Influence of moisture on the interface charge of oil–pressboard composite insulation under DC voltage

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Abstract: The distortion of the electric field in the oil–pressboard composite insulation caused by the accumulation of the interface charge is detrimental to both the insulation design and operation of converter transformers. The influence of moisture content on the surface charge accumulation of oil–pressboard insulation under DC voltage was studied in this study. In accordance with the Kerr electro-optic effect, the electric field strengths in transformer oil and the surface charge density were acquired after applying the positive and negative DC voltages in three oil–pressboard insulation models with different moisture content, respectively. The resistivities of the oil and pressboard in three models, namely Model 1\# with 3.8–4.2 ppm moisture in oil and 0.35–0.37\% moisture in pressboard, Model 2\# with 7.6–7.9 ppm moisture in oil and 0.79–0.82\% moisture in pressboard, and Model 3\# with 14.9–15.4 ppm moisture in oil and 1.39–1.42\% moisture in pressboard, was also measured. The results indicate that: (i) as negative charges in oil accumulated on the pressboard surface in a much greater speed than the positive ones, the electric field in transformer oil under negative DC voltage decreases more rapidly with time than that under positive DC voltage; (ii) the increase of the moisture content in both oil and pressboard, under either positive or negative DC voltage, leads to the decrease of both the electric field strength in transformer oil and the charge density with time; and (iii) the increase of moisture content could not only decrease the resistivity of both oil and pressboard, but also the ratio of the resistivity between the pressboard and the oil. On the basis of the Maxwell–Wagner theory, the decrease of the ratio between the pressboard and oil could lead to the decrease of the interfacial charge density, leading to the slow transient process of the electric field in transformer oil under DC voltage.

1 Introduction

Oil–pressboard composite insulation is widely used in high-voltage electrical apparatus. The rise of the moisture content in both oil and paper could lead to the increase of dielectric loss and decrease of insulation resistivity, and breakdown voltage, which will have a significant negative influence to the oil–pressboard insulating property \cite{1, 2}. Moreover, the moisture content plays an important role in the process of insulation ageing of electrical apparatus \cite{3, 4}. Accordingly, the moisture content should be under control during the apparatus production and operation. However, due to the mechanical sealing failure and insulation ageing \cite{5, 6}, the existence of moisture in oil and pressboard is unavoidable. The moisture content could lead to the breakdown of insulation in the worst scenario, and thus severely affects the safe and reliable operation of electrical apparatus \cite{7}. Furthermore, the moisture of within the oil–pressboard insulation can affect the relative space charge behaviour, which could enhance the local electric field and result in the field distortion.

The space charge in oil–pressboard composite insulation remains a great concern and has been studied by many scholars around the world. At present, a great number of studies use pulsed electro-acoustic method (PEA) to study the effect of temperature and voltage on space charge distribution of oil–paper insulation \cite{8–10}. In comparison, few researches report the impact of moisture content on the space charge of oil–paper insulation. Rongsheng and Albert \cite{11} used PEA method to measure the space charge with single-layer pressboard of 1 mm in thickness and found that the moisture content in pressboard has the significant influence on the space charge. Ruijin \textit{et al.} measured the space charge distribution of multi-layer paper with the PEA method. His experimental results revealed that as the content of moisture increased, the space charge with different polarities showed up. In addition, the dissipation of space charges was much faster after the removal of applied voltage \cite{12}. Maeno \textit{et al.} \cite{13} found that the increase of the moisture content led to the accumulation of space charge under the plate–plate model and eventually witnessed the distortion of electric field. The existing research considered the single insulation media and focused on either the transformer oil or paper/pressboard. There remains a gap of interface charge accumulation behaviour under different moisture contents in the oil–pressboard composite insulation, which would have an influence on the electric field distribution under DC voltage. To fill the existing gap, there arises the great necessity to explore the influence of moisture content on the interface charge accumulation in the oil–pressboard composite insulation under the application of DC voltage.

With reference to the Kerr-effect method, the present research measured the electric field dynamics in the oil and captured the surface charge accumulation at the oil–pressboard interface of the insulation under positive and negative DC voltage with different moisture contents in the oil and pressboard, respectively. On the basis of experimental findings, the influence of moisture content on the interface charge accumulation was discussed in the present paper.

2 Test model and methodology
2.1 Electric field measuring device

The Kerr-effect-based electric field measuring device used by this research is illustrated in Fig. 1. The device made use of a coaxial light beam structure. The 632.8 nm laser beam generated from the He–Ne laser was first turned into linearly polarised beam after passing the polariser. It was then turned into circularly polarised...
light after penetrating the quarter-wave plate. When passing in the test chamber, the incident circularly polarised light generated a phase difference that is directly proportional to the square of the electric field magnitude and was turned into elliptically polarised light. The polarised light interference was also generated when passing through the analyser.

In addition to the Kerr-effect-based measurement [14–16], the AC electric field modulation [17, 18] was also used in this research, so as to enhance the measuring sensitivity. Specifically, the test model was superimposed with low amplitude AC electric field \( E_{\text{ac}} \) in addition to the applied DC electric field \( E_{\text{dc}} \). The polariser orthogonally intersected with the analyser at the angle of polarisation. The polariser axis was fixed at 0° and the subsequent quarter-wave plate axis was fixed at 45°.

In (1), \( I_1 \) denotes the intensity of incident light and \( I_2 \) represents that of the emergent light after the Kerr-effect. \( I_{\text{dc}} \), \( I_{\text{lin}} \), and \( I_{\text{lmo}} \) mark the DC component, the fundamental frequency component and the multiplication frequency component of \( I_o \), respectively.

\[
\begin{align*}
\frac{I_{\text{dc}}}{I_o} &= \frac{1}{2} + \frac{\pi \beta E_{\text{dc}}^2}{2} + \frac{1}{2} \pi \beta E_{\text{dc}}^2 \\
\frac{I_{\text{lin}}}{I_o} &= 2\pi \beta E_{\text{dc}} E_{\text{ac}} \sin \omega t \\
\frac{I_{\text{lmo}}}{I_o} &= -\frac{1}{2} \pi \beta E_{\text{dc}}^2 \cos 2\omega t
\end{align*}
\]

Table 1

| Samples | Moisture content in oil, ppm | Moisture content in pressboard, % |
|---------|-----------------------------|---------------------------------|
| #1      | 3.8–4.2                     | 0.35–0.37%                      |
| #2      | 7.6–7.9                     | 0.79–0.82%                      |
| #3      | 14.9–15.4                   | 1.39–1.42%                      |

Calibration was carried out to conclude that the measurement sensitivity is 20 V/mm and the measurement error is <5%.

2.2 Experimental model

Fig. 2 shows the experimental model used in this research, which consists mainly two parallel electrodes and one single-layer oil-pressboard insulation sample between them. The oil clearance is 9 mm. The electric field measurement point is placed right in the middle of the oil clearance.

2.3 Test sample processing

The Karamay #25 transformer oil and the widely adopted high-density TIV pressboard were used for this research. The oil was degassed and dehydrated at the temperature of 80°C in vacuum for 48 h before tests. The pressboard was dried at the temperature of 105°C in vacuum for 48 h and then immersed in oil and vacuum for another 48 h before the test. The moisture content of oil was 3.8–4.2 ppm and the mass fraction of the moisture content in pressboard was 0.35–0.37%. The original test samples were placed in constant temperature and humidity to obtain two other groups of samples with higher moisture content. The moisture content of the oil and pressboard is shown in Table 1.

The moisture equilibrium between oil and pressboard is a dynamic progress, which is closely related to ambient temperature and humidity [19–21]. The test process, all samples were set up in a well-sealed chamber in order to prevent any possible interference from outside. Besides, the tests were managed to complete within a short period of time, so as to maintain the uniformity of the samples. In addition, there is a little charge for the moisture content of both oil and pressboard with the comparison before and after the relative experiments.

3 Test results

During the tests, the upper electrode of the experimental model was applied with +4 and −4 kV DC voltages, whilst the lower one was applied with +300 V and 1310 Hz AC modulation voltage. The dynamics of the electric field strength in transformer oil under both the positive and negative DC voltages were captured for the three oil–pressboard insulation samples with different moisture contents. The interface charge density was calculated accordingly.

3.1 Measured electric field strength

Fig. 3 shows the changes of the electric field in transformer oil with time under the application of 4 kV DC voltage for three oil–pressboard samples with different moisture contents. For all three samples, the maximum electric field strength appeared at the initial time of positive DC voltage application and the three values are similar around 411 kV/m, which is close to the theoretic value for initial capacitive electric field calculated by the resistive–capacitive model (421 kV/m).

As the voltage application prolonged, the electric field witnessed apparent attenuation. For test sample #1 with the lowest moisture content, the electric field strength in the oil witnessed a decrease of 34.9% to 309.1 kV/m after 5000 s of the voltage application. The electric field strength decrease was much slower for sample #3 with the highest moisture content. The moisture content in sample #2 was between the two above-mentioned samples and the attenuation speed was between the two samples. After 5000 s of positive DC voltage application, the electric field strength of sample #2 and sample #3 decreased by 14.9% to 350.3 kV/m and by 5.7% to 388.1 kV/m, respectively.

Fig. 4 presents the changes of the electric field in transformer oil with time in the context of −4 kV DC voltage application for three samples with different moisture contents. Similar to the situation of positive DC voltage application, all three test samples witnessed the maximum value of the electric field strength in oil at the initial time of negative voltage application, reading around 417

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Table 1: Moisture content of oil and pressboard

| Samples | Moisture content in oil, ppm | Moisture content in pressboard, % |
|---------|-----------------------------|---------------------------------|
| #1      | 3.8–4.2                     | 0.35–0.37%                      |
| #2      | 7.6–7.9                     | 0.79–0.82%                      |
| #3      | 14.9–15.4                   | 1.39–1.42%                      |
As the negative DC voltage application went on, the electric field strength also saw the apparent decrease trend. Comparing Fig. 3 with Fig. 4, however, it is found that the strength of electric field in transformer oil under negative DC voltage decreased much faster with time than that under positive DC voltage. In other words, the dynamic process of the electric field in the oil–pressboard insulation shows prominent polarity effect.

The moisture content in oil–pressboard insulation also has an effect on the electric field strength under negative DC voltage. The most rapid decrease in the electric field strength occurred in sample #1 with the lowest moisture content, which decreased by 71.2% to 116.0 kV/m after 5000 s of negative DC voltage application. The samples #2 and #3 with higher moisture content witnessed similar attenuation tendency in this process, the electric field strength of which reduced by 55.2% (184.4 kV) and 51.8% (201.1 kV), respectively, at 5000 s.

From the comparison between Figs. 3 and 4, it is inferred that with the increase of the moisture content, the attenuation speed of the electric field strength in oil slowed down under both positive and negative DC voltages. Besides, when the moisture increases to a certain extent, the attenuation process of the electric field in the oil–pressboard become almost convergent.

3.2 Measured interface charge characteristics

The electric field under DC voltage is a superposition of the applied voltage and the electric field caused by the interfacial charge density. With constant DC voltage application, the magnitude of the Laplace's electric field is constant, while the electric field generated by the interface charge which has an opposite direction to the Laplace's field could result in the decay of the vector-superimposed electric field in oil.

Under one-dimensional electric field, the density of interface electric field can be obtained through (3) based on the oil–pressboard interface dynamics [22]

\[
\begin{align*}
\varepsilon_{PB} E_{PB} - \varepsilon_{oil} E_{oil} &= \sigma \\
E_{PB} d_{PB} + E_{oil} d_{oil} &= U
\end{align*}
\]

where the relative dielectric constants for the oil-immersed pressboard and transformer oil are \( \varepsilon_{PB} = 4.4 \) and \( \varepsilon_{oil} = 2.2 \), respectively. The thickness of the oil-immersed pressboard and the length of the oil clearance are \( d_{PB} = 1 \) and \( d_{oil} = 9 \) mm, respectively. The applied voltage \( U = \pm 4 \) kV. According to (3), the interface charge density \( \sigma \) could be obtained after the acquisition of the electric field of oil \( E_{oil} \).

Fig. 5 depicts the time dependence of interface charge density under the +4 kV DC voltage. Positive charges concentrated at the oil–pressboard interface after positive DC voltage application on the three test samples with different moisture contents. After 5000 s of positive DC voltage application, the interface charge density for the test sample #1 with the lowest moisture content read 43 \( \mu \)C/m\(^2\), whereas that with the highest moisture content was recorded as 12 \( \mu \)C/m\(^2\). It indicates that the increase of the moisture content in both oil and pressboard leads to decrease of the interface charge density.

The time dependence of interface charge density under the −4 kV DC voltage is shown in Fig. 6. Under negative DC voltage, negative charges accumulated on the oil–pressboard interface after positive DC voltage application on the three test samples with different moisture contents. However, the three samples show different interface charge densities. After 5000 s of positive DC voltage application, the interface charge density for the test sample #1 with the lowest moisture content read 43 \( \mu \)C/m\(^2\), whereas that with the highest moisture content was recorded as 12 \( \mu \)C/m\(^2\). It indicates that the increase of the moisture content in both oil and pressboard leads to decrease of the interface charge density.

Comparing Fig. 5 with Fig. 6, it is observed that the interface charge density under the negative voltage is much higher than that...
under positive voltage with the same voltage magnitude and duration time. It indicates that the negative charges could accumulate at the oil–pressboard interface more easily compared with positive charges.

4 Discussion and analysis of test results

4.1 Polarity effect of electric field in oil

Figs. 5 and 6 indicate that the electric field in transformer oil shows different transition processes under different polarities of applied voltages. The magnitude difference of the surface charge is resulted from the different polarities of applied voltage.

Ieda et al. [23] provided explanations for such a phenomenon. The insulation pressboard used by transformers contains cellulose and lignin, both of which are with hydroxyl (–OH). In addition, the lignin also includes aldehyde (–CHO) and carboxyl groups (–COOH). The oxygen atoms within the hydroxyl groups have the second-largest electronegativity of any atom. For this reason, the electrons in hydrogen atoms are attracted to the oxygen atoms, polarising the oxygen atoms negative and the hydrogen atoms positive. The electropositive hydrogen atoms on the pressboard surface then absorb the negative charges in oil, which result in more negative interface charge accumulating.

4.2 Correlation between moisture content and interface charge accumulation

Under DC voltage, the various moisture contents in oil and pressboard changes the interfacial charge density and the relative electric field within the oil. As strong polar molecules, water is easily ionised in the presence of electric current, which would decrease the resistivity of oil and pressboard. The research sets up a detecting device based on three-electrode method [24] to measure the specific resistivity of pressboard. The resistivity of pressboard with different moisture contents was obtained with a Keithley#6514 electrometer, and that of the transformer oil was obtained by using JDC-1 oil dielectric loss and resistivity tester.

As is presented in Table 2, with the increase of moisture content, the resistivity of both oil and pressboard decreases. Given that the pressboard resistivity is more sensitive and decreases by a relatively larger margin, the ratio of pressboard resistivity to oil resistivity $\rho_{PB}/\rho_o$ keeps decreasing with the increase of moisture content in both the oil and pressboard.

The process of interfacial polarisation can be analysed with the Maxwell–Wagner theory. The equivalent model of the oil–pressboard insulation is shown in Fig. 7.

When it reached the steady state of charge behaviour after the voltage application, the interface charge density can be expressed as the below equation:

$$\sigma = \frac{\rho_{PB} d_{PB} - \rho_o d_{oil}}{\rho_{PB} + \rho_o} U = \frac{\rho_{PB} d_{PB} - \rho_o d_{oil}}{\rho_{PB} + \rho_o} \epsilon U$$

(4)

where $U$ represents the applied voltage, $\epsilon$ denotes the vacuum dielectric constant, $\rho_{PB}$ and $\rho_o$ represent the relative dielectric constants of transformer oil and oil-immersed pressboard, respectively. $\rho_{PB}$ and $\rho_o$ refer to the equivalent resistance and capacitance of the transformer oil, $d_{oil}$ and $d_{PB}$ indicate the thickness of oil gap and oil-immersed pressboard, $U_o$ and $U_{PB}$ equal the applied voltage to the oil and pressboard, $R_{PB}$ and $C_{PB}$ mean the equivalent resistance and capacitance of the pressboard, and $\rho_o$ and $\rho_{PB}$ refer the resistivity of the oil and pressboard, respectively.

The results show that if $\rho_{PB}/\rho_o > 0.5$, the accumulated interfacial charges have the same polarity with the applied voltage and the absolute value has the positive correlation with the $\rho_{PB}$. If $\rho_{PB}/\rho_o < 0.5$, the interfacial charge has the opposite polarity compared with the external electric field, and the absolute value has the inverse correlation with the $\rho_{PB}$.

With the measured values of $\rho_o$, $\rho_{PB}$, $\epsilon_{oil}$, $\epsilon_{PB}$, $d_{oil}$ and $d_{PB}$, as well as the applied voltage and the test model size parameters, the interface charge density could be obtained on the basis of Maxwell–Wagner theory model analysis. Fig. 8 indicates the relationship between the absolute value of the interfacial charge density and the moisture content in the oil and oil-impregnated pressboard.

As the moisture content increases, the ratio of oil resistivity to pressboard resistivity decreases and the interfacial charge density also decreases. On the basis of both Maxwell–Wagner theory and actual experimental results, they indicate the similar trend, but with the different magnitude of interfacial charge density. The calculations results based on the Maxwell–Wagner theory are generally higher than the experimental results under the positive DC voltages, while the theoretic values are smaller than the actual values measured of negative DC voltage.

This discrepancy in values is attributed to the fact that (i) the Maxwell-Wagner theory model-based calculation points to the saturation value interface charges when the voltage application time comes close to infinity, whilst in actual measurement, the interface charge density did not yet reach a saturation state after the voltage was applied for 5000 s; (ii) based on the Maxwell–Wagner theory, the interfacial charge density could be calculated considering resistivity and dielectric constants of each single insulation materials. However, it is not capable of taking into account the absorption effect of negative charges in oil and thus not be able to reflect the polarity effect of interface charge concentration under negative and positive voltage applications.

5 Conclusion

With the Kerr-effect method, this research measured the electric field strength in transformer oil under DC voltage application for three oil–pressboard insulation samples with different moisture contents. The experiment results indicate that:

### Table 2: Resistivity of oil and pressboard with different moisture contents

| Test sample | Oil resistivity $\rho_o$ (Ω • m) | Pressboard resistivity $\rho_{PB}$ (Ω • m) | $\rho_{PB}/\rho_o$ |
|-------------|-------------------------------|---------------------------------------|-------------------|
| #1          | $1.73 \times 10^{13}$         | $8.98 \times 10^{14}$                | 51.90751          |
| #2          | $1.47 \times 10^{13}$         | $1.37 \times 10^{14}$                | 9.31973           |
| #3          | $1.17 \times 10^{13}$         | $2.21 \times 10^{13}$                | 1.9386            |

![Fig. 7 Equivalent model of the oil-pressboard insulation](image-url)

![Fig. 8 Relationship between the interface charge density and the moisture content in oil and pressboard](image-url)
(i) Regardless of the degree of moisture content in pressboard and oil, the concentrations of positive and negative charges at the oil–pressboard interface shows prominent polarity effect under the applied DC voltage. This is attributed to the fact that negative charges within the oil could be easier to be absorbed by the pressboard, leading to the different accumulation rate of the negative and positive charges at the interface under the different polarity of applied voltage. However, as negative charges in oil accumulated faster than positive charges, the increase of moisture content resulted in different accumulation performance of positive and negative charges.

(ii) Regardless of the polarity of the applied DC voltage, with the increase of moisture content in both oil and pressboard, the interface charge density decreases and the transient process of the electric field in transformer oil slows down.

(iii) The resistivity of both oil and pressboard decrease with the increase of the moisture content. As the resistivity of pressboard is more sensitive to the change of moisture content, the ratio of the pressboard resistivity to oil resistivity also decreases, which could be attributed to the fact that the density of the interfacial charge density decreases with the increase of the moisture content in both oil and pressboard based on the Maxwell–Wagner theory.

(iv) Maxwell–Wagner theory provides qualitative analysis of interface charge accumulation process, but fails to take into account the different accumulation rates of the negative and positive charges. The results indicate that the interfacial charges based on the Maxwell–Wagner theory are discrepant from the experimental results.

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