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Research on breakdown characteristics of oil-paper insulation in compound field at different temperatures

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Abstract. The breakdown characteristics of oil-paper insulation in AC, DC and compound field at different temperatures were studied. The breakdown mechanism of oil-paper insulation at different temperatures and in AC and DC electric fields was analyzed. The breakdown characteristic mechanisms of the oil-paper insulation in the compound field at different temperatures were obtained: the dielectric strength of oil-paper compound insulation is changed gradually from dependence on oil dielectric strength to dependence on paperboard dielectric strength at low temperature. The dielectric strength of oil-paper compound insulation is always related to the oil dielectric strength closely at high temperature with decrease of AC content.

1. Introduction

Oil-gap breakdown characteristic plays a decisive role in the oil-paper insulation structure in the AC electric field. Therefore, oil gap breakdown characteristics are mainly focused in most studies [1-5]. Since the oil-paper insulation withstanding electric field at compound voltage is different from that at pure AC voltage, transformer oil gap breakdown characteristics, oil-paper surface flashover characteristics and insulation paperboard breakdown characteristics should be taken into account comprehensively when oil-paper insulation breakdown and flash characteristics are studied [6-8]. The breakdown and surface flashover characteristics of oil-paper insulation under the action of compound electric field are studied mostly at room temperature. Temperature is an important factor affecting oil-paper insulation of transformer according to previous research on relationship between ordinary AC transformer oil-paper breakdown characteristics and temperature as well as the investigation and analysis on transformer operation accidents [9-14]. In recent years, several insulation faults appeared in China when transformers were put into operation at low temperature. The breakdown data about transformer oil-paper insulation at low temperature or extremely low temperature is also urgent for transformer operation departments. It is necessary to study the aspect since there is no test data of oil - paper insulation in compound electric field about breakdown and flashover characteristics at alpine region temperature at present. In the paper, the breakdown characteristics of oil-paper insulation AC, DC and compound field at different temperatures were studied. The breakdown mechanism of oil-paper insulation at different temperatures in AC and DC electric fields was analyzed. The breakdown



characteristic mechanisms of the oil-paper insulation in the compound field at different temperatures were obtained.

2. Sample preparation and testing platform

2.1. Treatment of transformer oil

KIX45 transformer oil produced by Kunlun Company was selected in the experiment according to the temperature requirements of the project. Transformer oil underwent standardized treatment before testing; therefore it can meet various requirements regulated in national standards.

Oil filter was selected for treating transformer oil. The solubility of moisture and air in oil was reduced under vacuum and high temperature conditions, and the principle was utilized for dehydrating and degassing oil in the treatment equipment. The oil filter was used for filtering impurity particles with tiny particle size in oil. The transformer oil treated by the oil filter met the national standard GB 2535-90 Transformer Oil. The treatment process was shown in figure 1.

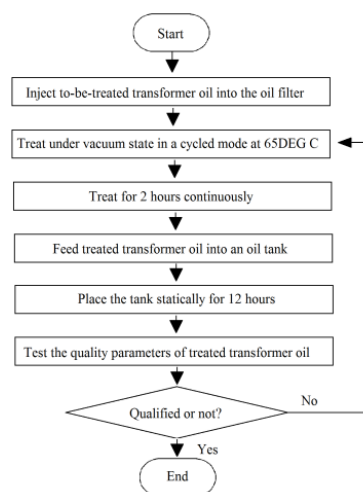


Figure 1. Treatment flow of transformer oil.

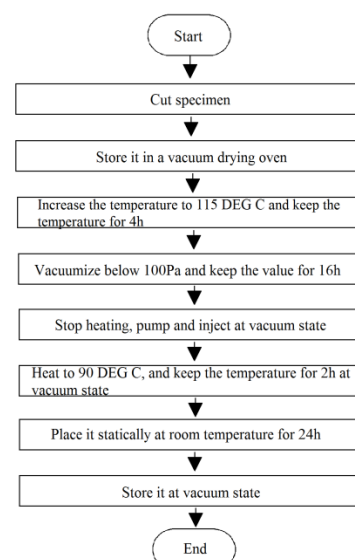


Figure 2. Treatment flow of oil impregnated paperboard.

The moisture content was measured firstly for the treated transformer oil, which was measured again at certain interval, thereby ensuring no change in the moisture content. The transformer oil was finally stored in a sealed oil tank.

2.2. Treatment of oil impregnated paperboard

The vacuum drying oven transformed in the laboratory was utilized for treating paperboard according to the national standard GB10580-89. The treatment process included vacuum drying and oil immersion. Related parameters of treated oil impregnated paperboard were tested. The operation flow was shown in figure 2.

The moisture content was measured firstly after treatment, which was measured again at certain interval, thereby ensuring no change in the moisture content. The treated paperboard was stored in transformer oil which was qualified in the test.

2.3. Testing platform

The main insulation structure of large exchange transformer is more complicated. In order to simplify the experimental model, the typical oil paper composite insulation structure is adopted. The simplified

structure of the electrode structure is shown in figure 3. For the sake of preventing the surface discharge during the breakdown test, the sample size is larger than the discharge distance of the surface discharge.

According to the temperature requirements of this paper, the temperature of sample temperature is divided into two parts: cooling and heating. The heating test section is implemented by temperature sensor, thermostat, contactor and heater. The low temperature test box is used for the cooling test. The testing platform is shown in figure 4.

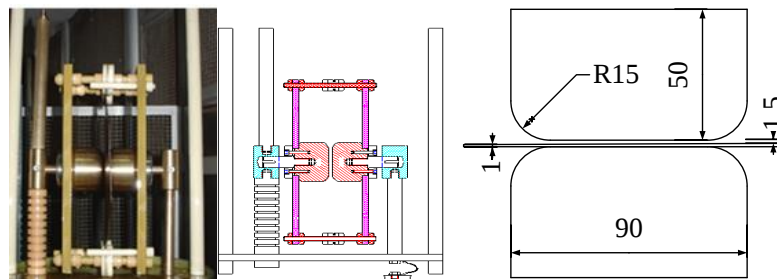


Figure 3. The electrode structure (mm).



Figure 4. The testing platform.

3. Breakdown characteristics of oil-paper compound insulation

3.1. Breakdown characteristics of oil-paper compound insulation at different temperatures

In the paper, AC/DC superposition equipment was used for studying the influence of temperature (-40°C to 100°C) on oil-paper compound insulation breakdown characteristics under AC content $\eta=0\%$ (pure DC), $\eta=50\%$ (DC superposed with AC) and $\eta=100\%$ (pure AC). Typical compound insulation structures composed of 1 mm oil-impregnated paperboard and 1.5mm transformer oil were adopted as specimens. The paperboard moisture content was between 0.45% and 0.6%. The moisture content was between 4.32ppm and 5.16ppm in transformer oil.

The average value of breakdown voltage data of oil-paper compound insulation under three voltage wave-forms was shown in figure 5: the breakdown voltage of oil-paper compound insulation showed a trend of decrease-increase-decrease with the temperature increase under the action of pure AC voltage and AC-DC superimposition voltage. Their trends were the same. Two extreme value points appeared at 0°C and 60°C or so. However, their change amplitude was not the same. The breakdown voltage of the oil-paper compound insulation showed a trend of increase-decrease under the action of pure DC voltage, and the maximum value appeared at 50°C or so.

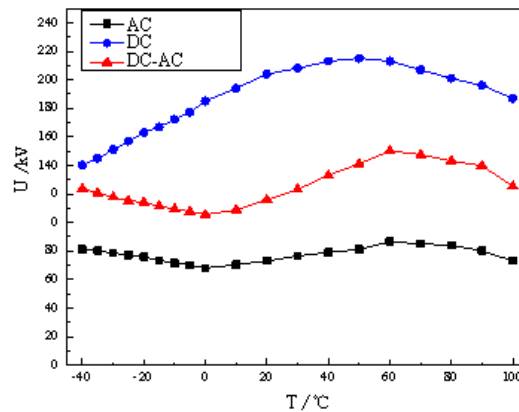


Figure 5. Breakdown voltage of oil-paper compound insulation at different temperatures.

3.2. Analysis on breakdown mechanism of oil-paper compound insulation under AC electric field

In the paper, corresponding theoretical values of field intensity in transformer oil and oil-impregnated paperboard was calculated according to the electric field distribution content in paper [15], wherein oil-paper compound insulation was broken down in pure AC electric field. The result was compared with the breakdown field intensity actual value of transformer oil and oil-impregnated paperboard at different temperatures to analyze the breakdown process of oil-paper compound insulation in the AC electric field quantitatively. The comparison was shown in figure 6 and figure 7.

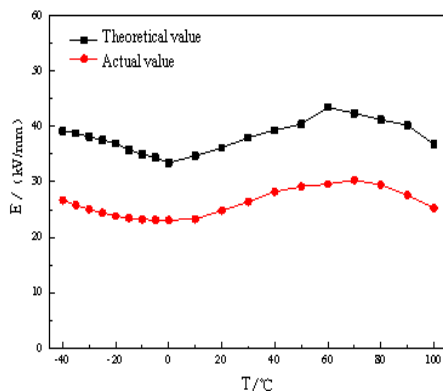


Figure 6. Field intensity in oil under different conditions.

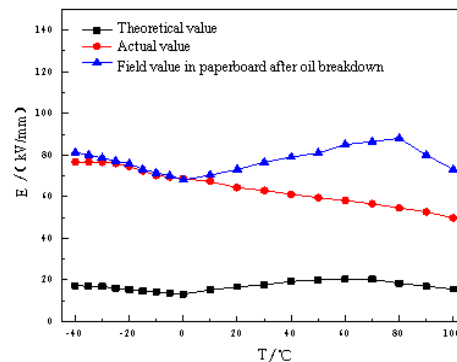


Figure 7. Field strength in oil and paperboard under different conditions.

Figure 6 showed the breakdown field intensity of pure oil gaps at different temperatures under the action of AC voltage and theoretical values of corresponding electric field distribution in oil gaps during breakdown of oil-paper compound insulation. Figure 7 showed the breakdown field intensity of oil-impregnated paperboard at different temperatures under AC voltage, theoretical values of corresponding electric field distribution in the oil-impregnated paperboard during breakdown of oil-paper compound insulation and the field intensity in oil-impregnated paperboard after breakdown of transformer oil.

Data comparison showed that transformer oil withstood most field intensity in oil-paper compound insulation under the action of pure AC voltage. The field intensity withstood by the paperboard was far lower than the breakdown field intensity thereof. Therefore, the breakdown process in AC can be concluded as follows: discharge breakdown occurred in the transformer oil firstly, and the field strength falling on the paperboard was higher than or close to the actual value of breakdown field strength in AC electric field after single medium breakdown in the oil, thereby leading to overall breakdown of compound insulation.

Figure 7 showed that the pure oil gap breakdown field intensity in AC voltage at different temperatures was much lower than the electric field intensity in oil-paper compound insulation oil gap possibly because AC breakdown field intensity was the result, which was obtained from breakdown voltage conversion of 2.5 mm standard oil gap. However, the oil gap thickness was 1.5mm in compound insulation. The field strength in the oil gap was higher due to influence of volume effect, wherein the strength was converted from oil-paper compound insulation breakdown voltage.

3.3. Analysis on breakdown mechanism of oil-paper compound insulation under AC electric field

In the paper, corresponding theoretical values of field intensity in transformer oil and oil-impregnated paperboard was calculated according to the electric field distribution content in paper [15], wherein the oil-paper compound insulation was broken down under pure DC electric field. The result was compared with the breakdown field intensity actual value of transformer oil and oil-impregnated paperboard at different temperatures to analyze the breakdown process of oil-paper compound insulation in DC electric field quantitatively. The comparison was shown in figure 8 and figure 9.

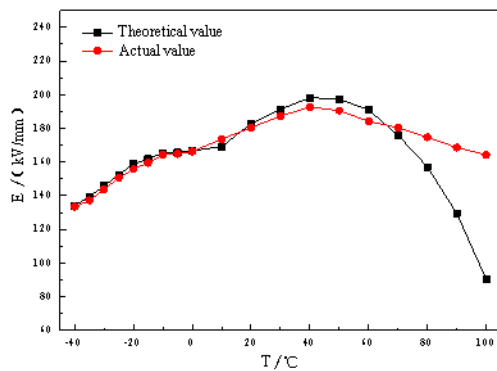


Figure 8. Field intensity in paperboard under different conditions.

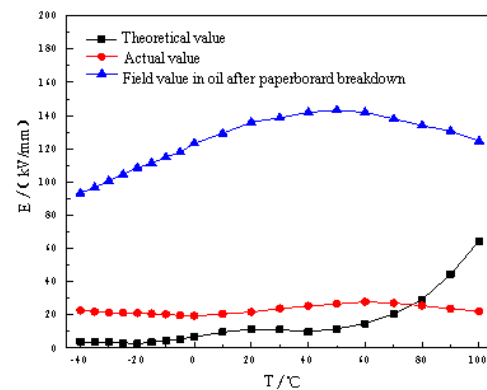


Figure 9. Field strength in oil and paperboard under different conditions.

Figure 8 showed breakdown field intensity of oil-impregnated paperboard at different temperatures under DC voltage and theoretical values of corresponding electric field distribution in oil-impregnated paperboard during breakdown of oil-paper compound insulation. Figure 9 shows the breakdown field intensity of pure oil gap at different temperatures under the action of DC voltage, theoretical values of corresponding electric field distribution in oil gap during breakdown of oil-paper compound insulation and the field intensity in oil gap after breakdown of oil-impregnated paperboard.

Data comparison showed that: paperboard withstood most field intensity between -40°C and 60°C under the action of pure DC voltage. The field intensity in the transformer oil did not reach the actual value of the breakdown field intensity. Therefore, it can be concluded that the paperboard suffered from breakdown firstly, and all voltage was applied on the oil after breakdown, thereby leading to overall breakdown of compound insulation. The field intensity in oil between 60°C and 100°C was higher than the actual breakdown voltage, and oil suffered from breakdown firstly, thereby leading to overall breakdown of compound insulation.

Figure 9 showed that the theoretical calculation field strength was greatly different from actual breakdown field intensity since the resistivity change law of the paperboard and oil was changed greatly in high field intensity. The difference magnitude order was significant between paperboard resistivity and oil resistivity at the low temperature interval, which had low influence on the calculation results. The resistivity difference was insignificant at high temperature, which had high influence on the calculation results, thereby leading to significant deviation in the calculation results.

3.4. Analysis on breakdown mechanism of oil-paper compound insulation under DC-AC superposition electric field

The AC content of voltage withstood by oil and paperboard was also always changed with temperature change, and it was difficult to analyze the AC content quantitatively in the oil-paper compound insulation structure under the action of DC-AC superposition voltage ($\eta=50\%$). The change trend of breakdown voltage of oil, paperboard and oil-paper compound insulation structure with temperature was shown in figure 10, figure 11 and figure 12 respectively under different AC contents.

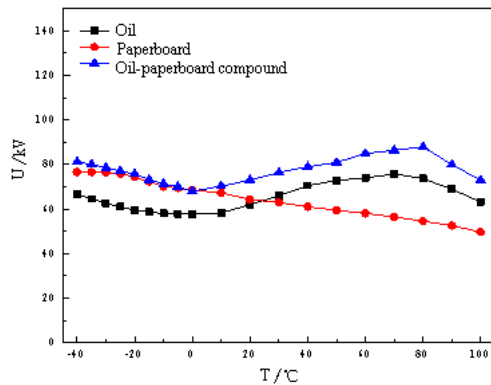


Figure 10. Breakdown voltage of oil, paperboard and oil-paper compound insulation under the action of AC voltage.

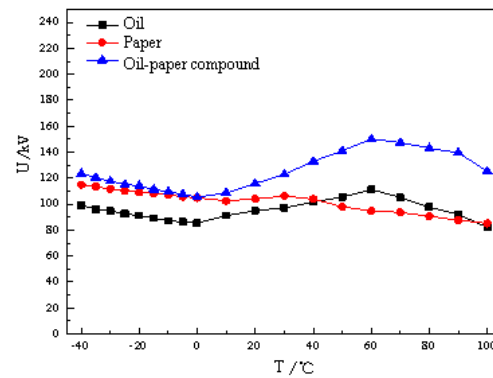


Figure 11. Breakdown voltage of oil, paperboard and oil-paper compound insulation under the action of DC-AC superposition voltage.

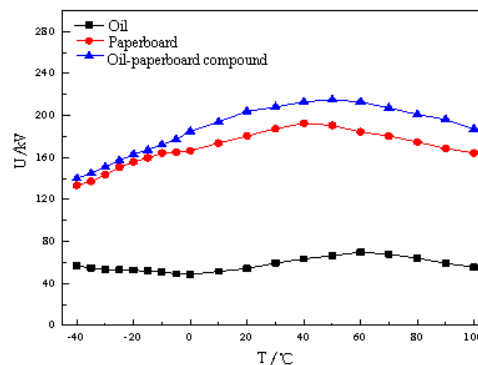


Figure 12. Breakdown voltage of oil, paperboard and oil-paper compound insulation under the action of DC voltage.

It was concluded in the above context that oil gaps were broken down firstly in oil-paper compound insulation under the action of AC voltage, and the compound insulation breakdown was consistent with oil change trend as a result. However, the paperboard was broken down firstly at low temperature, and oil was firstly broken down at high temperature in oil-paper compound insulation under the action of DC voltage. The breakdown law of the compound insulation was consistent with the paperboard at low temperature as a result, and the law was tended to oil at high-temperature. Figure 11 showed that the breakdown law of oil-paper compound insulation was similar with that under the action of pure AC voltage when $\eta=50\%$, and they were consistent with the breakdown trend of oil. It can be concluded according to the law that the breakdown of oil-paper compound insulation gradually tended to breakdown law of paperboard at low temperature with the decrease of AC content. However, the breakdown of oil-paper compound insulation was always consistent with the breakdown law of oil at high temperature.

4. Conclusion

The dielectric strength of oil-paper compound insulation is changed gradually from dependence on oil dielectric strength to dependence on paperboard dielectric strength at low temperature. The dielectric strength of oil-paper compound insulation is always related to the oil dielectric strength closely at high temperature with decrease of AC content.

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