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PS2: Materials

Effect of thermally aged oil on space charge dynamics in oil/paper insulation system

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SUMMARY

The formation of space charge in oil/paper insulation system can lead to material degradation in the high electrical field region and affect system reliability. Therefore, it is important to understand factors that affect space charge formation in oil/paper insulation system. In the present study the effect of thermally aged oil on space charge dynamics in oil/paper insulation system has been investigated using the pulsed electroacoustic (PEA) technique under different dc electrical fields at room temperature. The condition of oil was characterised. The ultraviolet/visible (UV/Vis) spectrum of oil shifts to visible wavelength and the oil acidity increased as the ageing time increased. It has been found that oil property has a significant effect on the space charge distribution of oil/paper insulation system. The more the deterioration of the oil and the higher the applied voltage, the larger the amount of negative charge injected into the paper near to the cathode and the positive charge accumulated at the paper-paper interface near to the cathode. The maximum electric field strength for oil/paper sample with seriously aged oil under 4kV and 6kV is more than 20% higher than its average electric field strength.

KEYWORDS

Space charge, electric field enhancement, oil/paper insulation, thermal ageing, transformer insulation

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1. INTRODUCTION

Pursuing high efficiency in electric power transmission and renewable energy has led to the rapid development in high voltage DC (HVDC) transmission systems. HVDC transformers are an essential part of the DC transmission system. Consequently, the electrical performance of the oil/paper insulation system for HVDC transformers is a new research area and has attracted significant interest from both manufactures and utilities.

Previous research on space charge formation in oil/paper insulation system by PEA method has found that homo-charge injection takes place in multi-layer paper impregnated with oil when subjected to dc electric field [1, 2]. Charge dynamics change with both electric field strength and temperature [1, 2]. The interface between paper layers acts as a barrier that blocks the charge movement. Taking into account that the level of oil contamination could determine the dielectric safety margin of both new and service aged oil/paper insulation system [3], and power transformers usually contain several tons of insulating liquid, the effect of oil on charge formation and transport in oil/paper insulation system is required to be investigated. Additionally, by separating the effect of oil and paper insulation it is possible to understand the mechanism of space charge formation in oil/paper insulation system.

In this paper, the mineral oil was thermally aged at 130°C for up to 22 days and fresh papers were impregnated with the oil aged for different times to form oil/paper insulation samples. Firstly, the property of oil with different ageing conditions is characterised. Secondly, space charge dynamics of oil/paper sample with oil aged for different times are investigated using the PEA technique under two dc voltages (4, 6 kV) at room temperature 15°C. And finally the influence of thermally aged oil on space charge dynamics in oil/paper insulation system is analyzed.

2. EXPERIMENTS

2.1 Materials

In order to investigate the effect of thermally aged oil on the charge dynamics of oil/paper insulation system, the PEA measurements were carried out on new insulation paper immersed in oil with different ageing conditions. The insulation oil used in this experiment was Gemini X mineral oil, which was provided by Nynas Oil Company. Gemini X is inhibited insulating oil with extremely good electrical and excellent ageing properties in accord with IEC 60296(03). The new cellulose insulation paper was provided by ABB Chongqing Transformer Co. Ltd with single layer thickness around 75 μm. The parameters of the paper meet the international standard IEC 554.2.

2.2 Accelerated thermal ageing of mineral oil

Accelerated thermal ageing experiment of mineral oil at 130°C was conducted for 22 days. 200 ml oil was placed in each glass beaker (500ml). In order to simulate plant conditions, an area of 128 cm2 copper plate (thickness 0.2mm) was added into every glass vial according to publication [7, 8]. All beakers containing samples were put into the ageing oven. The oven was then evacuated and purged with dry oxygen-free nitrogen three times before being heated to the required ageing temperature 130°C. After ageing for different times, the ultraviolet/visible (UV/Vis) spectroscopy of oil was carried out using a Perkin Elmer Lambda 35 instrument with quartz cells of path length 10 mm. The optical transmission of the samples was recorded over the wavelength range 190-1100 nm, and the oil acidity was also measured according to IEC 60296.

2.3 PEA measurement

The principle of the PEA can be seen in many literatures [4-6]. The PEA system (PEANUT, made by Five Lab) used in this study has a pulse voltage of up to 600V with a width of 5ns. The bottom electrode is made of 10mm thick aluminum plate and the top electrode is a semiconducting polymer to achieve a better acoustic match. The piezoelectric sensor used was a 9μm thick $LiNbO_3$ film. Before PEA tests on paper immersed in oil with different ageing conditions, several pretreatment were carried out upon paper samples. Firstly, the new insulation paper was cut into a round shape with a diameter of 35mm. Then a lot of paper samples were kept in a vacuum oven at 130°C for 30min and then the moisture content of paper was 0.28%. After that, the paper samples were impregnated with oil of different ageing conditions in a sealed oven under vacuum condition for one day.

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In practical application, oil/paper is usually used as multi-layer insulation. In the present study, the PEA tests were performed on three layers oil/paper samples (~210μm after oil immersed and being pressed by electrodes, as shown in Figure 1). The oil/paper samples were stressed at two different dc voltages (4kV and 6kV) at 15°C. The space charge measurements were taken at various times during the periods of both volt-on and volt-off (short-circuit condition) using the PEA technique. Al electrode serves as the cathode and semiconducting polymer as the anode. In addition, space charge behavior after the removal of the applied voltage was also measured. For each sample, a suitable signal measured at 2 kV was selected as its calibration signal [1, 2].

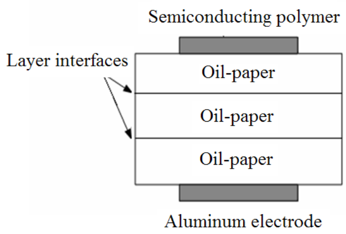


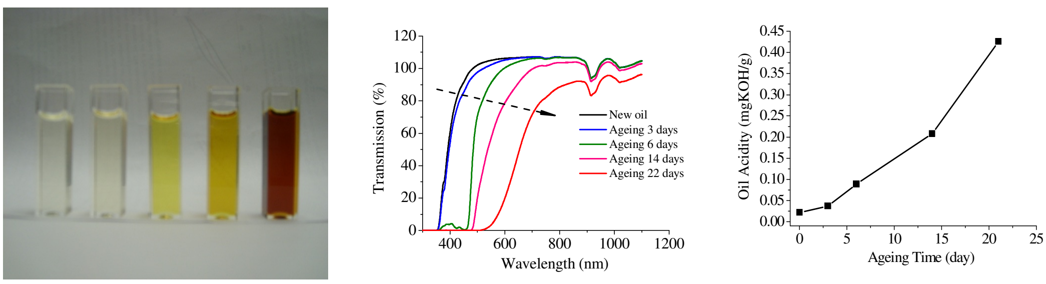
Figure 1. Schematic diagram of sample arrangement.

3. Experimental results

3.1 Oil Properties

The process of oil color change on ageing is generally thought to be associated with oxidation and the formation of extended conjugation [7, 8]. Oil color is an important quality characteristic of oil. In some cases, oil color may serve as an indication of the degree of oil deterioration. Figure 2(a) shows the photographs of oil aged at 130ºC for different times. The oil was bright and clear when un-aged. After the ageing, the oil turned yellow at first and then brown. The UV/Vis spectroscopy of the thermally aged oil is shown in Figure 2(b). The position of the absorption edge is closely related to the extent of oil ageing [7, 9], the broad absorption edge shifts from ultraviolet to visible wavelengths with the thermal ageing time. The results in Figure 2 show that the oil properties become inferior with the thermal ageing.

As a direct parameter to reflect the ageing degree of insulation oil, the oil acidity of oil samples aged for different times is shown in Figure 2(c). It is not surprising that the acidity of the aged oils is considerably higher than the new oil. The more the deterioration of the oil, the larger the value of the oil acidity.



(a) oil color (b) oil UV/Vis spectra (c) oil acidity

Figure 2. Color(a, from left to right is 0, 3, 6, 14, 22 days), UV/Vis spectra (b) and acidity of oil aged for different times

In the following, the space charge behaviors of fresh paper impregnated with oil aged for 0, 14 and 22 days were investigated to see the influence of thermally aged oil on the charge dynamics of oil/paper insulation system.

3.2 Space charge behaviors of thermally aged oil impregnated paper

3.2.1 Space charge behavior of thermally aged oil impregnated paper at 4kV

(1) Volt-on

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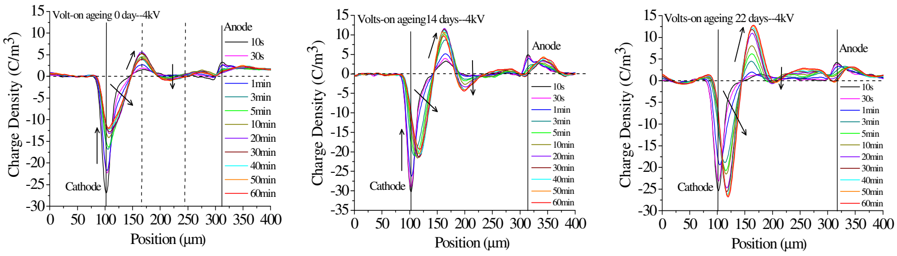
The space charge distribution of paper impregnated with oil aged for different times at 4kV is shown in Figure 3. Charge injection takes place quickly after the voltage is switched on, an approximate equilibrium of the positive and negative charge injection is observed after 30 min. No significant difference is noticed after that time. Homo-charge injection occurs at both electrodes, which leads to the quantities of charges on both electrodes decreases as the stressing time increases. Figure 3 shows that the negative charges accumulate adjacent to the cathode, while the positive charges in the vicinity of the anode. Along with charge injection, the cathode electrode peaks move towards the inner sample direction, and the anode electrode peaks move slightly towards the outer direction of the sample. The more the deterioration of the oil, the longer the distance the electrode peaks move.



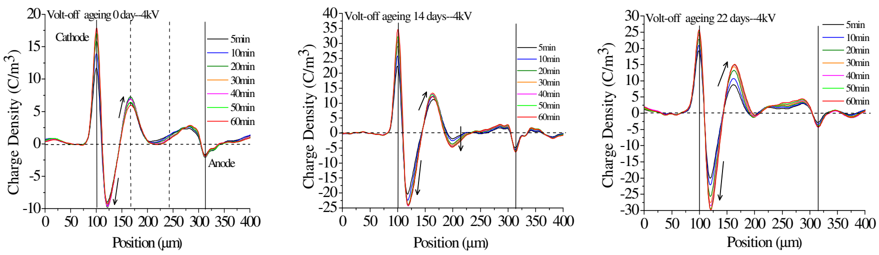
(a) 0 day (b) 14 days (c) 22 days

Figure 3. Space charge distribution of paper impregnated with oil aged for different time under 4kV

As presented in Figure 3, it is worth stressing that the charge profile is almost the same for paper immersed in oil with different ageing conditions except for the differences in charge density magnitude. There is an obvious positive charge peak in the bulk of the samples. Its position remains the same over the voltage application, which validates that the positive charge accumulates at the paper-paper interface near to the cathode. The more the deterioration of the oil, the larger the charge density the positive charge accumulated at the paper-paper interface near to the cathode. For each sample, there is also a small amount of negative charge in the middle layer of the oil/paper sample. Its amount also increases with the duration of the voltage application. There are positive charges and negative charges between the anode and the paper-paper interface near to it. However, the charge distribution between the anode and the paper-paper interface near to the anode is not easy to analyse due to the severe signal scattering [1, 2]. The cathode peak is sharp and evident. In contrast, the anode peak is wide and flat. Theoretically, in a PEA figure, the integral area of positive peaks should be the same as that of negative peaks. However, because of the severe acoustic scattering in oil/paper sample, the test results are somehow different from that predicted by the theory [1, 2].

(2) Volt-off

The volt-on measurement includes contributions from both fast and slow charges, while the volts-off measurement involves mainly slow charges. Taking into account charges trapped in the insulating material are often stable, i.e. slow charge, in this paper, the volt-off measurement on paper immersed in oil with different ageing conditions were carried out, as shown in Figure 4.



(a) 0 day (b) 14 days (c) 22 days

Figure 4. Volt-off (4kV) space charge distribution of paper impregnated with oil aged for different times

The general distribution profiles of the charge trapped in the oil/paper sample with different ageing condition oil is almost the same. Homo-charges were trapped in the vicinity of both electrodes due to charge injection from the electrodes into the oil/paper sample. Positive charge trapped at the paper-paper interface near to the cathode. In the middle layer paper of the oil/paper sample, in addition to the

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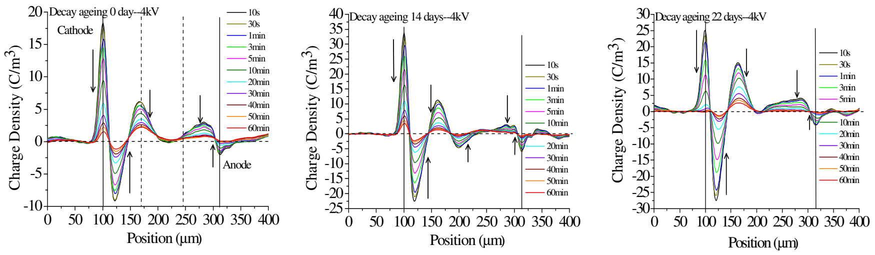
positive charge, there is a small amount of negative charge trapped in the middle position of the single layer paper, and in the single layer paper near to the anode, there is mainly positive charge trapped. All the charge trapped increases although the increasing rate becomes slow with the duration of voltage application.

Figure 4 also indicates that the oil property has great effect on the space charge behavior of oil/paper system. The more deterioration the oil, the larger the amount of homo-charges trapped in the vicinity of both electrodes at the same testing time. Both the maximum charge density of negative charge trapped in the vicinity of the cathode and positive charge trapped at the paper-paper interface near to the cathode increase with the deterioration degree of the oil.

(3) Decay

After 1 hour of 4kV stress, space charge distributions of paper immersed in oil with different ageing conditions after the removal of the applied voltage are shown in Figure 5. The charge distribution profile is similar for all three samples. The charges decrease fast with time in the decay process. After 30 minutes the majority of charges in the bulk including the charge at the interface diminish through either recombination or conducting away from the sample.



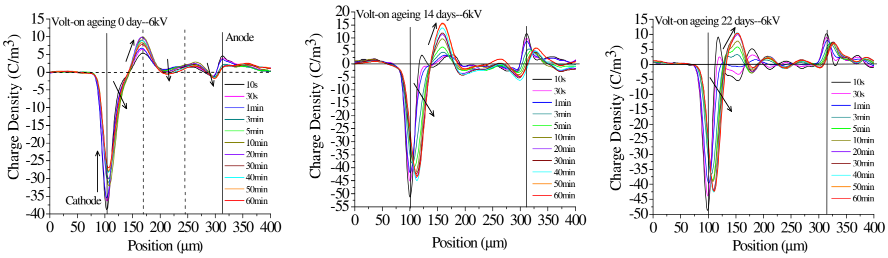
(a) 0 day (b) 14 days (c) 22 days

Figure 5. Decay (4kV) space charge distribution of paper impregnated with oil aged for different times

3.2.2 Space charge behavior of thermally aged oil impregnated paper at 6kV

(1) Volt-on

Figure 6 shows the space charge distribution for oil/paper samples with different oil ageing conditions at 6kV. Compared with the results at 4kV, charge injection phenomenon is more obvious. Homo-charge injection occurs at both electrodes, which leads to a reduction in the quantities of charges on both electrodes as the stressing time increases. The relative stable charge density value on the cathode at 6kV is higher than that at 4kV for the same sample. And the more the deterioration of the oil, the larger the relative stable charge density value on the cathode, i.e. $26C/m^3$ for the oil/paper sample with new oil, $31C/m^3$ for the oil/paper sample with oil aged for 6 days, $41C/m^3$ for the oil/paper sample with oil aged for 14days and $42.5C/m^3$ for the oil/paper sample with oil aged oil aged for 22 days.



(a) 0 day (b) 14 days (c) 22 days

Figure 6. Space charge distribution of paper impregnated with oil aged for different time under 6kV

There are a lot of positive charges accumulated at the paper-paper interface near to the cathode, and there is a small amount of negative charges in the vicinity of the anode, this phenomenon is more obvious than the results at 4 kV shown in Figure 3. Both the charge density of positive charges accumulated at the paper-paper interface near to the cathode and the charge density of the negative charges in the vicinity of the anode increase with the duration of voltage application. In addition, along

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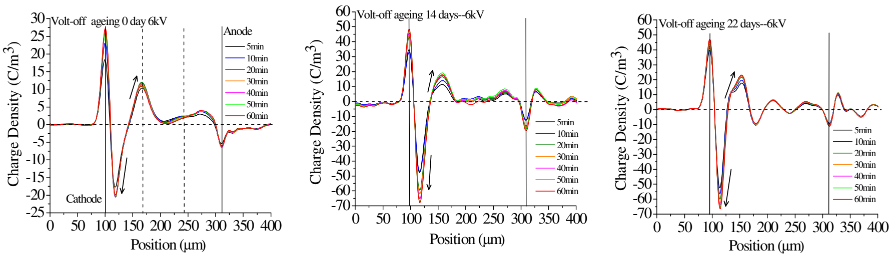
with charge injection, the cathode electrode peaks also move slightly towards the inner sample direction.

(2) Volt-off

The results of the volt-off measurements during the stressing period at 6kV are presented in Figure 7. The amount of negative charge in the vicinity of the cathode and the positive charge accumulated at the paper-paper interface near to the cathode increase with the duration of voltage application. The more the deterioration of the oil, the larger the amount of negative charge injected into the paper near to the cathode, and the larger amount of positive charge accumulated in the paper-paper interface near to the cathode. Compared with the volt-off results at 4kV, there are two features, the maximum charge density value of the negative charges injected into in the vicinity of the cathode and the positive charges accumulated at the paper-paper interface near to the cathode is much larger at 6kV. And the charge distribution profile is different, especially in the paper next to the anode. Negative charge appears. This may relate to charge injection from the cathode, travelling through the bulk and reaching the region.

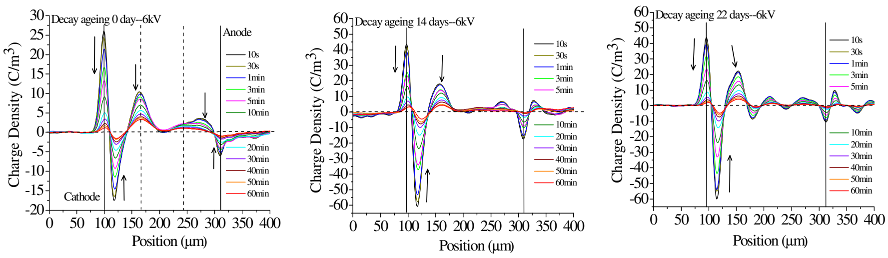


(a) 0 day (b) 14 days (c) 22 days

Figure 7. Volt-off (6kV) space charge distribution of paper impregnated with oil aged for different times

(3) Decay

Figure 8 shows the space charge distribution measured after the removal of the applied voltage 6kV. The charge density in all samples decreases quickly with time, which is similar to the sitution at 4kV. A majority of charge in the bulk diminishes after 30 min.



(a) 0 day (b) 14 days (c) 22 days

Figure 8. Decay (6kV) space charge distribution of paper impregnated with oil aged for different times

3.3 Electric field strength under volt-on

Along with charge accumulation in the bulk, the electric field inside the sample changes. The electric field distribution in the oil/paper sample due to trapped charge can be calculated by integrating the charge density as following [1, 5]:

$$E(x) = \int_0^x \frac{\rho(x)}{\varepsilon_0 \varepsilon_r} dx, \quad 0 \leqslant x \leqslant d.$$

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. During electric field stressing, the test results shown in Figure 3 and Figure 6 demonstrate that both negative and positive charge can be injected into the oil/paper samples, and a large amount of negative charges and positive charges are trapped as space charge in the vicinity of the cathode and at the paper-paper interface near to the cathode, respectively, which can

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lead to the relatively high electric field between the paper-paper interface near to the cathode and the cathode. In this paper, the percentage of the electric field enhancement appears at the paper-paper interface near to the cathode and the cathode during volt-on process under 4kV and 6kV is calculated as following:

$$\Delta E = \frac{E\text{max} - E\text{av}}{E\text{av}} \times 100\%$$

Where Emax, Eav are the maximum electric field and the average electrical field strength during volt-on process for oil/paper sample, respectively. ΔE is the percent of the maximum electrical field strength over the average electrical field strength. As shown in Figure 9, it is noteworthy that the ΔE value for oil/paper sample with oil aged for different times at 4kVand 6kV increases with the oil deterioration degree, but also depends on the applied voltage. Compared with the oil/paper sample with new oil, the maximum values of electrical field strength for oil/paper sample with seriously aged oil (22 days) at 4kVand 6kV are more than 20% higher than the average electrical field strength.

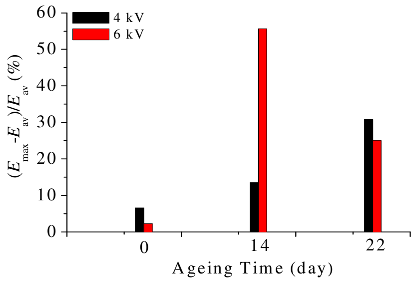

Figure 9. Electric field during volt-on under 4kVand 6kV for oil/paper sample with oil aged for different times.

4. Conclusions

In the ageing process, the mineral oil turned yellow at first and then brown. The broad absorption edge of UV/Vis spectroscopy of the thermally aged oil shifts from ultra-violet to visible wavelengths. The more the deterioration of the oil, the larger the oil acidity.

The negative charges accumulate adjacent to the cathode, and the positive charges accumulate in the vicinity of the anode. There is a significant amount of positive charge accumulated at the paper-paper interface near to the cathode. For oil/paper sample stressed at 4kV and 6kV, the more deterioration the oil, the larger the maximum charge density of the negative charge injected into the paper near to the cathode. And the higher the applied voltage, the larger the maximum charge density value the negative charge injected into the paper near to the cathode. The maximum charge density value of the positive charge accumulated at the paper-paper interface near to the cathode also increases with the deterioration of oil and the applied voltage.

The maximum value of electric field strength during volt-on process for oil/paper sample with oil aged for different times under 4kV and 6kV increases with the oil deterioration degree. Compared with the oil/paper sample with new oil, the maximum values of electrical field strength for oil/paper sample with seriously aged oil under 4kV and 6kV are more than 20% higher than its average electric field strength.

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