Study on partial discharge characteristics of oil-immersed paper in wrinkled state under alternating current and direct current compound voltage

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Abstract The insulation state of the converter transformer is closely related to the properties of the oil-paper insulation material. The study of the partial discharge characteristics of the wrinkled of the insulation paper has practical engineering significance for the fault diagnosis of the converter transformer. According to the actual operating environment inside the converter transformer, a set of oil-paper-insulated partial discharge measurement platform under the action of AC and DC composite voltage was built. The test results show that insulation paper wrinkles under the action of AC/DC composite voltage will cause insulation damage due to higher surface electric field and partial discharge; the discharge pulse repetition rate and discharge volume increase in the initial stage, development stage and final dangerous stage of discharge. The partial discharge caused by paper wrinkled significantly increases the CH4 content in the dissolved gas in the oil. This conclusion provides a certain basis for the realization of converter transformer fault diagnosis and condition monitoring.

1. Introduction
The converter transformer is the key equipment connected between the DC rectifier system and the AC system. It is one of the most important devices in the HVDC transmission system[1]. Due to the different types of voltages withstands the oil-paper insulation at different locations, different types of defects and different partial discharges may occur[2]. The same standard cannot be used as the basis for fault diagnosis and condition monitoring of converter transformers, which greatly increases the difficulty of fault diagnosis. The current identification and diagnosis methods still follow the standard and judgment basis of communication. Therefore, it is necessary to understand the discharge characteristics of different defect types to obtain a new judgment basis.

In 1976, Japan E. Takahashi first measured the partial discharge under the action of AC and DC composite voltage [3] and observed the change of the breakdown voltage of the transformer oil and oil-paper composite insulation. M.R. Raghuveer et al studied the influence of AC/DC ratio on breakdown voltage. At present, the research on the wrinkled discharge of insulating paper under the action of AC and DC voltage is still blank. A 220kV current transformer in a substation has air bubbles due to wrinkled insulating paper, and an air gap discharge occurs, which leads to an example of insulation failure[4,5]. Therefore, it is considered that due to the wrinkles of the insulating paper, an air gap or an oil gap appears in the insulating paper, which leads to partial discharge and damages the insulation. This paper
takes the wrinkle defect of insulating paper as the research object. According to the actual internal operating environment of the converter transformer, a measurement platform for the partial discharge of oil-paper insulation under the action of AC/DC composite voltage is built. Partial discharge characteristics and gas production characteristics of the development stage and the entire development process provide a certain basis for the realization of converter transformer fault diagnosis and condition monitoring.

2. Test Platform

2.1. Test platform composition
Since the test has certain requirements on temperature, oil flow, composite electric field and oil extraction, in order to achieve the above requirements. The test platform consists of a test chamber, heating box, oil circulation pump, flow meter, oil extraction port and circulation pipeline, as shown in Figure 1. Show.

![Figure1 Test platform composition](image1)

![Figure2 Test model](image2)

The test model is an inter-turn insulating paper wrinkle model, and the insulating paper is artificially wrinkled to simulate the air gap or oil gap discharge due to the insulating paper wrinkles in actual working conditions, as shown in the figure. Compared with the normal model, as shown in Figure 2, the paper used in the test is insulation paper for actual transformers, and the transformer oil is Kunlun Karamay 25# transformer oil, which is processed in accordance with the IEC60641-2 standard.

2.2. Test circuit
The internal environment of the oil-paper insulation of the converter transformer has requirements in terms of temperature, oil flow and composite electric field. This paper uses the test circuit shown in Figure 3. The compound electric field environment is composed of a power frequency transformer and a DC test transformer, and the AC and DC voltages are respectively applied to both ends of the test product. The rated voltage of the power frequency test transformer is 150kV, the rated power is 15kVA, and the partial discharge under the rated voltage is less than 5pC. The rated voltage of the DC test transformer is 200kV, and the partial discharge under the rated voltage is less than 5pC.
3. Test results
The normal model and the wrinkled model of oil-paper insulation are tested under the action of a 1:3 ratio AC/DC composite voltage. The discharge phenomenon of the two models of oil-paper insulation is described. The discharge process is divided into three stages: initiation, development and danger. Summarize the law of discharge change.

3.1. The partial discharge initial voltage characteristics
The experimental results are statistically shown in Figure 4, which shows the change trend of the initial voltage of the discharge between the oil-paper insulation turns under the wrinkle defect and the normal model. This paper defines the sum of the effective value of the initial AC voltage and the average value of the DC voltage as the total initial voltage $U_i$, and the sum of the amplitude of the breakdown AC and DC voltages is the total breakdown voltage $U_t$. Combining the experimental results, it can be found that compared with the normal model, the partial discharge initial voltage of the wrinkled model is significantly smaller, which is 11.8kV. Compared with the normal model, the initial voltage of the partial discharge of the wrinkled has dropped by 9.2\%.

The surface of the insulating paper of the wrinkled model is uneven and there are obvious rugged interfaces. The wrinkles on the surface of the insulating paper will distort the local electric field and cause partial discharge when the local electric field is too high. Therefore, the partial discharge initial voltage of the wrinkled model is lower than that of the normal model. In addition, the phenomenon recorded by video shows that there are no obvious bubbles or sparks during the entire process of discharge between the oil-paper insulated turns under the action of the composite voltage.

![Figure 4 Starting voltage of partial discharge](image1)

![Figure 5 Discharge pulse repetition rate](image2)
3.2. Variation rule of discharge pulse repetition rate of two models

Figure 5 shows the changing trend of the discharge pulse repetition rate of the two models of oil-paper insulation under the action of AC and DC composite voltage. The pulse repetition rate \( n \) is defined as the number of discharges per unit time. In the initial and development stages, the pulse repetition rate \( n \) of the two models is very small, and the number of discharges per unit time does not exceed 10 times. When it reaches the dangerous stage, the pulse repetition rate of the wrinkled model has reached 39.4 times, which is much higher than the initial stage. The pulse repetition rate of the two models develops with the partial discharge stage, and the number of partial discharges increases significantly. Compared with normal, the number of discharges of the wrinkled model is more in each stage, and the number of discharges increases greatly in the dangerous stage of partial discharge.

3.3. Discharge volume changing rule

Figure 6 a) shows the change trend of the maximum discharge capacity of the two models. The maximum discharge capacity \( q_{\text{max}} \) refers to the maximum value of all discharges at this stage. Figure b) shows the change trend of the average discharge volume (the ratio of the total discharge volume to the number of discharges at this stage) of the two models. Figure c) shows the change trend of the total discharge capacity of the two models. During the discharge development process, the maximum discharge capacity of the wrinkled model is higher than that of the normal model. This is because there are many local electric field distortion points on the surface of the wrinkled model, and the chances of partial discharge in these areas with higher electric fields are greater than that of the normal model.

3.4. Discharge phase changing rule

Table 1 shows the inter-turn discharge phase distribution of the two models. The phase distribution range and phase distribution width of the partial discharge development process under the action of AC/DC combined voltage are given, and the discharge repetition rate of positive and negative half cycles is compared. Under normal circumstances, there are few initial and developing discharge points, and the discharge phases in the dangerous phase are mainly concentrated in 120°~180°, 220°~260°, 330°~360°. The discharge repetition rate of the positive half cycle of discharge in the dangerous phase is higher than that of the negative half cycle. The discharge phase of the wrinkle paper is similar to the normal one, but the phase is narrower. The discharge repetition rate of the positive half cycle and the discharge repetition rate of the negative half cycle are approximately the same.
### Table 1. Discharge phase distribution under compound voltage of different models

| Discharge phase | Initial | Progression | Dangerous |
|-----------------|---------|-------------|-----------|
| Normal          | ![Graph](image1.png) | ![Graph](image2.png) | ![Graph](image3.png) |
| Wrinkle         | ![Graph](image4.png) | ![Graph](image5.png) | ![Graph](image6.png) |

3.5. Dissolved gases in oil characteristics

Figure 7 shows the gas generation characteristics of the inter-turn discharge under the two models. Under normal circumstances, after partial discharge occurs in the oil-paper insulation system, the hydrogen and acetylene dissolved in the oil change significantly. The main gas produced after the partial discharge occurs in the inter-turn wrinkled is hydrogen, followed by methane.

![Graph](image7.png) a) Normal model
![Graph](image8.png) b) Wrinkled model

**Figure 7 Gas production characteristics of different models**

4. Conclusion

1) According to the IEC standard and the CIGRE report, the wrinkle of the insulating paper sometimes cause partial discharges. In this paper, combined with actual failure cases on site, a partial discharge test was carried out on the paper wrinkle defect model under the action of AC/DC composite voltage. The electric strength of the wrinkle model is obviously lower than that of the normal model, which shows that it is necessary to study the wrinkle phenomenon of insulating paper.

2) The difference between the partial discharge and gas generation characteristics of the two models under the action of AC and DC composite voltage is compared. The partial discharge initial voltage of the insulating paper wrinkled model is reduced, the number of discharges increases, the total discharge volume increases, the discharge phase becomes narrower, and the gas is dissolved in the oil. As the content rises, the main types of dissolved gases in the oil have changed.

3) It is suggested that the follow-up study can set up a large-size wrinkled model, and explore the creepage characteristics and breakdown strength changes when large-size insulating paper is wrinkled. Studying the effect of different ratios of AC/DC composite voltage on the partial discharge characteristics of wrinkled insulation paper is also necessary.
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References
[1] Sarathi,R, Koperundevi,G. (2008) UHF technique for identification of partial discharge in a composite insulation under AC and DC voltages. Dielectrics and Electrical Insulation, 4(6):1724-1730
[2] Pearson,J. S., Hampton,B. F.,Sellars, A. G., (1997) A continuous UHF monitor for gas-insulated substations. IEEE Transactions on Electrical Insulation, vol. 26:469-478
[3] Takahashi,E, Tsutsumi,Y, Okuyama,K. (1976) Partial discharge characteristics of oil-immersed insulation under DC, composite AC-DC and DC reversed polarity voltage. IEEE Transactions on Power Apparatus and Systems, 95(1): 411-420
[4] Tulasi R (1994) Flashover behavior of converter transformer insulation subjected to superimposed ac and dc voltages. In: IEEE 1994 Annual Report Conference,10:810-815
[5] Sha,Y.C., Zhou,Y.X., (2013) Measurement and simulation of partial discharge in oil-paper insulation under the combined AC–DC voltage. Journal of Electrostatics, 71 (3): 540-546