Moisture effect on the dielectric response and space charge behaviour of mineral oil impregnated paper insulation

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Abstract. Dielectric response and space charge behaviour of oil-paper insulation sample with different moisture contents were investigated using the frequency dielectric spectroscopy (FDS) and the pulsed electroacoustic (PEA) technique, respectively. The influence of moisture on the dielectric response and space charge behaviour of oil impregnated paper insulation was analysed. Results show that the moisture has great effect on the FDS and space charge behaviour of oil impregnated paper insulation. In the frequency range of \( 10^{-2} \sim 10^{6} \) Hz, the conductivity and the capacitance of oil impregnated paper increases with its moisture content. The space charge distribution of oil-paper sample with lower and higher moisture contents is very different from each other. The higher the moisture concentration of the oil impregnated paper, the easier the negative charge penetration into the insulation paper. There is a significant amount of positive charge accumulated at the paper-paper interface near to the cathode for oil-paper sample with lower moisture content. However, the positive charge appears in the middle layer paper for oil-paper sample with higher moisture content. Due to the high conductivity, the charge trapped in the oil-paper sample with higher moisture content disappears much faster than that in the oil-paper sample with lower moisture content after removing the voltage.

1. Introduction
Oil/paper insulation system has been widely used in transformers and cables for quite a long time. However, the oil-paper insulation degrades under a combined stress of thermal, electrical, mechanical, and chemical stresses during routine operation [1-2]. Ageing of the oil/paper insulation system produces moisture [1-2]. At the beginning operation of a transformer, the moisture content is usually < 0.5%, but it can reach 4%~8% at the end of its life [3]. The hazard of water in transformers has been given attention in many studies [4-6]. Moisture is recognized to be the “enemy number one” for transformer insulation after the temperature [7]. The higher the water content in the oil-paper system, the more quickly the cellulose degrades. Moreover, moisture is detrimental to the dielectric properties of oil-paper insulation system.

The space charge measurements in oil impregnated cellulose insulation are much more complicated than that in polymers [8]. There are only a few studies that have been performed on oil/paper insulation at the present. Morshuis and Jeroense [9, 10] made some space charge tests on oil impregnated insulation paper, and concluded from the test results that whatever the combination of paper and oil, three general trends were observed. Firstly, homo-charge is always observed, both at the anode and the cathode. Secondly, specific charge growth/decay pattern occurs. Thirdly, the growth and decay of the charge profiles can be described by roughly two time constants. Ciobanu et al [11],
analyzed the space charge evolution in oil-paper insulation, and associated the mobility phenomena with the mineral content of cable paper, which is helpful to promote the criteria for the best choice of oil-paper insulation technology for dc cables application. Tang et al [12] investigate the space charge formation in oil/paper insulation system by the PEA method and found that homo-charge injection takes place in multi-layer paper impregnated with oil when subjected to DC electric field. Charge dynamics change with both electric field strength and temperature. The interface between paper layers acts as a barrier that blocks the charge movement. Rongsheng Liu et al [8] studied the distributions of electric field and space charge in oil impregnated pressboard using the pressure wave propagation (PWP) technique at different moisture under DC voltages. It has been found that the moisture plays a very important role in the distribution of space charge in oil-impregnated pressboard. The higher the moisture concentration, the faster is the establishment of space charge. However, the current measured can be affected by polarization and variation of permittivity versus the position of samples.

Taking into account that the moisture has great effect on the insulation life and reliability of the oil-paper insulation system, and in practical application, oil/paper is usually used as multi-layer insulation, in this paper, we have studied the effect of moisture on the FDS and space charge behaviour of three layer oil-paper insulation sample.

2. Experiments

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 meeting IEC 60296 (03). The new cellulose insulation paper used was provided by ABB Chongqing Transformer Co. Ltd. The single layer thickness of the insulation paper is 75 µm. The parameters of the paper meet the international standard IEC 641-3-1.

Before the PEA tests on oil-paper insulation sample with different moisture contents, several pre-treatment were carried out upon paper samples. Firstly, the new insulation paper was cut into round shape with a diameter of 35mm. A lot of paper samples were kept in the vacuum oven at 130°C for 1 hour for drying. After that, some dried paper samples were impregnated by oil at vacuum condition. And some dried paper samples were put in the air for moisture absorption. After absorbing the moisture for some time, the paper samples were also impregnated by oil under vacuum condition. All the dried paper samples and wet paper samples were impregnated by oil under vacuum condition for one day. Then the moisture content of the dried oil-paper samples and wet oil-paper samples was measurement using Karl Fischer Titration method. The capacitance and conductivity of the oil-paper sample with different moisture contents was measured by dielectric spectroscopy equipment S1260 Impedance/Gain-Phase Analyzer. The dielectric analyzer using a plate-plate geometry electrode with a diameter of 30 mm. Data were obtained over a frequency range of $10^{-3}$~$10^{6}$Hz.

The principle of the PEA can be seen in many literatures [12-14]. The PEA system (PEANUT, made by Five Lab) used in this study has a pulse width of 5ns. The bottom electrode is made of 10mm thick aluminium plate and the top electrode is semiconducting polymer to achieve a better acoustic match. The piezoelectric sensor used was a 9µm thick LiNbO$_3$ material. For each sample, a suitable signal measured at 2 kV was selected as its calibration signal [12, 15].

In practical application, oil-paper is usually used as multi-layer insulation. Therefore, in this experiment, 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 samples were stressed at two dc voltage levels (4kVand 6kV) at 15°C. Each time, an electrical stress time of 1 hour was tested. The space charge measurements were taken at various times during the periods of both volts-on and volts-
off (short-circuit condition) using the PEA technique. In addition, space charge evolution after the removal of the electric field was also measured.

![Schematic diagram of sample arrangement](image)

**Figure 1.** Schematic diagram of sample arrangement

3. Results and Discussions

3.1. FDS of oil-paper sample with different moisture content

As presented in Figure 2, moisture has significant impact on dielectric properties of oil-paper sample. The conductivity of oil impregnated paper increases significantly with increasing moisture content in the frequency range of $10^{-2} - 10^{3}$ Hz. However, there is little difference between the conductivity curves corresponding to different moisture contents at frequencies higher than $10^{3}$ Hz. The capacitance of oil impregnated paper also increases significantly with increasing moisture content in the frequency range of $10^{-8} - 10^{6}$ Hz, especially in the frequency lower than $10^{3}$ Hz.

![Conductivity and capacitance of the oil impregnated paper](image)

**Figure 2.** Conductivity and capacitance of the oil impregnated paper

3.2. Space charge behavior of oil-paper sample with different moisture contents

3.2.1 Volts-on

Figure 3 shows the space charge distribution of oil-paper sample with two moisture level under 4kV. Charge injection takes place quickly after voltage is switched on. Homo-charges injection occurs at both electrodes, which leads to the quantities of induced charges on both electrodes decreases as the stressing time increases. Positive charges accumulate in the vicinity of the anode, while the negative charges adjacent to the cathode. 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 severer acoustic scattering in oil/paper sample, the test results are somehow different from that from that predicted by the theory [12].

For oil-paper sample with 0.28% moisture content, the space charge distribution under 4kV and 6kV is nearly the same. An approximate equilibrium between positive and negative charge injection was observed after 30 min, no significant difference noticed after that time. Along with charge injection, the cathode electrode peaks move towards the inner sample direction. There is a significant amount of positive charge accumulated at the paper-paper interface near to the cathode. Its amount nearly increases with the duration of voltage application. However, the peak position of the positive charge
accumulated remains the same in the duration of the voltage application, which further validates the positive charge accumulate at the paper-paper interface. 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. The presence of both positive and negative charges in the sample suggests that the injection actually occurs at both electrodes. Charge distribution is also complicated between the anode and the paper-paper interface near to the anode due to the severer deterioration of acoustic signal in this region. Compared with 4kV, the relative stable charge density peak of negative charges at the cathode, and the charge density peak value of positive charges accumulated at the paper-paper interface near to the cathode under 6kV is much larger, as shown in Figure 3.

For oil-paper sample with 4.96% moisture content under 4kV and 6kV, the charge injection phenomenon is very different from the oil-paper sample with 0.28% moisture content. Compared with oil-paper with 0.28% moisture content, charge injects more quickly after voltage is switched on under 4kV and 6kV for oil-paper sample with 4.96% moisture content. A lot of negative charge injection occurs at the cathode, which leads to the quantities of negative charges on the cathode electrode decreases fast as the stressing time increases. There is a positive charge peak in the middle layer paper, and the peak value decreases with the voltage application under 6kV obviously. During the voltage application, there is also a negative peak that appears in the paper near to the cathode due to the significant negative charge injection. Compared with 4kV, the charge density peak of negative charges at the cathode and the positive charges accumulated in the middle layer paper under 6kV is larger, as shown in Figure 3(b) and Figure 3(d). Besides, there is mainly negative charge in the oil-paper sample under 6kV at the end of the voltage application.

3.2.2 Volts-off
As depicted in publication [12, 15], charges can be roughly classified as fast and slow charges. ‘Slow’ charges are those which are essentially trapped in deep traps while ‘fast’ charges are those which escape from the traps very shortly after the DC voltage is removed. The volts-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 volts-off measurement on oil-paper sample with different moisture content had been done, as shown in Figure 4. The distribution of the charge trapped in the oil-paper sample with different moisture contents is different.

For oil-paper sample with 0.28% moisture content under 4kV and 6kV, homo-charges were trapped in the vicinity of both electrodes. Positive charge trapped obviously at the paper-paper interface near to the cathode. In the middle layer paper of the oil/paper sample, apart from the 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. Compared to the results under 4kV, the trapped charge distribution under 6kV stress is similar except that the magnitude is higher.

For oil-paper sample with 4.96% moisture content, negative charge trapped in the whole layer paper near to the cathode under 4kV. While there are negative charges trapped in the two layers paper near to the cathode under 6kV, especially at the end of voltage application due to the significant negative charge injection under higher voltage and higher moisture content. Under 4kV, in the middle layer paper and the layer paper near to the anode there is mainly positive charge trapped. While in the layer paper near to the anode there is mainly positive charge trapped under 6kV. The density peak of charges trapped in the oil-paper sample with 4.96% moisture content is lower than that in the oil-paper sample with 0.28% moisture content at the same testing time under 4kV and 6kV. This maybe related to the high conductivity of oil/paper sample with high moisture content.

![Figure 4](image-url)

**Figure 4.** Volts-off space charge distribution of oil-paper sample with different moisture content

### 3.2.3 Decay

After 1 hour of DC voltage applied, space charge distributions of oil-paper sample with different moisture contents after the removal of the applied voltage were measured and are shown in Figure 5. For oil-paper sample with 0.28% moisture content under 4kV and 6kV, the charge decreases with time. After 30 minutes the majority of charge in the bulk including the charge at the interface diminishes through either recombination with the positive charge or conducting away from the sample.
At the initial of decay, as shown in Figure 5(a) and Figure 5(c), it is obvious that the higher of the applied voltage, the larger maximum charge density value of negative charge and positive charge accumulated near to the cathode at the initial stage of decay. While for oil-paper sample with 4.96% moisture content under 4kV and 6kV, the charge trapped in the oil-paper sample disappears within 10s due to the much high conductivity.

**Figure 5.** Decay space charge distribution of oil-paper sample with different moisture content

4. Conclusions

Moisture has significant impact on dielectric properties of oil-paper sample. The conductivity and the capacitance of oil impregnated paper increases significantly with increasing moisture content in the low frequency range.

Homo-charges injection occurs at both electrodes. Charge injected more quickly after voltage was switched on under 4kV and 6kV for oil-paper sample with 4.96% moisture content compared with 0.28% moisture content. There is a significant amount of positive charge accumulated in the paper-paper interface near to the cathode for oil-paper sample with 0.28% moisture content. There is only a positive charge peak in the middle layer paper for oil-paper sample with 4.96% moisture content.

For oil-paper sample with 0.28% moisture content, homo-charges are trapped in the vicinity of both electrodes. Positive charge trapped obviously at the paper-paper interface near to the cathode. While for oil-paper sample with 4.96% moisture content, negative charge trapped in the whole layer paper near to the cathode under 4kV and 6kV. The density peak of charges trapped in the oil-paper sample with 4.96% moisture content is lower than that in the oil-paper sample with 0.28% moisture content at the same testing time under 4kV and 6kV during volts-off measurement.

Due to the much high conductivity, the charge trapped in the oil-paper sample with 4.96% moisture content disappears much faster than that in the oil-paper sample with 0.28% moisture content after removing the voltage.

5. References

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