Space charge dynamics in the laminated insulation under different temperature conditions

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ABSTRACT

PPLP has been used as the replacement of conventional cellulose Kraft paper insulation to improve the electrical performance of power cables. High viscosity DDB oil impregnated PPLP sample has been studied in this paper. PPLP films with the same laminating processing and impregnated condition were tested at ambient temperature (20 ºC) and elevated temperature (40 ºC and 60ºC) respectively. Space charge distributions in the PPLP films under DC electric field at different temperatures were measured by the PEA technique. The results show that the charge characteristics in oil impregnated PPLP are electric field and temperature dependent. Higher temperature and higher electric field generally lead to higher charge mobility.

KEYWORDS

PPLP, Space charge, PEA technique, DDB oil, MI Cable

INTRODUCTION

PPLP (polypropylene laminated paper) has been used as a good replacement of conventional cellulose Kraft paper in the underground transmission cable. PPLP has higher impulse and DC breakdown strength than Kraft paper insulation. It has been used for insulation of both oil filled and mass impregnated (MI) cables [1, 2]. As the oil feeding is hard for the long distance transmission cable, for example, the submarine cable, therefore, the development of MI cable with PPLP in high viscous oil is very essential.

PP film has been thought as the barrier against the oil migration and cavity generation in the PPLP insulation under the high temperature condition. So it is possible to raise the operation temperature and increase the transmission capacity of DC MI cables. However, space charge dynamics in the oil impregnated PPLP insulation has not been paid much attention and the charges accumulated may affect the insulation performance of PPLP.

Instead of oil filled cable, the impregnated compound in MI cable is high viscosity oil. To better understand the dielectric performance, PPLP impregnated with the high viscosity DDB oil sample has been studied in this paper. The space charge distributions in the PPLP films under DC electric field at different temperatures were measured by the PEA technique.

EXPERIMENT SETUP

PPLP laminated insulation consists of one layer of polypropylene sandwiched by two layers Kraft paper. The sample used in our study is the laboratory made with 80 µm Kraft paper and 25 µm polypropylene with a total thickness of ~170µm when pressed together. Because of the porous structure of cellulose Kraft paper, it is likely that the melted PP will be pressed into paper during the laminating processing. The PP film used for laminated is thin (lower PP ratio in thickness), so the interface zone is narrower compare with the thicker PP (high PP ratio). Fig.1 shows the schematic structure of the PPLP laminated sample.

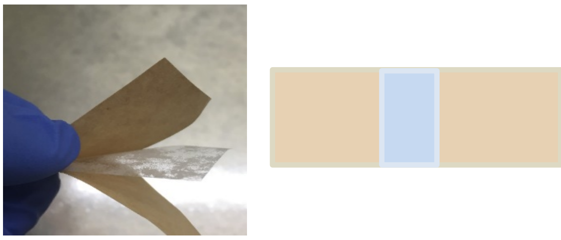

Fig.1: The structure of PPLP with two Kraft paper and one PP layer.

The impregnate compound is high viscosity DDB oil which is commercially available. The sample were dried in vacuum oven at 100ºC after being laminated and before the impregnated processing. The DDB oil was degassed at 100 ºC for 24 hours. Impregnating condition is at 100 ºC vacuum oven for 2 days. After being fully impregnated, the samples were kept in vacuum till test.

The space charge distribution in the PPLP sample was measured by the pulse electroacoustic technique (PEA), which is the most popular technique for the effective measuring space charge in solid and liquid dielectrics. The results give the distribution of net charge across the dielectric sample thickness.

Positive DC voltage was used in this study. The electrodes material are semiconducting layer for the anode and aluminium for the cathode. Since the moisture content is one of the most sensitive factors for oil-paper insulation, the impregnated oil moisture was tested and controlled less than 10ppm. Afterwards the sample can be taken out of the oil container. All the experiments were carried out under controlled humidity. The space charge measurements were started after the temperature became stable and data were collected every 5 minutes for 30 minutes. The charge decay characteristics were also monitored after the removal of the applied voltage.

Electrical conductivity of the oil impregnated Kraft paper under different temperatures was tested within the test cell which can be heated to the desired temperature.

RESULTS

Charge dynamics in the multilayer PPLP sample were studied under different electric fields and different temperatures, 20 °C, 40 °C and 60 °C. The PVDF piezoelectric sensor was attached to the cathode, so the left peak present in the results of PPLP represents the cathode, which is labelled as black solid line and the anode peak is labelled as red line. The two blue dashed lines are the interfaces between PP and Kraft paper.

Charge distribution in PPLP under 10kV/mm

Three PPLP samples were studied under the same DC electric field strength at three temperatures respectively (20°C, 40°C and 60°C). The charge distribution results are shown in Figure 2. It is obvious that charge dynamics change dramatically with temperature increasing. When the test temperature was 20°C as shown in plot (a), a small amount of homo charge injection occurred in the Kraft paper adjacent to the electrodes, especially near the cathode. The electrode peak decreases slightly over the period of voltage application. The interface region gradually accumulated small amount of homo charges, which has the same polarity with the adjacent electrode.

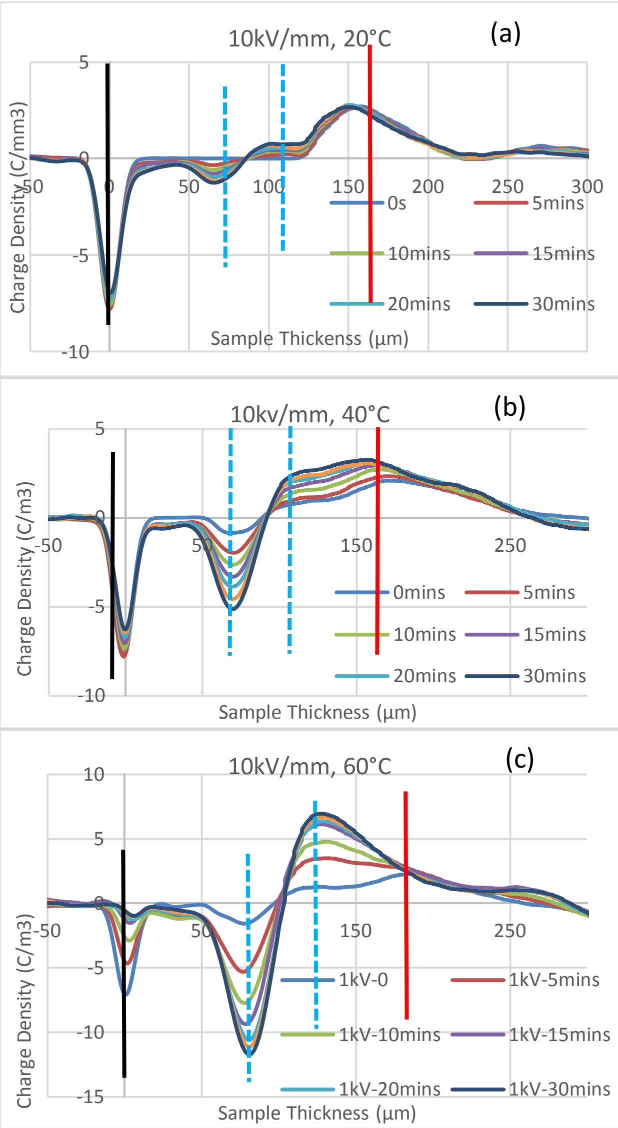

Fig. 2: Space charge distribution under 10kV/mm at (a)20°C, (b)40°C and (c) 60°C.

From plot (b) where the temperature rises up to 40°C, it can be seen that more charge accumulated in Kraft paper layer and at the interfaces. The peak of left interface which is close to the cathode is narrow with large magnitude compare to the right interface. Moreover the negative interface peak at 40°(5C/m^3) is over three times of that at 20°C (1.3C/m^3). Big positive charge package was found in the Kraft paper next to the anode. From plot (c), where the temperature rises to 60°C, the cathode peak decreased fast and only 10% of the initial magnitude remained after 30 minutes. Meanwhile the peak at both interfaces increased significantly, approximately twice of those in plot (b) under 40°C and 10 times in plot (a) under 20°C. And the interface peak after 10 minutes, is bigger than the initial cathode peak. This suggests that the charge mobility under 10kV/mm show the dependence of the temperature.

Decay:

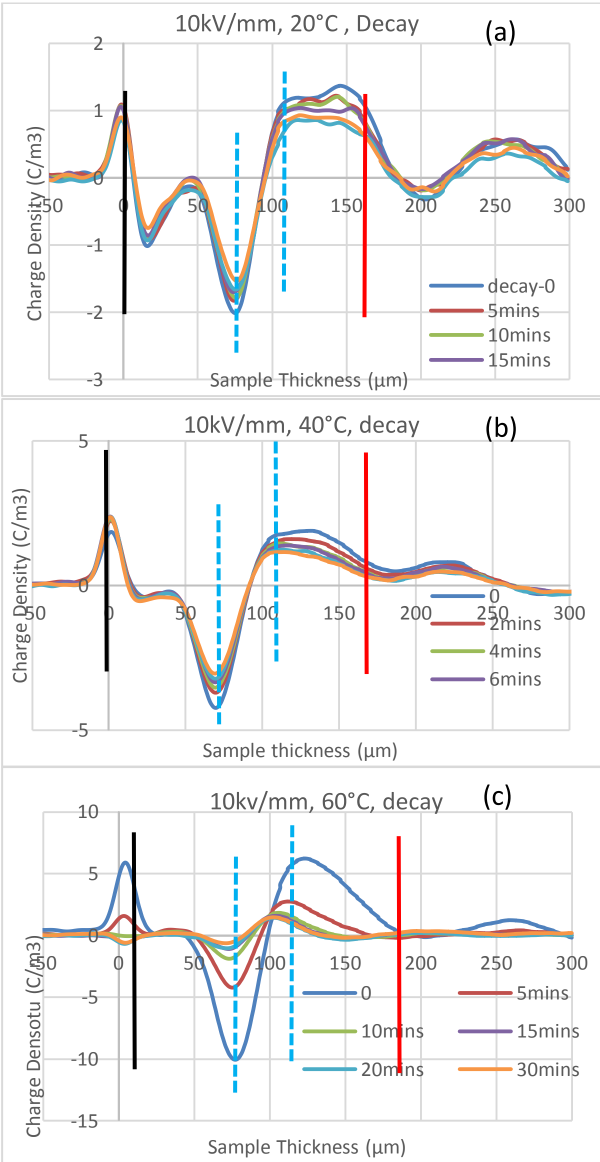

Fig. 3: Charge decay results after the removal of 10kV/mm at (a)20°C, (b)40°C and (c) 60°C.

Figure 4 shows the decay results of high viscosity DDB oil impregnated PPLP sample after the removal of 10kV/mm at three temperatures. Generally speaking, the charge decays faster at 60°C than at 20 and 40°C. Obvious negative peak can be found next to the cathode and positive next to the anode from plot (a) in Fig3. This gives an evidence that homo charge injection takes place from both electrode at 10kV/mm.

The distribution at 40°C shows more charges migrated through the oil Kraft paper layer and was blocked by the interface. The decay process is slow as shown in plot (b). The accumulated charge in plot (c) decay faster than that in plot (a) and plot (b), only 40% charge remains after 5 minutes.

Charge distribution in PPLP under 20kV/mm

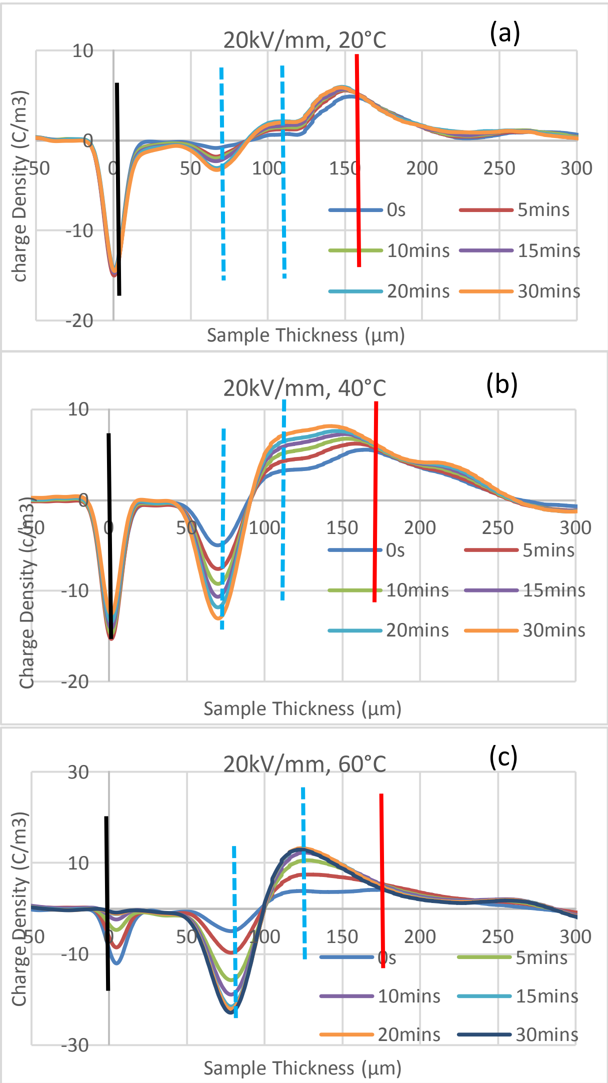

Fig. 4: Space charge distribution under 20kV/mm at (a)20°C, (b)40°C and (c) 60°C.

Figure 4 demonstrates charge dynamics under 20kV/mm at three temperatures. Similar trend can be observed from three plots. Homo charge injected from both electrodes and move into oil Kraft paper. The cathode peak decreased with time, less than 15% reduction at 40°C after 30minutes and even less at 20°C, but over 90% drop at 60°C, nearly disappear. The anode position was changing with temperature as well, small shift to Kraft paper at 20°C but significant shift at 60°C and it becomes hard to identify. It is found that positive charge injected has different mobility compared with negative charge from the cathode. The magnitude of charge peaks captured from the interface increases with temperature. For instant, the charge density is about 3C/m^3 at 20°C, 13C/m^3 at 40°C and 23C/m^3 at 60°C.

Decay:
The decay tests were carried out after removing the 20kV/mm and the results are shown in Fig. 5.

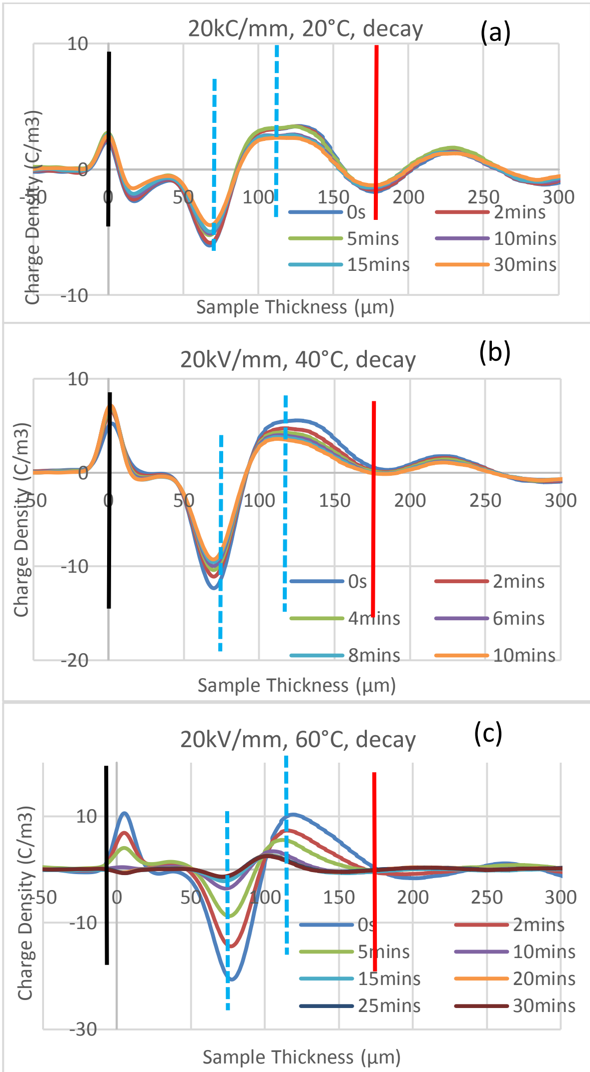

Fig. 5: Charge decay under 20kV/mm at (a)20°C, (b)40°C and (c) 60°C.

Generally, the charge decays slowly at 20°C and 40°C. The magnitude of the left interface peak drops down 17% at 20°C, and 24% at 40°C, after 10 minutes decay. But the charge decreases much faster at 60°C and only 17% remains for the left-hand side interface after 10 minutes. Moreover, based on the charge distributions shown, it seems that charges drift through oil impregnated Kraft paper and disappear from the electrodes at 20°C and 40°C. In contrast, at 60°C the charge accumulated at both interface may recombine in the middle of PP layer at 60°C as the electric field produced by the accumulated charge is high. From plot (c) the dominated charges in the PP Layer after 30 minutes decay are positive.

Charge distribution in PPLP under 40kV/mm

The charge dynamics of oil impregnated PPLP under 40kV/mm were tested at 20°C and 60°C respectively and the results are shown in Fig. 6. Comparing with the results in Fig. 2 and Fig. 4, it shows significant amount of charge injection occurs, resulting in more charge accumulation in the different layers of PPLP. The higher the applied electric field the more charges accumulated at the interface of laminated sample.

At higher temperature, charge dynamics are dramatically enhanced. The interface peaks immediately appeared after the voltage applying and 3 times large after 15 minutes. Most of the charge accumulated at both side of interface and this is looked like the electrodes shift to the interface boundary. Again the interface peak magnitude is bigger than the initial cathode peak after two minutes voltage supply. The charge movement is very fast.

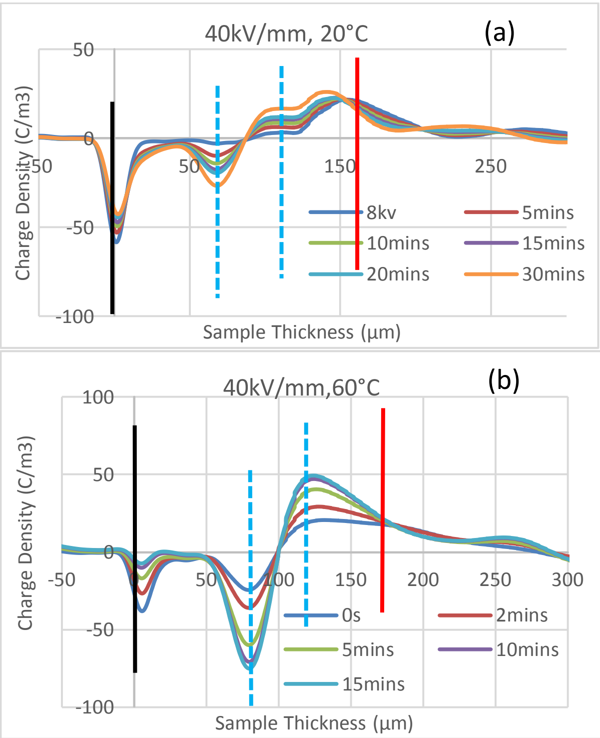

Fig. 6: Space charge distribution under 40kV/mm at (a)20°C, (b) 60°C.

Decay:

Fig.7 shows the decay results of PPLP sample after the removal of applied voltage. Plot (a) shows the very slow charge dissipation processing at 20°C as expected. The remaining charge after 30 minutes decay still counts 70% of the amount charge just after the removal of the applied voltage. On the other hand, from the results shown in plot (b), about 65% charge disappears in the first 3 minutes at 60°C, either from electrode or neutralized by the opposite polarity of charge. It is very interesting to notice that a small package of positive charge still can be captured after 17 hours decay, when the whole measurement system was cooled down to room temperature. This positive charge is believed to the result of the charge injected from the anode and moved across the interface under the influence of the electric field during the volts-on stage.

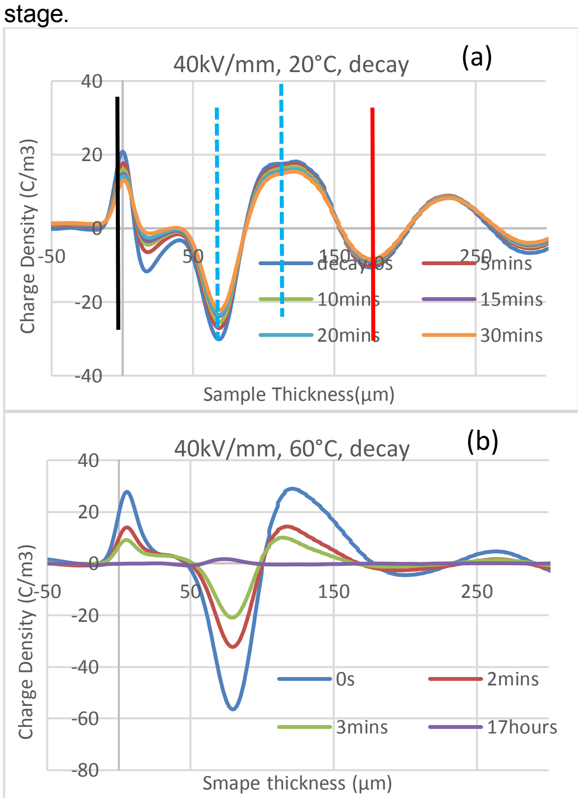

Fig. 7: Charge decay under 40kV/mm at (a)20°C, (b) 60°C.

DC Conductivity in Oil Kraft paper under 20kV/mm

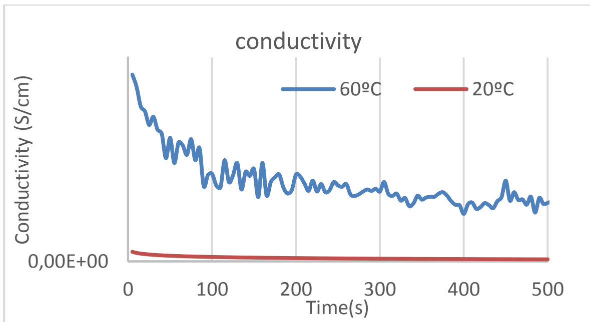

Fig. 8: Conductivity of oil impreganted Kraft paper under 20kV/mm at different temperatures.

The conductivity of oil impregnated Kraft paper is calculated from the measured conduction current, taking the electrode area and sample thickness into consideration. The Kraft paper was tore from the impregnated PPLP sample. The time dependent conductivity results for 20°C and 60°C under an electric field of 20kV/mm is shown in Fig.8. The results of steady state weren't shown in this figure. However the Initial conductivity difference between two temperatures are obvious. It suggests that the ions drift processing in the oil plays an important role in the behavior conductivity in oil Kraft paper.

DISCUSSION

Oil property with temperature

One of the important factors affect the dielectric property in laminated insulation is the impregnated compound. As the high viscosity DDB oil used as impregnated compound in this study, charge dynamics show dramatically different with the low viscosity mineral oil which was presented in our previous work [3]. The viscosity of the present oil is over 20pa/s at room temperature, only 0.005pa/s for lower viscosity oil. From the charge distribution results at 20°C, the charge accumulation is not significant and the movement trend shows gently and slowly. It is believed that the viscosity features of degassed oil affect the dielectric property of PPLP.

When the temperatures rise up to 40°C and 60°C, the charge accumulation gets faster with temperature. The viscosity of the oil is significant reduced with temperature, about 4pa/s at 40°C and 1.5pa/s at 60°C.

The oil viscosity decreases with the increasing of temperature. Increasing temperature generally leads to increasing charge mobility. That means viscosity is inversely proportional to the charge mobility, higher viscosity with lower charge mobility.

The conductivity of the oil or oil paper varies with temperature, water content and ageing condition [4]. In this paper all fresh oil and samples were used and water content is controlled. The temperature dependence of conductivity can be observed in Fig.8. It is consistent with the relations among temperature, viscosity and conductivity. Higher temperature leads to lower viscosity, lower viscosity with higher charge/ion mobility, results in higher conductivity. As the results presented, the charge distribution shows faster movement trend, both injection and extraction, under higher temperature under the same applied electric field.

Electric field distortion across PP layer

Because the homo charge injected from both electrodes and accumulated at the interface, the electric field across the PP layer will be enhanced. It is the sum of external electric field and the electric field produced by the accumulated charge. The more charge accumulated, the large distortion of electric field across PP layer. The enhanced field will force the charge to move into the PP film. This is why the positive charge can be captured in PP layer in plot (b) of Fig. 7 after 17 hours decay. High electric field may accelerate the degradation of polymer.

CONCLUSIONS

Space charge dynamics in the laminated insulation with high viscosity impregnated compound at different temperatures have been studied in this paper.

Under the action of electric fields, homo charge could inject from both electrodes to the oil impregnated Kraft paper, and injected charge accumulate at the interfaces between Kraft paper and PP layer. Interface generally acts as a barrier and hinders the movement of charge carriers. If PP ratio is lower as the sample in this study, it is still possible for the charge carriers moving into pp layer due to higher electric field formed. The injection is both electric field and temperature dependence. There are more charges injected under higher electric field at the same temperature. And more charges are injected at higher temperature when subjected to the same electric field.

The ionisation in the oil Kraft paper is another possible charging processing in the high viscosity impregnated PPLP, especially under high electric field or high temperature. Further research is required to understand the effect of ionisation on charge accumulation in PPLP insulation.

Temperature dependent viscosity of impregnated oil affects charge mobility in PPLP insulation. Higher temperature, lower viscosity, and then higher charge mobility, results in high conductivity of oil and oil paper. Therefore, space charge accumulate faster and more as shown in PPLP at 60°C compared with that at 20°C.

Acknowledgments

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For a Conference citation:

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GLOSSARY

PPLP: Polypropylene laminated paper