

The impacts of the temperature and electric field on the electrical characteristics in semicon-bonded XLPE insulation

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Abstract — HVDC cables play a vital role in the power transmission system for renewable energy and global power trade. Nowadays, the crosslinked polyethylene (XLPE) extruded cables have been widely applied in power industry due to the superior performance on the thermo-mechanical properties and dielectric properties. The low volume conductivity and the minimized space charge accumulation are the two key requirements for a reliable high voltage direct current (HVDC) cable insulation. This paper reports on the impact of temperature and electric field on the space charge behavior and DC conductivity in XLPE material for cable insulation. The samples were carefully prepared to simulate the real cable insulation structure. A layer of LDPE film mixed with DCP (dicumyl peroxide) was sandwiched between two layers of semicon (also contain crosslink agent) and then crosslinked at 200 °C to ensure the semicon layers were thermally bonded with the XLPE insulation. The crosslinked samples were then degassed in the vacuum oven with for 6 days at 80 °C. The space charge characteristics and the conductivity of the semicon-bonded XLPE samples were measured at room temperature and high temperature. The electric fields were kept at 20 kV/mm and 40 kV/mm and the influences of the electric field and the temperature on space charge dynamics and conductivity in the semicon-bonded XLPE samples are discussed.

Keywords — Space charge; PEA; XLPE; HVDC cable; charge injection; conductivity

I. INTRODUCTION

In general, the demand of direct current (DC) transmission for long distance and high voltage applications is increasing due to the advantages of low energy loss [1]. Therefore, the interest in the field of insulation materials for HVDC applications is increasing. Polyethylene (PE) is the most widely used thermoplastic with several desirable properties that can be achieved. For example, to achieve a better dimension stability during heat exposure, crosslinks are introduced in order to create three dimensional network [2]. The network not only improves the heat resistance, but also can enhance durability such as more resistance towards chemical and stress cracking [3]. Thermal and mechanical properties of PE can be significantly enhanced by the crosslinking process [4] and for this reason, XLPE cables are the best choice in power industry for high voltage applications. In crosslinking, the polymer chains are linked

together through chemical reaction by the activation of crosslinking agent under high temperature. In general, DCP is widely used for industrial applications such as AC power cables [5]. However, space charge accumulation in the insulation system is a major concern for DC applications. In Ref [1], the authors reported the dielectric properties of XLPE insulation significantly affected by temperature and space charge characteristics. For example, one of the drawbacks associated with crosslinking is easy formation of space charge, and the presence of space charge is known to affect electrical conduction and can greatly distort electric field distribution and even cause breakdown of the insulation [6, 7]. Other studies suggest the localized charge trapping caused by the crosslinking byproducts can result in increased space charge accumulations and leading to enhancement of local electric field distortions in the XLPE [2, 8, 9]. The enhanced electric stress could further cause breakdown, particularly, under the operational high temperature (70-90 °C) [10-12]. Therefore, the investigation on space charge formation under the conditions of different electric fields and temperatures is vital for understanding the space charge characteristics of XLPE material.

In this paper, the effects of temperature and electric field on the space charge formation in semicon-bonded XLPE under DC electric stress are investigated by the pulsed electro acoustic (PEA) technique. The space charge characteristics and the measurements were recorded at different conditions: 25 °C and 60 °C, 20 kV/mm and 40 kV/mm. In addition, the conductivities of the XLPE samples were also evaluated under 25 °C and 70 °C with 40 kV/mm. All XLPE samples were degassed under the vacuum for 6 days at 80 °C to remove volatile residual by-products.

II. EXPERIMENTAL

A. Materials

Bulk samples used in this study were produced from the cable grade low density polyethylene (LDPE) and the semicon electrodes were made from the same grade of PE material loaded with carbon black. Both materials were provided by the Smart Grid Research Institute (China). Crosslinking agent for the bulk material was dicumyl peroxide (DCP) supplied by Sigma-Aldrich.

B. Sample Preparation

LDPE and DCP (2%) were processed at temperature of 120 °C for 15 min using Thermo PolyLab mixer and then the bulk sample (~300 μm thickness) and the semicon (~50 μm thickness) were separately prepared by hot pressing at lower temperature to avoid the activation of crosslinking agent. The semicon layers were then hot pressed (double sided) into the bulk insulation sample at 200 °C for 10 min to achieve good crosslinking and interfacial bond. The resultant thickness of the samples was approximately 300 μm . Melting of PE material prior to crosslinking is the key function in sample processing [13], therefore to ensure homogeneous dispersion and to facilitate the semicon penetration into the bulk, both materials were allowed to melt for 2 min at 120 °C. The applied load was maintained during the cooling process and the sample was removed from the hot press once 120 °C was reached to avoid bubble formation and further cooled down at room temperature. The schematic diagram of the bonded sample is shown in Fig. 1, the effective bonding of the layered structure was checked by microscope and the electrical resistant test.

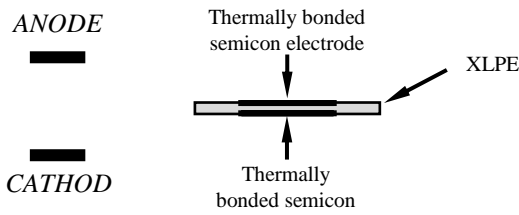


Fig. 1. Schematic illustration of the semicon electrode setups used for PEA and conductivity measurements.

C. Degassing

In common with other crosslinking agents, DCP also produces byproducts (curing decomposition product) within the material from the crosslinking reactions and this can influence electrical and thermal properties of the material [14, 15]. The most common approach to remove the byproducts adopted by the cable manufacturer is degassing. For this, XLPE is subjected to a moderately high temperature to remove volatile residual byproducts. In this work, similar procedure was followed, in which degassing was carried out for semicon bonded XLPE samples in a vacuum oven at a constant temperature of 80 °C for 6 days with the aim of expelling crosslinking byproducts and to highlight any influence this may have on the material performance. The samples were then cooled down at room temperature for 15 min and then sealed in a polyethylene bag, ready for the tests. In this work, some by-products or impurities are still observed, which indicates that the current degassing condition cannot fully remove all the by-products or impurities.

D. Sample Characterization

For space charge characteristics, the pulsed electroacoustic (PEA) method is the most widely used [14]. In this work, the space charge evolution was measured using the PEA technique. For this, the sample was inserted between the lower and upper electrodes and an electric field of 20 kV/mm or 40 kV/mm was applied. Space charge data were acquired both

with the field applied to the sample and during its subsequent decay under short circuit condition. PEA tests were carried out at either 25 °C or 60 °C, and the evolution of charge, polarization (voltage on) and depolarization (voltage off) for each stressing period lasted 60 min. The calibration for PEA tests was done by applying a low voltage (2 kV) for a short period of time (5 seconds) to avoid charge formation in the testing sample.

For electrical conduction measurements, the sample was placed into a test cell with opposing 25 mm diameter electrodes. A constant voltage of 8 kV (40 kV/mm) was applied and the conductivity measurement was recorded for 3 h at 25 °C and 70 °C.

III. RESULTS AND DISCUSSION

A. Space charge profiles under 20 kV/mm 25 °C

Fig. 2 shows the space charge evolution of degassed XLPE sample tested at room temperature under 20 kV/mm. The formation of hetero-charge can be observed at the cathode and homo-charge at the anode in both volts on and volts off space charge profiles. With the voltage application, the accumulation of positive charges can be observed near the cathode, resulting the constant increasing of the cathode peak. This suggests that the ionization of the byproducts, which remain within the sample after degassing process, dominates the space charge behavior in the region adjacent to the cathode. On the other hand, very limited charges can be observed in region near the anode. The charges can be more clearly recognized in the volts off result, as shown in Fig. 2(B): positive charges distribute in a broad region near the anode. This indicates the homo-charge injection dominates the space charge behavior in the region adjacent to the anode. Considering the symmetrical structure of the sample, the differences in space charge distribution near the anode and cathode suggest that the bonded semicon layer may have enhances the positive charge injection rather than negative charge injection. This impact of semicon layer was also reported in Ref [15].

B. Space charge profiles under 40 kV/mm 25 °C

Fig. 3 shows the space charge distribution of degassed XLPE sample tested at room temperature with a higher electric field (40 kV/mm). Similar with the sample tested under 20 kV/mm, hetero-charges accumulated near the cathode and homo-charges distributed near the anode can be observed. However, it can be seen that the amount of hetero-charges reaches to the maximum value shortly after the voltage application, leading to the maximum induced charges on the cathode. The amount of hetero-charges is then gradually decreasing with the voltage application, and a negative peak can be observed in the bulk at the position of 64 μm . This suggests that the large amount of negative charges is injected from the cathode under 40 kV/mm. These negative charges partly overlapped or neutralized with the positive charges adjacent to the cathode, and propagated further into the bulk of the sample. Comparing it with the space charge profiles under 20 kV/mm it seems that the injection of negative charges from the cathode can be significantly enhanced by increasing the applied electric field. Moreover, the increased electric field may also enhance the ionization of the byproducts, leading to the large amount of

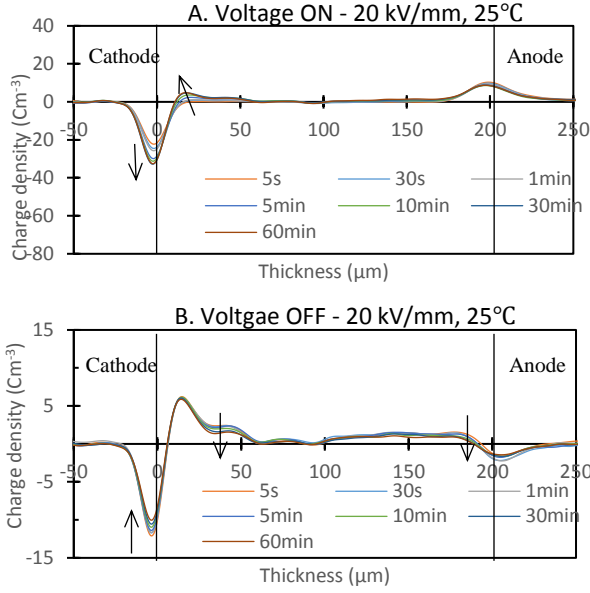


Fig. 2. PEA charge density profile of XLPE (6 days degassed) thermally bonded Sc electrodes. The applied voltage was 20 kV/mm at room temperature (25 °C).

hetero-charges near the cathode at 5 sec. The accumulation of these hetero-charges can greatly enhance the local electric field in the region adjacent to the cathode, leading to the further enhancement of the negative charge injection. Moreover, compared with the charge decay profile under the lower electric field, as shown in Fig. 2(B), a faster charge dissipation process can be observed in Fig. 3(B) - the magnitude of the positive peak adjacent to the cathode quickly drops from 6.1 C/m³ at 5 sec to 3.1 C/m³ at 60 min. And the peak is slightly moving towards to the cathode. A possible reason is that the negative charges, accumulated in bulk of sample, neutralize the positive charges adjacent to the cathode.

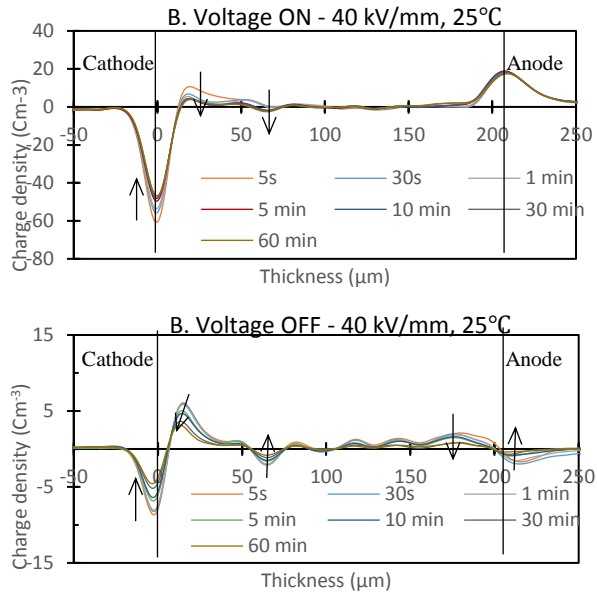


Fig. 3. PEA charge density profile of XLPE (6 days degassed) thermally bonded Sc electrodes. The applied voltage was 40 kV/mm at room temperature (25 °C).

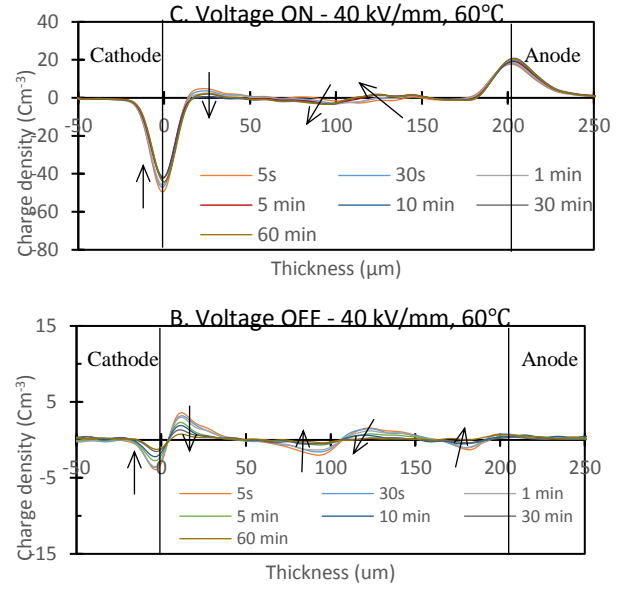


Fig. 4. PEA charge density profile of XLPE (6 days degassed) thermally bonded Sc electrodes. The applied voltage was 40 kV/mm at temperature of 60 °C.

However, the decrease of these negative charges seems less than the reduction of the positive charges adjacent to the cathode. This may indicate that the quick dissipation of these positive charges may also result from other reasons, e.g. the negative charge injection from the cathode to neutralize these positive charges under the electric field caused by the accumulated charges. On the other hand, as shown in Fig. 2(B), the decrease of the accumulated positive charges is very small and slow due to the weak negative charge injection under 20 kV/mm. However, unlike the Fig. 3(B), very few negative charges are further injected from the cathode to neutralize the positive charges, although the interfacial field near the cathode caused by the residual charges are similar (or even higher) with the Fig. 3(B). Based on these facts, an assumption could be made that charges could be more easily injected from electrodes after the application of high electric fields. In other words, the property of interface between the thermally bonded semicon and the XLPE sample could be influenced (or aged) by the charges that are injected and passing through the interface. Further evidences are essential to validate this assumption.

C. Space charge profiles under 40 kV/mm - 60 °C

It can be seen from Fig. 4 that increasing the temperature to 60 °C the space charge profiles became more complex. It can be also observed that the maximum amount of hetero-charges appears immediately after the voltage application, however, the peak value (4.8 C/m³) is much smaller than the one (10.7 C/m³) at room temperature shown in Fig. 3. This may suggest that the large amount of negative charge is injected into the sample within the first 5 sec to neutralize positive charges. The negative peak is observed in the bulk of the sample and this may have resulted from the injected negative charges by the cathode. Comparing with the space charge profile at room temperature (Fig. 3), the mobility of these injected negative charges seems to be significantly

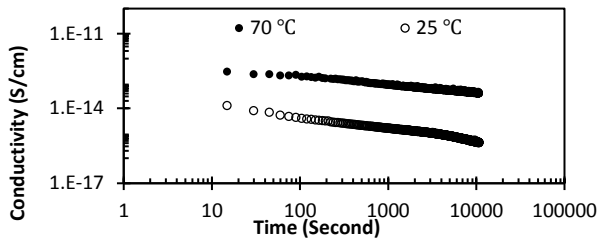


Fig. 5. DC conductivity plots of XLPE sample with thermally bonded Sc electrodes. The applied voltage was 40 kV/mm, (a) tested at 25 °C and (b) tested at 70 °C. Both samples were degassed at 80 °C in a vacuum oven for 6 days.

enhanced due to the high temperature. For instance, in Fig. 4, the negative peak is located at the position of 116 μm at the first 5 sec, and then gradually moves to the position of 96 μm . On the other hand, positive peak can be observed at the position of 96 μm after 5 min, which may have resulted from the positive charge injection by the anode. The dynamics of these negative and positive peaks reflect the differences of charge characteristics between the injected negative and positive charges, e.g. the injected negative charges shows higher mobility than the positive ones.

In the voltage off result shown in Fig. 4(B), small amount of negative charges can be observed adjacent to the anode. The formation of these negative charges may have resulted from the injection by the cathode, then moved and accumulated near the anode. It is also possible that this observed effect may have caused by the enhanced ionization of the byproducts due to the high temperature. These two possible processes may occur at the same time. Moreover, the accumulated charges at high temperature decay much faster and very few charges remain in the sample after 60 min, in comparison with the volts off results at room temperature (Fig. 3). This also indicates the mobility of charges is greatly enhanced by the high temperature. This phenomenon is further validated by the conduction measurement and it is clear from Fig. 5 that the conductivity at 70 °C is about 100 times higher than that of the room temperature.

IV. CONCLUSIONS

In this paper, the influence of temperature and electric field on space charge and DC conductivity of XLPE samples thermally bonded with a HVDC cable grade semicon is reported. Although the by-products or impurities were not fully removed by the degassing process, the result still clearly suggests the space charge dynamics are significantly affected by the applied electric field and the temperature. Some conclusions can be proposed as follows:

1. Under the low temperature and electric field condition, the thermally bonded semicon layer could enhance the injection of positive charges rather than negative charges.
2. By applying the high electric field, charge injection are enhanced, particularly the negative charge injection.
3. Both space charge and conductivity results show that the high temperature can greatly enhance the charge mobility.

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