SPACE CHARGE CHARACTERISTICS AND THE ELECTRIC FIELD DISTORATION AFTER POLARITY REVERSAL OPERATION IN TWO LAYERS OF OIL-IMPREAGNATED PAPER AND OIL

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Abstract: The formation of space charge in the oil-impregnated paper and oil insulation system under HVDC condition can influence the electric field distribution. In the case of HVDC converter transformer, the distortion of electric field may affect its performance. It is, therefore, important to analyse factors that can affect space charge formation and dissipation characteristics such as moisture, temperature, electric stress level and ageing process. This paper mainly focuses on the effect of oil ageing on space charge characteristics in the oil-impregnated paper and oil system. The pulsed electroacoustic method was used to monitor space charge dynamics and these data were further incorporated into the model established using COMSOL software to estimate its impact on electric field distribution. The results show that there is a significant electric field enhancement after polarity reversal operation due to the injected charges. It is also noticed that the status of the oil has a profound effect on the injected charge dynamics, therefore, the electric field enhancement.

1 INTRODUCTION

The lower cost for long distance bulk power transmission, the ability of interconnect ac systems with different frequencies, the ability of interconnect two large ac system without guaranteeing the synchronism are main advantages for HVDC compared to HVAC transmission systems [1]. These advantages promote rapid development of HVDC networks requiring higher reliability of its power equipment. Therefore, the reliability of the most expensive equipment in HVDC system, converter transformer, is of paramount importance. As the main insulation materials within converter transformer: oil and oil-impregnated pressboard is vital for maintaining safe and reliable operation of the equipment.

Under the application of HVDC voltage, space charge could form within the insulation materials. It has been shown that the presence of space charge has a close relationship with the electrical performance of insulation materials [2]. For instance, space charge could lead to the localized electric field enhancement, resulting the partial discharge and even breakdown of insulation materials [3]. Therefore, it is extremely important to analyse the factors which could affect the space charge formation and dissipation characteristics such as the sample thickness, temperature, moisture, electric strength, aging property, various types of oil [4][5][6]. Various researches have been made to understand the space charge behaviours within oil and paper insulation considering different factors above. The aim is to have quantitative knowledge of the behaviour of oil and paper insulation under HVDC voltage to improve the safety and reliability of HVDC power equipment. In 1997, Morishuis and Jeroense firstly measured the space charge distribution of the oil-impregnated paper using pulsed electroacoustic (PEA) method [7]. Homocharge injection was observed for oil-impregnated paper from both anode and cathode, which could lead to the increase of electric field of interface between electrode and sample after the polarity reversal operation. Tang et al, analysed the space charge evolution within multi-layers oil-paper caused by different electric fields and temperatures. The results showed that dc voltage determines the amount of space charge injection while the temperature affects charge mobility and its distribution within the oil-paper samples [2]. Tang et al also extracted parameters such as the total charge injection, apparent charge mobility and trap energy distribution based on space charge dynamics [8].

Wang et al [3] analysed that the aged paper effect on the space charge behaviour within the oil-impregnated pressboard. With the aging of the paper, larger amount of homocharge could be injected into the sample. Hao et al [9] concentrated on the moisture effect on the space charge characteristics within the oil-paper insulation. Higher moisture of the oil-paper could increase its conductivity, leading to rapid space charge injection and dissipation rate. Zhu et al [10] measured the space charge distribution within oil-impregnated paper under temperature gradient. The results reflected that heterocharge appeared in the vicinity of lower temperature electrode and its amount increased with the rise of the temperature gradient and applied electric field. It has been recognised that fewer researches analyse the electric field in the oil and oil-impregnated pressboard after polarity reversal operation. The accumulated homocharge could increase the electric field of the surface between electrode and sample after polarity reversal operation [11]. Therefore, it is important to acquire the electric field distribution after polarity reversal operation for oil paper insulation. The effect of space charge in layered insulation material has been often analysed using the Maxwell-Wagner theory. It is determined by the conductivity and dielectric constant of the involved materials. However, the actual experimentally measured space charge density is not consistent with the theory, which is higher in reality compared to the theoretical calculation [12]. Therefore, the conventional electrical calculation based on Maxwell-Wagner theory is not reliable and the difference compared to the experimental results should be evaluated.

In this paper, the aging effect on the space charge characteristics within the oil and oil-impregnated pressboard is analysed. Afterwards, the acquired space charge is further imported into the COMOSOL software for electric field simulation with an emphasis on the electric field after different polarity reversal operation time. Moreover, the relationship between the electric field calculated from Maxwell-Wagner theory and space charge density is also investigated.

2 EXPETIMENTAL METHODOLOGY

2.1 Sample preparation

With the purpose of analysing the aging effect on the space charge characteristics within the oil and oil-impregnated pressboard, both fresh and aged samples were prepared. The fresh oil was Shell Diala ZX-I, which was widely used in the current converter transformer. The aged oil was taken from a serviced transformer, showing dark brown colour. The detailed sample preparation procedures could be seen in our previous work [4] . Through using the DC conductivity and dielectric spectroscopy measurements, the dielectric properties such as the conductivity and permittivity were obtained for both fresh and aged oil and oil-impregnated pressboard, which was shown in Table 1 [13].

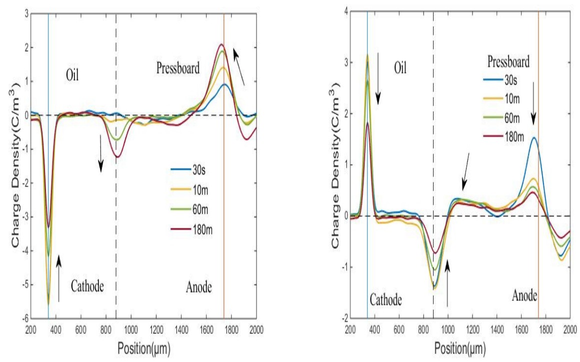
Table 1 The properties of the four dielectric materials

	Thickness	Permittivity	Resistivity
Fresh oil-PB	1(mm)	3.2	140(TΩ)
Fresh oil	0.5(mm)	2.2	7 (TΩ)
Aged oil-PB	1(mm)	4.2	0.3(TΩ)
Aged oil	0.5(mm)	2.6	0.1 (TΩ)

The PEA method was selected for space charge measurement [14][15]. The pulse generator used in our experiment was 1kV, 1kHz with 5ns width [4]. 12kV/mm was applied on both fresh and aged oil and oil-impregnated pressboard for comparison. The duration of the voltage application lasted 3 hours and after that, voltage was switched off and the space charge characteristics under decay process was monitored [13].

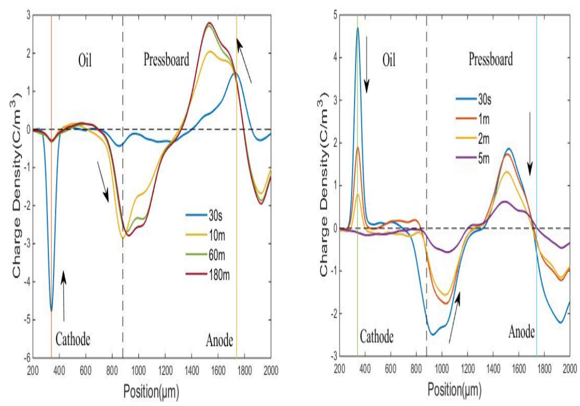
3 EXPERIMENTAL RESULTS AND DISCUSSION

Figure 1 (a) shows space charge behaviour within the fresh oil and oil-impregnated pressboard under an applied electric field of 12(kV/mm). It could be seen that the cathode peak is sharp while the anode peak is much broad. As the pressboard is consisted of cellulose fiber, the acoustic waves could be distorted when they pass through the bulk porous pressboard combined with the oil layer, leading to the acoustic waves scattering and attenuation [3]. Therefore, the acoustic wave recovery is necessary for measuring the multi-layer think oil and oil-impregnated pressboard.



(a)Under 12(kV/mm) (b)Charge decay

Figure 1 Space charge density of the fresh oil and oil-impregnated pressboard under an applied electric field of 12 kV/mm and its decay process.



(a)Under 12(kV/mm) (b)Charge Decay

Figure 2 space charge density of aged oil and oil-impregnated pressboard under electrical field of 12(kV/mm) and its decay process.

From Figure 1(a), homocharge injection is observed from two electrodes, leading to the formation of positive charge adjacent to the anode and negative charge on the interface between the oil and pressboard. The interfacial negative charge could produce positive image charges on the electrodes, leading to the decrease in the charge density on the cathode due to cancelation.

The net negative charge could be explained by two reasons. According to Maxwell theory $\sigma = \frac{Q}{S} = \frac{\varepsilon_0(\rho_{oil}\varepsilon_{oil}-\rho_{PB}\varepsilon_{PB})}{\rho_{oil}\delta_{oil}+\rho_{PB}\delta_{PB}}$, where σ is the charge density on the interface, ρ_{oil} and ρ_{PB} represent the resistivity of the oil and pressboard, while ε_{oil} and ε_{PB} are the permittivity of the oil and pressboard. Therefore, the polarity of the interfacial charge should be negative after substituting the parameters from Table 1. Moreover, due to the higher conductivity of the oil, electrons injected from the cathode could easily migrate to the interface due to its higher mobility compared to positive ion mobility[16][17].

Figure 1(b) illustrates space charge distribution of the fresh oil and oil-impregnated pressboard during the decay process. It can be seen that the polarity of space charge on both electrodes is positive, which is mainly caused by the negative interfacial charges.

It can be seen from Figure 1(b), the general dissipation rate is quite slow which decreases by 1(C/m^3) for both electrodes after around 180 minutes. It is believed that deep traps mainly exist at the interface and within oil-impregnated pressboard which could lead to the slow dissipation of the trapped space charge [4]. Moreover, it could be seen that some positive charge distributes in the vicinity of the interface. This is the positive charge injected from the anode and dissipates gradually during the decay process.

Figure 2(a) shows the space charge distribution of the aged oil and oil-impregnated pressboard under an applied electrical field of 12(kV/mm). Compared to Figure 1(a), larger amount of space charge injection and faster space charge movement are two obvious features for aged samples. Lager amount of charge injection mainly accounts for the higher trap density of the aged oil-impregnated pressboard [4]. The reason contributing to the higher mobility of charge within the aged samples may be attributed to the increase of the conductivity for the aged oil and oil-impregnated pressboard. Moreover, larger amount of charge injection for aged samples could lead to higher electric field enhancement under the steady state.

Figure 2(b) shows space charge distribution for the aged oil and oil-impregnated pressboard during the decay process. It could be seen that there is little space charge left after 5 minutes, while the space charge density does not have obvious reduction for the fresh samples after 180 minutes. The rapid dissipation rate of the space charge could be attributed to the higher conductivity.

4 ELECTRIC FIELD SIMULATION

4.1 Simulation preparation

The simulation was performed using commercial software COMSOL. The electrical current physics was selected to analyse the time dependent electric field. The configuration of the model is consisted of two layers: oil and pressboard. The parameters used are from Table 1. The layout of model could be seen in Figure 3. With the purpose of simulating the electric field distribution of oil paper simulation after polarity reversal operation, the applied voltage profile in the simulation could be seen in Figure 4.

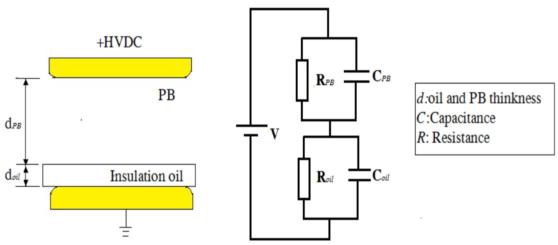


Figure 3 The equivalent circuit of the oil/pressboard insulation [18].

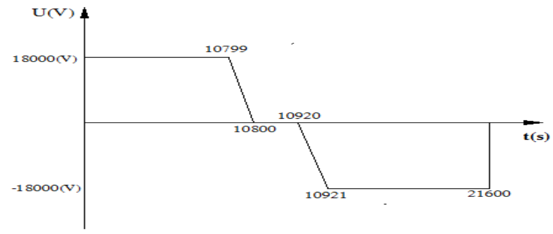


Figure 4 Voltage profile for polarity reversal where 120s is used to complete the operation.

4.2 Maxwell-Wagner theory

Based on the equivalent circuits shown in Figure 3, the oil and paper could be regarded as the parallel configuration of the resistor and capacitor according to Maxwell-Wagner theory. It is possible to acquire the electric field distribution across the oil and pressboard. From the Laplace equation derivation, the voltage and electric field of the oil and pressboard could be calculated through the equations below.

$$U_1(t) = \frac{R_1 U}{R_1 + R_2} + \left(\frac{C_2}{C_1 + C_2} - \frac{R_1}{R_1 + R_2}\right) U \times e^{-\frac{t}{\tau}} \quad (1)$$

$$E_1(t) = \frac{R_1 U}{(R_1 + R_2) d_1} + \left(\frac{C_2}{C_1 + C_2} - \frac{R_1}{R_1 + R_2}\right) \frac{U}{d_1} \times e^{-\frac{t}{\tau}} \quad (2)$$

$$U_2(t) = \frac{R_2 U}{R_1 + R_2} + \left(\frac{C_1}{C_1 + C_2} - \frac{R_2}{R_1 + R_2}\right) U \times e^{-\frac{t}{\tau}} \quad (3)$$

$$E_2(t) = \frac{R_2 U}{(R_1 + R_2)d_2} + \left(\frac{C_1}{C_1 + C_2} - \frac{R_2}{R_1 + R_2}\right)\frac{U}{d_2} \times e^{-\frac{t}{\tau}} \quad (4)$$

$$\tau = \frac{C_1 + C_2}{\frac{1}{R_1} + \frac{1}{R_2}} \quad (5)$$

where U is the applied voltage between two electrodes, R_1 and R_2 are resistances of the pressboard and oil. C_1 and C_2 are capacitances of the pressboard and oil respectively. τ is the time constant.

After substituting the parameters from Table 1 into equations above, the voltage and electric field results for oil and pressboard under different states can be summarized in Table 2.

Table 2 The voltage and electric field of the oil and pressboard

Time(s)	$U(kV)$	$E_1(kV/mm)$	$U_2(kV)$	$E_2(kV/mm)$
0	10.42	10.42	7.58	15.16
100	12.26	12.26	5.74	11.48
10799(∞)	17.38	17.38	0.62	1.24

After setting up the parameters of the materials within COMSOL software, the electric field distribution of oil and paper could be seen in Figure 7(a) for time 10799s. Comparing with the calculation results shown in Table 2, it can be seen that a good agreement has been achieved, suggesting that the simulation has been correctly implemented for electric field calculation based on the Maxwell-Wagner theory.

4.3 Methodology for adding space charge into COMSOL simulation

In order to add the space charge density into the oil and pressboard, the space charge density should subtract the reference calibration data to remove the capacitor charge on the electrode. Figure 5 shows the reference calibration space charge density and charge density at time 180 minutes. After subtraction, Figure 6 shows the results for pure space charge injection within the oil and oil-impregnated pressboard at time 180 minutes. With the purpose of inputting this data into COMSOL software, the oil layer and pressboard has been divided into 5 and 10 sub-regions respectively.

Through analysing characteristics of space charge density in each region versus time, the relationship between the space charge density and time for each region can be obtained using the curve fitting technique in MatLab. For example, two exponential functions are utilized to fit the space charge density versus time under the voltage application process, representing deep and shallow traps at the interface and in the pressboard. However, for a short duration, only one exponential function is used for 2 minutes of decay process, representing shallow traps [19].

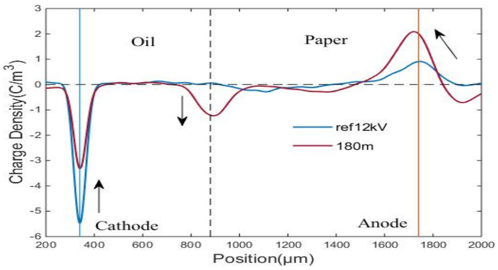


Figure 5 Space charge for fresh oil and oil-impregnated pressboard under an applied electric field of 12 kV/mm.

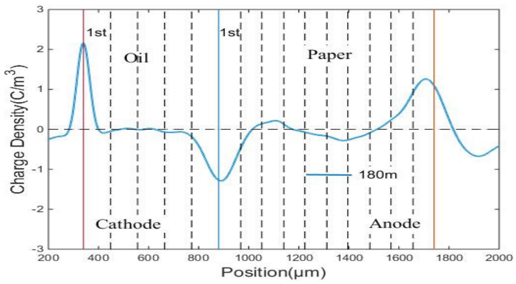


Figure 6 Configuration of the space charge density after subtracting the calibration charge density at time=180 minutes.

5 SIMULATION RESULTS AND DISCUSSION

5.1 Fresh oil and oil-impregnated pressboard under 12(kV/mm)

Figure 7(a) shows the electric field distribution of fresh oil and pressboard under 12(kV/mm) based on the Maxwell-Wagner theory. It could be seen that the electric field at steady state satisfies the resistive electric field distribution. As a result, the electric field in pressboard is significantly higher than that of oil due to the higher resistivity of the pressboard.

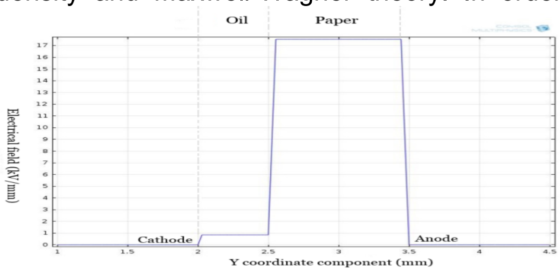
Figure 7(b) illustrates electric field of fresh oil and pressboard after adding space charge under 12(kV/mm) at t=10799s. It could be seen there is a protruding region for the electric field in the pressboard, which is related to the homocharge effect on the electric field. Homocharge injection and migration from the two electrodes within the pressboard could be shown in Figure 6. The electric field caused by the homocharge within the pressboard superimposes to the external electric field, leading to the electric field enhancement in the middle of the pressboard. From figure 7(b), there is a concave region for the electric field in the oil. Heterocharge could account for this phenomenon.

Figure 8(a) represents the electric field of the fresh oil and pressboard under 12(kV/mm) after polarity reversal operation time 60s based on the Maxwell-Wagner theory. It could be seen that the transient state electric field satisfies the capacitive electric field distribution. Therefore, the electric field of pressboard is lower than that of the oil due to lower permittivity of the oil.

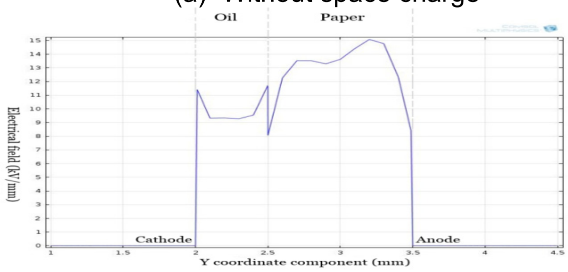
Figure 8(b) indicates the electric field of the fresh oil and pressboard after adding the space charge under 12(kV/mm) after polarity reversal time 60s. It is noticed that there is a concave region for the electric field of the pressboard. The homocharge injected into the pressboard prior to the reversal operation acts as the heterocharge, therefore, the electric field in the vicinity of the cathode and the interface will be enhanced after polarity reversal operation. For oil part, the enhancement of the electric field could also be attributed to the existence of space charge. The heterocharge formation prior to the polarity reversal acts as homocharge after the operation, leading to the electric field enhancement within the oil.

There is obvious difference in electric field simulation between considering space charge density and Maxwell-Wagner theory. In order to provide evidence for industry to select proper polarity reversal time, Table 3 summarizes the electric field using the Maxwell-Wagner theory and the electric field with consideration of space charge for the fresh pressboard under various polarity reversal operation time.

From Table 3, it is noticed that the electric field in pressboard using the Maxwell-Wagner theory E_{max2} increases gradually while the electric field considering space charge E_{max1} decreases with time. The amount of the charge density decreases slowly from 1.5(C/m^3) to 1(C/m^3) in 2 minutes as shown in Figure 1(b). Therefore, this small amount of charge density could not produce the higher electric field distortion within the pressboard. The electric field enhancement factor $f=(E_{max1}-E_{max2})/E_{max2}$, where E_{max1} is the electric field in pressboard after adding space charge, E_{max2} is the electric field in pressboard calculated from the Maxwell-Wagner theory. The factor f decreases from 407.91% to 124.59% with the increasing time.

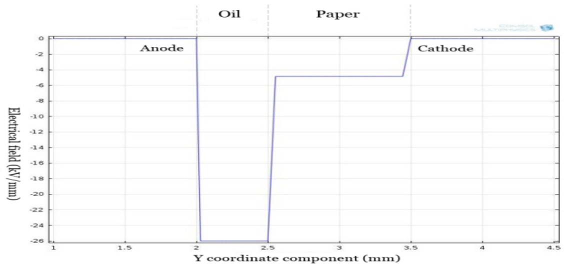


(a) Without space charge

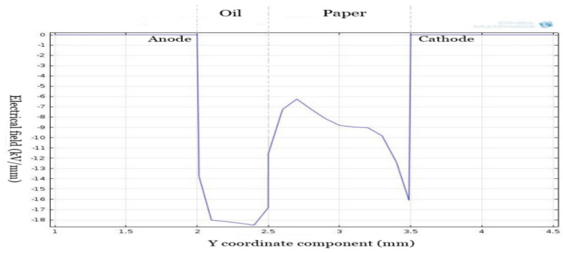


(b) With space charge

Figure 7 Electric field of fresh oil and oil impregnated pressboard under 12(kV/mm) adding and without adding space charge at 10799s for a polarity reversal time of 60s.



(a) Without space charge



(b) With space charge

Figure 8 Electric field of fresh oil and oil impregnated pressboard under 12(kV/mm) adding and without adding space charge at 10861s for a polarity reversal time of 60s.

Table 3 Electric field of the fresh oil pressboard under 12 kV/mm for various polarity reversal time

PR time(s)	E_{max1}(kV/mm)	E_{max2}(kV/mm)	f
10	-18.31	-3.605	407.91%
20	-17.82	-3.833	364.91%
30	-17.35	-4.182	314.87%
40	-16.90	-4.446	280.12%
50	-16.47	-4.700	250.43%
60	-16.06	-4.943	224.90%
70	-15.67	-5.175	202.80%
80	-15.29	-5.398	183.25%
90	-14.93	-5.611	166.08%
100	-14.58	-5.816	150.69%
110	-14.24	-6.011	136.90%
120	-13.92	-6.198	124.59%

Table 4 Electric field of the aged oil pressboard under 12 kV/mm for various polarity reversal time

PR time(s)	E_{max1}(kV/mm)	E_{max2}(kV/mm)	f
10	-19.38	-10.278	88.56%
20	-17.81	-10.492	69.75%
30	-16.72	-10.538	58.66%
40	-15.74	-10.539	49.35%
50	-15.05	-10.539	42.80%
60	-14.38	-10.539	36.45%
70	-13.82	-10.539	31.13%
80	-13.51	-10.539	28.19%
90	-13.13	-10.540	24.57%
100	-12.83	-10.540	21.73%
110	-12.57	-10.631	18.24%
120	-12.38	-10.631	16.45%

5.2 Aged oil and oil-impregnated pressboard under 12(kV/mm)

Table 4 summarizes the electric field of aged pressboard using the Maxwell-Wagner theory and the electric field when considering the effect of space charge under different polarity reversal operation time. Compared to Table 3, it is noticed that the electric field E_{max1} shown in Table 4 decreases rapidly. The reason is that the amount of charge density decreases rapidly from 2 (C/m^3) to 1 (C/m^3) within 2 minutes as shown in Figure 2(b). The electric field enhancement factor range in the aged oil-impregnated pressboard varies from 88.56% to 16.45%, which is smaller than the electric field enhancement factor range in the fresh oil pressboard. However, the electric field in the aged pressboard considering space charge E_{max1} is higher than that of the fresh pressboard.

6 CONCLUSIONS

In this paper, the effect of oil-aging property on space charge dynamics in oil and oil-impregnated pressboard has been studied. The electric field based on both space charge density and Maxwell-Wagner theory has been simulated using COMSOL software. Some conclusions may be drawn from the study.

(1) The electric field in oil and oil-impregnated pressboard insulation should be evaluated using the measured space charge rather than the conventional Maxwell-Wagner theory. The difference between the electric field calculated using measured space charge and the Maxwell-Wagner theory for the fresh samples is higher, while this difference is smaller with the aging of samples.

(2) After polarity reversal operation, the homocharge injected within the pressboard act as the heterocharge, which can enhance the electric field in the vicinity of the electrode and the interface between the oil and pressboard. The electric field enhancement factor decreases with the increasing polarity reversal time.

(3) The electric field distortion adding space charge compared to the applied electric field within the pressboard is higher for aged oil samples. The decease in the electric field is more with same polarity reversal operation time for aged oil samples.

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