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RESEARCH ARTICLE

Effect of Electric-Field Components on the Flashover Characteristics of Oil-Paper Insulation Under Combined AC-DC Voltage

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ABSTRACT Flashover characteristics are closely related to the electrical field distribution on the surface of oil-paper insulation. In this study, the effects of electrical field and DC voltage components on the creepage flashover characteristics of oil-paper insulation under combined AC-DC voltage (CADV) are investigated using two electrode models. The results demonstrate that when the DC voltage component is large, the flashover voltage under the influence of strong parallel electric field component is approximately 1.2 times higher than that under the influence of strong normal electric field component. When the DC voltage component value increases under the influence of strong normal electric field component, the value of corresponding AC voltage component of the creepage flashover voltage exhibits a decreasing trend. It is believed that due to the strong normal electric field component, the electrons intensify the collision on the surface of the insulating pressboard. Under the influence of the DC voltage component and due to the presence of space charge on the insulating pressboard, the distribution shape of carbonized particles on the surface of the insulating pressboard after creepage flashover is different. Furthermore, the instantaneous energy release during creepage flashover under CADV is higher than that under AC voltage, and the greater the DC voltage component value, more severe is the damage to the fibers on the insulating pressboard surface.

INDEX TERMS Oil-paper insulation, AC-DC combined voltage, DC voltage component, creepage discharge, electrical field component, flashover voltage, space charge.

I. INTRODUCTION

Ultra high voltage direct current (UHVDC) transmission is the preferred long-distance DC transmission method in China owing to its advantages of low line loss, low cost, reliable system operation, and stability [1]. As the core equipment of the DC transmission system, with the rapid increase in power load, the capacity of a converter transformer needs to be increased, which implies that the transmission voltage level should be increased from ± 800 kV to ± 1100 kV [2]. Compared with conventional AC transformers, converter transformers have a specific insulating structure and operating condition: the valve-side winding is subjected to AC, DC, impulse, and combined AC-DC voltage (CADV) during operation, which makes their operating conditions more complex and changeable [2], [3].

According to the statistical data supplied by the International Council on Large Electric Systems (CIGRE), the failure rate of a converter transformer is twice that of an AC transformer, wherein the insulation failure type accounts for approximately half of all failures. However, a considerable proportion of insulation failure instances can be attributed to creepage discharge at the oil-paper insulation (OPI) interface [4], [5]. Thus, the OPI interface remains the weak point

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of the insulation characteristics of the converter transformer. The creepage discharge tends to occur in the shield, bushings, and spacers between the windings, wherein the normal electric field component is stronger than the parallel electric field component [6], [7], [8].

The creepage discharge of OPI is a discharge phenomenon that occurs along the surface of the insulating pressboard at the interface between the insulating oil and insulating pressboard. Moreover, the creepage discharge of OPI has been a popular research topic. With the development of the UHVDC transmission system, researchers focused on the creepage discharge characteristics of OPI. Previous studies mainly focused on the breakdown characteristics, partial discharge characteristics [9], [15], [17], [19], space charge characteristics [10], [11], aging characteristics, gas generation characteristics [16], [17], [18], insulation status evaluation [13], [19], creepage discharge voltage, and flashover location of OPI under CADV [12], [14], [20]. Yuanxiang et al. examined the influence of DC voltage component on the flashover of OPI under CADV. The breakdown and flashover characteristics of OPI under AC voltage and CADV were compared and analyzed [21]. Previous studies on the creepage discharge characteristics under CADV mainly focused on the creepage discharge strength, the creepage discharge position, and analyzed the deterioration traces (such as white spots) on the surface of the pressboard. However, it did not conduct in-depth analysis and research on the destruction mechanism of OPI under the influence of various factors, such as creepage discharge.

Despite the creepage discharge being closely related to the electric field distribution of the insulation structure, very few studies investigate the effects of the electric field components on the creepage discharge characteristics of OPI under CADV. Therefore, a creepage discharge experimental setup that comprises two electrode models was used in this study to simulate the effects of the different electric field components. The mechanism behind the effect of the electric field and DC voltage components on the creepage discharge characteristics of an OPI under CADV was studied by varying the amplitude of the DC voltage component in the CADV.

II. EXPERIMENTAL SETUP AND METHODS

A. ELECTRODE MODEL

The two electrode models (models I and II) used in the experiment are shown in Fig. 1. Brass electrodes were used in both models; the distance between the high-voltage and ground electrodes was set at 3 mm. In the experiment, both electrode models were placed in the treated transformer oil for experimentation.

As shown in Fig. 1a, electrode model I is used to study creepage discharge characteristics under a strong parallel electric field component wherein the insulating pressboard is pressed under the two electrodes. Pressure is applied to the insulating pressboard using polymethyl methacrylate fasteners to ensure a tight and reliable contact between the electrodes and insulating pressboard surface. A back electrode is set in electrode model I to form electrode model II, as shown in Fig. 1b. The back electrode is grounded. The strength of the strong normal electric field component in electrode model II is changed by adjusting the distance d between the back electrode and high voltage electrode. Electrode model II is used to study the creepage discharge characteristics under a strong normal electric field component.

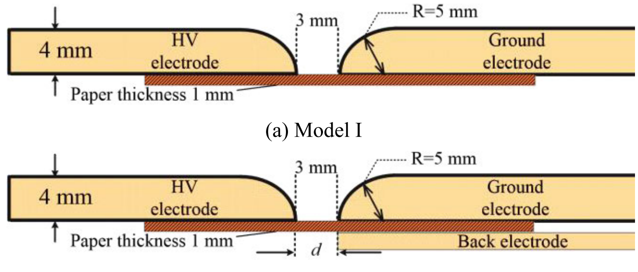


FIGURE 1. Electrode models.

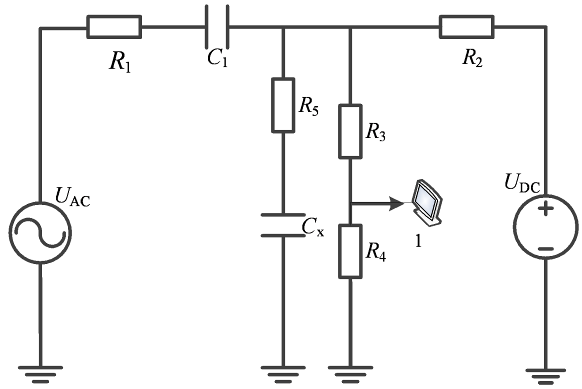


FIGURE 2. Schematic of experimental platform. $R_1 = 10$ MΩ, $R_2 = 1$ MΩ, R_3/R_4 is a resistive voltage divider (10000:1), $R_5 = 5$ MΩ, and $C_1 = 0.2$ μF. The component labeled 1 is the partial discharge detection system.

B. SAMPLES

Karamay 25# transformer oil was used in the experiment. Before the experiment, the oil was degassed and dried, and the impurities were removed to ensure that the gas volume fraction and microwater volume fraction of the oil were less than 2% and 5 ppm, respectively, in accordance with the requirements of GB/T7595 [21].

The insulating pressboard was cut into 60 mm × 60 mm squares and dried at 100 °C for 72 h. Subsequently, the square specimens were impregnated with the previously treated transformer oil for 72 h in vacuum under a pressure of 10 Pa and a temperature of 60 °C. Thus, an oil-impregnated insulating pressboard with a moisture content of approximately 0.3% was prepared for the creepage discharge characteristics test [21].

C. EXPERIMENTAL PLATFORM

Fig. 2 shows the circuit diagram of the experimental setup. U_{DC} denotes a 100 kV DC high-voltage generator connected to the detection circuit through a current limiting resistor

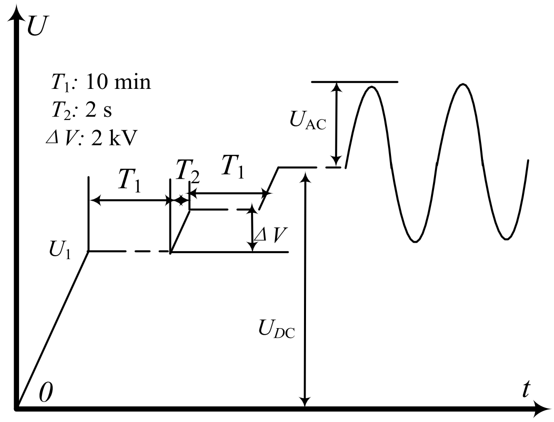


FIGURE 3. Voltage application method.

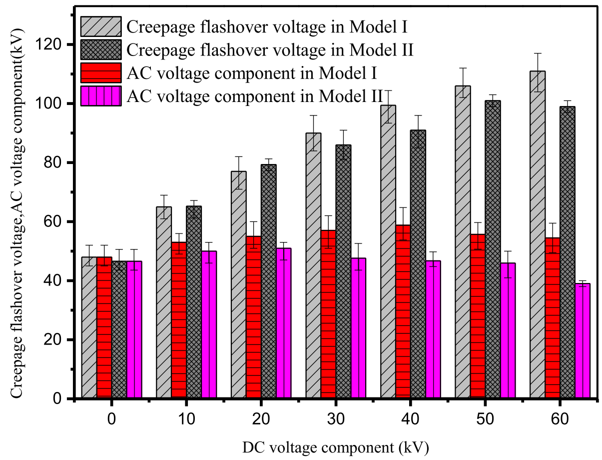


FIGURE 4. Creepage flashover voltage in two models.

R_2; U_{AC} represents a 100 kV AC high-voltage generator connected to the detection circuit through a current limiting resistor R_1 and an isolating capacitor C_1. The applied voltage is connected to the constant temperature test box through high-voltage bushing, and then, the voltage is applied to the OPI sample C_x. R_1, R_2, and R_5 are current limiting resistances; R_3/R_4 represent the resistance voltage dividers for measuring the CADV at the voltage division ratio of 10000:1. A digital oscilloscope is used to record real-time voltage and discharge current waveforms [21].

D. VOLTAGE APPLICATION METHOD

The system uses a parallel superposition method to obtain the CADV. The voltage is measured as follows: the DC voltage is increased to a certain amplitude at a rate of 1 kV/s and held for 30 min. Thereafter, the AC voltage is increased to U_1, as shown in Fig. 3 (U_1 is 20% of U_b, where U_b denotes the breakdown voltage of the transformer oil), and is held for 10 min. Subsequently, the step-up method is used to increase the AC voltage component at a rate of 1 kV/s and step-voltage of 2 kV; it is held for 10 min at each step. In this method, the voltage is gradually increased until the occurrence of a flashover [21].

Each group of tests is performed 10 times, and the average value is calculated. Following the flashover, the old specimens are replaced and the oil is re-filtered; then, the above procedure is repeated.

III. RESULTS AND DISCUSSION

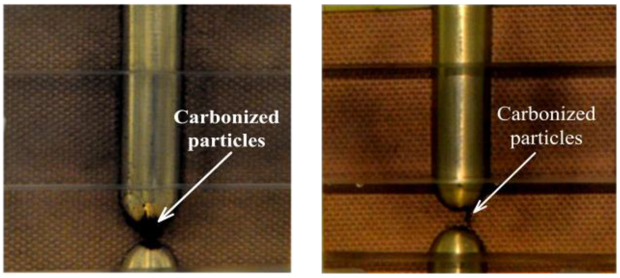
In the experiment, the peak value of the CADV was used as the creepage flashover voltage value. The horizontal axis (x-axis) represented the CADV, where the AC component was 0 kV (AC) and the DC voltage component was 10–60 kV. The vertical (y axis) represented the creepage flashover voltage and the amplitude of the AC voltage component under different values of the DC voltage component.

A. CREEPAGE FLASHOVER VOLTAGE IN MODEL I AND MODEL II

The creepage discharge characteristics under CADV were studied for model I and model II. In model I, the electric field on the surface of the insulating pressboard comprised the parallel electric field component; the contribution of the normal electric field component was low. As shown in Fig. 4, creepage flashover voltage under the influence of pure AC voltage is approximately 48 kV. The creepage flashover voltage under the influence of pure DC voltage was approximately 75 kV. The creepage flashover voltage under pure DC voltage was approximately 1.56 times that under the pure AC voltage. Further, the creepage flashover voltage gradually increased with an increase in the DC voltage component. The amplitude of the AC voltage component increased slightly; however, the change was small.

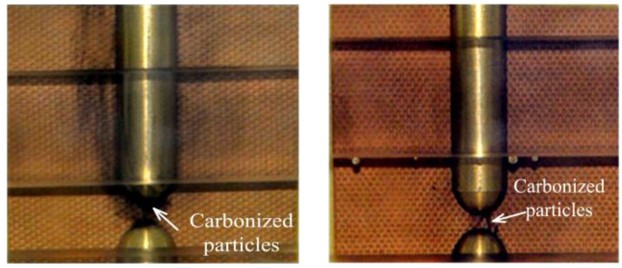
In model II, the surface of the insulating pressboard is subjected to a strong normal electric field component under the CADV because of the back electrode. The creepage flashover voltage gradually increases with an increase in the value of the DC voltage component in the CADV. The creepage flashover voltage of the OPI under DC voltage is 1.52 times of that under pure AC voltage. The AC voltage component required for the occurrence of creepage flashover decreases gradually with an increase in the value of the DC voltage component. A strong field area is formed at the junction of the high-voltage electrode tip, transformer oil, and insulating pressboard because the permittivity values of the transformer oil, electrode, and paper are different. Therefore, the transformer oil gets ionized easily and generates charge under a low-amplitude AC voltage [22].

Further, due to the presence of the back electrode, the normal electric field component acting on the surface of the insulating pressboard is strengthened; therefore, electrons intensify the collision on the surface of the insulating pressboard under the effect of the AC voltage. The OPI material exhibits space charge injection and extraction under the effect of DC voltage. Therefore, under CADV, the charge is more likely to move directionally along the electric field on the surface of the insulating pressboard, which intensifies the collision on the surface of the insulating pressboard [23]. The collision disturbs the space-charge equilibrium, and it easily causes creepage flashover under the AC voltage component.



(a) AC voltage(AC 46 kV) (b) CADV (AC 45 kV, DC 50 kV)

FIGURE 5. Carbonized particles on the electrode and insulating pressboard surface observed after flashover under different voltage conditions.



(a) AC voltage(AC 46 kV) (b) CADV (AC 43 kV, DC 40 kV)

FIGURE 6. Carbonized particles on the electrode and insulating pressboard surface observed after flashover under different voltage conditions.

As shown in Fig. 4, under the same DC voltage component, when the DC voltage component is large, the AC voltage component required for creepage discharge in model II is lower than that in model I. Thus, the creepage flashover voltage of the OPI under CADV is greatly affected by the electric field component. The creepage flashover voltage under the influence of the strong parallel electric field component is approximately 1.2 times of that under the influence of the strong normal electric field component when the DC voltage component is large.

B. CREEPAGE FLASHOVER IN MODEL I

Fig. 5a shows that the oil gap breaks down first when a creepage flashover occurs between the two electrodes under pure AC voltage. The discharge ionizes the transformer oil, which decomposes to form many carbonized particles that attach to the tip of the high-voltage electrode and electrode edges. However, no obvious remnant ablation marks can be observed on the surface of the insulating pressboard after the flashover. This is because creepage flashover occurs in the transformer oil gap between the two electrodes under pure AC voltage. The oil gap close to the surface of the insulating pressboard or the small oil gap in the insulating pressboard is often the creepage flashover path under the CADV, and it can be attributed to the increase in the DC voltage component value. The oil gap breaks down and leaves discharge carbonization traces on the surface of the insulating pressboard near the electrode tip; the ablation traces resulting from the discharge are shown in Fig. 5b.

Fig.s 5a and 5b indicate considerable carbonization and ablation traces on the surface of the insulating pressboard when creepage flashover occurs under the CADV. However, the carbonized particles are not accumulated in large amounts on the electrode surface unlike the observation under pure AC voltage. The oil gap between the two electrodes often breaks down instantaneously when the electric field stress of the transformer oil increases because the ability of the transformer oil to withstand the electric field is considerably lower than that of the insulating pressboard. Further, the electric field stress in the insulating pressboard increases because of the increase in the value of the DC voltage component; this leads to an increase in the amount of space charge accumulated on the insulating pressboard [21]. Accordingly, the space-charge equilibrium in the OPI is unbalanced, which results in a flashover on the surface of the insulating pressboard under the AC voltage component. The damage to the insulating pressboard caused by the flashover under CADV is considerably greater than that under pure AC voltage, based on the carbonization trace of the insulating pressboard surface resulting from creepage discharge.

C. CREEPAGE FLASHOVER IN MODEL II

The flashover phenomenon in model II is shown in Fig. 6. As shown in Fig. 6a, the OPI surface between the two electrodes is covered with black carbonized particles, but no obvious signs of damage or ablation are observed on the surface of the insulating pressboard. The discharge energy decreases the viscosity of the local transformer oil that causes the carbonized particles in the transformer oil to move upward. Therefore, the black transformer oil accumulates around the electrode, and the carbonized particles adhere to the surface of the insulating pressboard in contact with the electrode edge. After the experiment, the insulating pressboard is de-oiled and dried, and the adhered carbonized particles are clearly observed. The carbonized particles are distributed along the edge of the electrode, as shown in Fig. 7d.

Model II aggravates the damage to the insulating pressboard surface; this results in a significant remnant carbonized channel on the surface of the insulating pressboard, as illustrated in Fig. 6b. Compared to the effect of pure AC voltage, a small amount of black carbonized particles accumulates on the electrode surface under the CADV. In addition, there are fewer black carbonized particles in the transformer oil around the electrode, but there is an obvious black trace on the surface of the insulating pressboard.

D. DAMAGE MECHANISM OF OPI ATTRIBUTED TO CREEPAGE FLASHOVER IN MODELS I AND II

Under CADV, models I and II exhibited different extents of damage to the surface of the insulating pressboard.

1) SURFACE CONDITION OF INSULATING PRESSBOARD AFTER CREEPAGE FLASHOVER

The carbonized particles on the surface of the insulating pressboard have different distribution characteristics because

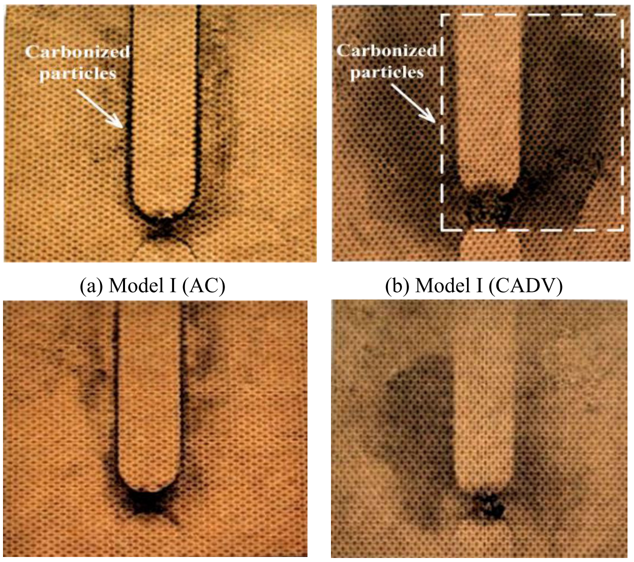


FIGURE 7. **Surface condition of insulating pressboard after flashover.**

of the different conditions of the voltage applied to model I and II. The carbonized particles are concentrated and accumulated at the point of contact of the electrode edge and insulating pressboard under pure AC voltage.

Fig.s 7a and 7c indicate that the edge profile of the electrode is replaced by the distribution of black carbonized particles in the shape of a capital letter ''U''. No obvious accumulation of black carbonized particles is found elsewhere on the surface of the insulating pressboard. However, under the CADV, the carbonized particles accumulated on the surface of the insulating pressboard, rather than at the edge of the electrode (Fig.s 7b and 7d).

Under CADV, the distribution area and concentration of the carbonized particles on the insulating pressboard surface for model I were found to be larger than those for model II. Fig. 7d shows that the surface of the insulating pressboard in model II is more severely ablated than that in model I. The OPI in model II is subjected to the strong normal electric field component, which exacerbates the collision of electrons on the insulating pressboard surface. Thus, the collision caused defects on the insulating pressboard surface that aggravated under the influence of an external electric field; eventually, it caused a creepage flashover.

Creepage flashover occurs in the transformer oil gap between the two electrodes under pure AC voltage, and the energy generated by the discharge is consumed by the transformer oil around the electrodes. The carbonized particles have the same polarity as that of the electrode; thus, the particles are repelled from the electrode after colliding with it. The polarity of the AC voltage changes periodically, the mass of the carbonized particles is relatively large, and speed of the particles is considerably smaller than that of the AC voltage polarity change. Thus, the repelled carbonized particles are quickly attracted by the electrode with the opposite polarity

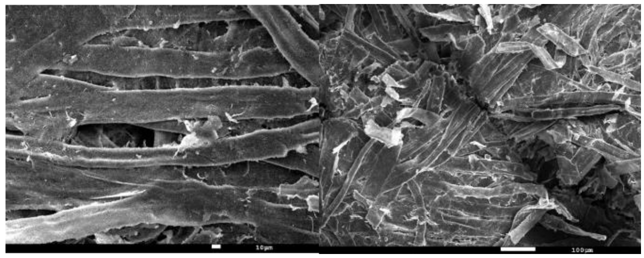


FIGURE 8. **SEM image of insulating pressboard after flashover under different voltage.**

when the polarity changes. Finally, the black carbonized particles accumulate near the edge of the electrode.

Under CADV, the AC electric field component is concentrated in the transformer oil, and the DC electric field component is concentrated in the insulating pressboard. Creepage flashover occurs close to the surface of the insulating pressboard that destroys the surface of the insulating pressboard and cracks the transformer oil to generate many carbonized particles. The carbonized particles move towards the electrode immediately after being generated but they are repelled because they have the same polarity after being attracted to the high-voltage electrode. Meanwhile, a large amount of space charge is injected onto the surface of the insulating pressboard under the influence of the DC electric field. After the occurrence of creepage flashover, a large amount of residual space charge dissipates and forms an electric field on the surface of the insulating pressboard. Eventually, these carbonized particles are adsorbed on the top surface of the insulating pressboard. Thus, many carbonized particles cannot be accumulated in the transformer oil after flashover under the CADV; the particles adhere to the surface of the insulating pressboard.

2) MICROMORPHOLOGY OF INSULATING PRESSBOARD AFTER FLASHOVER

The carbonization trace on the surface of the insulating pressboard exhibits different features. The surface of the insulating pressboard at the middle position between the two electrodes was analyzed with a scanning electron microscope (SEM); the results are shown in Fig. 8.

Fig. 8a shows that the fiber of the insulating pressboard is relatively intact after the flashover under AC voltage; there are no obvious break traces, and the fiber surface is smooth. Although the fibers on the surface of the insulating pressboard do not break, the amount of broom fiber of the insulating pressboard is greatly reduced because of the ablation effect of the discharge. Under AC voltage, there is less damage to the surface of the insulating pressboard. The transformer oil gap between the two electrodes breaks down to cause flashover under pure AC voltage. However, no obvious discharge carbonization trace can be observed on the surface of the insulating pressboard; this indicates that there is a certain distance between the flashover channel and the insulating pressboard surface. Thus, the fiber of the insulating pressboard is not ablated and damaged after the flashover. The heat released because of the discharge has an ablation effect on the broom fiber of the insulating pressboard, which smoothens the fiber surface; however, it does not break.

The micromorphology of the surface of the insulating pressboard after the flashover under the CADV is shown in Fig. 8b. After the flashover, the surface of the insulating pressboard is broken and delaminated. Internal fibers of the insulating pressboard are broken, and the fiber fracture is significant. The damage shifts from the surface of the insulating pressboard inwards. The damage to the surface of the insulating pressboard resulting from the creepage flashover is severe under the CADV; the greater the DC voltage component value, more severe is the damage to the surface of the insulating pressboard.

3) MECHANISM OF DAMAGE OF THE DIFFERENT ELECTRIC FIELD COMPONENTS ON OPI

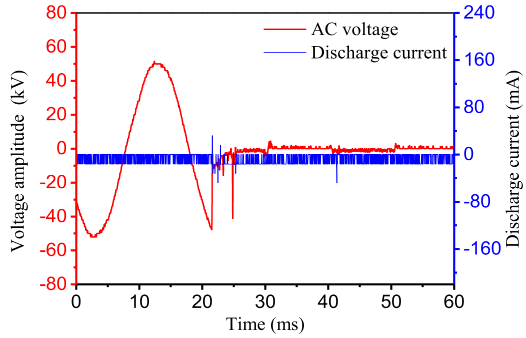
The damage caused by creepage flashover on the surface of the insulating pressboard under CADV was greater than that under pure AC voltage. The damage in model II was greater than that in model I. Moreover, the energy released when flashover occurs along the surface of OPI is analyzed, and the damage mechanism of OPI caused by different electric field components is examined. The voltage and current waveforms of the two electrode models for the flashover occurring under pure AC and CADV are shown in Fig. 9.

Fig. 9a shows the voltage and current waveforms of model I when the flashover occurs under pure AC voltage. The AC voltage drops to zero immediately after the occurrence of the creepage flashover. At this moment, there is a spike pulse with an amplitude of approximately 40 mA in the discharge current; thereafter, there is no discharge.

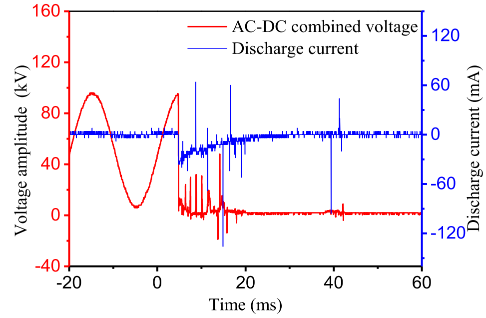
Fig. 9b shows the voltage and current waveforms of model I when the flashover occurs under CADV. The discharge does not stop immediately after the flashover occurs, and there is still a large fluctuation in the voltage waveform in the subsequent period. However, there are some small discharge pulses in the current waveform. This phenomenon is very similar to the discharge characteristics observed under the pure DC voltage.

Fig. 9c shows the voltage and current waveforms of model II when the flashover occurs under CADV. As shown, the oil gap regains its insulation characteristics 15 ms after the flashover because the transformer oil is a recoverable insulating material. Then, it is broken down again by being decomposed during the discharge process. This generates a considerable amount of bubbles. Additionally, as the breakdown voltage of bubbles is relatively low, the bubbles are broken after the voltage is reloaded.

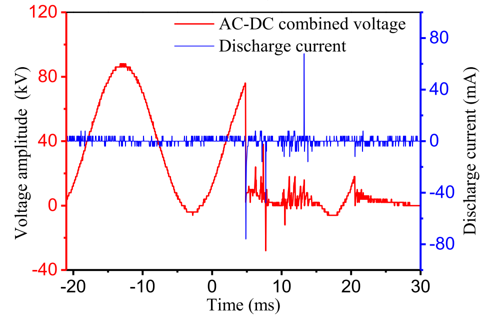
Space charge injection and extraction is observed when the OPI is subject to CADV; the corresponding voltage and current waveforms are shown in Fig.s 9b and 9c. Therefore, a considerable amount of space charge is accumulated on the OPI under the DC voltage component, and the space charge significantly distorts the electric field distribution on the OPI



(a) Voltage and current waveforms in model I (AC 46 kV)



(b) Voltage and current waveforms in electrode model I (AC 44 kV, DC 50 kV)

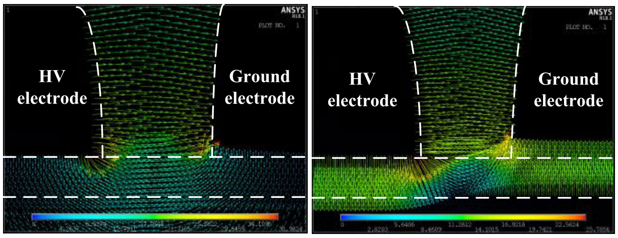


(c) Voltage and current waveforms in electrode model II (AC 43 kV, DC 40 kV)

FIGURE 9. Creepage flashover voltage and current waveforms under different electrode models.

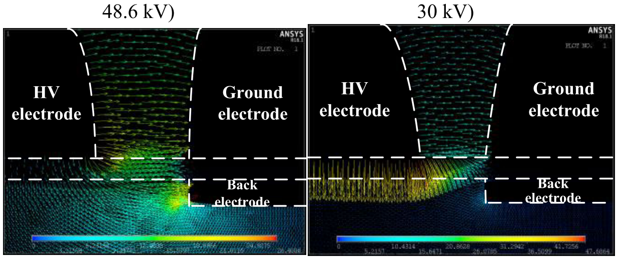
surface, which has an effect on the flashover characteristics of the OPI. The space charge on the OPI layer requires time to dissipate and migrate. Thus, even if the power is turned off when a flashover occurs, the discharge does not stop immediately. The oil gap or bubble breaks down again because the electric field formed by the residual space charge reaches the breakdown field strength of the surrounding oil gap or bubble. Therefore, the discharge occurs intermittently.

Transformer oil is a mixture of aromatic hydrocarbons, naphthene, olefins, and paraffins. Transformer oil, which is a hydrocarbon, contains many C-C bonds and CH_3^*, CH_2^*, and CH^* chemical groups [24]. The ionization energy of each part is different because of the molecular structure. When a discharge or overheating fault occurs in the transformer oil, the C-H and C-C bond are broken, which generates unstable free radicals such as H, CH_3, CH_2, CH, and C. These free radicals recombine to form other molecules such as CH_4, C_2H_2, H_2, and solid particles of carbon. Among



(a) Distribution diagram of pure AC electric field of model I (AC 48.6 kV)

(b) Distribution diagram of pure DC electric field of model I (DC 30 kV)



(c) Distribution diagram of pure AC electric field of model II (AC 50 kV)

(d) Distribution diagram of pure DC electric field of model II (DC 50 kV)

FIGURE 10. Vector diagram of AC and DC electric field distributions of the two electrode models.

them, the ionization energy (Δ_1) of the aromatic hydrocarbon molecules is approximately 9.6×10^{-19} J (6 eV, 1 eV $= 1.6 \times 10^{-19}$ J), and the ionization energy (Δ_2) of naphthene is approximately 1.58×10^{-18} J (9.86 eV). The energy of the C-H, C-O, and C-C bonds of the insulation paper cellulose molecule is only a few electron volts. According to the arrangement of the molecular energy density of the transformer oil, the products of the cracked transformer oil are in the order of alkanes, alkenes, alkynes, and carbonized particles. When the insulating pressboard is affected by electricity, heat, mechanical stress, oxygen, and moisture, the insulating pressboard undergoes oxidation decomposition, cracking, and a hydrolysis reaction that breaks the C-O, C-H, and C-C bonds and generates CO, CO_2, a small amount of hydrocarbon gas, water, and furan compound (furfural).

The energy generated by the creepage flashover is estimated using u_i and the current (i_i) values at a particular time instant t from the flashover waveform shown in Fig. 10 as

$$W = \iiint dudidt = \sum |\Delta u_i| \, |\Delta i_i| \, \Delta t \qquad (1)$$

The average discharge energy under the pure AC voltage is the smallest, at approximately 0.0058 J. The average discharge energy is approximately 0.3 J when the DC voltage component is 50 kV. The average discharge energy increases with an increase in the value of the DC voltage component. The energy released because of the creepage flashover under the CADV causes chemical bonds of the OPI medium molecules to break, which causes considerable damage to the OPI. Therefore, the damage to the OPI under the CADV is greater than that under the pure AC voltage. The results indicate that under the CADV, the damage to the surface of the insulating pressboard in the two electrode models is significantly different. This phenomenon has a significant relationship with the electric field distribution of the OPI in the combined AC-DC electric fields.

Fig. 10a shows that, in model I, the electric field is composed of parallel electric field components; the normal electric field components are low. Further, the electric field is concentrated in the transformer oil under pure AC voltage. The electric field stress of the insulating pressboard is low, and the maximum electric field stress appears at the junction of the insulating pressboard, electrode, and transformer oil. In Fig. 10b, the electric field stress is concentrated on the insulating pressboard under the influence of pure DC voltage. Fig. 10c shows the electric field distribution of model II under the influence of pure AC voltage; the electric field at the back electrode is relatively concentrated. Under DC voltage, the electric field is concentrated in the insulating pressboard, and the maximum electric field stress appears on the upper surface of the insulating pressboard in contact with the high-voltage electrode. The electric field distribution in the insulating pressboard consists of the normal electric field component; there are less parallel electric field components in the transformer oil. Finally, Fig. 10d shows that a strong normal electric field component appears in the insulating pressboard due to the presence of the back electrode.

The two electrode models have different electric field distribution characteristics under different voltage conditions. Therefore, under AC voltage, the transformer oil molecules in this area are first ionized and consequently generate more electrons because the electric field stress of the transformer oil at the electrode end is slightly greater than the surrounding transformer oil. The generated electrons are accelerated under the influence of the electric field, and they collide with the transformer oil molecules to ionize; thereafter, they gradually form an electron collapse. Approximately 30% of the energy generated during the bubble discharge is consumed by the bubble itself; a part of the overall energy is absorbed by the transformer oil around the bubble that causes the transformer oil temperature to rise and gasify [24]. High temperature causes the transformer oil to be heated and gasified because a large amount of energy is released at the moment of discharge, which causes high temperature in the small area of the transformer oil. The energy generated by the discharge can easily cause the transformer oil to crack and form microbubbles which gradually develop into discharge channels under the AC electric field; this eventually leads to a flashover. Simultaneously, many carbonized particles are generated in the transformer oil cracking because of the dual effects of thermal ionization and photoionization; a large number of black carbonized particles are accumulated on the electrode tip after the flashover.

IV. CONCLUSION

When the DC voltage component is large, the creepage flashover voltage under the influence of the strong parallel electric field component is approximately 1.2 times of that under the influence of the strong normal electric field component. Under the influence of the strong normal electric field component, as the DC voltage component increases, the corresponding AC voltage component in the creepage flashover voltage shows a decreasing trend. It is considered that the space-charge equilibrium of the OPI is easily disturbed and destroyed under the influence of the AC voltage component.

The instantaneous energy release during creepage flashover under CADV is approximately 50 times of that under pure AC voltage, and the greater the DC voltage component value, more severe is the damage to the fibers on the surface of the insulating pressboard. Under pure AC voltage, the flashover path is the oil gap between the two electrodes, and the broom fiber on the surface of the insulating pressboard is slightly ablated and damaged. Under CADV, the flashover path is close to the oil gap on the surface of the insulating pressboard, and the greater the DC voltage component value, more severe is the damage to the fibers of the insulating pressboard surface.

Under pure AC voltage, the carbonized particles mainly accumulate at the contact point of the electrode edge and insulating pressboard. Under CADV, the carbonized particles are mainly distributed on the surface of the insulating pressboard, rather than being attached to the edge of the electrode. The main reason for this phenomenon is the space charge injection in the OPI under the action of the DC voltage component.

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