Space Charge Dynamics in Lapped Dielectric

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***Abstract*—The lapped dielectric which has superior electrical, mechanical and chemical properties has been used for HVDC cable insulation for many years. Space charge dynamics in such insulation have been studied in this paper. Three kinds of laboratory made samples with polypropylene and Kraft paper laminated have been investigated by the pulsed electroacoustic (PEA) technique under 5kV/mm up to 50kV/mm at room temperature. No charge injection was observed in polypropylene sample when stressed from 5kV/mm to10 kV/mm. The results of polypropylene lapped Kraft paper (PPLP) sample show that charge peaks at the two electrodes drop very quickly after applying voltage. At the same time, a large amount of charges accumulate at the interface area with the same polarity as the closed electrode. The other lapped sample with Kraft paper between two polypropylene layers was also studied at 5kV/mm. The opposite charge polarity peaks were found from the interfaces, suggesting that the ionization in Kraft paper may have a major influence on the electrical performance of the lapped dielectric.**

Keywords—PPLP; space charge; polypropylene; Kraft paper; PEA

I. INTRODUCTION

The lapped type insulation material such as polypropylene laminated paper (PPLP) has been used as a replacement of Kraft paper to improve the AC, impulse and DC breakdown strength and develop lower dielectric loss in some commercial HVDC projects [1-3]. PPLP insulation has been used in different type of underground transmission cable such as oil-filled cable, mass-impregnated cable and high temperature superconductor cable. Liquid insulation, such as low/high viscosity oil, mineral oil or liquid nitrogen, is often added to improve its electrical and thermal performance [3-5].

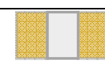
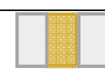
Easy formation of space charge is a major issue for HVDC polymeric cables and charge dynamics in the insulation play a critical role in the efficient and reliable HVDC cable operation. Consequently, significant amount of work has been carried out on charge characteristics in polymeric insulation. On the other hand, the research on space charge dynamic in lapped insulation lags behind. Limited studies about space charge dynamic in oil impregnated PPLP or in liquid nitrogen were available [6-8]. With its potential use for very high voltage DC cable insulation in perspective, it is important to develop a good understanding of charge dynamics and interface in such insulation. In this paper the lapped dielectric samples were made in the laboratory and space charge dynamics in differently configured samples have been investigated under different applied electric fields.

II. EXPERIMENT SETUP

A. Sample preparation

Table 1 shows three kinds of sample tested this paper. Samples B and C were laboratory made laminated samples with Kraft paper and polypropylene film. The Kraft paper thickness is 80µm. It was dried in fan oven at 90°C for 20 minutes to reduce moisture content. After 20 minutes drying, the weight of the sample did not change much. Polypropylene (PP) film is homo-polymer with 100µm thickness. Sample B was made by sandwiching PP film by two layer papers under 5 ton pressure at 160°C for 4 minutes. It has been found that the three layers were reasonably adhered to each other. Sample C was made where the paper was inserted in the middle of two PP films.

Table 1 Sample details used in this paper.

Sample	Structure (Cathode-sample-Anode)	Thickness
A: PP film		100µm
B:PPLP (lapped paper)		220µm
C:PLPP (Lapped polypropylene)		220µm

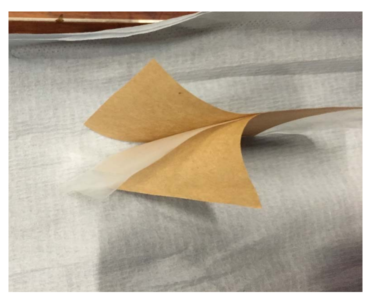


Fig. 1 PPLP sample made in Laboratory.

Fig.1 shows the image of a typical PPLP sample. After the laminated, the total sample thickness is about 220µm which is thinner than the sum of the three layers. If carefully, the each individual layer can be tore apart from the sample as illustrated in Fig. 1. The thickness measurement of each layer after being tore apart remains close to its original thickness. Additionally, the surface of PP film becomes rough, indicating that PP was pushed into pore in the structure of Kraft paper. So the interface between paper and PP in the laminated sample may not be considered as the strict interface but rather as the interface zone.

B. Experimental eqipment

The pulsed electroacoustic (PEA) technique was used to investigate the space charge profile. PEA has been considered as the most effective technique for measuring space charge in solid and liquid dielectrics [7]. The PEA system for the present research has a good spatial resolution and sensitivity because a thin PVDF piezoelectric sensor (9µm thickness), a narrow width pulse generator (2ns width) and 1kV amplitude was used.

Only positive voltage was applied to the samples in this study, the lower cathode is aluminium electrode and the upper anode is semiconducting polymer electrode. All the experiments were carried out at room temperature and under controlled humidity. Space charge characteristics in three kinds of samples were mainly analysed under an electric field range from 4.5kV/mm to 50kV/mm.

Space charge distribution was taken at various times during both volts-on and volts-off conditions and the decay results after the removal of the electric field were also monitored.

III. Results and Discussion

After lapping processing, the samples were tested for space charge distribution straightaway. This will reduce the influence of possible moisture taken by the surface of the Kraft paper from the environment of laboratory on charge dynamics.

A. Charge distribution in Sample A

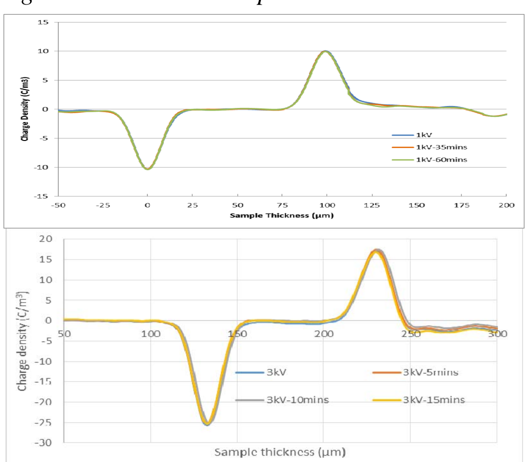


Fig. 2 Space charge distribution in PP film under 10kV/mm and 30kV/mm

Because PP is the selected polymer sandwiched between two Kraft papers, it is therefore logical to study charge dynamics in PP film first. Sample with 100µm thickness was investigated at 10kV/mm initially. As no charge is observed, the applied electric field was then increased to 30 kV/mm. Fig.2 shows the results of charge distributions under10kV/mm and 30kV/mm. Even at an applied electric field of 30kV/mm no obvious charge injection or ionisation takes place up to 15 minutes.

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B. Charge distribution in Sampe B

Fig. 3 shows the space charge distribution in PPLP sample under an applied voltage of 1kV. The dash line is the reference signal of sample under the pulse electric field, which can give the location of the cathode and anode. The anode peak is not as narrow and clear as the cathode peak because of the signal attenuation and scattering of acoustic waves through the PPLP sample. The negative peak captured from the cathode is very small after 1kV was applied. And the expected positive peak can not be observed. This is not simply due to the attenuation of the paper. The net charge captured by PEA is the resultant charge from the injected homo-charge, electrode induced charge and possible ions caused by the applied electric field. In addition, from the early description the interface zone is expected which should influence the charge movement in the sample. The obvious negative and positive peaks in the bulk are believed to be the charge accumulated around the interface zone between Kraft paper and polypropylene.

Volts-off results after 6 minutes of 1kV applied voltage are shown in the lower half of Fig. 3. It shows the information about space charges that remain in the sample. More importantly, it can reveal clearly the interface zones and charge polarity close to the electrodes as the capcitive charge due to the applied voltage is eliminated. Hetero charge can be found in the area of lower paper next to the cathode.

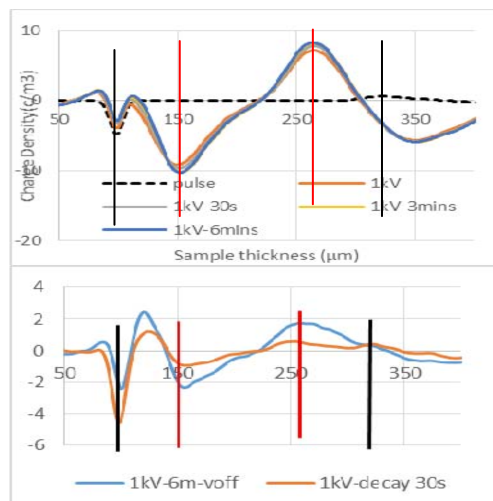

Fig. 3 Space charge distribution in PPLP film under 4.5kV/mm.

Fig. 4 shows volts-on and volts-off results of the charge distribution when the applied voltage was increased to 5 kV. The trace changed obviously in the beginning 30 seconds. The peak at the cathode decreases quickly and on the other hand, both interface peak increase. Again, no peak can be observed at the anode. The volts-off results show that the negative charge in the paper adjacent to the cathode and positive charge in the paper next to the anode decay very fast in the first 30 seconds. In the following 2 minutes, the positive peak in the paper next to the anode and in the interface zone are decreasing, shown as the blue arrow. The negative charge in the interface zone close to the cathode decreases faster than the other interface. And stable amount of positive charge is left, ocuppying half of lower paper and similar amont of the induced charge found at the electrode.

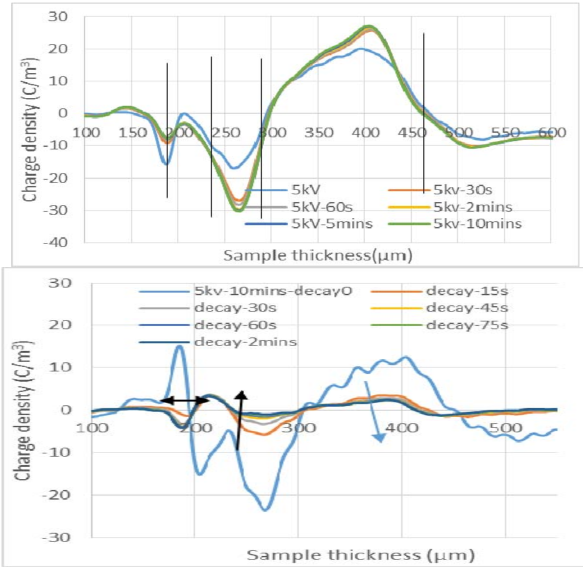

Fig. 4 Space charge distribution in PPLP under 5kV applied voltage.

When the applied voltage was increased to 8kV and the charge profile only changes slightly over a period of 60 minutes as shown in Fig. 5. The decrease in the negative charge at the cathode is faster than that at 5kV and it drops over 50% in the first 15 seconds following voltage application. The positive charges accumulated in PP film drift from the interface to PP bulk slowly. The volts-off result shows a similar trend to that under lower electric field but the decay rate is faster initially. After that the positive charge adjacent to the cathode changes little in 24 minutes.

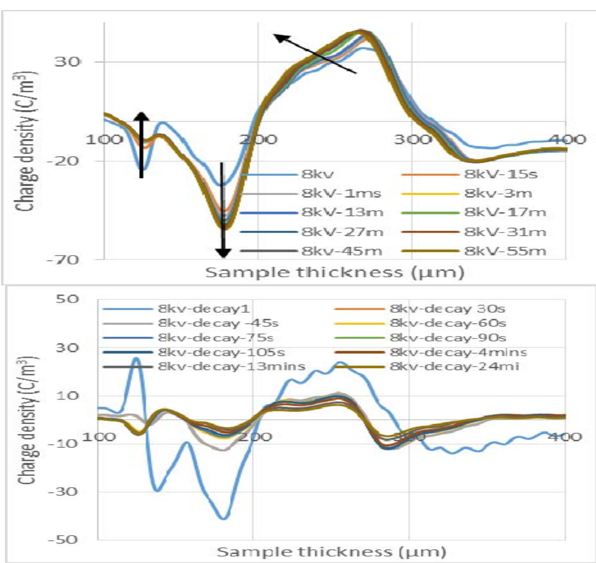

Fig. 5 Space charge distribution of PPLP sample under 8kV applied voltage.

When the applied voltage was increased to 10kV, a similar result was obtainted as shown in Fig. 6. Even though the voltage application time is just 2 minitues, the accumulated charge is obvious. The decay resoult shows that the positive charge decay gently and only negative charge decay gradually.

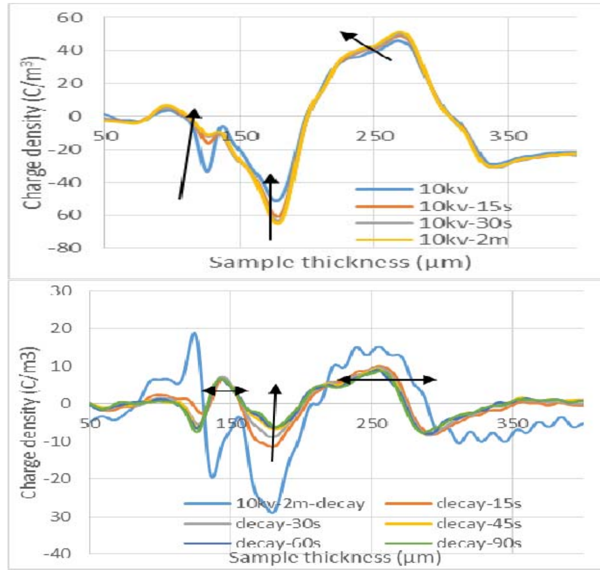

Fig. 6 Space charge distribution under 10kV applied voltage.

C. Charge distribution in sample C

To understand the charge formation in sample B it would be helpful if the charge dynamics in paper can be revealed. However, the thin paper without impregnate is prone to breakdown when high voltage is applied. So we make the sandwich sample with paper between two PP films. The applied voltage was 1kV. Based on the result shown in Fig. 2, no charge injection from the two electrodes should occur. Fig. 7 shows charge distribution observed. Clearly, there are two peaks with the opposite polarity showing in the bulk. The positions are consistent with the location of the two interfaces. The positive charge peak locates at the interface on the cathode side and the negative charge peak on the anode side. The two peaks have a slightly different dynamics.

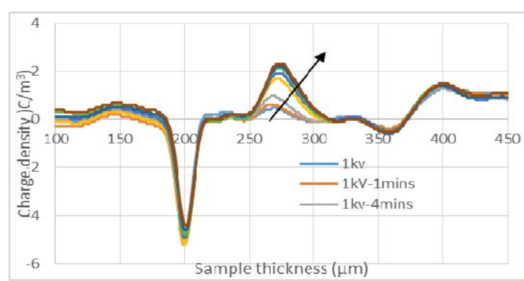

Fig. 7 Space charge distribution of PLPP sample under 1kV applied voltage.

IV. DISCUSSTION

A. Ionization in Kraft paper.

The Kraft paper was made from natural wood pulp and has lots of pores within. It is possible that ionization may take place when the Kraft paper is subjected to the external electric field because of the metal ions from the Kraft pulps [9]. This can explain the results observed charge formation in Fig. 7 as the charge injection from the electrodes can be eliminated.

Fig. 8 shows a schematic representation of charge formation in sample B. Charges in black and red represent charges on the two electrodes, the green one represents the injected charges from the electrode. Charges in blue are the symbol for ions due to ionization occurred in Kraft paper under the applied electric field. Both injected charges and ions will move under the influence of the electric field, i.e. positive charges to the left and electrons to the right. The interfacial zones between Kraft paper and PP may serve as a barrier to slow down or trap charge carriers, leading a charge distribution schematically represented in Fig. 8. Due to limited resolution of the PEA system and attenuation of signals, the resultant charge profiles under various applied electric fields shown in Figs. 3 to 6 are observed.

Fig. 9 shows a schematic representation of charge dynamics in sample C. Because of the lower electric field applied and PP in close contact with the two electrodes, there will be no injected charge in the sample. However, the ionization in Kraft paper can still take place and ions will move under the influence of the applied electric field, i.e. positive ions to the left and electrons/negative ions to the right. Due to the barrier effect of the two interfacial zones, charges stop/slow down, resulting a charge profile observed in Fig. 7.

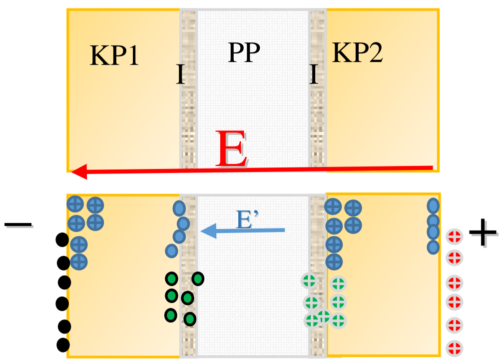

Fig. 8 The illustration of charge in the PPLP sample.

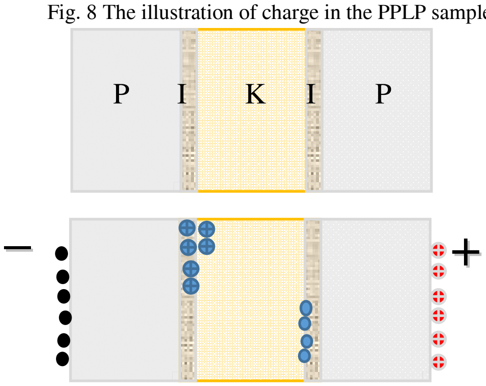

Fig. 9 The illustration of charge in the PLPP sample.

B. The interface zones.

Because of the presence of porosity in Kraft paper, PP and Kraft paper adhere to each other very well when subjected to laminating process. From the volts-off results described earlier, it can be seen, electrically, the charge can be easily trapped in the interface region. When a higher electric field is applied to the sample B (which is the common form used for HVDC cable insulation), more charges, from both injection and ionisation processes, will be formed in the interfacial zones. This will result in a severer electric field enhancement in PP as observed earlier.

C. The sample moisture content.

The sample is not impregnated by the oil in the present study. The layer of Kraft paper should be avoided to absorb the moisture in the process of experiment. But the test was carried out in the open environment. The moisture which is kept in the sample will increase the conductivity and affects the speed of charge build-up in the sample. In addition, water itself can be ionised and contribute to the charges formed in the sample. In reality, oil is used to impregnate Kraft paper to eliminate the effect of moisture.

V. Conlusions

Space charge behaviors in laminated dielectric (PPLP) have been investigated under different applied electric field in this paper. No obvious charge injection for PP sample has been observed when an external field of 30kV/mm was applied. Charge injection from the electrode takes place at very low field when the Kraft paper is in contact with the electrode. The ionization in the Kraft paper is also a major concern for the lapped sample. The interfacial zones in the lapped samples can trap/slow down charge resulting in electric field enhancement in PP.

Acknowledgment

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