Space charge dynamics in Oil and thick pressboard combined system under polarity reversal voltage

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***Abstract*- In this study, the space charge dynamics in an oil and oil impregnated pressboard combined insulation system are investigated by the means of pulsed electroacoustic (PEA) technique under voltage polarity reversal conditions. To be closer to the real case in convertor transformers, a 1mm thick pressboard covered with a 0.5mm thick oil film were used as the testing sample. For comparison, three types of oil with different aging stages were used: fresh oil, medium aged oil and severely aged oil. The external electric field was firstly applied +10kV/mm for 1hour, then reversed to -10kV/mm in 1min period. After that, the -10kV/mm was applied for 1 hour. The results have clearly shown the impact of the oil film and the interface between oil and pressboard on charge dynamics under polarity reversal conditions. The electric field enhancement and the time constant of the 'mirror image effect' have been analyzed for different cases.**

I. INTRODUCTION

Due to the increasing trend of power trade, more polarity reversals will be applied in HVDC power transmission system, which challenges the reliability of the insulation system used in the HVDC equipment, such as convertor transformers [1]. In convertor transformers, oil/pressboard combined insulation system is widely used as the main insulation. It has been demonstrated that the dielectric properties of oil/paper or pressboard can be significantly influenced by the presence of space charge under DC stresses [2-7]. It is generally believed that the accumulated charges can distort the electric field distribution in the dielectric material, resulting in local electric field enhancement and leading to accelerate ageing and eventually breakdown. Moreover, many studies in HVDC power cable with polymeric insulating materials [8-10] suggested that the accumulated charges can enhance the electric field after reversing the applied voltage. Recently, researchers paid more attentions to the charge dynamics under polarity reversal voltage in single layer oil impregnated paper/pressboard [11-13]. The accumulated homo charges could lead to the electric field enhancement in the region close to sample surface shortly after the voltage is reversed. However, in a real convertor transformer, the insulation system is much more complex, i.e. the thick pressboards are immersed in the large quantity of insulating oil. In this complex condition, the charge dynamics and its impact are still poorly understood. Moreover, the 'mirror image effect' is defined as an inversed space charge distribution at the steady state when an opposite polarity voltage is applied [10,14]. Therefore, the time constant of the presence of this effect reflects the impacts of accumulated charges on the charge movement to reach steady state after applying a voltage with the opposite polarity and the same magnitude.

In this study, the space charge dynamics in the oil and impregnated pressboard combined insulation system are investigated by the means of pulsed electroacoustic (PEA) technique under voltage polarity reversal condition at room temperature.

II. EXPERIMENTAL SETUP

A. *Sample preparation*

Three types of oil were used in this work, as a comparison, to investigate the impact of oil statuses on charge dynamics, including dry fresh oil, oil with high moisture content and service aged oil. The pressboards used in this work were 1mm thick pressboards with pressed pattern surface. The pressboards were cut into 10 cm in diameter to avoid flashover. The fresh oil was dried and degased at 105 °C for 24 hours. Similarly, the pressboards were dried at 105 °C for more than three days until the mass did not change. After that, the pressboards were immersed into the degased fresh oil and aged oil separately under 60 °C in vacuum for three days to make sure the pressboards were fully impregnated with oil. Then, the samples were natural cooled to the room temperature. The dry fresh oil samples and aged oil samples were directly kept in the vacuum condition. The high moisture ones absorbed certain moisture, and then kept in the vacuum condition. The moisture content of the dry fresh oil is less than 1 ppm, the high moisture oil is about 8 ppm and the aged oil is about 18 ppm, measured by Karl Fischer titration method.

B. *Measurement setup*

The pulsed electroacoustic (PEA) technique was chosen to investigate the space charge profile in this work. Due to the measurement object is a liquid and solid combined system, a purposed built PEA system was established as shown in Fig.1. The ground electrode, a 15mm thick aluminum plate, was modified to a container with 12 cm in diameter and 5mm in depth. This container can contain about 3 mL oil. A 0.5 thick PTFE film ring was applied between the pressboard and the ground electrode to create a 0.5 mm thick oil gap. Moreover, a PVDF film with 40 μm in thickness was used as piezoelectric sensor to overcome the large acoustic attenuation in thick pressboard samples. The high voltage pulse used in this work is 1 kV, 1 kHz with 5ns in width. Compared with the applied

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voltage (15kV), the effects caused by the pulse voltage can be ignored.

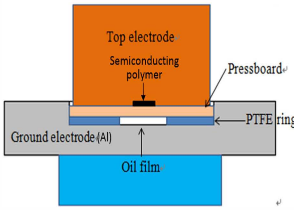


Fig. 1 Experimental setup for PEA system.

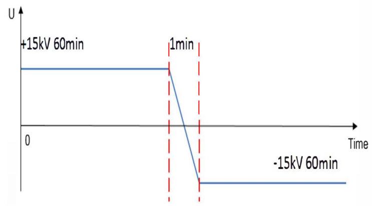


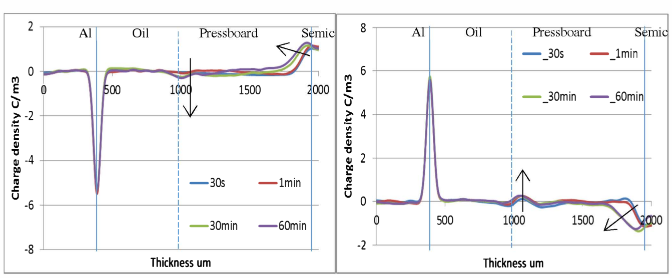
Fig.2 Polarity reversal voltage.

As shown in Fig.2, the applied voltage begins from +15 kV for 60 mins (pre-stressing process), which is the first stage. Then, the second stage is the applied voltage gradually decreases and reverses to -15 kV within 1 min (polarity reversal process). After that, the -15 kV is applied for another 60 mins, which is the third stage.

III. EXPERIMENTAL RESULTS

A. *Dry fresh oil samples*

The charge dynamics during the polarity reversal voltage application are shown in Fig.3. The subplot A) shows the space charge profile during the first stage of pre-stressing process. In general, very limited charges are injected and accumulated in the insulation system within the 1 hour stressing time. A small interfacial peak is observed between the oil gap and the pressboard with the same polarity as the aluminum electrode (cathode in pre-stressing process). This agrees with the Maxwell-Wagner polarization [9], i.e. $(\sigma_p/\sigma_o) < (\varepsilon_p/\varepsilon_o)$, that the polarity of the interfacial charges are the same as the polarity of oil side electrode (Al). , where the σ_p and σ_o represent the conductivity of impregnated pressboard and oil; the ε_p and ε_o represent the permittivity of the impregnated pressboard and oil. At the semiconducting polymer electrode (anode) side, the anode peak is moving into the sample. This suggests that positive charges are injected into the pressboard bulk. The subplot B) shows the charge dynamics after the polarity reversal. Due to that very little charges are injected and accumulated during the pre-stressing process, the polarity of space charges is quickly reversed with the external voltage. Therefore, the 'mirror image effect' can be quickly observed.



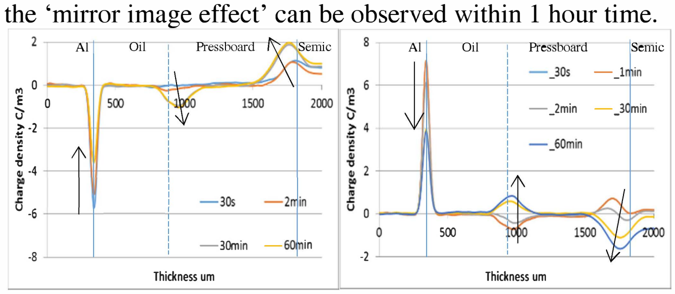
A) B)

Fig. 3 Space charge profile for dry fresh oil samples before (A) and after (B) polarity reversal.

B. *High moisture oil samples*

As illustrated in Fig.4 A), by using oil samples with high moisture, much more substantial space charge injection can be observed during the first stage of pre-stressing process. The cathode peak and anode peak are decreasing with the voltage application, indicating homo-charge injection. The amplitude of the interfacial peak increases significantly due to more injected negative charges from the cathode. Meanwhile, it can be observed that the interfacial charges do not stay at the interface, but move into the pressboard bulk slowly. This phenomenon has been reported in our previous work [15].

After the polarity reversal process, as shown in the subplot B) of Fig. 4, the polarities of both electrodes have changed with the applied voltage. However, a large amount of charges which were accumulated during the first stage of pre-stressing process remain for more than first two minutes after reversal in the insulation system. The presence of negative charges at the interface and the positive charges near the semiconducting polymer electrode (which becomes the cathode after polarity reversal), act as the hetero charges. Therefore, the peak at anode is obviously enhanced, comparing with the negative peak in the first stage of stressing process. Theoretically, the peak at cathode should also be enhanced due to the accumulated positive charges near the cathode. However, it is difficult to be observed due to the large acoustic attenuation. Moreover, with the negative voltage application (also see subplot B of Fig. 4), charges with opposite polarities are injected into the insulation system, thus the hetero charges gradually disappear and were replaced by the homo charges again. In other words, the negative interfacial peak decreases initially and gradually reverse to a positive peak. In this case, the 'mirror image effect' can be observed within 1 hour time.



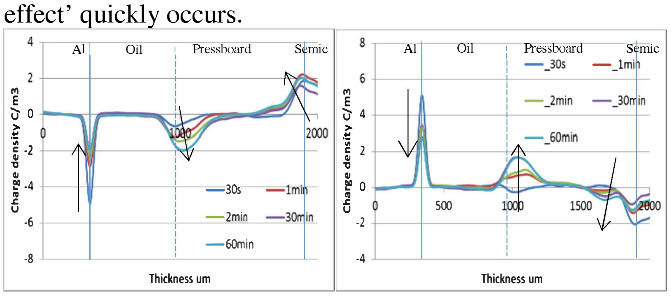
A) B)

Fig. 4 Space charge profile for high moisture fresh oil samples before (A) and after (B) polarity reversal.

C. *Service aged oil samples*

As shown in Fig. 5, the charge dynamics are greatly enhanced in the service aged oil. During the first stage of stressing process, as shown in the subplot A), negative charges quickly inject from the cathode and accumulate at the interface. Moreover, large amount of negative charges move into the pressboard bulk from the interface. At the anode side, positive charges inject into pressboard and then move towards the middle of the sample. Compared with the fresh oil samples above, the amount of the interfacial charges is greatly increased within the same time period. And the injected homo charges distribute deeply near the middle of pressboard. Therefore, the electric field at the middle of the pressboard is greatly enhanced.

After 1minute polarity reversal process, as shown in the subplot B), only little negative interfacial charges and injected positive charges remain in the insulation system. The reason is that charge carriers in the aged oil samples move much faster than that in the fresh oil samples. Thus, on one hand, most of the accumulated charges have decayed during the polarity reversal process. On the other hand, the injection of the charges with the opposite polarities also quickly takes place, which can neutralize the accumulated charges significantly during the reversal and short after the polarity reversal process. In this case, very small increase in the peaks of the both electrodes can be observed. And moreover, the 'mirror image effect' quickly occurs.



A) B)

Fig. 5 Space charge profile for service aged oil samples before (A) and after (B) polarity reversal.

IV. DISCUSSIONS

A. *Electric field distribution*

According to space charge distributions above, the electric field distributions for the three types of samples can be calculated by

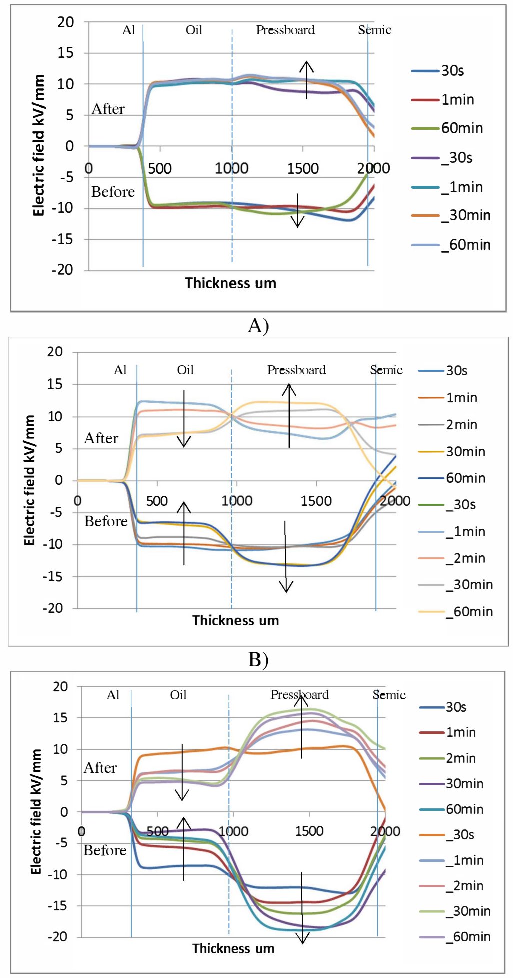
$$E(x) = \int_0^x \frac{\rho(x)}{\varepsilon_0 \varepsilon_r} dx \qquad 0 \le x \le d \tag{1}$$

where $\rho(x)$ is the charge density, ε_0 is the vacuum permittivity, ε_r is the relative permittivity of test sample, d is the thickness of the sample. The results of electric field distributions are shown in Fig.6.

As shown in the subplot A), due to very little space charge accumulated in the insulation system, the electric field distribution changes little (only a small increase in the pressboard). Therefore, after polarity reversal, the electric field distribution is very similar except in opposite direction.

For the high moisture oil samples, as shown in the subplot B), the electric field has been obviously distorted during the first stage of stressing process, i.e. the electric field in the oil keeps decreasing but increasing in the pressboard. After polarity reversal, the electric field in oil is enhanced to 12.5 kV/mm, while the electric field in the pressboard is about 7.5 kV/mm. Moreover, as a consequence of the remaining charges in the pressboard bulk, the electric field at the surface of the pressboard is elevated. Following the injection of charges with opposite polarities, in the oil starts to decrease and while the electric field increases in the pressboard, until the 'mirror image effect' occurs.

For the aged oil samples from service condition, as shown in the subplot C), the electric field is significantly distorted during the first stage of stressing process. After polarity reversal, most of space charges have dissipated, consequently, only a small electric field enhancement in the oil can be observed. Then significant homo charge injection occurs again and quickly reaches to the 'mirror image effect'.



A) B) C)

Fig. 6 Electric field distribution in dry fresh oil sample (A), high moisture fresh oil sample (B) and service aged oil sample (C).

B. *Electric field distortion*

Electric field distortion is one of the major concerns caused by space charge accumulation, especially after polarity reversal. Based on the results of electric field, the electric field enhancement ΔE can be easily calculated by

$$\Delta E = \frac{E_{max} - E_{av}}{E_{av}} \times 100\% \tag{2}$$

where the E_{max} is the maximum value of the electric stress in the dielectric bulk due to the space charge accumulation; E_{av} is the average value of the applied electric stress.

In order to have a better understanding of the electric field distortion under polarity reversal voltage, the electric field enhancements in the oil gap and pressboard are separately analyzed, as shown in Fig.7.

The results above indicate that: the electric field in the dry fresh oil sample is slightly distorted in general; in the high moisture oil sample, the electric field distortion approaches between oil gap and pressboard, around 35%, which is the largest electric field enhancement in the oil gap; and in the aged oil sample, the electric field distortion in the pressboard is very severest (above 80%), but the impact of polarity reversal seems very limited.

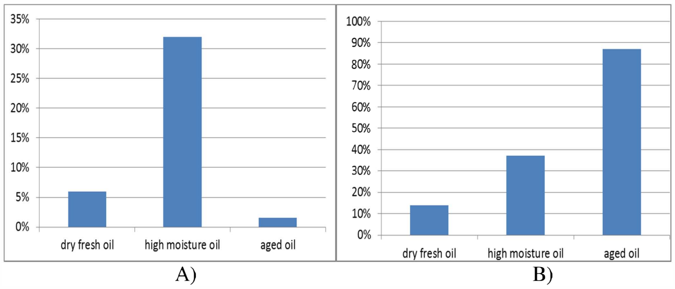


Fig. 7 Electric field enhancement in the oil gap (A) and pressboard (B).

C. *Time to reach 'mirror image effect'*

Due to the different status of the oil, the time constants that the 'mirror image effect' occurs are very different. As shown in Table.1, both dry fresh oil and aged oil can quickly reach to 'mirror image effect' shortly after polarity reversal, although the reasons are very different: for the dry fresh oil samples, very little charges are accumulated in the insulation system, while for the aged oil samples, most of accumulated charges have dissipated away during the 1min polarity reversal process. For the high moisture oil samples, a large amount of charges are accumulated in the insulation system and most of them decay slowly. Therefore, longer time is needed to reach the 'mirror image effect'.

TABLE I
Time for 'mirror image effect' occurring

Sample Types	Time constant (min)
Dry fresh oil sample	2
High moisture fresh oil sample	45
Service aged oil sample	5

V. CONCLUSIONS

The space charge dynamics in an oil and oil impregnated pressboard combined insulation system under polarity reversal conditions have been studied by using the purposed built PEA system. The results clearly show the influence of oil status on space charge dynamics in such an insulation system.

When using dry fresh oil, the space charge phenomenon is very weak, only little charges are injected and accumulated in the insulation system. Therefore, the electric field enhancement is very small and the 'mirror image effect' occurs quickly.

When using high moisture oil, the charge injection is greatly enhanced. A large amount of charges accumulate at the interface between oil and pressboard, and also in the pressboard bulk. These charges decay slowly during the polarity reversal and enhance the electric field in oil and pressboard surface as hetero charges shortly after polarity reversal.

When using service aged oil, the charge injection is further enhanced. More fast moving charges accumulate in the insulation system, which could decay very quickly. Most of charges disappears within the 1min polarity reversal time. Therefore, the electric field is greatly enhanced in the pressboard during the DC voltage application, but less affected by the polarity reversal.

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