Correlation of traps inside XLPE and polypropylene with space charge dynamics under polarity reversal condition

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Abstract
Polypropylene (PP) is being considered as a suitable alternative to the cross-linked polyethylene (XLPE) insulation as the latter is prone to the space charge accumulation when subjected to the voltage polarity reversals in line-commutated converter high voltage direct current transmission. This novel contribution correlates the space charge accumulation with the trap distribution inside XLPE and PP under the polarity reversal condition. The pulse electro-acoustic and surface potential decay methods are used to measure the space charge and trap distributions, respectively. These measurements are carried at different poling durations (1 and 6 h at each polarity) and cycles of voltage polarity reversal (one and three cycles) at the electric field of 60 kV/mm. The XLPE shows more homo and hetero charge accumulation than PP. Dominant shallow traps in the XLPE are responsible for the space charge accumulation, whereas deep traps with higher trap density inhibit space charge accumulation within the PP. Furthermore, the positive and negative threshold fields for the space charge accumulation are measured. It is observed that the space charge can be easily accumulated under the negative electric field. Interestingly, the space charge decays rapidly inside the XLPE with the increased number of polarity reversal cycle. A valid theoretical model is developed to explain the space charge accumulation inside the XLPE and PP. The field-assisted ionization plays a key role in the space charge accumulation inside the XLPE.

1 INTRODUCTION

A continually evolving high voltage direct current (HVDC) power transmission has put the focus on the development of new electrical insulations. Despite having better electrical, mechanical, and thermal properties, the extruded cross-linked polyethylene (XLPE) insulation used in the HVDC suffers the problem of space charge accumulation under the high electric field [1–5]. The space charge accumulation distorts the electric field distribution thereby causing the accelerated degradation of cable insulation [6].

Amongst two types of HVDC transmission, the design of line-commutated converter (LCC) based HVDC transmission allows the voltage polarity reversal to realize the bi-directional power flow whenever needed. The voltage polarity reversal results in a severe amount of space charge accumulation, which may reduce the service life of the cable due to its aging. Moreover, it is observed that the breakdown strength of insulation is reduced by nearly 10% after encountering the polarity reversal [7]. Therefore, the development of new materials for HVDC insulation which could perform better under the polarity reversal condition is recently being explored. The nanocomposite insulations have shown a considerable space charge suppression due to the assumed deep traps induced by the nanofiller addition [8, 9]. However, the long-term performance of the nanocomposites remains doubtful [10, 11]. Moreover, as the XLPE cannot be recycled, being recyclable, polypropylene (PP) is considered a suitable alternative to XLPE amid the growing awareness of climate changes. The PP exhibits higher breakdown strength, lesser space charge accumulation, and dielectric loss than XLPE [12–18].

The trapping and de-trapping processes of the charge carriers are closely related to the space charge accumulation. Hence, the trap energy level and trap density remain vital in the space
charge theory. The space charge accumulation in the XLPE is mainly attributed to the presence of the cross-linking by-products [19, 20]. The better performance of the PP towards the space charge suppression is attributed to its morphology [13]. It is found that the number of polarity inversions can reduce the life of the cable insulation [21, 22]. However, the correlation of traps with space charge under the polarity reversal condition is not reported hitherto. Hence, a comprehensive analysis can be performed and presented.

This paper presents the comparative analysis of the space charge accumulation inside the XLPE and PP under the polarity reversal. The measurement consists of different poling durations (1 and 6 h at each polarity) and different cycles of polarity reversal (one and three cycles) at 60 kV/mm. The surface potential decay (SPD) measurement is carried out to analyse the trap distributions. Moreover, the applied electric field is increased at the rate of 10 kV/h to analyse the threshold field for the space charge accumulation.

2 EXPERIMENTAL DETAILS

2.1 Material preparation

XLPE and PP were available in the form of pellets. XLPE preparation: The low-density polyethylene pre-mixed with the anti-oxidant and cross-linking agent were supplied by Zhejiang Wanma Macromolecule Material Co. Ltd., China. The as-received pellets were pre-heated for 5 min and pressed at 180 °C for 30 min under the 20 MPa pressure. Samples were cured with the circulated water cooling.

2.1.1 PP preparation

PP samples were prepared in three steps. First, the PP pellets were pre-heated for 10 min in a stainless steel mould, then hot pressed at 180 °C for 10 min under 20 MPa pressure. Second, the same mould was heated to 200 °C for 5 min under 15 MPa pressure. Last, water-cooling is used to complete the curing process.

Samples with 90 cm diameter and an average thickness of 150 μm are used for the space charge and SPD measurements.

2.2 Space charge measurement

The space charge distribution is measured using the pulsed electro-acoustic (PEA) method. Thin-film sample is placed between the high voltage (Al) and semiconducting (SC) electrode of 1.8 cm diameter. According to the principle of PEA method, the pressure waves are generated in the sample using the pulse generator (magnitude of 500 V, frequency of 100 Hz, the pulse width of 10 ns) and direct current (DC) source (Trek-20/20C). These waves are converted into the electrical signal using the polyvinylidene fluoride (PVDF) transducer. The electrical signal in millivolts (mV) is amplified and recorded continuously in the digital storage oscilloscope (Tektronix MDO3104). LabVIEW signal processing program is used to further process the obtained space charge signal. The space charge signal measurement is carried at 25 °C.

The average space charge density is calculated as follows [23],

\[ Q(t) = \frac{1}{L} \int_{0}^{L} q_p(x, t) \, dx, \]

where \(0, L\) are the cathode and anode positions, respectively and \(q_p(x, t)\) is the space charge distribution.

The residual space charge density is calculated from Equation (1) using the depolarization curves of the space charge measurement.

2.3 Surface potential decay measurement

The trap parameters such as trap energy level and trap density can be extracted from the SPD curves. The corona charging with the needle-plate electrode arrangement is used for the charge injection. Moreover, the mesh grid is chosen to ensure the uniform charge distribution. The distance between needle tip to grid electrode and grid electrode to the sample surface is 5 mm each. The applied DC voltage at the needle tip is 8 kV. After the polarization, the sample is transported under the Kelvin probe of the electrostatic voltmeter to measure the decay of the surface potential at 25 °C. The trap energy level \((E_t)\) and trap density \(N(E_t)\) are calculated from the SPD measurement (i.e. \(V–t\) characteristics) as follows [24],

\[ E_t = kT \ln(\gamma t), \]

\[ N(E_t) = \frac{\varepsilon_r \varepsilon_0 t}{kT_j0(E_t) L^2 q} \frac{dV}{dt}, \]

where \(V\) is the surface potential, \(V; k\) is the Boltzmann constant, 1.38\times10^{-23} \text{ J/K}; \(T\) is the surrounding temperature, 298 K; \(\gamma\) is the escape frequency of the trapped charge carriers, 4.17\times10^{13} \text{ s}^{-1}; \(\varepsilon_0\) is the dielectric constant, 8.85\times10^{-12} \text{ F/m}; \(\varepsilon_r\) is the dielectric constant of the sample under study, 2.8; \(t\) is the time; \(j_0(E_t)\) is 1; \(L\) is the thickness of the sample, 150\times10^{-6} m; \(q\) is the unit electron charge, 1.6\times10^{-19} \text{ C}.

2.4 Voltage application protocol

For the space charge and SPD measurements, same voltage application procedures are used to establish a valid correlation between the space charge dynamics and the trap distribution. It must be noted in the SPD measurement that the electric field is calculated using the grid electrode voltage \((V_g)\) and thickness of the sample \(d\) (i.e. \(E = V_g / d\)), as the role of the needle electrode is only to inject the charge. To realize the
voltage polarity reversal condition, different poling durations and different cycles are used as shown in Figure 1. Hereafter, the space charge measurement consisting of one cycle having the polarity reversal after 1 and 6 h of the positive polarity application will be referred as the 3 h (1 h positive polarization + 1 h negative polarization + 1 h depolarization) and 14 h (6 h positive polarization + 6 h negative polarization + 2 h depolarization) measurements, respectively. Moreover, the cyclic measurement consisting of three cycles of polarity reversal will be referred as 7 h measurement. The poling duration of measurement and number of the cycles are chosen considering the short term (3 h) and long term conditions (14 h) which may prevail in the actual operation of the cable. Also, the safety of the available DC source is the key parameter while choosing the duration of the measurement.

Moreover, the threshold field under the positive and negative electric field is also analysed. To measure the threshold electric field, applied electric field is increased at $\pm 10$ kV/h from $\pm 10$ kV/mm upto $\pm 60$ kV/mm.

3 | SPACE CHARGE ANALYSIS

3.1 | Space charge accumulation threshold

3.1.1 | XLPE

Figure 2 shows the space charge distribution in XLPE under the stepwise increasing electric field at the rate of $\pm 10$ kV/h. This approach is used to analyse the threshold electric field for the space charge accumulation inside the test sample. Anode (A)
and cathode (C) electrodes are marked to highlight the polarity of electric field application at the particular instance. Figure 2(a) shows that under the influence of incremental positive field, significant positive space charges are accumulated within the sample bulk. Also, the charge injection and/or extraction at both the electrodes becomes more severe with the increasing electric field (note that the electrode size becomes bigger). Significant space charge accumulation can be observed at ≥ 20 kV/mm. Moreover, homo charges near the anode can be observed. Since the charge accumulation near the anode is shifting towards the sample bulk, it is believed that the anode injects the positive charges into the sample bulk.

Interestingly, under the stepwise increasing negative electric field, the space charge is accumulated within the sample bulk at the lower electric field (i.e. −10 kV/mm) compared to the stepwise increasing positive electric field. Similar to stepwise increasing positive field, the space charge injection and/or extraction at both electrodes is significant. With the increasing negative field, the positive charges remain dominant within the sample bulk throughout the poling duration. However, the positive charges within the sample bulk located near the anode remain consistently present whereas the positive charges near the cathode exhibit inconsistency. Moreover, the anode injects more charges into the sample than the cathode, similar to the stepwise increasing positive electric field. The charge distribution within the sample bulk is different at 60 kV/mm and −60 kV/mm. This may be due to the cumulative effect of the space charges accumulated from 10 up to 50 kV/mm and −10 to −50 kV/mm, respectively.

3.1.2 PP

Figure 3(a,b) shows the space charge distribution within the PP under the stepwise increasing positive and negative electric fields at the rate of +10 kV/h and −10 kV/h, respectively. It can be observed that the PP exhibits less space charge accumulation than the XLPE. The visible space charge accumulation (homocharges near the anode and positive as well as negative space charges within the sample bulk) can be observed ≥ 20 kV/mm under the stepwise increasing positive electric field. It can be seen that the anode injects the space charge at ≥ 40 kV/mm. But, the space charge accumulation near the anode remains inconsistent. e.g. at 40 kV/mm, the anode injects the positive charges inside the bulk which remain present up to 50 kV/mm. However, the positive charges are extinguished at 60 kV/mm and likely are converted into the negative charges. Hence, the negative charges are accumulated within the sample bulk at 60 kV/mm. It is important to highlight the charge carrier injection from the cathode. It can be observed that the charges remain accumulated within the sample above 40 kV/mm. Also, the cathode peak seems to be slightly shifting towards the sample bulk. Hence, it is believed that the cathode is primarily responsible for the negative space charges that are accumulated within the sample bulk. This observation contradicts with the space charge dynamics inside the XLPE under the stepwise increasing positive as well as negative electric fields (Figure 2).

Table 1 shows the threshold electric field for space charge accumulation calculated using Equation (1) under the positive and negative electric field. It can be seen that the space charge can be accumulated within the XLPE at very low electric field as compared to PP under both polarities. Furthermore, the space charge is accumulated at lower value under the negative electric field application than positive electric field inside XLPE and PP.

Moreover, under the stepwise increasing negative electric field, the space charge is accumulated at a comparatively low electric field as compared to positive field (Figure 3(b)). Similar to the stepwise increasing positive electric field, the anode exhibits the inconsistent space charge accumulation (homo charge). The homo charges that are accumulated at −40 kV/mm are extinguished at −60 kV/mm.
3.2 One cycle consisting of polarity reversal after 1 h

3.2.1 XLPE

Figure 4(a) shows the space charge distribution inside the XLPE. It can be observed from Figure 4(a) that the significant hetero charges are accumulated near the cathode during the positive half cycle. These bulk charges remain present throughout the positive half cycle and increase with time. Moreover, small amount of hetero charges accumulated near the anode (highlighted by the dotted circle). It can be observed that higher amount of space charges are accumulated within the sample bulk under the negative half cycle. The space charge accumulation during the depolarization shows that the space charges extinguish within short amount of time (~15 min).

The location of charges near the electrode remains same even after the polarity reversal. This phenomenon is called as the mirror-charge accumulation [25], e.g. hetero charges near the cathode before the polarity reversal mirror its pattern and type (i.e. hetero) to the corresponding electrode after the polarity reversal (anode in Figure 4(a)). After the polarity reversal (i.e. during negative half cycle), the mirror charges can be observed near the anode. Moreover, the amount of hetero charges is more and remains persistently present after the polarity reversal until the end. The space charges can be also observed within the sample bulk after the polarity reversal. This may be due to the electrode charge injections (particularly anode) as the hetero charges near anode are marginally more.

3.2.2 PP

Figure 4(b) illustrates the space charge accumulation inside the PP. Figure 4(b) shows that a small amount of homo charges are accumulated near the anode. Moreover, no visible space charges can be observed inside the PP bulk during positive half cycle. A significant amount of homo charges can be observed near the anode after polarity reversal (Figure 4(b)). Moreover, a small amount of negative charges are accumulated within the sample bulk after the polarity reversal. Hence, the charge injection from the anode is believed to contribute the negative space charge accumulation within the sample bulk. Since negligible space charges are present before and after the polarity reversal, a small amount of residual charges can be observed during the depolarization.

3.3 One cycle consisting of polarity reversal after 6 h

3.3.1 XLPE

Figure 5(a) shows the space charge accumulation inside XLPE under the polarity reversal after 6 h of positive electric field application. A significant amount of hetero charges can be observed near the cathode under the positive electric field. Moreover, a small amount of hetero charges can be also observed near the anode, which extinguish after ~3 h. The space charge measurement of 3 h does not show such accumulation, particularly near the anode. This clearly demonstrates the prominent effect of higher poling duration on the space charge accumulation. Moreover, the amount of charges near both electrodes and within the sample bulk is more as compared to 3 h measurement.

During the negative half cycle, comparatively more space charges can be observed. Interestingly, the significant amount of the mirror charges can be seen near the anode after polarity reversal. It is important to highlight the decay of the space charge during the depolarization. The space charges during the depolarization can be seen decaying slowly (~2 h) as compared to 3 h measurement (decay time ~15 min). Moreover, the hetero charges near the both electrodes can be observed nearly in the same position during the depolarization. It is reported by Tzimas et al. that the DC poling duration affects the decay profile of the XLPE. The un-aged cable peelings were subjected to the 2 and 26 h of poling at 50 kV/mm followed by the 20 and 93 h of the depolarization. The authors reported that the longer the poling duration, slower will be the space charge decay [26].
3.3.2 PP

The space charge accumulation inside the PP are shown in Figure 5(b). Similar to the XLPE, most amount of the hetero charge is located near to the cathode during the positive half cycle. Interestingly, these bulk charges can be observed till the end of the positive half cycle. Moreover, a small amount of homo charges can be observed near the anode. During the negative half cycle, homo charges can be seen near the cathode. Also, the small amount of the homo charges can also be seen near the anode. Due to very less space charge accumulation inside the PP (before and after the polarity reversal), few residual space charges can be observed during the depolarization. This observation is similar to that of the 3 h measurement of PP as shown in Figure 4(b). In case of PP, the homo and hetero charges near both electrodes can be attributed to longer DC poling duration.

3.4 Three cycles consisting of polarity reversal after every 1 h

3.4.1 XLPE

In order to understand the effect of multiple cycles of the polarity reversal on the space charge accumulation, three cycles consisting of the polarity reversal after every 1 h are applied (First, the positive half cycle is applied for 1 h followed by polarity reversal after every 1 h). Figure 6(a) shows the dynamic space charge accumulation inside XLPE. The polarities are mentioned on the right side of the space charge profile to clearly differentiate between the positive and negative half cycles during the poling.

The space charge distribution shows that homo charges are accumulated near the anode and remain persistent even after polarity reversal. e.g. the homo charges near both electrodes in the 1st positive half cycle can be observed even after the polarity reversal. No visible hetero charges can be observed near both electrodes during the 1st positive half cycle. Positive charges can be observed within the sample bulk during the 1st positive half cycle. The subsequent polarity reversals result in the mirror space charge accumulation that are accumulated near both electrodes (highlighted by the dotted rectangle). Moreover, the homo charges increase near the anode under the negative half cycles. Similar to the 3 h measurement, a small amount of mirror charges are also accumulated within the sample bulk. Moreover, the space charge density increases under the subsequent cycles. It can be observed that a significant amount of space charges still remain at the end of depolarization. This shows that as the...
number of cycles increase as significant space charges are still present inside the sample bulk.

3.4.2 | PP

Figure 6(b) shows the space charge dynamics inside PP after three cycles of polarity reversal. A small amount of homo charges are accumulated near both electrodes during the positive half cycle. The space charge accumulation within the PP sample is observed only during the negative half cycle. In comparison to the space charge dynamics under 3 h measurement (Figure 4(b)), the charge injection from both electrodes is higher as shown in Figure 6(b). Moreover, it is observed from the space charge dynamics after three cycles of the polarity reversal that no visible space charge can be observed during depolarization. Also, homo charges accumulated near both electrodes have been extracted at the beginning of depolarization.

4 | TRAP ANALYSIS

4.1 | Increasing electric field

4.1.1 | XLPE

The trap distributions under the stepwise increasing positive and negative electric field are shown in Figure 7. It must be noted here that the trap distributions shown in Figure 7 are extracted from the SPD curve. Hence, it is not possible to obtain the trap distributions after every step increase of the electric field. Thus, the individual trap distribution is plotted at 10 kV/mm to understand the nature of the traps under the initial electric field. This puts a limitation on the extraction of the trap parameters from the SPD curves under either polarity as the decay process can only start after the completion of the polarity reversal process.

Figure 7(a) shows that the shallow traps (∼0.92 eV) are formed in addition to the deep traps (∼1.08 eV) under the influence of the stepwise increasing positive electric field. Particularly, at the low values of the positive electric field (10 kV/mm), the trap density and trap energy level is significantly higher than 60 kV/mm. Hence, the space charge cannot be easily accumulated at the low electric field. As the electric field increases to 60 kV/mm, the shallow traps (∼0.92 eV) in addition to the deep traps with lower trap density are formed. It can be inferred that the trap energy level and trap density decrease with the increase of electric field. It is important to highlight the absence of shallow traps at 10 kV/mm. Primarily, the impurities and cross-linking by-products are responsible for the shallow traps due to the field-assisted ionization. It is believed that this phenomenon may not take place at the low electric field (discussed later in Discussion Section).

Similarly, under the stepwise increasing negative electric field, the shallow traps having low trap density are formed. Moreover, the trap energy level of the shallow traps is significantly lower as compared to the positive field. It is considered that this may further facilitate the space charge accumulation as the trapped space charge can be easily de-trapped from the shallow traps with the low energy level and density due to the lower number of trapping sites and their energy level. The shallow traps (∼1.02 eV) at 10 kV/mm are further reduced to ∼1.02 eV. This suggests that due to less trap level and trap density the space charge is easily accumulated under the low negative electric field.

4.1.2 | PP

The trap distributions for the corresponding polarities are shown in Figure 8(a,b). It can be seen that only deep traps are formed in PP under both polarities. Under the stepwise increasing positive electric field, the deep traps with high energy level and trap density remain even after applying the high electric field. The trap parameters remain significantly unchanged after increasing the electric field from ∼1.03 eV at 10 kV/mm are further reduced to ∼1.02 eV. This suggests that due to less trap level and trap density the space charge is easily accumulated under the low negative electric field.

FIGURE 7 | Trap distribution inside XLPE under the (a) increasing positive voltage and (b) increasing negative voltage
4.2 | One cycle consisting of polarity reversal after 1 h

4.2.1 | XLPE

The trap distribution in Figure 9(a) shows that the shallow (≈0.95 eV), as well as the deep traps (≈1.09 eV), are formed in the XLPE. The shallow trap density is nearly $1 \times 10^{19}$ eV$^{-1}$m$^{-3}$. Corresponding space charge accumulation in Figure 4(a) shows that the mirror charges are present after the polarity reversal. Trap distribution consistently show the presence of the shallow traps inside XLPE. Hence, it is believed that the shallow traps are primarily responsible for the space charge accumulation inside XLPE. Hence, the space charges are persistently present near both electrodes and within the sample bulk.

4.2.2 | PP

The trap distribution in Figure 9(b) shows that only deep traps are formed inside the PP. Moreover, the trap energy level of the PP is significantly higher (≈1.14 eV) than the XLPE. Besides, the trap density is marginally higher as compared to the XLPE. However, it must be highlighted here that the trap energy level and trap density may have slightly decreased after the polarity reversal as the small number of space charges can be observed near both electrodes and within the sample bulk. Hence, the space charge suppression inside the PP can be attributed to the higher trap energy level and trap density.

4.3 | One cycle consisting of polarity reversal after 6 h

4.3.1 | XLPE

The trap distribution after the polarity reversal of 6 h is shown in Figure 10(a). It shows that the shallow traps (≈0.96 eV) with the higher trap density and trap depth are formed, whereas the deep traps are extinguished. The higher poling duration of 6 h results into the extinction of the deep traps as compared to 3 h measurement. The trap distribution under the polarity reversal after 1 h exhibits the trap depth of 0.95 eV with very few shallow traps. Hence, it can be inferred that the shallow traps become dominant over the deep traps with the increasing poling duration. The volatility of the cross-linking by-products could be responsible for the presence of the shallow traps inside the XLPE. Hence, the calculation of the carbonyl indices may be useful for the further in-depth analysis in the future. Furthermore, the shallow trap density is nearly $6 \times 10^{19}$ eV$^{-1}$m$^{-3}$. 
4.3.2 PP

The trap distribution in Figure 10(b) shows that the PP exhibits the deep traps despite being subjected to a longer poling duration of 6 h under each polarity. Moreover, the trap energy level (≈1.13 eV) decreases slightly compared to 3 h measurement consisting polarity reversal after 1 h (1.14 eV shown in Figure 7(b)). Furthermore, the trap density also remains nearly same ≈8.1 x 10^19 eV m^{-3}. Hence, in a nutshell, PP exhibits the deep traps irrespective of the poling duration. Hence, the lesser space charge accumulation inside the PP is distributed to the persistent deep traps. Interestingly, trap density nearly remains same in 3 and 14 h measurement. This shows that the trapping sites remain nearly unaffected by the poling duration. It is hypothesized that the morphological structure of the PP creates a strong polymeric structure which remains unaffected at the high electric fields.

4.4 Three cycles consisting of polarity reversal after every 1 h

4.4.1 XLPE

Figure 11(a) shows the trap distribution inside the XLPE after three cycles of polarity reversal. The shallow traps (≈0.97 eV) along with the deep traps (≈1.05 eV). It is noteworthy to mention that the trap distributions under 3 h measurement are in good agreement with these results. As shown in Figure 9(a), the deep traps exhibit an energy level of ≈1.09 eV. Hence, it can be inferred that the number of polarity reversals significantly change the trap distributions inside XLPE. Moreover, the shallow trap density is significantly increased under the polarity reversal consisting of three cycles. Furthermore, the deep trap density nearly remains the same. It shows that the irrespective of the type of electrical field application (with or without polarity reversal), the shallow traps are consistently observed inside the XLPE.

4.4.2 PP

The trap distribution illustrated in Figure 11(b) shows that the PP still exhibits deep traps even after three cycles of the polarity reversals. However, the trap energy level is slightly reduced to ≈1.12 eV. The slight change in the trap parameters can be clearly observed under the different number of the polarity reversal cycles (Figures 9(b) and 11(b)). The trap energy level under one cycle of the polarity reversal (≈1.14 eV shown in Figure 9(b)) decreases for three cycles of the polarity reversals.
4.5 Calculated parameters

4.5.1 Residual space charge density

Figure 12 shows the residual space charge density obtained from the depolarization space charge profiles of XLPE and PP.

The residual space charges are dependent on the poling duration and number of cycles. It can be observed from Figure 12(a,b) that the residual space charges inside the PP are significantly less than XLPE. The residual space charges inside the XLPE after applying one cycle of 3 h (consisting of the polarity reversal after 1 h) shows that the space charges decay slowly during the initial time and subsequently decreases rapidly. Moreover, as poling duration and number of polarity reversal cycles increase, rapid initial decay can be observed inside the XLPE. However, the amount of residual space charges increases after three cycles of the polarity reversal. Moreover, the poling duration of 6 h under one polarity significantly increases the residual space charges indicating the difficulty to dissipate the space charges. Similarly, in the case of the PP, the space charge decays appears to be slow during the initial period.

| Material  | 3 h (C/m³ s) | 7 h (C/m³ s) | 14 h (C/m³ s) |
|-----------|--------------|--------------|---------------|
| XLPE      | $5.32 \times 10^{-5}$ | $2.599 \times 10^{-4}$ | $8.94 \times 10^{-5}$ |
| PP        | $8.78 \times 10^{-5}$ | $7.15 \times 10^{-5}$ | $3.26 \times 10^{-5}$ |

To understand the space charge decay further, space charge decay rate is calculated as follows,

$$Q_{\text{rate}} = \frac{Q_{\text{avg-initial}} - Q_{\text{avg-final}}}{t}$$

where $Q_{\text{rate}}$ is the decay rate (C/m s), $Q_{\text{avg-initial}}$ is the average space charge density at the beginning of depolarization (C/m³), $Q_{\text{avg-final}}$ is the average space charge density at the end of depolarization (C/m³), and $t$ is the depolarization time.

The calculated values of decay rate are tabulated in Table 2. In the XLPE, the decay rate of 3 h measurement (one cycle of polarity reversal) is slower as compared to 7 h measurement (three cycles of polarity reversal), i.e. as the number of the polarity reversal cycles increases, the space charge decays rapidly. Moreover, the higher poling duration (14 h measurement) further accelerates the decay process as compared to the 3 h measurement.

Similarly, PP exhibits faster decay rate in the 3 h measurement than XLPE, which may be due the higher charge carrier mobility. Furthermore, the space charge decay after the three cycles of the polarity reversals appears to be faster than XLPE. This may be due to the faster combination-recombination (or trapping–detrapping) process of the charge carriers. The space charge decay rate inside the PP for 14 h measurement is also slower than XLPE.

4.5.2 Electrical field distortion

Table 3 shows the electric field distortion due to the accumulated space charges inside XLPE and PP. To understand the effect of polarity, the electric field distortions are tabulated for the positive as well as negative polarity. It can be observed that the poling duration and the number of polarity reversal cycles significantly affect the electric field distribution inside the insulation. Moreover, the negative electric field application leads to a severe amount of distortion than the positive electric field.

First, the effect of poling duration under the respective polarity can be seen in Table 3. The 3 h measurement shows 25% electric field distortion before the polarity reversal, whereas the polarity reversal distorts the electric field by 31.67% within the XLPE. However, the poling duration of 6 h distorts the electric field by 41.67% under the positive polarity. Similarly, the negative polarity distorts the electric field by 45%. This shows that the poling duration can significantly affect the electric field distribution within the XLPE sample bulk. Similarly, the polarity reversal consisting of the three cycles distorts the electric field within the XLPE. The electric field distortion in the next cycle...
TABLE 3 Electric field distortion due to the space charge accumulation

| Material | Positive (%) | Negative (%) | Positive (%) | Negative (%) | 1st cycle | 1st cycle | 2nd cycle | 2nd cycle | 3rd cycle | 3rd cycle |
|----------|--------------|--------------|--------------|--------------|-----------|-----------|-----------|-----------|-----------|-----------|
| XLPE (%) | 25           | 31.67        | 41.67        | 45           | 21.67     | 33.33     | 28.33     | 40        | 33.33     | 46.67     |
| PP (%)   | 3.33         | 5            | 10           | 11.67        | 3.33      | 5         | 3.33      | 5         | 6.67      | 8.33      |

(e.g. 2nd cycle) increases after every polarity reversal with reference to its previous cycle (e.g. 1st cycle). This could be due to the cumulative effect of the accumulated space charges in the previous cycle and freshly injected space charges in the next cycle.

As the space charge profiles of PP show negligible space charge accumulation, the electric field is slightly distorted under the different poling durations and polarity reversal cycles. However, the electric field distortion under the 14 h measurement remains larger as compared to the 3 and 7 h measurements. The maximum electric field distortion of 11.67% is observed after the polarity reversal (i.e. under the negative polarity) of 14 h measurement of PP. An increased electric field distortion in the 3rd cycle must be noted here. This is attributed to the cumulative space charges accumulated in the 1st and 2nd cycle. The 3rd cycle shows that marginally higher amount of homo charges are accumulated which justifies the cumulative effect of the space charges accumulated in the previous cycles.

5 | DISCUSSION

The results show that XLPE shows significant homo as well as hetero charge accumulation (near both electrodes and within the sample bulk) than PP. Moreover, the XLPE shows mirror effect in the space charge accumulation after the polarity reversal. This is mainly attributed to the impurities and/or by-products such as acetophenone, cumyl alcohol, and α-methyl styrene, since they tend to be ionized under the DC electric field [19, 20, 26, 27]. It is reported that the space charge in the XLPE primarily originates from the unequal charge injection and extraction rates at cathode or anode, or from the ionization of cross-linking by-products, and/or impurities. Generally, under the influence of high electric field, neutral-ion pair (rather considering cross-linking by-products and impurities) can be activated thermally i.e. field-assisted ionization, and is dissociated into positive and negative ions and vice versa referred as recombination. According to the Onsager mechanism, the dissociation and recombination rates are dependent and independent of the electric field, respectively [28]. Hence, the field-assisted ionization [29] of the by-products is shown in Figure 13(a). Multiple studies have suggested that the field-assisted ionization of the cross-linking by-products and impurities is mainly responsible for the hetero charge accumulation inside the XLPE.

The results show that the XLPE shows shallow traps, whereas the PP inherits the deep traps with higher trap density irrespective of the poling duration and the number of polarity reversal cycles. As mentioned earlier, the space charge accumulation is mainly due to the field-assisted ionization. Hence, a valid correlation can be established between the space charge and trap distribution under the polarity reversal considering the field-assisted ionization. It is noteworthy to mention here that the equilibrium (i.e. when new charges are injected to replace the...
already present charges) will only be attained once the charges between the interface and bulk are redistributed after the polarity reversal [28]. However, the presence of the charges in the sample bulk complicates the redistribution after the polarity reversal. Hence, these two conditions are used to develop a valid theory to explain the space charge injection, neutralization, and recombination processes.

Figure 13 illustrates the model with (i.e. XLPE) and without (i.e. PP) the bulk charges to correlate the space charge accumulation with the trap distribution. The hypothesized model shows a typical hetero charge accumulation near the cathode and homo charge near the anode. To explain, the type of space charge (homo or hetero) primarily depends on the charge carrier mobility (mainly, electron). The higher mobility ensures the rapid transportation of the electrons freed due to the ionization of impurities near to cathode, and those injected into the sample bulk towards the anode. This will result into the hetero charge accumulation near the cathode. Similarly, hetero charge can be also be accumulated near the anode when the rate of electron injection is higher than the extraction rate. If the charge carrier mobility lesser than the threshold value, homo charge will be formed [30]. The results show that, as there are no cross-linking by-products inside PP, there is no hetero charge accumulation. Small or negligible space charge accumulation is attributed to the molecular structure of PP.

It is important to discuss here the origination of mirror space charges near the electrodes after the voltage polarity reversal. When the electric field is applied to the insulation, two processes simultaneously occur at the cathode, i.e. electron injection from the cathode into the insulation bulk and ionization of the impurities. Similarly, at the anode, extraction of the electrons from the insulation bulk and ionization of the impurities occurs. The barrier height at the cathode decreases, whereas it increases near the anode due to space charge accumulation. If the injection and extraction rate of electrons is unequal, space charges will remain near to the respective electrodes. This can also be visualized by assuming the either polarity charge accumulation near to the anode and cathode. If the polarity of the applied field is reversed, the accumulated space charges would remain near to the respective electrodes, however, having an opposite polarity. This is called as a mirror effect, which mainly occurs inside the XLPE due to its molecular structure.

In the XLPE, the results (similarly illustrated in Figure 13(a)) show that significantly more space charges are accumulated under the negative half cycle than positive half cycle. It is believed that the hetero charges injected from the respective electrodes under the positive half cycle are converted into homo charges (in small amounts near to the respective electrodes) under the negative half cycle. This amplifies the electric field at the interfaces between the sample bulk and electrode, which facilitates the charge injection at the electrodes [28]. Hence, the electric field distortion is significantly higher under the negative polarity (i.e. after the voltage polarity reversal) as shown in Table 3. However, the space charge dynamics within the XLPE bulk is different due to the presence of the cross-linking by-products. The trap depth and trap levels are relatively lower under the negative half cycle than the positive half cycle. This further changes the space charge dynamics i.e. The shallow traps with less trap depth and trap density facilitate the space charge de-trapping process, as it is easier to de-trap from the traps with the low energy level. Hence, the space charge accumulation is attributed to the shallow traps having lower trap density, which may be due to the impurities and by-products. A similar observation is reported elsewhere in [19, 20]. Moreover, the homo charges in the XLPE are attributed to the charge injection (having low electron mobility) by the electrodes, whereas the hetero charges are assumed to be contributed by the by-products (having higher electron mobility) [25]. Furthermore, homo charges are converted into the hetero charges. It is believed that the cross-linking by-products and/or impurities become highly charged under high electric fields. These highly charged by-products or impurities gain higher electron mobility by generating an additional acceptor or donor sites for hopping conduction [31, 32].

In the PP, it can be seen that the homo charges are dominant over the hetero charges. This implies that the electron mobility is below its threshold value as discussed earlier. Moreover, the PP exhibits less space charge accumulation within its bulk. Hence, Figure 13(b) shows homo charges in its illustration. The results show that the onset time (i.e. the time in between the injection and extraction of the space charges) of the homo charges is comparatively less than the hetero charges.

It is believed that the accumulated homo charges are neutralized (after the polarity reversal) by the freshly injected charges with the opposite polarity [29, 33]. As the trap energy level and trap density are significantly higher in the PP, the replacement of the charges can happen quickly which reduces the onset time.

Generally, the trap distribution is analysed under the positive or negative polarity. This limits the application of the trap distribution to either of the polarity. However, in HVDC, the power demand necessitates the reversal of the voltage polarity. The novelty of this study is that it correlates the trap distribution with space charge accumulation under the voltage polarity reversal condition. PP is considered as an alternative to the XLPE due to its ability to recycle, enhanced dielectric properties. However, the study of space charge accumulation in PP under the voltage polarity reversal is not reported, to the date. With this context, this study comparatively highlights the space charge accumulation in XLPE and PP under the voltage polarity condition. In-depth analysis of the space charge accumulation is carried out and correlated with the trap distribution. A valid model is developed to explain the role of traps in the space charge accumulation based on the obtained results. This study offers to contribute a results based comparative study between XLPE and PP, and proposes a PP as a suitable alternative to the XLPE.

6 | INSIGHTS ON THE LIFE OF INSULATION

The effect on the life of the insulation due to the accumulated space charges under the polarity reversal will be briefly discussed here. However, this method requires the data of time...
to breakdown due to the space charge to plot the Weibull distribution. Hence, the calculation of the life is not presented here as the present study only consists of the space charge study under the pre-breakdown conditions. Kashyap et al. [34] reported the effect of voltage polarity reversal duration on the life of polymeric insulation. This method generally used the inverse law of power aging as follows,

\[ L = tV^n, \]

where \( L \) is the life of the insulation, \( t \) is the time to breakdown, and \( n \) is the life exponent.

This method uses the Weibull plots of time taken to breakdown for different voltage levels with considered time interval between the polarity reversals. Another study by Vu et al. [22] shows that the life of the insulation decreases as the number of polarity reversal cycles increase.

\[ \frac{L}{L_1} = \left( \frac{1}{K} \right) \frac{Q(F_{app})}{Q(F_{app})_{1}} f^n, \]

where \( L \) and \( L_1 \) are the life of insulation before and after the inversion, respectively, \( Q \) is the amount of the trapped average space charge, and \( f \) is the frequency of polarity reversal. The above equation shows that the life of the insulation decreases with the increase in frequency of polarity reversal, amount of the trapped space average charge, and the applied electric field. The details of this model can be referred from ref. [22].

In the near future, it may be interesting to study the effect of the nanofiller addition due to the continuous development in the field of nanodielectrics. The in-depth studies such as space charge analysis based on the trap distribution, electric field characterization, and morphology may be helpful [34–39].

7 | CONCLUSION

This novel study presents the correlation of the space charge dynamics with trap distribution inside XLPE and PP under the polarity reversal condition. The space charge accumulation threshold under the positive and negative polarities shows that the XLPE exhibits a lower values of threshold electric field as compared to PP. This implies that the space charge can be easily accumulated inside the XLPE at the lower electric field. The pronounced effect of shallow as well as deep traps level and trap density on the space charge distributions is clearly visible. The XLPE shows a severe amount of homo and hetero charge accumulation near both electrodes and within the sample bulk, respectively. The dominant shallow traps facilitate the space charge accumulation due to its lower trap depths. Moreover, the mirror-like space charge accumulation is also observed. The polarity of DC electric field also has a significant effect on the space charge accumulation inside XLPE. The higher amount of space charges are accumulated under the negative half cycle of the electric field than positive cycle. It is proposed through the hypothesized model that the bulk charges within the XLPE bulk amplify the space charge accumulation. It is believed that the field-assisted ionization of the cross-linking by-products and impurities facilitates the space charge accumulation inside XLPE.

The PP shows significantly less space charge accumulation than XLPE under the different polarization times and cycles of polarity reversal. It is observed that homo charges are more dominant inside the PP than hetero charges. The SPD measurement shows that only deep traps with higher trap density are present inside PP. This hinders the charge carrier’s movement since it is difficult to escape from the deep traps due to their higher trap depth. Moreover, limited space charges are accumulated within the sample bulk. This may be attributed to the absence of cross-linking by-products, as they facilitate the field-assisted ionization. Moreover, the threshold space charge accumulation measurement shows that the space charges are accumulated inside the XLPE at the lower electric field than PP. Lastly, significantly higher amount of the residual charges were observed inside the XLPE compared to PP. The statistical analysis shows that the space charge decays rapidly inside XLPE as the number of the voltage polarity reversal cycle increases.

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