Research on breakdown characteristics of converter transformer oil-paper insulation under compound electric field in alpine region

C Xu[1], Z W Gao, S Lan, H X Guo and M C Gong

State Grid Heilongjiang Electric Power Company Limited Electric Power Research Institute, 7 Xiangjiang River Road, Harbin, China

[1] E-mail: 704777887@qq.com

Abstract. In the paper, existing research and operating experience was summarized. On the basis, the particularity of oil-paper insulation operation condition for converter transformer was combined for studying the influence of temperature on oil-paper insulation field intensity distribution of converter transformers under different AC contents within wide temperature scope (-40℃~105℃). The law of temperature gradients on space charge accumulation was analyzed. The breakdown or flashover characteristics of typical oil-paper compound insulation structure under the action of DC, AC and AC-DC superposition voltage at different temperatures were explored. The design principles of converter transformer oil-paper insulation structures in alpine region was proposed. The principle was adjusted and optimized properly according to the operation temperature scope and withstood AC-DC proportion. The reliability of transformer operation was improved on the one hand, and the insulating medium can be rationally utilized for reducing the manufacturing cost of the transformer on the other hand.

1. Introduction

According to the relation between the characteristics of oil paper breakdown and temperature in common AC transformer, and the investigation of transformer operation accident, it shows that temperature is an important factor affecting oil paper insulation of transformer [1]. The transformer operation department urgently needs the breakdown data of transformer oil paper insulation at low temperature, because there are several insulation faults when the transformer is put into operation at lower temperature in recent years. At present, there is no oil paper insulation experimental data on breakdown and flashover characteristics under complex electric field at low temperature. It is necessary to carry out research in this field [2-3].

2. Influence of temperature on electric field distribution of oil-paper compound insulation

2.1. Physical model of oil-paper insulation structure

In the paper, a typical double-layer oil-paper insulation structure model was adopted for facilitating research on electric field distribution of oil-paper insulation. Relative dielectric constant, conductivity and thickness of paperboard and oil were ε_p, γ_p, d_p and ε_o, γ_o, d_o respectively. Its equivalent circuit was shown in figure 1. The voltage was U at both ends of the oil-paper compound insulation structure. The

equivalent voltage, capacitance and resistance at two ends of the paperboard and oil were U_p, C_p, R_p and U_o, C_o, R_o respectively.
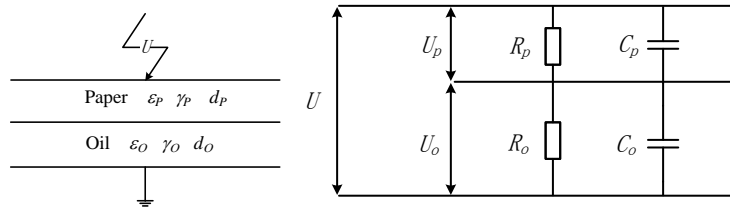
Figure 1. Oil-paper insulation model and equivalent circuit.

The space charge was set as zero on the oil-paper interface before voltage application. Namely, the equivalent circuit was in the zero state as shown in figure 1. The follows was concluded according to Ohm's law and first-order circuit solution:

Voltage on the paperboard was shown as follows at any time:

$$u_p = \frac{R_p}{R_p + R_0} U_{dc} + \left(\frac{C_0}{C_p + C_0} - \frac{R_p}{R_p + R_0} \right) U_{dc} e^{-\frac{t}{\tau}} + u_{ac} \frac{C_0}{C_p + C_0} \tag{1}$$

Voltage on the oil was shown as follows:

$$u_0 = \frac{R_0}{R_p + R_0} U_{dc} + \left(\frac{C_p}{C_p + C_0} - \frac{R_0}{R_p + R_0} \right) U_{dc} e^{-\frac{t}{\tau}} + u_{ac} \frac{C_p}{C_p + C_0} \tag{2}$$

In the formula, U_{dc} and U_{ac} were DC voltage and AC voltage at both ends of the oil-paper compound insulation structure, $\tau = \left(C_p + C_0 \right) \left(\frac{1}{R_p} + \frac{1}{R_0} \right)^{-1}$, was a time constant.

2.2. Mathematical expression of electric field distribution of oil-paper compound insulation

The mathematical expression of voltage on the paperboard and oil was shown as follows in the steady state:

$$\begin{cases} u_p = \dfrac{\rho_p d_p}{\rho_p d_p + \rho_0 d_0} U + \left[\dfrac{\varepsilon_0 d_p}{\varepsilon_0 d_p + \varepsilon_p d_0} \sin(\omega t) - \dfrac{\rho_p d_p}{\rho_p d_p + \rho_0 d_0} \right] \eta U \\[2mm] u_0 = \dfrac{\rho_0 d_0}{\rho_p d_p + \rho_0 d_0} U + \left[\dfrac{\varepsilon_p d_0}{\varepsilon_0 d_p + \varepsilon_p d_0} \sin(\omega t) - \dfrac{\rho_0 d_0}{\rho_p d_p + \rho_0 d_0} \right] \eta U \end{cases} \tag{3}$$

Maximum value was obtained for u_p and u_o when $\sin(\omega t) = 1$. Then,

$$\begin{cases} u_p = \dfrac{\rho_p d_p}{\rho_p d_p + \rho_0 d_0} (1-\eta) U + \dfrac{\varepsilon_0 d_p}{\varepsilon_0 d_p + \varepsilon_p d_0} \eta U \\[2mm] u_0 = \dfrac{\rho_0 d_0}{\rho_p d_p + \rho_0 d_0} (1-\eta) U + \dfrac{\varepsilon_p d_0}{\varepsilon_0 d_p + \varepsilon_p d_0} \eta U \end{cases} \tag{4}$$

It was believed that AC and DC electric fields can be superposed linearly in the project since compound electric fields were distributed between oil and paperboard, and equivalent parallel impedance value was much higher than capacitive reactance value. It was assumed that the electric fields were distributed evenly in the media, the electric field intensities Ep and Eo in oil-impregnated paperboard and transformer oil were respectively concluded as follows according to Ep and Eo [4].

$$\begin{cases} E_p = \dfrac{\rho_p}{\rho_p d_p + \rho_0 d_0}(1-\eta)U + \dfrac{\varepsilon_0}{\varepsilon_0 d_p + \varepsilon_p d_0}\eta U \\[3mm] E_0 = \dfrac{\rho_0}{\rho_p d_p + \rho_0 d_0}(1-\eta)U + \dfrac{\varepsilon_p}{\varepsilon_0 d_p + \varepsilon_p d_0}\eta U \end{cases} \qquad (5)$$

In the formula, ρ_0, ρ_p, ε_0 and ε_p were functions of temperature T. Therefore, the field intensities Ep and Eo in the paperboard and oil were functions of temperature T and AC content η.

2.3. Numerical calculation results of electric field distribution of oil-paper compound insulation
The expression of resistivity and relative dielectric constant change with temperature was obtained through fitting. The expression was brought into formula (5). U=150 kV, dp=1mm and do=1.5mm were taken, and the change trend of Ep and Eo with η and T was shown in figure 2.
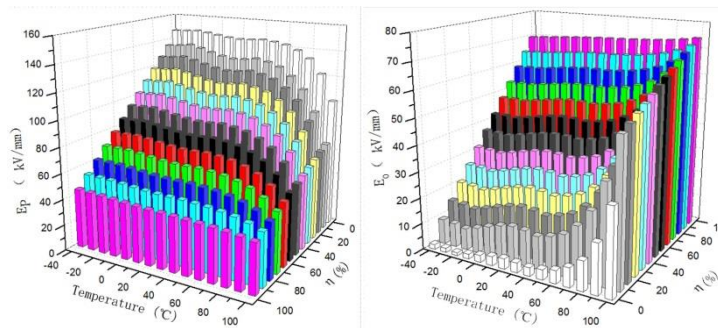

Figure 2. Field intensity in transformer oil and oil-impregnated paperboard at different AC contents and temperatures.

When AC content was a fixed value, the field intensity in the paperboard was decreased with temperature increase as a whole. When temperature was a fixed value, the field intensity in the paperboard was increased monotonously with decrease of AC content. However, the field intensity change in oil was just opposite because electric field distribution mainly depended on oil-paper relative dielectric constant ratio mainly during high AC contents, and the electric field distribution mainly depended on oil-paper resistivity ratio during low AC content. The maximum value of field intensity in paperboard appeared at low temperature and low AC content (η= 0,T= -20 ℃), and the maximum value of field intensity in oil appeared at high temperature and high AC content (η = 100%,T= 100 ℃). Therefore, the insulation margin at high temperature and high AC content should be focused aiming at oil gaps when the converter transformer was designed. The insulation margin at low temperature and DC should be focused aiming at insulation paperboard.
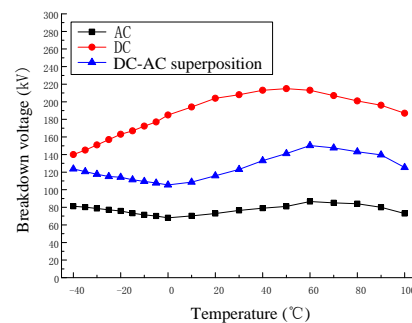
3. Space charge characteristics of oil-paper insulation under different temperature gradients
Voltage of -20kV was applied on double-layer insulation paperboard at different temperature gradients (Δ=0℃, Δ=20℃ and Δ=40℃). The space charge accumulation condition was studied. The voltage was applied for one hour. The space charge distribution was shown in figure 3.
The measurement data showed that prominent space charge was produced in double-layer paperboard interface at different temperature gradients. Different temperature gradients had different influences on space charge accumulation. The interface space charge was the least when the temperature difference was 20 ℃. The space charge of lower insulation paperboard near the low electrode was the maximum when Δ=0℃, and they belonged to like charges. The electrical polarity was gradually changed from like charges to opposite charge with temperature difference increase in the lower paperboard. The space charge accumulation near the upper electrode was decreased with temperature difference increase.
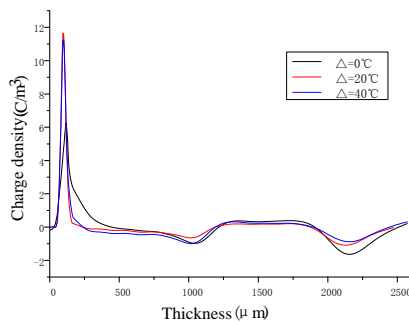
Figure 3. Space charge distribution of double-layer insulation paperboard at different temperature gradients.

Figure 4. Breakdown voltage of oil-paper compound insulation at different temperatures.

## 4. Influence of temperature on breakdown characteristics of oil-paper compound insulation

4.1. Breakdown characteristics of oil-paper compound insulation at different temperatures
In the paper, AC/DC superposition equipment was utilized for studying the influence of temperature (-40℃ to 100℃) on breakdown characteristics of oil-paper compound insulation at AC content $\eta=0\%$ (pure DC), $\eta=50\%$ (DC/AC superposition) and $\eta=100\%$ (pure AC). Specimens were typical compound insulation structures composed of 1mm oil-impregnated paperboard and 1.5mm transformer oil. The paperboard moisture content was between 0.45% and 0.6%, and moisture content in transformer oil was between 4.32 PPM and 5.16 PPM.

The average value of breakdown voltage data of oil-paper compound insulation under three voltage wave-forms was shown in figure 4: 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 ℃ and 60 ℃ 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 ℃ or so.

4.2. Analysis on breakdown mechanism of oil-paper compound insulation under AC electric field
Corresponding theoretical values of field intensity in transformer oil and oil-impregnated paperboard 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, wherein oil-paper compound insulation was broken down in pure AC electric field. The comparison results were shown in figure 5 and figure 6.
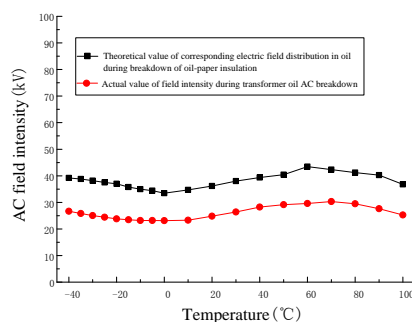
Figure 5. Field intensity in oil under different conditions.
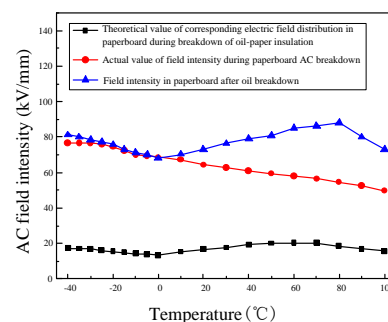
Figure 6. Field strength in oil and paperboard under different conditions.
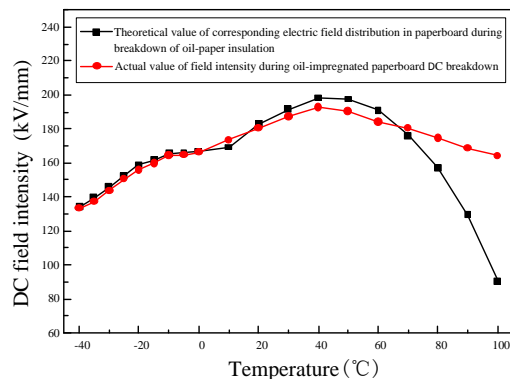
Figure 5 showed the breakdown field intensity of pure oil gaps at different temperatures under the action of AC voltage and theoretical values of corresponding electric field distribution in oil gaps during breakdown of oil-paper compound insulation. Figure 6 showed the breakdown field intensity of oil-impregnated 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 5 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.

4.3. Analysis on breakdown mechanism of oil-paper compound insulation in DC electric field
Corresponding theoretical values of field intensity in transformer oil and oil-impregnated paperboard 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 DC electric field quantitatively, wherein oil-paper compound insulation was broken down in pure DC electric field. The comparison results were shown in figure 7 and figure 8.

Figure 7. Field intensity in paperboard under different conditions.
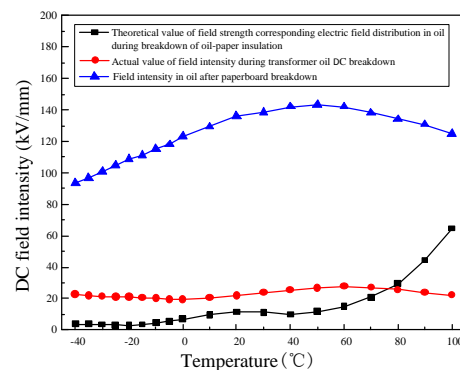
Figure 8. Field strength in oil and paperboard under different conditions.

Figure 7 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 8 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℃ and 60℃ 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 thereof. 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℃ and 100℃ was higher than the actual breakdown voltage, and oil suffered from breakdown firstly, thereby leading to overall breakdown of compound insulation.

Figure 8 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.

4.4. 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 (*η*=50%). The change trend of breakdown voltage of oil, paperboard and oil-paper compound insulation structure with temperature was shown in figure 9, figure 10 and figure 11 respectively under different AC contents.
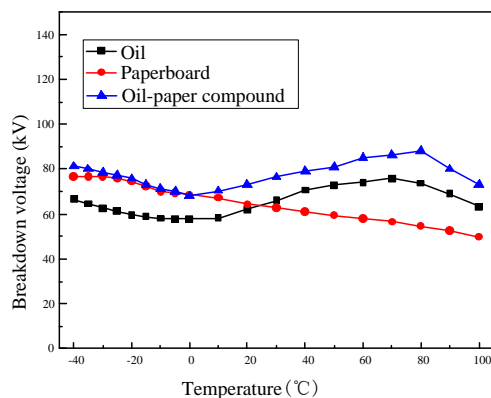
Figure 9. Breakdown voltage of oil, paperboard and oil-paper compound insulation under the action of AC voltage.
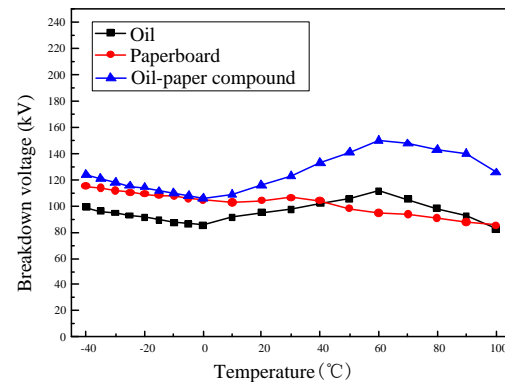
Figure 10. Breakdown voltage of oil, paperboard and oil-paper compound insulation under the action of DC-AC superposition voltage.
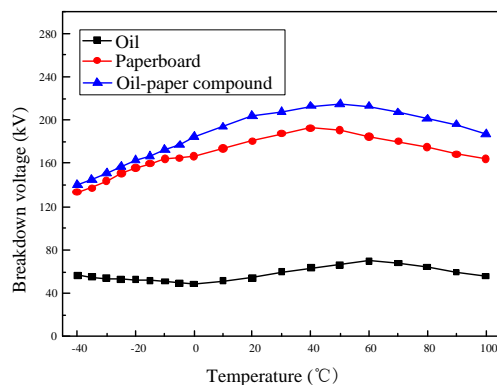
Figure 11. Breakdown voltage of oil, paperboard and oil-paper compound insulation under the action of DC voltage.

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 10 showed that the breakdown law of oil-paper compound insulation was similar with that under the action of pure AC voltage when η=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.

In other words, the dielectric strength of oil-paper compound insulation is changed gradually from dependence on oil dielectric strength to dependence on paperboard dielectric strength at the low temperature interval, and the dielectric strength of oil-paper compound insulation is always related to the oil dielectric strength more closely at the high temperature interval with the reduction of AC content.

5. Conclusion

The breakdown of oil-paper compound insulation under AC-DC superimposition voltage is jointly determined by transformer oil and oil-impregnated paperboard. The whole insulation structure can be broken down if any one of the two media is broken down firstly. Since the electric field distribution in the two media is affected by temperature, AC content and oil-paper proportion, and the dielectric strength of the two media is also affected by temperature and AC contents at the same time, the dielectric properties of one medium cannot be fully utilized [5]. The overall breakdown voltage of the oil-paper insulation structure is decreased. The 'bucket effect' reflects the irrationality of the oil-paper insulation structure.

The most ideal insulation structure is shown as follows because of uneven distribution of electric fields and the dielectric strength differences between the two media: oil and paperboard are broken down synchronously, and the oil-paper compound insulation structure is broken down, therefore the utilization rate of oil-paper insulation material can be improved. However, the electric field distribution is greatly changed with AC content and oil-paper proportion between -40℃ and 100℃. For example, 95.1% field intensity is concentrated on the paperboard at most under the action of low temperature and low AC content voltage [6]. In theory, the oil gap thickness should be reduced to nearly one tenths of the original value for synchronous breakdown of the two media. However, the field intensity distribution between two media is also extremely similar at high temperature interval. The insulating medium is wasted if the oil-paper proportion is too low under the circumstance.

The converter transformers in different converter stations are operated under different conditions. Therefore, the main insulation structure on the side of converter transformer valve should be designed according to actual condition of transformer operation in a targeted mode to improve the reliability of the equipment and reduce the manufacturing cost. The design should be adjusted properly according to the operation temperature scope and the withstood AC-DC proportion, thereby ensuring safe, stable and reliable operation of the converter transformer.

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