Space Charge Patterns under Thermal Gradient

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Abstract- Direct observation of space charge injection and transport in solid dielectrics, as well as their spatial evolution over time, is of great importance in the investigation of design stress and the aging mechanism of engineering dielectrics under high electrical DC field. Through model-aided design, the parallel plate, pulsed-electroacoustic space charge profiling technique is extended to include thermal gradient in thin films. The space charge behavior and dynamics within flat dielectric specimens in the presence of thermal gradient have been studied extensively through the modified pulsed-electroacoustic system, to provide insights into the high-field aging mechanisms of new materials developed for energy efficient power devices and renewable integration.

I. INTRODUCTION

High-voltage direct current (HVDC) offers efficient non-synchronized bulk electric power transmissions with economic benefits of reduced power loss and enhanced stability, and has been used widely for grid interconnection, renewable integrations and grid decongestions \cite{1,2}. Free from reactive power loss, HVDC cables become viable solutions for submarine power transmission, off-shore wind power integration, harsh environment electrification and city in-feeds.

Compared with HVDC cables with lapped insulation (mass impregnated or oil filled), HVDC cables with extruded insulation are preferred due to ease of manufacturing, field deployment and maintenance, as well as environmental friendliness \cite{1-3}. However, the application of extruded HVDC cables to date is limited mostly to HVDC system with Voltage Source Converter (VSC) topology where polarity reversal is not required. Charge injection and accumulation as space charge in extruded cable insulation, such as cross-linked polyethylene (XLPE), deteriorate the insulating performance under HVDC \cite{4}. Therefore, it is essential to clarify the formation mechanism and its dependence on aging of space charge \cite{4,5}.

Moreover, the electrical conductivity of typical polymeric insulating materials depends strongly on the temperature \cite{6}. In general, the temperature dependence of electrical properties of insulating materials in HVDC power cables affects all aspects of the formation of space charges, such as the injection, accumulation, transport and recombination, which often develops complicated charge patterns that evolve over time \cite{4}.

Space charge studies have been conducted varying temperature. For example, Fukuma et al. reported space charge measurements at a uniform temperature of up to 90 °C \cite{7}. Furthermore, Choo et al. investigated temperature gradient effects using actual cables \cite{8}. Chen et al. controlled the temperature of upper and lower electrodes using oil and water, and used their improved equipment in which a temperature gradient can be formed \cite{9}.

However, it is becoming of utmost importance, in the light of the diffusion of HVDC links, and considering the need of implementing design and diagnostic procedures able to ensure insulation system reliability, to study space charge injection and accumulation under thermal gradient in the development phase of new extruded HVDC materials.

To speed up the characterization process and investigate in depth the space-charge related mechanisms, it would be advisable to work on thin films, but in the presence of a thermal gradient. In this study, a thin film pulsed-electroacoustic (PEA) system is adapted to include thermal gradients, by incorporating electrical heaters along with a thermostatic oven.

II. EXPERIMENTAL

A. Sample Preparation

In this study, XLPE and EPR (ethylene-propylene rubber) were hot pressed into thin films of 4 cm × 4 cm in size. The thickness of the XLPE and EPR specimens was 300 μm and 450 μm, respectively. For PEA measurement, specimens were metallized on both sides with 80/20 wt% of gold/palladium. Upon sample loading in the PEA cell, a torque of 15 N·m was applied to ensure good contacts and uniform application of pressure.

B. Experimental Procedure

Figure 1 shows schematically the extended PEA system for thermal gradient generation. The acoustic pulse was obtained by the application of HV impulses with 1 to 2 nanosecond rise time and a peak voltage of 350V, over samples DC stressed up.
to ±30 kV. The acoustic waves were detected by a polyvinylidene fluoride (PVDF) sensor with a thickness of 9 μm. Thin film electric heaters were designed and incorporated to heat up the bottom aluminum electrode with sufficient power to generate adequate thermal gradient across sample. Numerical simulation shown in Fig. 2 indicates the generation of a thermal gradient of ΔT=2.2 K through this specific heater design. Furthermore, resistance-temperature detectors (RTD) were deployed to sense the temperatures in the upper part and lower part of the specimen for simulation validation. When needed, the entire equipment can be placed in a thermostatic oven set at a specific temperature.

Results reported in this paper are based on the study performed with an additional thermal gradient of 1.2K across thin films over ambient condition. In actual polymeric HVDC transmission cable, the electric field is designed to be 10-30 kV/mm. However, in this research higher electrical fields of 100 kV/mm for XLPE and 66.7 kV/mm for EPR were employed to study space charge injection and transport phenomena under extreme conditions. Lower test field and higher temperature gradients are being investigated as well. The measurement time of the space charge was 3 h (180 min).

III. RESULTS AND DISCUSSION

A. Space Charge Patterns in XLPE

Figures 3 and 4 show the space charge patterns in XLPE under DC bias of +30 kV and -30 kV, respectively. Figs. 3(a) and 4(a) show the results for a thermal gradient of ΔT=0 (room temperature) and Figs. 3(b) and 4(b) show the results for a thermal gradient of ΔT=1.2 K.

Figure 3 shows that space charges move from the anode to the cathode. In particular, Fig. 3(b) highlights marked space charge transport with the addition of thermal gradient; in this test, dielectric breakdown occurred after 100 min.

In the case of opposite voltage polarity, Fig. 4, space charges move from the cathode to the anode, that is, the opposite direction of Fig. 3. The transport of space charges is more active when there is a thermal gradient, similarly to the results summarized in Fig. 3.
As reported by Hozumi et al., it can be seen that hetero charges accumulated in the vicinity of both electrodes immediately after the application of a voltage [3]. This accumulation of hetero charges is common in both Figs. 3 and 4. Another explanation for this phenomenon has been proposed by Montanari et al., involving a brand new conduction mechanism based on soliton injection and transport [10, 11].

In the case of a thermal gradient, the transport of electric charges is more active and occurs sooner after the application of a voltage.

B. Space Charge Patterns in EPR

Figures 5 and 6 show the space charge patterns in EPR under DC bias of +30 kV and -30 kV, respectively. Specifically, Figs. 5(a) and 6(a) report results for a thermal gradient of \( \Delta T=0 \), while Figs. 5(b) and 6(b) summarize results for a thermal gradient of \( \Delta T=1.2 \text{ K} \).

It can be seen that electric charges in EPR do not readily accumulate or undergo transport with the same extent as that observed in XLPE, although hetero charges are seen accumulated in the vicinity of both electrodes, similarly to XLPE [3]. Therefore, it seems that in EPR there is little transport of electric charges as compared with XLPE. However, in the case shown in Fig. 5(b), dielectric breakdown occurred, similarly to the case of XLPE, after 130 min.
C. Comparison between XLPE and EPR under Thermal Gradient

Space charges appear to become more active in the presence of the additional thermal gradient. The thermal gradient produces an electrical conductivity gradient which depends exponentially on temperature and determines the final distribution of space charges in the bulk [6]. It is noteworthy that the thermal conductivity of EPR is more stable with temperature than for XLPE [11].

The glass-transition temperature \( T_g \) of polyethylene is as low as -120 \(^\circ\)C, and melting point (MP) of crystallites is between 100-120 \(^\circ\)C. \( T_g \) for EPR is about -50 \(^\circ\)C, much higher than that for polyethylene and its crystallinity is extremely low. Structurally, the copolymer Ethylene-Propylene disturbs the molecular arrangement of polyethylene, thus reducing crystallization.

Since EPR loses the double bond of the main chain upon copolymerization, its thermal characteristics improve, in contrast to the monomer of ethylene or propylene, as shown in Fig. 7 [11]. Therefore, this inhibition of molecular arrangement and crystallization, as well as the loss of double bond, may restrict the accumulation and transport of space charges in EPR, and reduce the dependence on thermal gradient.

In XLPE, the accumulation and transport of electric charges is fast, and the effect of the thermal gradient is also large. In particular, dielectric breakdown occurred when a thermal gradient was applied to a bias of positive polarity, as shown in Fig. 3(b).

In EPR, although there is little accumulation and transport of electric charges, breakdown eventually occurred when a thermal gradient was applied to a bias of positive polarity, as shown in Fig. 5(b). Further study of the aging mechanism for both materials is under way.

Table 1 summarizes the above results. It is important to note that dielectric degradation in the bulk seems to accelerate when a thermal gradient is added to a high electric field with positive polarity.

![Chemical structures of ethylene, propylene, and EPR](image)

**TABLE I**

<table>
<thead>
<tr>
<th>Material</th>
<th>Bias (kV)</th>
<th>( \Delta T ) (K)</th>
<th>Accumulation</th>
<th>Transport</th>
<th>Breakdown</th>
</tr>
</thead>
<tbody>
<tr>
<td>XLPE</td>
<td>+30</td>
<td>0</td>
<td>1.2</td>
<td>active</td>
<td>evident</td>
</tr>
<tr>
<td></td>
<td>-30</td>
<td>0</td>
<td>1.2</td>
<td>active</td>
<td>breakdown</td>
</tr>
<tr>
<td>EPR</td>
<td>+30</td>
<td>0</td>
<td>1.2</td>
<td>not evident</td>
<td>breakdown</td>
</tr>
<tr>
<td></td>
<td>-30</td>
<td>0</td>
<td>1.2</td>
<td>active</td>
<td>not evident</td>
</tr>
</tbody>
</table>

IV. Conclusions

The space charge behavior and dynamics in flat dielectric samples with thermal gradients and high electric fields have been investigated by a modified PEA system. Some of the findings are as follows.

1. When there is a thermal gradient, the transport of electric charges is more active and occurs sooner after the application of voltage.
2. Electric charges in EPR accumulate or undergo transport less than in XLPE.
3. Dielectric degradation in a bulk accelerates when a thermal gradient is added to a high electric field with positive polarity.

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References