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Effect of applied DC voltages and temperatures on space charge behaviour of multi-layer oil-paper insulation

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Abstract. In this paper, space charge in a multi-layer oil-paper insulation system was investigated using the pulsed electroacoustic (PEA) technique. A series of measurements had been carried following subjection of the insulation system to different applied voltages and different temperatures. Charge behaviours in the insulation system were analyzed and the influence of temperature on charge dynamics was discussed. The test results shows that homocharge injection takes place under all the test conditions, the applied DC voltage mainly affects the amount of space charge, while the temperature has greater influence on the distribution and mobility of space charge inside oil-paper samples.

1. Introduction

Insulating paper and oil are widely used as major insulation materials in high voltage direct current (HVDC) equipment, such as converter transformers, DC bushings and DC cables. The formation and dynamics of space charge under high electric fields will change the distribution of electric field inside the insulation material, greatly affecting the insulation performance. For example, trapped or low-mobility electrically charged species within the bulk can give rise to space charge, resulting in localized electric stress enhancement. This can cause further concentration of charge and lead to premature failure of the material [1, 2]. As the insulating paper inside the HCDV equipment takes the form of a multi-layer winding structure, a better understanding of charge dynamics becomes increasingly important in terms of the specific variation of the charge distribution in multi-layer insulation system.

Most of the discussion in the literature has concerned materials such as polymers and ceramics. Compared to measurements in polymers, the measurement of space charge in oil-impregnated materials is much more difficult. A few papers have reported the charge measurements in oil-impregnated insulating materials [3-6], such as space charge in impregnated pressboard and polypropylene laminated paper (PPLP). However, few have reported the space charge behaviour in multi-layer oil-paper insulation under different applied voltages and temperatures.

In this paper, using the PEA technique, a series of measurements were carried after subjecting the insulation system to different applied voltages and temperatures. Charge dynamics in the insulation system during the volts-on condition had been analyzed, and the influence of temperature on charge dynamics discussed.

2. Experiments

In this study, the insulation paper (Croylek Ltd.), has a thickness of ~ 60 μm for single layer. The insulation oil is Nytro 10X transformer oil, provided by Nynas Oil Company.

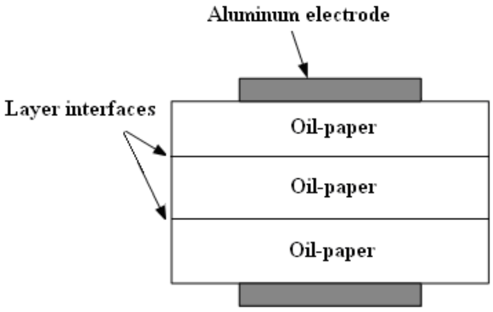


Figure 1. Schematic diagram of sample arrangement.

Before PEA tests, several pre-treatment steps were carried out upon samples. Firstly, the virgin samples were cut into round shapes with a diameter of ~ 2 cm. Then the paper samples were dried in a vacuum oven at 393 K (120 °C) for 20 min, reducing the moisture content to less than 0.2 %. After that, the paper samples were impregnated by fresh degassed insulation oil in sealed oven. As thin paper were used, the sample can be fully impregnated over a time of 24 h. As we know, oil-paper are usually used as multi-layer insulation in practical applications. Therefore, in this experiment, the PEA tests were performed on three layers oil-paper samples (~ 120 μm after oil immersed and being pressed by electrodes, in Figure 1). The samples were stressed at three different DC voltage levels (4 kV, 6 kV, 8 kV) and three temperatures (20 °C, 40 °C, 60 °C). Each time, an electric stressing time of 1 hour was tested.

3. Experimental results and discussion

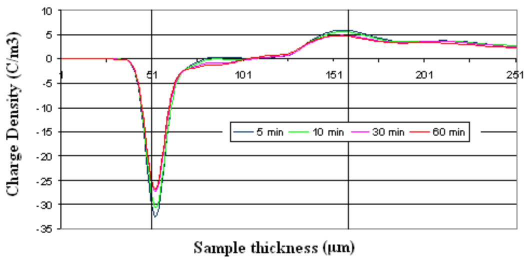
3.1. PEA tests at 20 °C

Obviously from the space charge distributions shown in Figure 2, the cathode peak is sharp and evident; in contrast, the anode peak is wide and flat, this is because of attenuation and scattering of the acoustic waves by the oil-paper sample. As shown in Fig. 2 (a), (b) and (c), the peak value at the electrodes increases with the applied voltage from 4 kV to 8 kV. Under each applied voltage, because of homocharge injection at both electrodes, the amount of electric charge on both electrodes decreases as the stressing time increases. The positive charges accumulate in the vicinity of the anode, while the negative charges adjacent to the cathode. Charge was injected quickly after the voltage was switched on; an approximate equilibrium between positive and negative charge injection was observed after 30 min. No big difference noticed after that time. However, it may take a relatively long period (e.g. up to l0 000 s), to reach global equilibrium, i.e. the equilibrium between charge injection, extraction and transport [7].

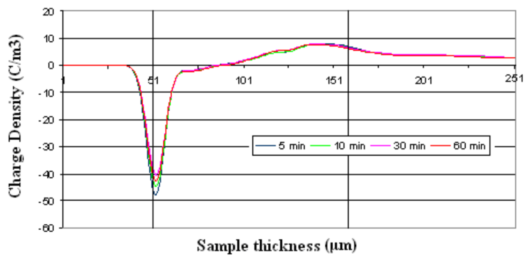
The concentration of injected charge deepens into the bulk with the increase of the applied voltage. Under 4 kV, homocharge of each polarity penetrate no more than one layer. Under 6 kV, homocharge of each polarity enter more than one layer. It is possible that a small quantity of charge was neutralized in the middle layer. Under 8 kV, some homocharge reach the layer near to the opposite electrode.

Along with charge injection, the electrode peaks move slightly towards the centre of the sample, especially for the anode peak. There is less negative charge observed in the region adjacent to the cathode. There may be two reasons for this phenomenon. Firstly, compared to positive charge, the amount of negative charge injection did not increase as much as positive charge with the applied voltage. This indicates that negative charge may travel faster and be subjected to less blocking, reaching the anode quickly or being neutralized on the way. Secondly, the PEA technique only shows the net charge: the injected charge may be present together with the positive charge blocked at the interfaces.

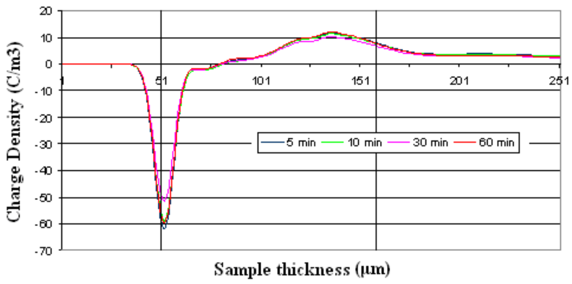
Theoretically, in a PEA figure, the integral area of positive peaks is basically the same as that of negative peaks. However, because of the signal attenuation in oil-paper sample and the contribution of pulse, the test results are somewhat different from the theory. Besides, as a result of the deviation in paper thickness, the positions of electrodes shown in the test results are not exactly the same, which will not effect the final analysis. It is worth stressing that the shape of the charge profile image is not the same for the two electrodes, being broader on the electrode the further away from the detector (anode, right side), as a result of acoustic waves having travelled through the whole insulation thickness.



(a) 4 kV



(b) 6 kV



(c) 8 kV

Figure 2. Space charge dynamics at different DC electric fields (volts on at 20 °C)

3.2. PEA tests at 40 °C

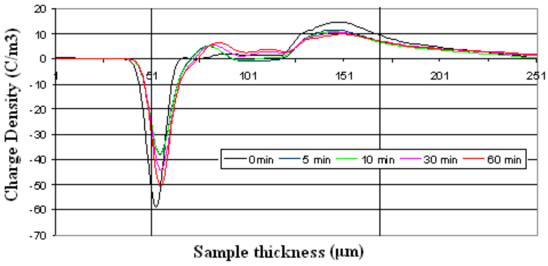
When the test temperature was increased to 40 °C, the volts-on space charge dynamics at different DC electric fields are shown in Figure 3. As we can see, the temperature has a significant effect on space charge behaviour. Compared to 20 °C, the charge density on the electrodes increases at 40 °C. The homocharge injection takes place from both anode and cathode under three applied voltages.

At 4kV (Figure 3 (a)), homocharge injection from the electrodes takes place upon the voltage application, then charges move to the bulk of the oil-paper sample. After 5 minutes DC stressing, positive charges have already reached and began to accumulate at the oil-paper layer interface near to the cathode, and the peak value of charge density there is about 6.0 C/m^3 after 60 minutes DC stressing.

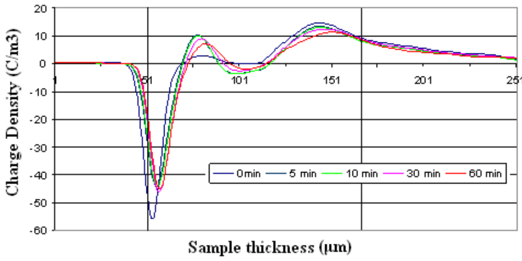
At 6 kV and 8 kV (Figure 3 (b), (c)), once the applied voltage was on, homocharge was rapidly injected into the oil-paper layer interface near to the cathode. More charges were injected compared to 4 kV. After 60 minutes DC stressing, the peak value of charge density in the oil-paper layer interface near to the cathode increased to 7.5 C/m^3 (6 kV) and 12.5 C/m^3 (8 kV).

The effect of temperature on charge dynamics is two-fold. On the one hand, the injected charges move quickly due to increased mobility. On the other hand, space charges gain more energy so that they can conquer the restraint of the first oil-paper layer interface near the anode and travel towards the second layer interface.

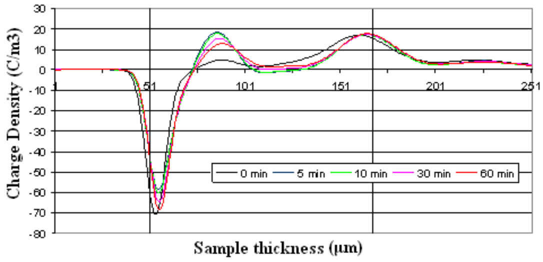
Apart from the charge magnitude, the distribution of space charge inside the oil-paper samples is hardly changed with the increase of the applied voltage.



(a) 4 kV



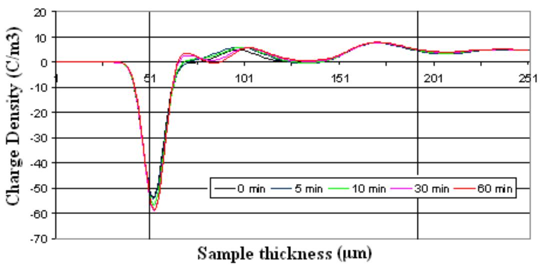
(b) 6 kV



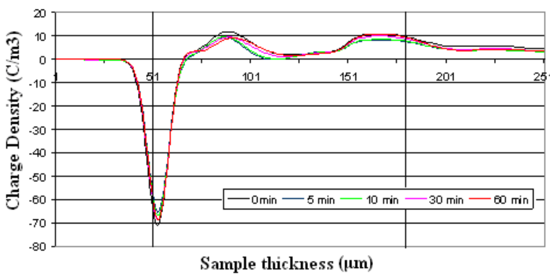
(c) 8 kV

Figure 3. Space charge dynamics at different DC electric fields (volts on at 40 °C)

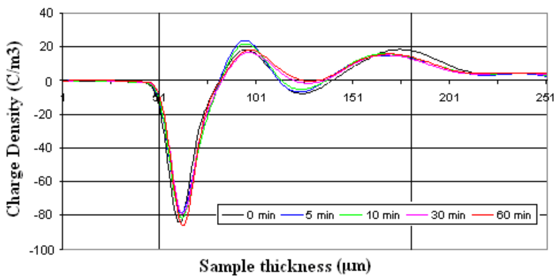
3.3. PEA tests at 60 °C



(a) 4 kV



(b) 6 kV



(c) 8 kV

Figure 4. Space charge dynamics at different DC electric fields(volts on at 60 °C)

When the experimental temperature was increased to 60 °C, space charge measurements were done under different applied voltages (Figure 4). Similar to the situation at 20 °C and 40 °C, homocharge injection from both electrodes are observed. It is worth noting that the positive charges move extremely fast at 60 °C. Significant amount of positive charges have already accumulated at the layer interface near to the cathode once the voltage has been applied, and not much increase in the charge density was observed during the next 60 minutes of DC stressing. Measuring the time for the space charge to reach its saturation (steady-state equilibrium) distribution gives a practical method to describe the charge accumulation rate [8]. The increase in test temperature leads to the increase of the charge accumulation rate as it shortens the time for space charges to reach saturation.

4. Conclusions

Test results of PEA measurements on oil-impregnated paper samples were presented. Space charge dynamics under volts-on condition are analyzed. The following conclusions may be drawn:

(1) Once the external voltage is applied across the sample, homocharge injection takes place under all the test conditions. Positive charges are found to be dominant, and they tend to accumulate at the layer interfaces, increasing with applied voltage. This indicates that the oil-paper layer interfaces act as a barrier for positive charges. This will effect the distribution of electrical field and deteriorate the electrical behaviour of oil-paper insulation.

(2) The positive charges accumulate in different layers at different temperatures. At 20 °C, most of the positive charges accumulate in the layer near to the anode. When the temperature was increased to 40°C, charges move to the bulk and most of positive charges accumulate at the oil-paper layer interface near to the cathode. At 60 °C, both two layer interfaces have some positive charge accumulation.

(3) The amount of injected charge, charge mobility and charge distribution in oil-paper insulation are affected by the applied DC voltage and temperature. As far as the results showed in this paper are concerned, the applied DC voltage mainly effects the amount of space charge, while the temperature has greater influence on the distribution and mobility of space charge inside oil-paper samples.

5. References

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