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Influence of temperature and moisture joint action on oil-paper insulation compound electric field distribution

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Abstract. In the paper, the electric field change in transformer oil and oil-impregnated insulation paperboard within wide temperature range (20℃~100℃) was studied. The influence law of temperature on oil-paper insulation electric fields was summarized. Oil-paper insulation electric field distribution under the action of different wave-form voltages was simulated for analysis. The electric field distribution condition during moisture balance steady state and transient state was obtained. The reasons of electric field distribution change were analyzed.

1. Introduction

EHV/UHV transformer is an important device in the power transmission system. Its operating reliability has direct influence on safe operation of the system. Existing operation experience shows that moisture dynamic balance process and existence form between oil and insulating paper in the transformer has important influence on oil paper insulation breakdown characteristics and surface flashover characteristics. Temperature is an important factor affecting the above-mentioned process [1-4]. In recent years, transformer insulation faults occurred in Northeast China and Northwest China for several times, which were related with changes of transformer operating temperature. Domestic electric power operation departments attach great importance to related research. The space charge accumulation characteristics of transformer oil-paper insulation under the action of compound electric field are mostly studied at room temperature and narrow temperature scope. It is necessary to study space charge accumulation of oil-paper insulation and its influence on electric field distribution characteristics in the possible operation temperature scope in view of actual working condition of oil-paper insulation.

2. Specimen pre-treatment and testing

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. The dielectric properties of the transformer oil were reduced since moisture and gas must be mixed in the transformer oil during delivery, carbon black was produced in transformer oil after breakdown test, and moisture was absorbed during refrigeration temperature-reversion. Transformer oil underwent standardized treatment before test, 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.

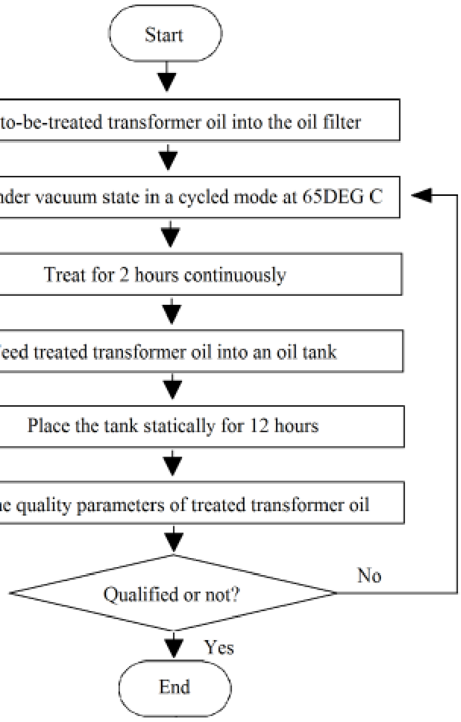


Figure 1. Treatment flow of transformer oil.

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.

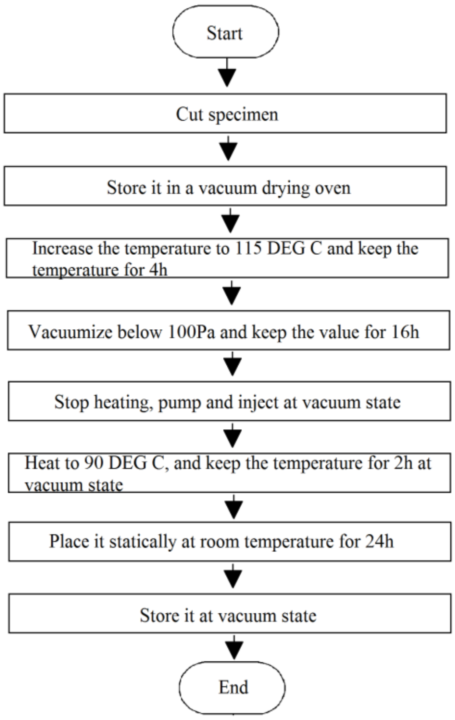


Figure 2. Treatment flow of oil impregnated paperboard.

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.

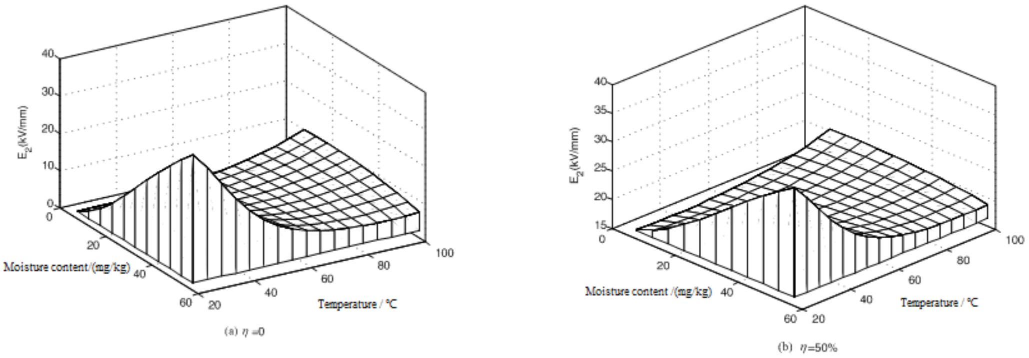
3. Influence of temperature and moisture joint action on oil-paper insulation compound electric field distribution

3.1. Influence of temperature on electric field distribution during moisture balance

Moisture of oil and paperboard was estimated through the moisture balance equation given by ABB Company [5]. The relation equation of oil-paperboard electric field distribution and moisture content under moisture balance state was obtained:

$$\begin{cases} E_1 = \dfrac{\rho_1}{\rho_1 d_1 + \rho_2 d_2}(1\text{-}\eta)U + \dfrac{\varepsilon_2}{\varepsilon_2 d_1 + \varepsilon_1 d_2}\eta U \\ E_2 = \dfrac{\rho_2}{\rho_1 d_1 + \rho_2 d_2}(1\text{-}\eta)U + \dfrac{\varepsilon_1}{\varepsilon_2 d_1 + \varepsilon_1 d_2}\eta U \\ \rho_1 = \mathrm{A}_1 \times e^{-\left(\frac{C_{paper}}{\alpha_1}+\frac{T}{\beta_1}\right)} + \mathrm{B}_1 \\ \rho_2 = \mathrm{A}_2 \times e^{-\left(\frac{C_{\mathrm{oil}}}{\alpha_2}+\frac{T}{\beta_2}\right)} + \mathrm{B}_2 \\ \varepsilon_1 = \mathrm{C}_1 + \mathrm{D}_1 \times e^{\theta_1 \times C_{\mathrm{paper}}} \\ \varepsilon_2 = \mathrm{C}_2 + \mathrm{D}_2 \times e^{\theta_2 \times T} \\ C_{\mathrm{paper}} = 2.06915 e^{-0.02970T} \times C_{\mathrm{oil}}^{\;0.40489T^{0.09733}} \end{cases} \tag{1}$$

η=the content of AC voltage in compound voltage, ε=dielectric constant ρ=volume resistivity, d_1=2mm, d_2=4mm and U=150kV were set in the equation (1). The electric field intensity change trend in transformer oil and its corresponding oil impregnated paperboard under AC-DC superposition voltage was shown in figure 3 and figure 4, wherein different temperatures and different moisture contents during moisture balance were considered.



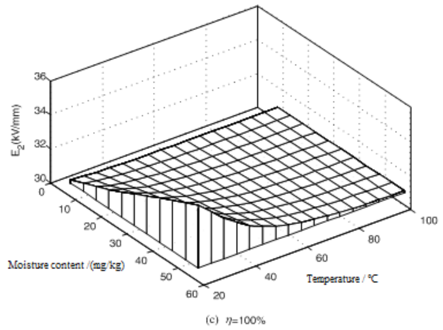
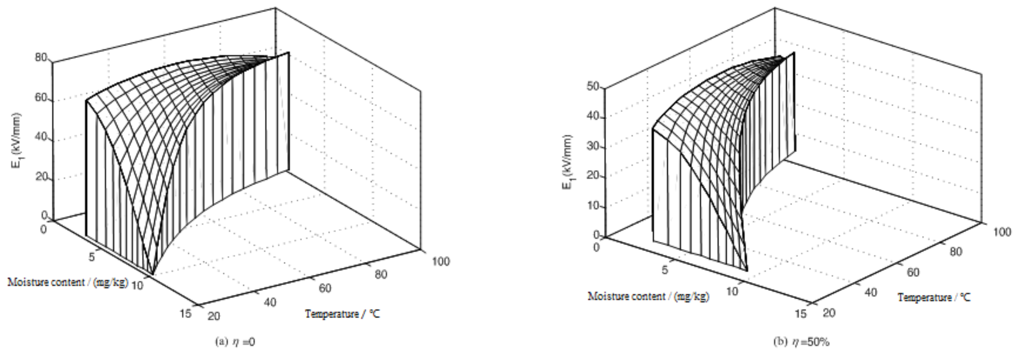


Figure 3. Field intensity distribution in oil at different temperatures and moisture contents.

Figure 3 showed that the field intensity in transformer oil was the lowest at low temperature and low moisture content when AC content was low (namely η=0), and it was the highest at low temperature and high moisture content. However, the lowest electric field value was discovered at high temperature and low moisture content when AC content was high (namely η=100). The field intensity was reduced according to exponential law with temperature rising or moisture content reduction. The AC content was lower, the electric field change amplitude was larger.

Figure 4 showed that the field intensity change trend in the oil impregnated paperboard was just opposite to that in the transformer oil. The field strength in the oil impregnated paperboard was the lowest at low temperature and high moisture content, and it was the highest at low temperature and low moisture content. The field intensity was increased according to exponential law with temperature rising or moisture content reduction. The AC content was lower, the electric field change amplitude was larger.

Moisture contents-temperature planes in figure 3 and figure 4 were compared. It was obvious that oil projection on the plane was rectangle, the projection of corresponding paperboard on the plane was irregular graphics, namely: the paperboard moisture content corresponding to oil with high moisture content was not high at high temperature.



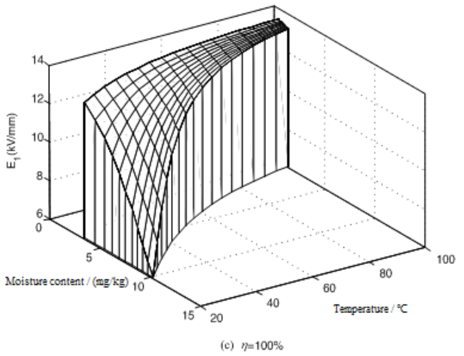


Figure 4. Field intensity distribution in oil impregnated paperboard at different temperatures and moisture contents.

T=20℃ and Coil=7.7mg/kg during moisture balance were regarded as the initial states to analyze the influence of temperature on oil-paper insulation electric field distribution under AC-DC superposition electric field concretely. The change of electric fields in oil impregnated paperboard and oil with temperature rising was analyzed. The change of electric field intensity in paperboard and oil with temperature at moisture balance was shown in figure 5 and figure 6.

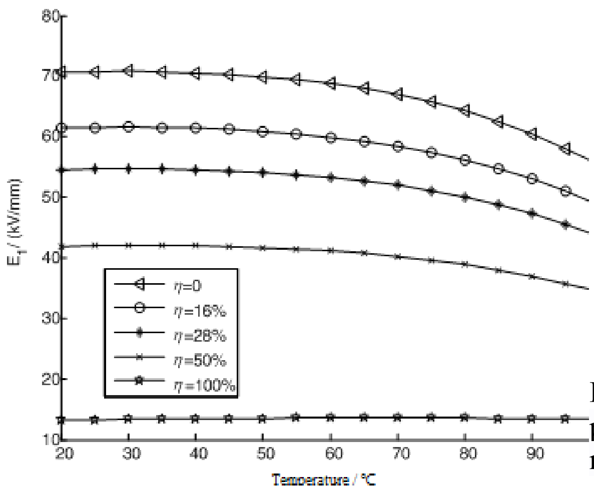


Figure 5. Field strength in oil impregnated paperboard at different temperatures during moisture balance.

Figure 5 showed that the field intensity increase with temperature in the paperboard under compound electric field was decreased gradually during moisture balance. The temperature was higher, the field intensity decrease speed was faster. AC content η was lower, the phenomenon was more prominent. The electric field was not changed basically with temperature when AC content η was equal to 100% (namely pure AC).

The field intensity change in transformer oil at different temperatures was shown in figure 6 during moisture balance. Figure 6 showed that the field intensity change condition in oil was just opposite to that in the paper under compound electric field during moisture balance. The field intensity in the oil

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was gradually increased with temperature rising. The temperature was higher, the field intensity rising was faster. Similarly, AC content η was lower, and the phenomenon was more prominent.

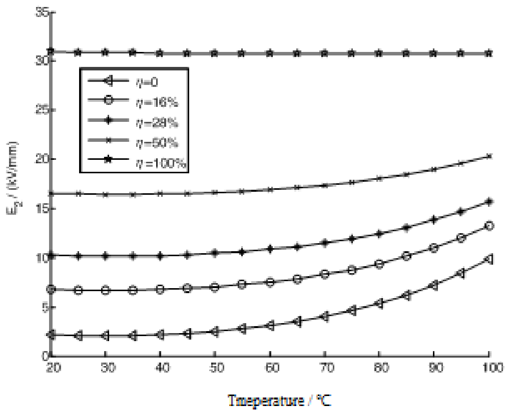

Figure 6. Field intensity in oil at different temperatures during moisture balance.

3.2. Influence of temperature on electric field distribution during moisture unbalance

When the temperature of oil-paper insulation suddenly rose, it was believed that resistivity and relative dielectric constant were changed due to temperature change only rather than moisture content because of slow moisture movemen.

Similarly, T=20℃ and C_{oil}=7.7mg/kg were set as initial states. The moisture content C_{paper} in the paper during T=20℃ was obtained through calculation, namely 3.45%. Therefore, the change trend of respective electric field strength with temperature was shown in figure 7 and figure 8 when moisture content in paper and water was constant.

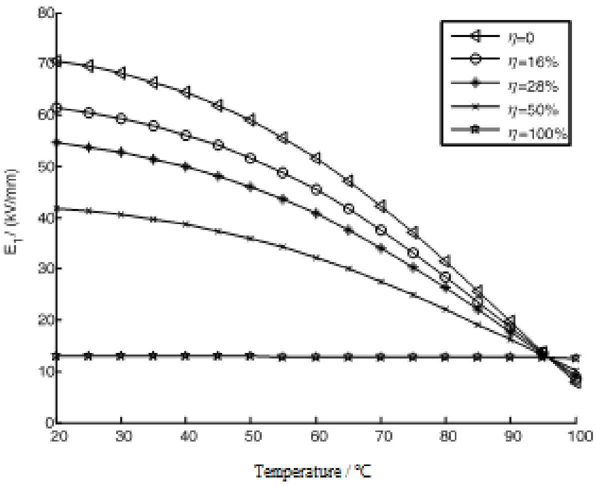

Figure 7. Field intensity of oil impregnated paperboard at different temperatures under moisture unbalance state.

Figure 7 showed that the change trend of electric field intensity in paperboard under compound electric field with temperature was basically the same as that under moisture balance, but the change amplitude value was far higher than that under moisture balance when the moisture content of the paperboard was constant. When the AC content was high (such as η=100%, namely pure AC), the field intensity was not changed with temperature change basically. When AC content was low, the field intensity in the paperboard was gradually decreased with temperature rising. When the temperature rose to 95 ℃ or so, the field strength under compound electric field was almost equal to the field intensity under pure AC, the temperature rose continuously, and the field intensity under compound electric field was lower than that under pure AC.

Figure 8 showed the change of field intensity in transformer oil with temperature under moisture unbalance state.

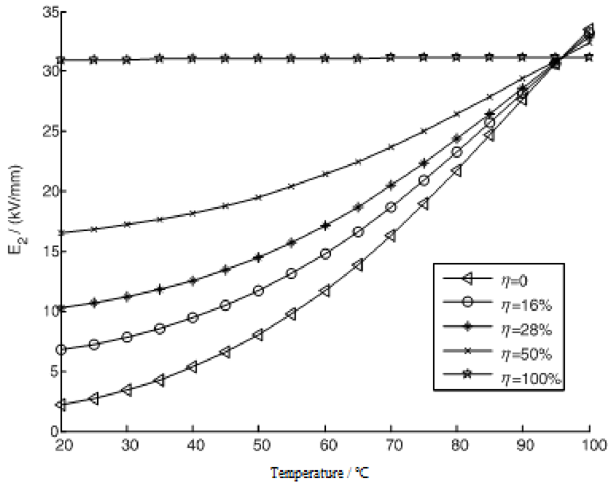

Figure 8. Field intensity in oil at different temperatures under moisture unbalance state.

Figure 7 showed that the change law of field intensity in transformer oil was just opposite to that in the paperboard. The electric field intensity in oil was gradually increased with temperature rising under compound electric field. The temperature was higher, the change speed was faster. The AC content η was lower, the change amplitude value was larger. When the AC content was the highest (such as η =100%, namely pure AC), the field intensity was not changed with temperature change basically. When AC content was lower, the field intensity in the oil was gradually increased with temperature rising. When the temperature rose to 95 ℃ or so, the field strength under compound electric field was almost equal to the field intensity under pure AC. The temperature rose continuously, and the field intensity under compound electric field was lower than that under pure AC.

3.3. Analysis on simulation results

Figure 5 and figure 8 were compared. It was discovered that the field intensity change amplitude was large at low AC content, and the field intensity change was small at high AC content with temperature rising because electric field distribution mainly depended on the ratio of relative dielectric constant at high AC content. The electric field distribution mainly depended on the resistivity ratio at low AC content.

The change of relative dielectric constant ratio of paper and oil with temperature was shown in figure 9.

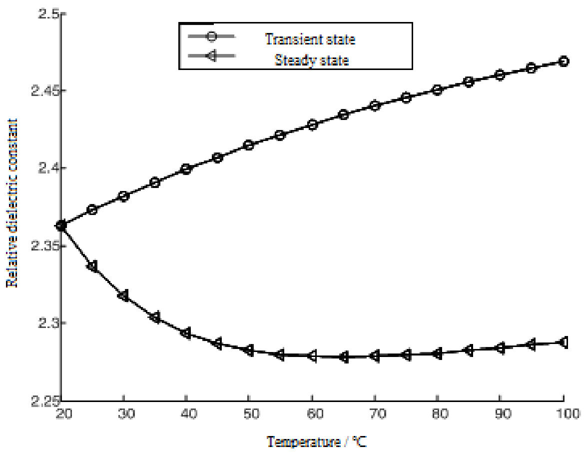

Figure 9. Relative dielectric constant ratio of paper and oil at different temperatures.

Figure 9 showed that the relative dielectric constant ratio of paper and oil under moisture unbalance state was increased with temperature rising. However, the ratio was increased from 2.36 to 2.47 only with amplitude of 4.6%. The ratio change law during moisture balance was different from that under short-time influence. Its ratio was decreased with temperature rising. The highest value was 2.36, and the lowest value was 2.28. The amplitude was only 3.3%. It was obvious that relative dielectric constant had small change amplitude, and it was the main reason why electric field change was small during high AC content.

Figure 10 showed the change of resistivity ratio between oil and paper at different temperatures.

Figure 10 showed that the resistivity ratio under moisture unbalance state was slightly different from that during moisture balance with temperature increase. However, it showed a decrease trend as a whole. The resistivity ratio was decreased gradually with temperature rising under water unbalance state, namely it was decreased from the highest ratio 32.34 at 20℃ to the lowest ratio 0.23 at 99℃. The decrease amplitude was 99.28%. The ratio was increased firstly and decreased then during water balance. It was decreased from the highest ratio 33.71 at 30℃ to the lowest ratio 5.60 at 99℃. The amplitude of fluctation was 83.39%. Resistivity ratio was changed greatly because the decrease speed of paper was much higher than that of oil though the volume resistivity of oil and paper was decreased exponentially with temperature rising. It was obvious that oil and paper resistivity was not proportionally changed with temperature, and it was the main reason why electric field was greatly changed with temperature at low AC content.

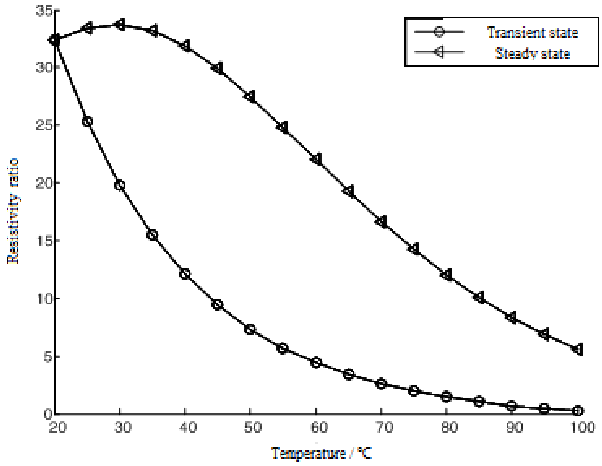

Figure 10. Resistivity ratio of paper and oil volume at different temperatures.

Figure 6 and figure 8 were compared. It was obvious that the electric field change amplitude in transformer oil was much larger than that during moisture balance at low AC content under moisture unbalance state. Field intensity in oil was gradually increased with temperature rising during moisture balance. However, the highest value of compound electric field was not higher than 2/3 under its AC condition. The value under pure DC condition $(\eta=0)$ was only 29% of AC condition. However, the electricity field in oil was changed significantly under moisture unbalance state, and the field intensity in oil was even higher than that under AC at high temperature. Pure DC $(\eta=0)$ was adopted as an example. The electric field was increased from 2.18kV/mm to 9.86kV/mm when the temperature rose from 20℃ to 99℃ during moisture balance. The electric field was increased from 2.18kV/mm to 33.55kV/mm under moisture unbalance state. The highest value was nearly 4 times of that during moisture balance. However, the AC field intensity $(\eta=100\%)$ was always kept at 30.7 kV/mm or so during the process.

4. Conclusion

Temperature change affects the resistivity and relative dielectric constant of oil and paper on the one hand, and the moisture balance point between oil and paper is moved on the other hand. Therefore the resistivity relative dielectric constant of oil and paper is changed, and electric field distribution of oil-paper insulation under compound electric field is further affected.

Electric field is changed with temperature slightly during moisture balance due to the following reasons: the moisture balance point is moved with temperature rising during moisture balance, and moisture in paper is moved to oil, thereby lowering the moisture content of paper and further reducing the decrease speed of the resistivity. The resistivity ratio decrease amplitude is much smaller than that under the moisture unbalance state, and many electric fields are concentrated in paper. Time is limited for moisture movement with temperature rising under the moisture unbalance state, and many electric fields are concentrated in oil as a result.

In conclusion, temperature has more prominent influence on oil-paper insulation in compound electric field compared with AC electric field. Oil test of oil-paper insulation in compound electric field during sudden temperature rising is more stringent than that during high temperature moisture balance.

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