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To cite this article: Xie Bangpeng *et al* 2020 *IOP Conf. Ser.: Earth Environ. Sci.* **512** 012122

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Research on the Failure Process of Oil Paper Insulation of Surface Partial Discharge under Fluctuating DC voltage

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Abstract. Partial discharge along the surface seriously damages the oil-paper insulation performance and ultimately leads to insulation failure, which greatly reduces the safety and reliability of the converter transformer operation. It is important to understand the failure process of oil-paper insulation under partial discharge along the surface to avoid fault occurrence. In this paper, the failure process of oil-paper insulation under partial discharge of pulsating DC and AC voltage is studied. A partial discharge test platform for oil-paper insulation under pulsating DC voltage was built. The partial discharge test of oil-paper insulation along the extremely uneven electric field was simulated by using the needle plate and column plate discharge model. The oil-paper insulation under two kinds of voltages under the extremely uneven electric field was analyzed in depth. The similarities and differences of the failure process and their causes, the insulation design and operation and maintenance recommendations for preventing flashover under the extremely uneven electric field are proposed.

1. Introduction

During the operation of converter transformer, the main insulation of valve side winding bears the joint action of AC, DC and harmonic voltage, and the operation temperature is relatively high [1]. The complex electromagnetic environment and bad operating conditions make the main insulation of the valve side winding prone to defects and lead to partial discharge. In order to bear DC voltage, the main insulation of valve side winding of converter transformer increases the amount of paperboard compared with that of AC transformer, so the probability of surface partial discharge of main insulation of valve side winding is relatively high [2]. Along the surface partial discharge seriously damages the insulation performance of oil paper and eventually leads to insulation failure, which greatly reduces the safety and reliability of converter transformer operation [3-4].

It is very important to know and understand the failure process of oil paper insulation under the condition of surface partial discharge to avoid the occurrence of fault and diagnose the discharge fault. Some studies have shown that under the extremely uneven and slightly uneven electric field, the white mark can greatly increase the intensity and development speed of the along surface partial discharge, so the insulation failure of the oil paper caused by the along surface partial discharge is closely related to the white mark on the surface of the oil immersed cardboard and its development [5-6]. At present, it is only known that the white trace is actually a fault gas channel, but there is no systematic and in-depth understanding of the failure process of oil paper insulation caused by pulsating DC and AC voltage discharge, and there is no rule and mechanism of the influence of DC component on the failure. Therefore, it is necessary to deeply study and understand the whole process from white mark generation to oil paper insulation failure, analyze the influence rule and mechanism of DC component on the failure



process, and finally put forward corresponding operation and maintenance suggestions and fault diagnosis methods.

In this paper, the failure process of oil paper insulation under pulsating DC and AC voltage surface partial discharge is studied. A test platform of oil paper insulation partial discharge under pulsating DC voltage is built. The needle plate and column plate discharge models are used to simulate the surface partial discharge test of oil paper insulation under the extremely uneven electric field. The failure process of oil paper insulation of surface partial discharge under fluctuating DC voltage is analyzed. The insulation design and operation to prevent the surface flashover under the extremely uneven electric field are proposed Dimensional suggestion.

2. Partial discharge test platform for oil paper insulation under pulsating DC voltage

Figure 1 shows the partial discharge test platform of oil paper insulation under pulsating DC voltage set up by the laboratory. The high-voltage lead adopts aluminum foil tube with diameter of 10cm to prevent corona discharge. The system is composed of 200kV/20mA AC power supply and 200kV/10mA DC power supply in parallel. The AC power supply outputs the high-voltage AC through the protective resistor R_2 (10 k Ω) and the isolated DC capacitor C_1 (0.2 μ F), and the DC power supply outputs the high-voltage DC through the isolated AC resistor R_1 (10 M Ω); the AC and DC are connected to the resistance voltage divider together to obtain the pulsating DC voltage. The resistance voltage divider is composed of resistance R_3 (10 M Ω) and R_4 (10 k Ω) in series, and its voltage ratio is 1000:1; the resistance voltage divider signal is transmitted to the console (CP) and oscilloscope (o) at the same time, and the console can display the AC effective value and DC amplitude separately, and the voltage waveform can be viewed in real time through the oscilloscope. In addition, the AC and DC power supply have their own voltage regulators, and the boosting speed can be controlled separately, which can generate various AC / DC ratio pulsating DC voltage as required.

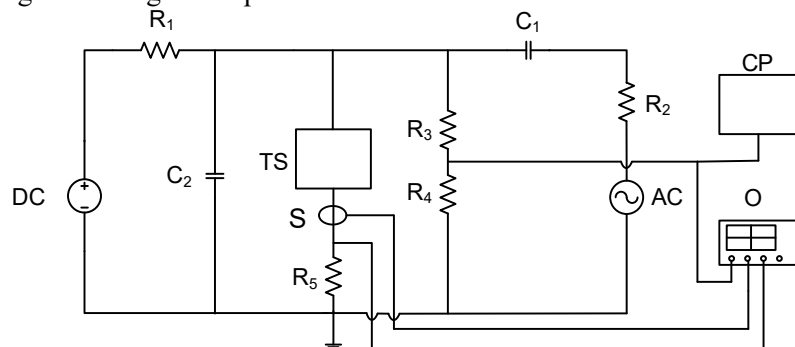


Fig.1 PD experiment setup under pulsating DC voltage

High voltage coupling capacitor C_2 (1nF) is used to couple partial discharge signals. PD signal is detected by Wide-Band Rogowski coils and connected to LecroyHD4096 digital oscilloscope through coaxial cable. The oscilloscope collects and stores the partial discharge signal. Because the upper limit frequency of the pass band of Rogowski coil is 16MHz, the sampling rate of the oscilloscope is set to 50ms/s.

In this paper, a single discharge current signal is collected by a self-made 50 Ω non-inductive resistance. In order to reduce self-induction, the 50 Ω non inductive resistance is composed of four 200 Ω non inductive resistances in radial parallel, and the angle between adjacent resistances is 90 $^\circ$. In order to prevent the damage of the oscilloscope caused by flashover, the gas discharge tubes are connected in parallel at both ends of the non-inductive resistance. The measured upper pass band frequency of 50 Ω non inductive resistance is up to 150MHz, and the sampling rate of oscilloscope is set to 2.5GS/s.

The ripple factor is defined as $RF = U_{AC} / U_{DC}$, where U_{DC} is the amplitude of DC component and U_{AC} is the effective value of AC component. Figure 2 shows the measured test voltage waveform, which RF is set to 1.

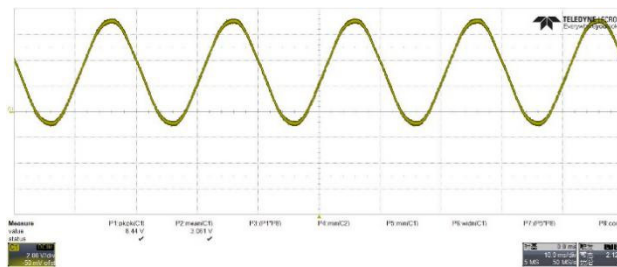


Fig. 2 Measured waveform of pulsating DC voltage ($RF=1$)

In this paper, the pin plate discharge model is used to simulate the partial discharge along the surface under the extremely uneven electric field. The front and side views of the pin plate discharge model are shown in Figure 3. The stainless steel needle with a radius of curvature of $70\ \mu\text{m}$ was used as the high-pressure electrode. In order to make the needle electrode fit the paper surface better, the needle electrode was 30° to the cardboard. The diameter of flat electrode is 30mm and the thickness is 8mm. The oil cup used in the test is a rectangle made of plexiglass, which has good light transmittance and is easy to observe. In the test, the oil gap is fixed at 30mm.

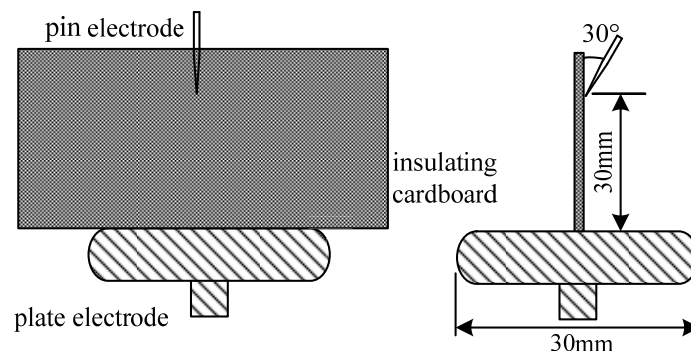


Fig.3 Needle-plate electrode model for discharge

3. Failure process of oil paper insulation under pulsating DC voltage

Under the pulsating DC voltage, the phenomenon of partial discharge along the surface is the same on the dry oil impregnated board and the 3.1% moisture content oil impregnated board. The discharge remained stable, and only appeared in the positive half cycle. After pressurization for a period of time, carbon traces would also appear on the surface of the oiled cardboard in the tip area, but the area of carbon traces was smaller than that under the same AC voltage. In addition, when the pressure is 5-30 minutes, the flashover along the surface occurs randomly, and the flashover does not cause over-current to trip the power supply; if the pressure is continued after the first flashover along the surface, the flashover along the surface will also occur randomly, and there is no obvious change on the surface of the oil immersed cardboard after multiple flashovers, which indicates that the flashover along the surface and the development of the white mark under the pulsating DC voltage will eventually lead to the different total discharge.

In order to observe the development rule of oil paper insulation along the surface partial discharge under the pulsating DC voltage after the generation of the white mark, the paper firstly uses the $30\ \text{RMS kV}$ AC voltage to trigger the white mark on the oil paper board surface with 3.1% moisture content. When the length of the white mark grows to about 5 mm, the 30 kV DC component is added. After superposing DC, the phase distribution of PD along the surface is similar to that under AC voltage, and the negative discharge occurs stably. The discharge spectrum is shown in Figure 4. However, the white mark stops growing forward, and the color of the white mark has gradually faded. After 30 minutes, only the tip of the needle can be seen faintly, as shown in Figure 5. In addition, flashover still occurs randomly during pressurization, and the first flashover time is earlier than when no white mark is generated.

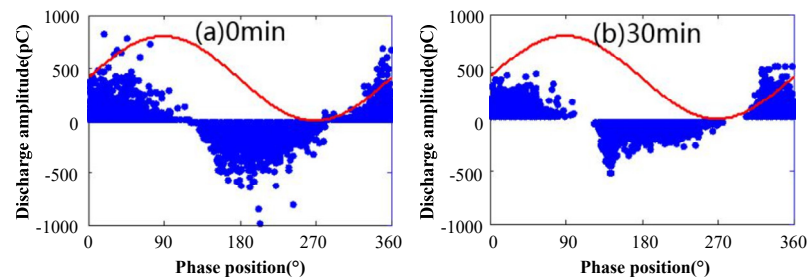


Fig. 4 Statistical spectrogram of discharge after white mark occurrence under pulsating DC voltage

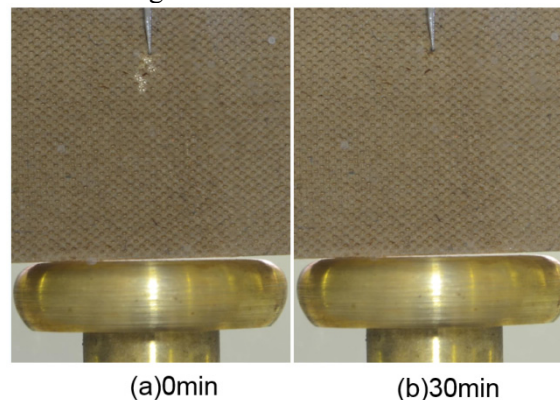


Fig. 5 white mark development process after white mark occurrence under pulsating DC voltage

There are two possible reasons for the discoloration of white mark under pulsating DC voltage. One is that the gas surface in the white trace adsorbs the residual charge of the discharge and is charged. Under the constant DC electric field generated by the DC component, the gas in the white trace is separated from the cardboard and enters the transformer oil under the action of the Coulomb force; the other is that when the voltage is the pulsating DC voltage, the transformer oil moves under the action of the current body dynamics, and the moving transformer oil takes part of the gas in the white trace. Therefore, the decrease of gas in the existing white trace channel makes the white trace fade away, and makes it difficult for the white trace to develop forward, so that the PD along the surface under the pulsating DC voltage is difficult to develop forward compared with the AC voltage.

It can be seen from the above tests that the process of oil paper insulation failure caused by surface partial discharge under extremely uneven electric field is as follows: the white mark starts from the needle electrode first, then the discharge develops along the white mark channel, when the white mark is close to the ground electrode, the ground electrode appears brush discharge, and finally the white mark channel bridge the needle electrode and the ground electrode leads to the full discharge. Under the AC voltage, white mark is easy to be produced on the water containing paperboard, but under the pulsating DC voltage, it is difficult to produce and develop. Therefore, compared with the AC voltage, the partial discharge along the surface of oil paper insulation is difficult to develop and lead to the full discharge under the uneven field of pulsating DC voltage, that is to say, the discharge under the uneven field of pulsating DC voltage is more difficult to lead to the failure of oil paper insulation.

4. Conclusion

In this paper, the failure process of oil paper insulation under pulsating DC voltage PD along the surface is studied. The conclusions are as follows:

(1) PD along the surface develops to the ground electrode along the white trace channel, and there are bubbles overflowing from the white trace to the transformer oil; the most bubbles overflowing at the head of the white trace indicates that the discharge is the most intense at the head of the white trace.

(2) The process of oil paper insulation failure caused by partial discharge along the surface under the extremely uneven electric field is as follows: the white mark starts from the needle electrode first, then the discharge develops along the white mark channel, when the white mark approaches the ground

electrode, the brush discharge occurs at the ground electrode, and finally the white mark channel bridges the needle electrode and the ground electrode to cause the full discharge.

(3) Compared with the AC voltage, the discharge under the pulse DC voltage extremely uneven electric field is more difficult to lead to oil paper insulation failure.

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