new problems have already arisen. The existing design experience cannot be totally and directly applied to ultra-high-voltage (UHV) transformers. The scale effect must be taken into consideration. It is significant to spread the test results to the application in larger-scale insulation design in a sense. Therefore, the AC surface flashover characteristics of PB under different gap distances are worth investigating. Since both the electrode gap distance and the electrode diameter could influence the degree of electric field inhomogeneity. It is also meaningful to study the effect of electrode diameter.

In the previous study, the needle-plane electrode was usually used to initiate discharge. Although the needle electrode could simulate the surface flashover initiated by the localized defect in PB, it is unrealistic in a transformer. According to reference [17], surface flashover tends to occur on the insulation pad between the winding screen and the winding layer within the transformers. In these areas, the electric field distribution is slightly inhomogeneous. Therefore, sphere-sphere electrode configuration was used to build a symmetrical and slightly inhomogeneous electric field distribution in this experiment. In this paper, the effects of the electrode gap distance and the electrode diameter on the AC flashover characteristics of oil-PB were studied based on sphere-sphere electrodes, respectively. In addition, to simulate the realistic oil-paper insulation structure in transformers, the oil gap was taken into consideration. The influence of the relative position of the pure oil gap (POG) and PB was investigated. The obtained results could provide a reference for the insulation margin design in UHV transformers.

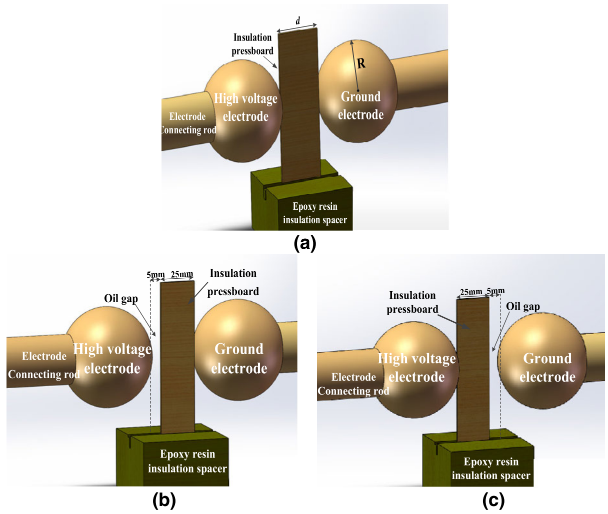


FIGURE 1. **The sketch map of the experimental electrodes.**

II. EXPERIMENTS

A. EXPERIMENTAL ELECTRODES AND SPECIMENS

The sphere-sphere electrodes used in this experiment were made of brass and highly polished. Firstly, four different gap distances (20mm, 30mm, 40mm, and 50mm) were chosen with a constant electrode diameter of 40mm. Secondly, a comparative study was conducted between two different gap distances (20mm and 30mm) with two different electrode diameters (40mm and 80mm). The sketch map of the test setup in this experiment was shown in Figure 1(a). R represents the electrode diameter and d represents the gap distance. PB specimen was placed with its bilateral sides directly contacting electrodes. In this way, PB was subjected to the slightly inhomogeneous tangential electric field and the perpendicular electric field could be neglected. An insulation block made of epoxy resin was placed on the bottom to fix PB's position. Moreover, in the experiment to study the effect of relative location of POG and PB, the electrode gap was set at a constant distance of 30mm. The width of PB was 25mm and that of POG was 5mm, as shown in Figure 1(b) and (c). The whole experimental setup was fixed and immersed in an oil tank.

The transformer oil used in the experiment was Karamay #25 mineral oil. The oil was filtered by a vacuum filter, then

TABLE 1. Parameters of transformer oil and insulating pressboard.

Parameters	Mineral oil	Pressboard
Density/ g/cm^3 (20°C)	0.89	1.1
Permittivity (20°C, 50Hz)	2.21	4.3
Volume resistivity/ Ω·m (20°C)	1.7×10^{12}	1.24×10^{14}
Moisture content	10ppm	0.5%

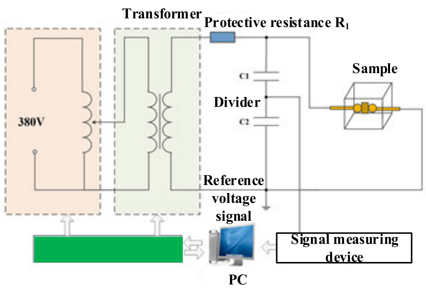


FIGURE 2. The real and schematic picture of the test circuit.

degassed and dried in a vacuum drying oven at 90°C for 48 hours. The moisture content of the mineral oil after the above treatment was 10ppm reaching the IEC 60422-2005. The 1mm thickness PBs were purchased from Weidmann Company and cut into rectangles with a length of 100mm. The width of PBs in each experiment was cut corresponding to the gap distance. Clipped PBs were treated according to the standard IEC-60641-1079 to obtain the test specimens. To be specific, PBs were dried at first in a vacuum oven at 110°C and 0.9Pa for 72 hours. Then the well-dried PBs were impregnated in the treated mineral oil at 40°C and 50Pa for 48 hours to ensure full impregnation. The moisture content of the treated PB was approximately 0.5% by weight. The physiochemical parameters of the oil and PB were listed in Table 1.

B. TEST CIRCUIT AND DATA PROCESSING

The schematic picture of the test platform used in this experiment was shown in Figure 2. The test platform consisted of the control cabinet, the testing transformer, a protective resistor, and a coupling capacitor. The testing transformer (YUTW-500kV/500kVA) was made by Jiangsu ShengHua Electric Co., Ltd. The partial discharge magnitude of this transformer was no more than 2pC under rated voltage. The value of the protective resistor R_1 was 10.5kΩ. In the experiment, the procedure of the surface breakdown test was conducted according to IEC 60243-1: 2013, though the sphere-sphere electrodes were not suggested in this standard. The increasing ramp of the applied voltage which was set as 5kV/min in this case was also selected according to the test standard and our previous trials. The corresponding voltage levels were recorded at the moment when the surface flashover occurred. To ensure repeatability, each flashover breakdown experiment was repeated 6-8 times. During the experiments, a high-speed camera (Motion Pro) was also hired to record optical pictures of the flashover process. The temperature was kept at 25°C during the experiment.

The Weibull distribution model is widely used in the reliability analysis of engineering due to its strong applicability and high accuracy [18]. The two-parameter Weibull distribution model was used to analyze the obtained flashover voltage values in this paper. The failure distribution function of the two-parameter Weibull distribution model is shown in (1):

$$F(t;\alpha,\beta) = 1 - \exp[-(\frac{t}{\alpha})^{\beta}] \tag{1}$$

where α is the scale parameter and β is the shape parameter, t represents the surface flashover voltage, and $F(t)$ is the corresponding probability of failure at voltage t. The scale parameter α represents the voltage level at which the corresponding surface flashover probability is 63.2%. The shape parameter β is the measure of the spread of the experimental data. The larger β is, the smaller the range of flashover voltages is. As for the estimation of Weibull distribution parameters, the empirical distribution function $F_n(t_i)$ proposed by Blom as shown in (2) was applied to all the test data [19].

$$F_{\mathrm{n}}(t_{\mathrm{i}}) = \frac{i - 0.375}{n + 0.25} \times 100\% \tag{2}$$

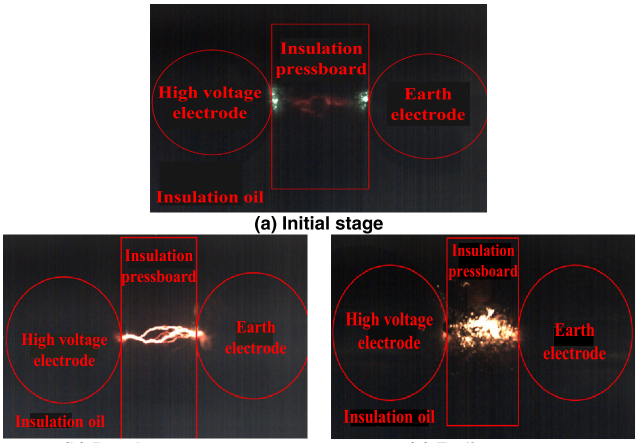
where $F_n(t_i)$ is the probability of failure, i represents the order of test samples, and n is the total number of test samples. The values of α and β could be estimated using the least square method.

III. RESULTS AND DISCUSSION

A. THE IMAGE OF SURFACE FLASHOVER PROCESS

Different gap distances and electrode diameters influenced the uniformity of the electric field distribution as well as the flashover voltage levels. However, the development processes of the surface flashover under different conditions were of the same pattern. The discharge was first generated from the electrode-oil-PB interface (also called triple junction) near both electrodes and then developed along PB surface towards the opposite electrode. Here only the images of the surface flashover process under the gap distance of 30mm were presented in Figure 3.

The development of a typical surface flashover could be divided into three stages. The first stage was the initial stage corresponding to the generation of charge carriers as shown in Figure 3(a). This stage was marked by the generation of streamers at the triple junction. The second stage corresponded to the discharge development and was called the development stage as shown in Figure 3(b). When the electric field strength was high enough, the surface discharge propagation from both electrodes met each other at the middle point, thus forming throughout flashover channels. In this process, the surface discharge arcs and channels were like bunches of a tree. The last stage was the ending stage marked by the formation of a self-sustained surface flashover as shown in Figure 3(c). Sharp arc discharge appeared and burned like fire along with lots of bubbles and dark smoke on PB surface. When the electric field was removed, lots of bubbles could be observed and carbide burnt traces left on PB surface.

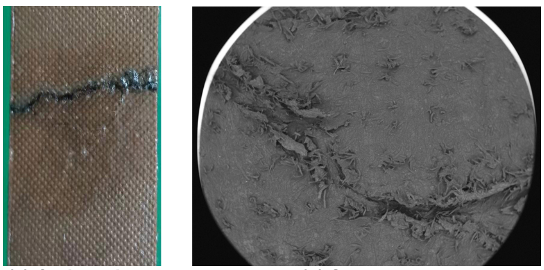


(a) Initial stage

(b) Development stage

(c) Ending stage

FIGURE 3. The different stages of surface flashover development.



(a) Optical picture

(b) SEM results

FIGURE 4. Surface morphology of the PB after flashover.

This tree-like discharge trace only appeared on one side of the PB surface as shown in Figure 4(a) while no obvious damage could be observed on the reverse side. PB is a kind of non-uniform material. Different surface conditions with varied roughness result in the random location of the discharge propagation trace. Figure 4(b) gave the scanning electron microscope (SEM) picture of the flashover trace under the magnification of ×25. The picture showed a deep groove along the surface flashover channels. The deformation of cellulose near the groove was observed, indicating severe and irrecoverable damage on PB surface. The underlying reason might be that the cellulose deformed under the impact of collision from the generated charged carriers. This deformation would influence the surface charge accumulation furtherly, thereby distorting the local electric field distribution. The strengthened local electric field might induce and accelerate the decomposition of cellulose in turn, thus creating a vicious cycle.

B. FLASHOVER CHARACTERISTICS UNDER DIFFERENT GAP DISTANCE BETWEEN ELECTRODES

In this experiment, the surface flashover voltages of PB were recorded, and also those of POG were tested as a comparison. The experimental results of the AC flashover voltages under different gap distances were shown in Table 2. Both the values of scale parameter α of Weibull distribution and the mathematic average flashover voltage values were calculated.

TABLE 2. Experimental results of oil pressboard insulation.

AC Flashover Voltages				
Gap distance (mm)	20	30	40	50
α-POG (kV)	255.8	285.1	333.2	358.5
β-POG (kV)	22.57	42.2	22.3	60.22
AV-POG (kV)	249.5	282.8	325.3	356.7
f-POG	1.33	1.54	1.74	1.96
α-PB (kV)	161.7	222.8	267.2	300.6
β-PB (kV)	8.52	24.1	19.12	22.8
AV-PB (kV)	175.1	227.7	274.6	313.2
f-PB	2.61	2.9	3.3	3.7

The degree of electric field inhomogeneity f was also given in Table 2 based on the field calculation using the finite element method (FEM). A simulation model was built in COMSOL software and the geometry size of the electrode and the thickness of PB were set the same as in the experiments. The following equations are to be solved to calculate the electric field distribution.

$$\nabla \bullet \boldsymbol{J} = -\frac{\partial \rho}{\partial t} \tag{3}$$

$$\boldsymbol{J} = \gamma \boldsymbol{E} + \frac{\partial \boldsymbol{D}}{\partial t} + \boldsymbol{J}_e \tag{4}$$

$$\boldsymbol{E} = -\nabla V \tag{5}$$

where J is the current density (A/m^3), ρ is the free charge density (C/m^3), J_e is the external current density (A/m^3), E is the electric field strength (V/m), and V is the electric potential (Volt). Also according to the basic polarization theory, we have $D = \varepsilon E$ where ε is the dielectric constant (F/m). The parameters of oil and PB was set according to the measured values in Table 1. The degree of electric field inhomogeneity f could be calculated according to (6).

$$f = E_{\max}/E_{ave} \tag{6}$$

where E_{max} and E_{ave} presented the maximum and average electric field strength in the simulation results, respectively. The spot with the maximum field strength is located at the point where electrode-oil-PB is contacted. It is right at the middle spot of PB's cross-section considering the thickness.

It could be seen from Table 2 that both the flashover voltage of POG and PB increased linearly with the increment in the electrode gap distance. The flashover voltage of POG under 50mm gap distance was 1.46 times of that under 20mm gap distance while the figure for PB was 1.86. This indicated that gap distance played a bigger role in the surface flashover of PB rather than POG. Besides, the flashover voltages of POG were always higher than the figures for PB under the same gap distance. To be specific, the presence of PB reduced the average flashover voltages by approximately 20% to 30% compared to POG. Also, the introduction of PB made the degree of electric field inhomogeneity roughly twice. This could be explained by the local electric field enhancement due

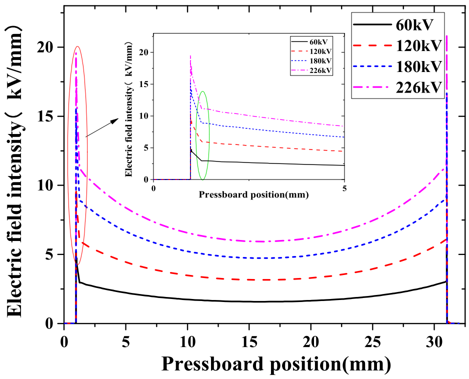


FIGURE 5. The electric field distribution and the maximum field intensity spot between the electrodes under AC.

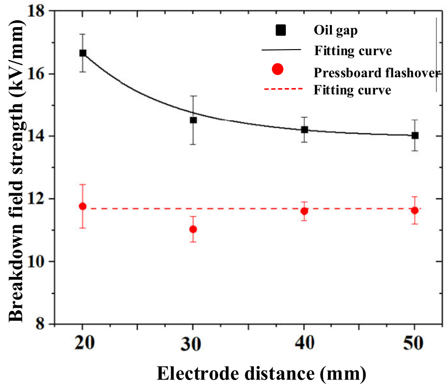


FIGURE 6. The breakdown field strength of oil gap and PB under different electrode distance.

to the space charge effect and residual low-density channel effect [6]. Besides, the degree of electric field inhomogeneity always increased with an increment in the gap distance. This indicated that in UHV transformers, the electric field distortion due to the long gap distance must be considered.

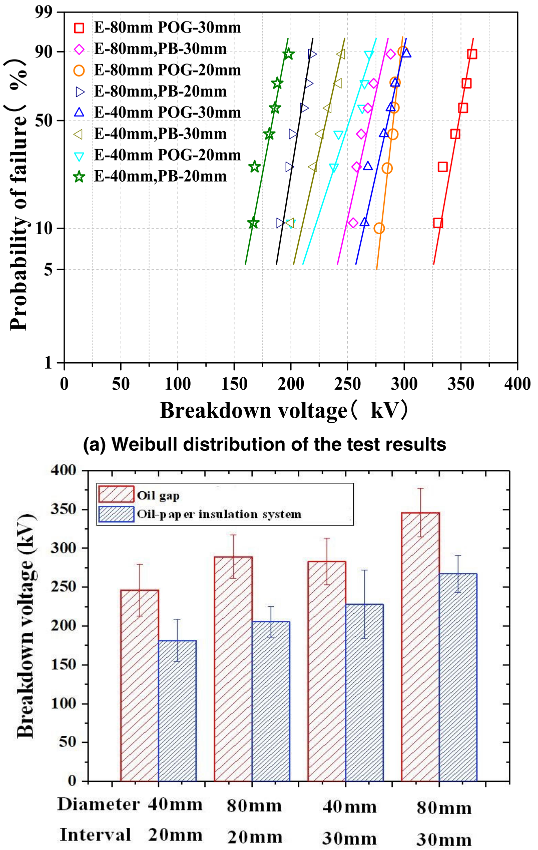
It is obvious and easy to understand that the flashover voltages increased with the gap distance. But the effect of the gap distance on the breakdown strength corresponding to the moment when a flashover occurred remained to be seen. In the following, the spot with the maximum electric field strength on PB surface under AC stress was located. Here only the simulation results of the electric field distributions along the middle line of PB surface under 30mm gap distance were shown in Figure 5 as an example. PB position of 0mm at the horizontal axis referred to the spot in the vicinity of the triple junction near the anode. It was noteworthy that this spot was not in direct contact with the electrode because of PB thickness. A tiny oil gap existed between the electrode and PB surface. We can see that the electric field intensified sharply as the red circle shown in Figure 5. This corresponded to the electric field strength in the tiny oil gap. It is known that the electric field distribution under AC stress was adversely proportional to the permittivity. Hence the electric field strength decreased dramatically on PB surface at position 0mm as the green circle labeled in the inset picture of Figure 5. Then the electric field intensity gradually decreased along the surface position until the middle point. As the applied voltage gradually increased, both the maximum field strength of the oil gap and PB increased linearly. When the maximum field strength reached the threshold value of discharge field strength, the electrode-oil-PB interface started to discharge and developed toward the opposite electrode, resulting in the final flashover breakdown. The simulation results were consistent with the arc starting spot observed in Figure 3(a).

Here the electric field strength at the PB edge was taken as the maximum field strength of PB. Then the value of electric field strength corresponding to the occurrence of flashover was noted as the breakdown electric field strength. Based on the AC flashover voltage test results, both the breakdown field strengths of POG (without PB) and PB were simulated for comparison. The calculated results were shown in Figure 6 with the error bars labeled. With the increase of electrode gap distance, the breakdown field strength of POG gradually reduced from about 16.5kV/mm to about 14kV/mm, indicating a decrease of 15.2%. This trend was consistent with the result in reference [5]. The average breakdown strength E of POG against the gap distance followed the following relationship [20].

$$E(d) = Kd^{-N} \tag{7}$$

where $E(d)$ is the breakdown field strength (kV/mm), d is the electrode gap distance (mm), K is the estimated breakdown field strength of the sample with a gap distance of 1mm, and parameter N measures the sensitivity of the breakdown field strength to d. The decrease in breakdown field strength of POG with the increment in gap distance could be attributed to the volume effect of liquid dielectric. Longer gap distance raised the probability of impurities existence in pure oil. These impurities would dissociate under the high voltage and bridge the gap [21]. A saturation effect appeared when the distance reached a certain value. Hence the relation between POG breakdown field strength and the gap distance presented an inverse power function. In this case, the fitting formula was $E(d) = 16.49d^{-0.12}$.

On the other hand, the breakdown field intensity on PB surface showed a different trend. The breakdown values slightly fluctuated around 11.8kV/mm with an increase in the gap distance under AC stress. The occurrence of the flashover was decided by the maximum field intensity on PB surface. Flashover would occur when the electric field strength at the electrode-oil-PB interface reached the threshold value. This threshold value was mainly determined by the surface property of PB. Therefore, the flashover breakdown field strength along the PB surface changed marginally with the increment in gap distance. Reference [13] showed that the creepage strength under DC voltage was affected adversely by the surface distance. This phenomenon may be explained by the space charge or surface charge effect. Charge behavior must be taken into consideration under DC electric field. When the electrode distance is increased, the longer creepage length means more defects at the interface of oil and PB [16]. As a



(a) Weibull distribution of the test results

(b) Average values of the test results

FIGURE 7. Breakdown voltages under different electrode diameters.

result, the severer space charge accumulation distorted the electric field distribution and led to a decrease in breakdown values. On the other hand, it could be seen that the creepage electric field strength under AC stress was marginally affected by the increase in gap distance. Under the AC electric field, the space charge accumulation was not easy due to the constantly changing polarity of the applied sinusoidal voltage and the electric field distortion could be neglected. Based on these experimental results, the breakdown strength electric field tested under the shorter distance and lower stress could be applied to inverse calculating the flashover voltage under longer gap distance based on FEM methods. This could provide a reference for UHV transformers' insulation design.

C. INFLUENCE OF THE ELECTRODE DIAMETER ON THE SURFACE FLASHOVER CHARACTERISTICS

Both the Weibull distribution and the mathematics average values of the flashover voltage under different electrode diameters (noted as E-40mm and E-80mm) were shown in Figure 7. As the electrode diameter increased, both the flashover breakdown voltage of POG and PB increased. Specifically speaking, the breakdown voltage of the oil gap under 80mm electrode diameter was about 1.4 times as large as the one under 40mm electrode diameter. As for the flashover voltage of PB, the figure under 80mm electrode diameter was 1.15 times large of that under 40mm.

TABLE 3. Experimental results of oil and insulating pressboard.

The degree of electric field inhomogeneity f				
Gap distance (mm)	20		30	
Electrode diameters (mm)	40	80	40	80
f-POG	1.3	0.7	1.5	0.7
f-PB	2.6	1.9	2.9	2.03

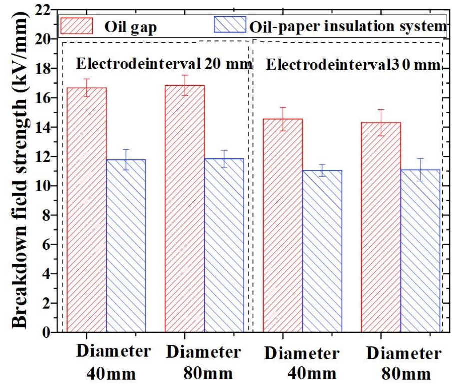
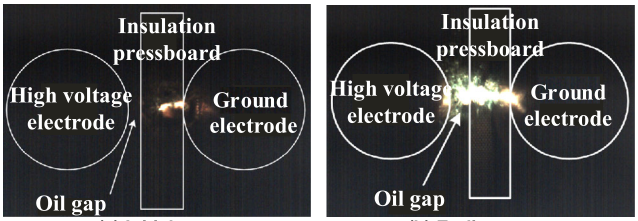


FIGURE 8. Failure electric field strength under different conditions.

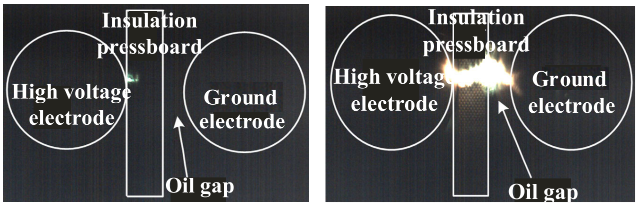
Table 3 showed the influence of the electrode diameters on the degree of electric field inhomogeneity. It could be seen that f-POG decreased by over 50% when the electrode diameter doubled. The figure for f-PB was about 30%. It is concluded that a larger electrode diameter led to lower f which meant a more uniform electric field. As a result, the flashover voltage increased with the increase in electrode diameters under the same gap distances. The degree of electric field inhomogeneity is sensitive to both the gap distance and electrode diameters. It could be inferred that for the flashover test of dielectrics under long gap distance, proper electrode diameter must be chosen to have a proper f.

The simulation results of the breakdown field strength of POG and PB based on the flashover test under different electrode diameters were shown in Figure 8. It could be seen that under the same gap distance, the breakdown field strength of both PB and POG changed little with the increase of the electrode diameter. When the electrode distance was 20mm, the breakdown field strength was about 16.5kV/mm for POG and 11.8kV/mm for PB. When the electrode distance increased to 30 mm, the figure was roughly 14.2kV/mm for POG and 11.5kV/mm for PB. The underlying reason might be explained as follows: under a constant gap distance, the electric field distribution became more uniform as the electrode diameter increased. As a result, a higher applied voltage was necessary to induce flashover discharge when the electrode diameter became larger. In particular, both the breakdown field strength of the oil gap and the PB hardly increased with the increment in electrode diameter. Hence the inverse calculation of breakdown voltage under other electrode diameters could also be applied based on some of the test results using FEM methods in COMSOL.



(a) Initial stage (b) Ending stage

FIGURE 9. Images of flashover with oil gap contacting HV electrode.



(a) Initial stage (b) Ending stage

FIGURE 10. Images of flashover with oil gap close to the ground electrode.

D. EFFECT OF DIFFERENT RELATIVE LOCATION OF OIL GAP AND PB ON FLASHOVER CHARACTERISTICS

The surface flashover characteristics under the resultant effect of POG and PB were studied in this section. The experiment was designed two-fold. One was the oil gap directly contacting the high voltage electrode and the other was directly contacting the ground electrode. Figure 9 showed the development of surface flashover of the former condition. The arc first started at the triple junction near the ground electrode, then gradually developed towards the opposite side of the PB and finally went through the entire gap along with the generation of a large number of bubbles and carbonized particles. The images of the latter were also shown in Figure 10. It could be seen that the arc started at the triple junction near the high voltage electrode. After the PB flashed, the arc formed a penetrating flashover channel, accompanied by strong dazzling white light as well as the generation of gas and carbonized particles. In summary, creeping discharge always started at the electrode-oil-PB interface. The propagation direction was from the pressboard to the oil gap. This observation further demonstrated that the presence of a pressboard made the triple junction spot a relatively weak point for discharge.

All the breakdown voltage data in this experiment were shown for comparative study in Figure 11. The results showed that the flashover voltage was approximately 280kV when there was only POG. However, the figure decreased to about 225kV when both sides of the cardboard contacted the electrodes, indicating that the presence of the oil-paper interface along the electric field direction would greatly reduce the breakdown voltage by more than 20%. The flashover voltage was roughly 220kV when PB directly contacted the high voltage electrode, while it was about 240kV when PB directly contacted the ground electrode showing a nearly 10% increase. There was no significant difference between the flashover voltage when the two sides of the PB contacted the electrode and when the oil gap touched the ground electrode.

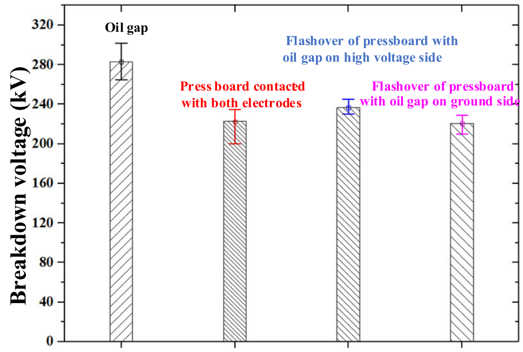


FIGURE 11. The comparison results of the flashover voltages for oil-PB composite system.

The difference in the breakdown voltage resulted from the relative position of the oil gap and PB could be explained as follows. When the applied voltage increased to a certain value, the triple junction on PB was the first to discharge. Partial discharge generated solid products and micro-bubble impurities aligned in the direction of electric flux lines. When PB contacted the ground electrode, the solid products and micro-bubble impurities generated by the partial discharge started to accumulate on the PB surface. These impurities carried negative charges after ionization thus forming negative space charges at the triple junction. The accumulation of homo-charge near the ground electrode reduced the electric field strength of the electrode-PB interface. Therefore, the presence of negative space charges raised the flashover voltages. On the other hand, when PB contacted HV electrode, the decomposition products and tiny bubbles generated by the discharge near the high voltage electrode were also adsorbed on the PB surface. But these negative space charge became hetero-charge accumulation, thereby intensifying the electric field strength of the high voltage electrode-PB interface. Hence the flashover voltage was decreased when there was a pure oil gap near the high voltage electrode.

It could also be analyzed from the perspective of the electric field distribution by simulation. The simulation models were constructed using FEM methods in COMSOL software as shown in Figure 12. The AC voltage of 220kV was applied in this model to obtain the electric field distribution as presented in Figure 13. The maximum field strength with PB contacting the ground electrode was 16.6kV/mm, which was 10% lower than the figure (118.6kV/mm) with PB contacting the high voltage electrode. It could be seen that the lower interface electric field strength resulted in the higher breakdown voltage when PB was placed close to the ground electrode. Different relative positions of the oil gap and PB affected the interface polarization near the electrode. Under the condition of PB contacting the high voltage electrode, the electric field strength at the interface was relatively concentrated. Hence the triple junction was more likely to reach the threshold electric field strength to induce electron avalanche. The electrons moved across the PB, then the applied voltage all exerted on the oil gap after

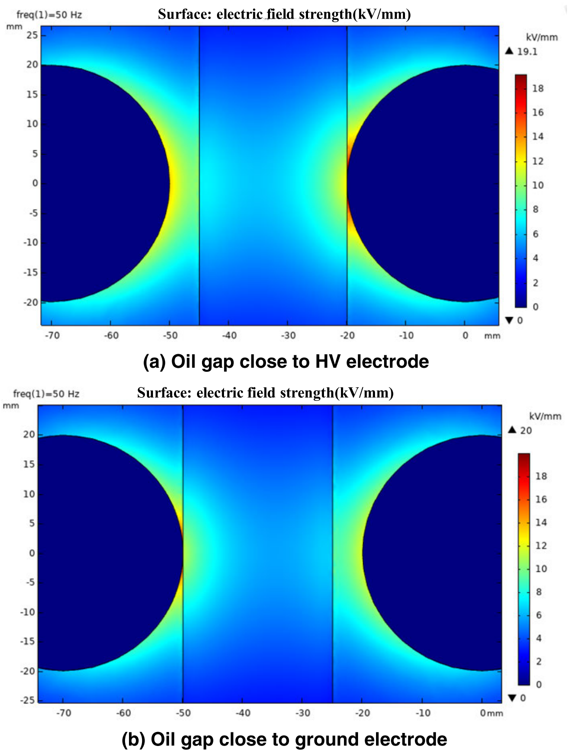


FIGURE 12. Field distribution of oil-paper composite system under different relative location of the oil gap and PB.

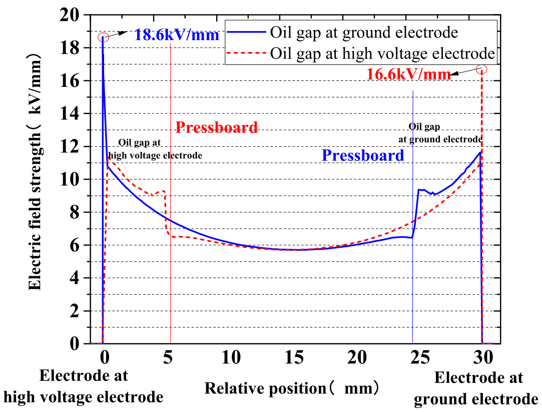


FIGURE 13. The comparison results of electric field distribution in oil-paper composite system under AC 220kV.

the PB discharge occurred. Finally, the breakdown of the oil gap caused the flashover breakdown of all the dielectric. However, under the condition with PB contacting the ground electrode, the electric field strength was reduced by the polarization effect at the interface. It was not easy to reach the threshold field strength at the triple junction. The ionization process could not be simulated, so this difference was mainly attributed to the effect of interface polarization and surface charge accumulation. Hence a higher applied voltage was required to induce discharge. From the above, the flashover voltage when there was an oil gap to partition HV electrode and PB was higher. This result could provide a reference for the insulation design within the transformer.

IV. CONCLUSION

According to the above analysis and discussion, the conclusions are summarized as follows.

Under AC stress, the discharge started at the triple junction near both electrodes and then developed into surface flashover. The breakdown field strength of POG was decreased with the increment in the gap distance due to the volume effect. However, the breakdown field strength for PB was hardly influenced. The surface condition of PB decided the value of breakdown electric field strength. An inverse calculation could be conducted to estimate the flashover voltage level under longer gap distance in UHV transformers based on this conclusion. Moreover, the electrode diameter had little impact on both the breakdown electric field intensity of the oil gap and PB. This could also be applied to the inverse calculation to estimate the flashover voltages under other electrode diameters. The degree of electric field inhomogeneity was sensitive to electrode diameters. It is indicated that proper gap distance and electrode diameters should be designed to match for flashover test under long gap distance.

The discharge always started at the triple junction, then developed across the PB surface, and finally through the oil gap reached to the opposite electrode. This pattern was not influenced by the relative position of the oil gap and PB. Nevertheless, the breakdown voltage with the oil gap close to the high voltage electrode was 10% higher than that with the oil gap close to the ground electrode. This could be linked with charge behavior. All these results could provide a reference for the insulation margin design in transformers.

REFERENCES

[1] X. Yi and Z. Wang, "Creepage discharge on pressboards in synthetic and natural ester transformer liquids under AC stress," *IET Electr. Power Appl.*, vol. 7, no. 3, pp. 191–198, Mar. 2013.

[2] *HVDC Converter Transformers Design Review, Test Procedures, Ageing Evaluation and Reliability in Service*, CIGRE Joint Working Group A2/B4.28, Paris, France, 2010.

[3] *HVDC Converter Transformers Guide Lines for Conducting Design Reviews for HVDC Converter Transformers*, CIGRE Joint Working Group A2/B4.28, Paris, France, 2010.

[4] P. M. Mitchinson, P. L. Lewin, B. D. Strawbridge, and P. Jarman, "Tracking and surface discharge at the oil-PB interface," *IEEE Elect. Insul. Mag.*, vol. 26, no. 2, pp. 35–41, Mar. 2010.

[5] J. Dai, Z. Wang, and P. Jarman, "Creepage discharge on insulation barriers in aged power transformers," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 17, no. 4, pp. 1327–1335, Aug. 2010.

[6] X. Yi and Z. D. Wang, "The influence of solid surface on the propagation of creepage discharge in insulating liquid," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 22, no. 1, pp. 303–313, Feb. 2015.

[7] T. Zhao, X. Cheng, Y. Liu, F. Wang, and F. Lv, "The formation characteristics of bubble in oil-paper insulation and its effect on the breakdown," in *Proc. IEEE 2nd Int. Conf. Dielectr. (ICD)*, Jul. 2018, pp. 9–18.

[8] H. Okubo, K. Okamura, M. Ikeda, and S. Yanabu, "Creepage flashover characteristics of Oil/Pressboard interfaces and their scale effects," *IEEE Power Eng. Rev.*, vol. PER-7, no. 1, pp. 44–45, Jan. 1987.

[9] Y. Kamata, A. Miki, and S. Furukawa, "A singular flashover path observed on the surface of synthetic-resin-bonded paper cylinders immersed in transformer oil under switching impulse voltage conditions," *IEEE Trans. Electr. Insul.*, vol. 26, no. 2, pp. 300–310, Apr. 1991.

[10] A. Beroual, V.-H. Dang, M.-L. Coulibaly, and C. Perrier, "Investigation on creeping discharges propagating over pressboard immersed in mineral and vegetable oils under AC, DC and lightning impulse voltages," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 20, no. 5, pp. 1635–1640, Oct. 2013.

[11] Y. Cheng, J. Wei, C. Zhao, and H. Song, "Experimental research on creepage discharge between oil-impregnated pressboard layers," in *Proc. IEEE Conf. Electr. Insul. Dielectr. Phenomena (CEIDP)*, Oct. 2016, pp. 999–1002.
[12] J. Jadidian, M. Zahn, N. Lavesson, O. Widlund, and K. Borg, "Surface flashover development on transformer oil-PB interface," in *Proc. IEEE Power Modulator High Voltage Conf.*, San Diego, CA, USA, Jun. 2012, pp. 39–42.
[13] Y. Ebisawa, S. Yamada, S. Mori, and T. Teranishi, "DC creepage breakdown characteristics of oil-immersed insulation," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 16, no. 6, pp. 1686–1692, Dec. 2009.
[14] F. B. Y. X. Jin; Zhou, B. Liang, Z. L. Zhou, and X. B. Li, "Effects of temperature on characteristics of creepage discharge in oil-impregnated PB insulation under combined AC-DC voltage," in *Proc. Int. Conf. Properties Appl. Dielectr. Mater.*, Xi'an, China, May 2018, pp. 546–549.
[15] Y. Zhou, F. Jin, Q. Sun, Y. Sha, and M. Huang, "Surface flashover characteristics of oil-paper insulation under combined AC-DC voltage," in *Proc. IEEE Int. Conf. Solid Dielectr. (ICSD)*, Jun. 2013, pp. 1005–1008.
[16] B. Qi, Z. Wei, and C. Li, "Creepage discharge of oil-pressboard insulation in AC-DC composite field: Phenomenon and characteristics," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 23, no. 1, pp. 237–245, Feb. 2016.
[17] *EHV Transmission Company of Chinese Southern Power Grid, Typical Fault Analysis of HVDC Equipment*, China Electric Power Press, Beijing, China, 2009, pp. 66–77.
[18] L. A. Dissado, J. C. Fothergill, *Electrical Degradation and Breakdown in Polymers*. London, U.K.: Peter Peregrinus Ltd, 1992, ch. 4, sec. 14, pp. 323–324.
[19] W. Nelson, *Applied Life Data Analysis*. New York, NY, USA: Wiley, 1982.
[20] G. Chen, J. W. Zhao, and S. T. Li, "Origin of thickness dependent dc electrical breakdown in dielectrics," *Appl. Phys. Lett.*, vol. 100, no. 22, p. 2904, May 2012.
[21] Y. L. Chong, G. Chen, and Y. F. F. Ho, "The effect of degassing on morphology and space charge," in *Proc. IEEE Int. Conf. Solid Dielectr., ICSD*, May 2004, pp. 162–165.
[22] N. J. Western, W. I. Perez, and S. R. Wenham, "Point-contacting by localized dielectric breakdown with breakdown fields described by the Weibull distribution," *IEEE Trans. Electron Devices*, vol. 62, no. 6, pp. 1826–1890, Jun. 2015.

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