Effect of AC Ageing on Space Charge Evolution in XLPE

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Abstract: This paper reports on space charge dynamics in XLPE samples, which have been pre-stressed under ac electric stress, when subjected to $30kV_{dc}$/mm dc electric stress for 24 hours. The samples used for this study were planar XLPE samples of ~ 220 μm thick aged under 30 kV_{pk}/mm, 30 kV_{rms}/mm and 60 kV_{pk}/mm at 50 Hz ac condition for 24 hours. In addition, the experiments were also extended to samples that were pre-aged under 1 Hz and 10 Hz ac 30 kV_{pk}/mm for 24 hours.

Introduction

Cross-linked polyethylene (XLPE) is widely used as an insulation medium for both ac and dc power cables because of its high electrical resistivity, high intrinsic electric breakdown strength and low dielectric loss. However, after prolong period of operation, the insulating material can be degraded, causing insulation breakdown at stress level well below the anticipated values.

Space charge measurement in XLPE under dc electric field has been one of the most widely investigated areas in dielectric material phenomena. It is believed that space charge is one of the main reasons of premature failure of cable operating in dc condition. In recent years, the field of space charge measurements has also been extended to insulating material subjected to ac electric stress. However, understanding of space charge mechanism in dielectrics under ac electric stress is often difficult as many factors such as the varying amplitude of sinusoidal ac voltage, voltage reversal, charging injection/ extraction, charge trapping, material degradation, etc, need to be considered.

The study presented will mainly focus on the effect of ac ageing on charge trapping characteristics in XLPE. To do that, space charge evolution in XLPE, which has been pre-aged under ac electric stress were subjected to dc electric stress. The samples used for this study were planar XLPE samples of ~ 220 μm thick aged under 30 kV_{pk}/mm, 30 kV_{rms}/mm and 60 kV_{pk}/mm at 50 Hz ac condition for 24 hours. In addition, the experiments were also carried out on samples that were pre-aged under 1 Hz and 10 Hz ac 30 kV_{pk}/mm conditions for 24 hours.

Sample details

The test samples were approximately 220 μm thick (bulk) made by the cable grade cross-linked polyethylene (Borealis XL4201S). Semicon electrodes were hot press into the plaque sample at 200 ^{O}C for about 10 minutes on both sides. The electrodes were made of the same grade of polyethylene material, but were loaded with carbon black to increase its conductivity (Borealis LEO592). In order to remove volatile by-products of crosslinking agent, all samples were degassed in a vacuum oven at 90 ^{o}C for 48 hours.

All samples were electrically aged for a duration of 24 hours at ambient in a Pulsed electroacoustic (PEA) system which is capable of measuring space charge under ac electric stress at various frequencies [1]. The samples were then stored in ambient temperature for one month to allow accumulated charge to decay. The ageing conditions of the samples are listed in table 1.

Sample	Pre-aged condition
S1	None
S2	AC 1 Hz at $30kV_{pk}$/mm
S3	AC 10 Hz at $30kV_{pk}$/mm
S4	AC 50 Hz at $30kV_{pk}$/mm
S5	AC 50 Hz at $30kV_{rms}$/mm
S6	AC 50 Hz at $60kV_{pk}$/mm

Table 1. Sample details

Experimental procedures

The space charge measurement technique choosen for this study is the PEA technique, the principle of which is well doucumented [2-3]. To summarise, acoustic pressure waves are produced when an electrical pulse, applied externally, interacts with charge layers at the electrodes and/or in the material. The pressure waves, which are proportional to the amount of charge in the charge layers, are detected by a piezo-electric transducer.

A typical output signal from a PEA is shown in figure 1.

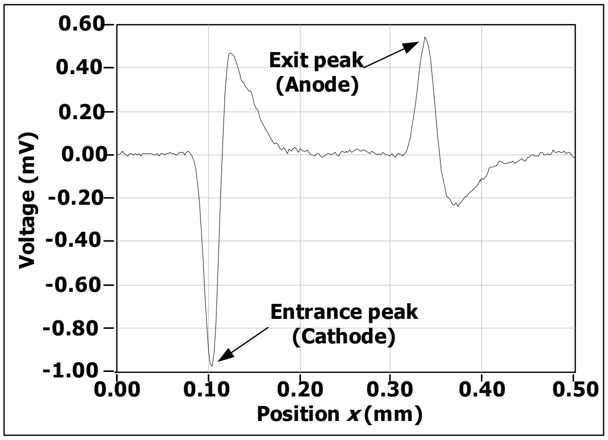

Figure 1. A typical PEA output signal

The peak between the cathode and anode is not due to space charge but rather the frequency response of the system. Deconvolution has to be employed to restore the orignal signal [4]. Furthermore, due to the elastic nature of polymer, pressure waves tend to attenuate and disperse as they transverse across the material [4]. However, this is not taken into consideration in the present study because its influence in thin sample is not significant.

The threshold voltage at which space charge initiates in each sample was determined by the ramp rate experiment (r.r.e). In this experiment, voltage was increased from 0 kV, at a voltage step of 1 kV every 30 secs interval, until a stress of level of 30 kV_{dc}/mm was reached. Space charge measurements were taken at every incremental voltage step. The final voltage which depends on the sample thickness is between the range of 6 to 7 kV. The entrance and the exit peaks of the measured output, which is proportional to the stress at the electrodes, were then plotted against the applied voltage.

Immediately after the r.r.e, the sample was aged at 30 kV_{dc}/mm for a duration of 24 hours. Space charge profiles with voltage on were measured every 30 mintues interval.

After 24 hours of ageing, the applied voltage was removed and decay of charge trapped in the sample was monitored for 2 hours. All experiments were conducted under ambient temperature.

Results and discussion

The results of the r.r.e of samples S1 and S6 are shown in Figure 2.

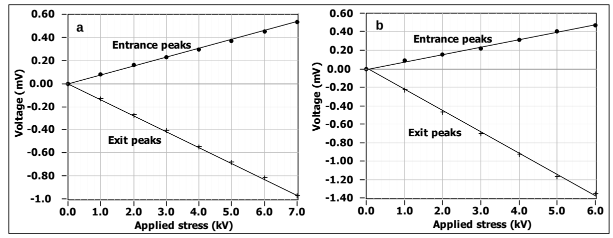

Figure 2. Results of rate rate experiment: (a) S1 and (b) S6

Space charge modifies the stresses at the interfaces which in turn causes the entrance and exit peaks to deviate from the extrapolated trend line. However, this is not seen in figure 2 suggesting no space charge formation in the bulk up to a stress level of 30 kV_{dc}/mm. The r.r.e results of samples S2 to S5 are similar to that of sample S1 and S6 and hence will not be shown in this paper. While the results in this experiment suggest that the threshold voltage is not affected by ac ageing, but it is worth pointing out that this only holds true for applied stress of 30 kV_{dc}/mm and below. Further investigation is required before any firm conclusions can be drawn.

Figure 3 shows the space charge profiles (with voltage applied) of samples S1 to S 6 during ageing.

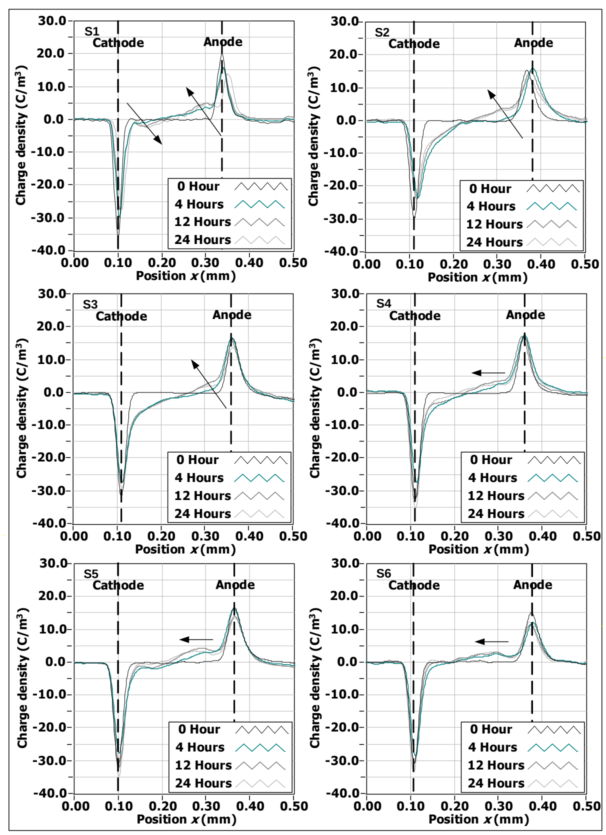

Figure 3. Space charge profiles of samples S1 to S6 during ageing

It can be seen that no significant space charge can be seen in all six samples at 0 hours, i.e. immediately after the r.r.e. This is in agreement with the results of the r.r.e.

At 4 hours, charges of the same polarity, otherwise known as homocharges, can be seen accumulating near the vicinity of both electrodes. These homocharges are believed to be caused by charge injection from the semicon electrodes.

In the case of sample S1, both positive and negative homocharges continue to increase over the stress period. On the other hand, samples S2 and S3 only shows increase in positive homocharge with increasing stress period, with the negative homocharge reaching its maximum amount after 4 hours of ageing.

Similar behavior can be observed for the negative charge in samples S4 to S6, which appears to reach its maximum amount after 4 hours of ageing. However, at vicinity of the anode, positive packet charge can be seen; less obvious in sample S4 as compare to S5 and S6.

It has been reported that packet charge formation may be caused by charge carrier generation under high electric field (above 100 kV_{dc}/mm), antioxidant deteriorated by oxidation [5] and local ionization of impurities through salvation by acetophenone [6]. The samples used in this experiment, however, do not contain antioxidant and acetophenone is believed to be largely removed after the degassing process while the stress applied is much lower. Therefore, formation of packet charge is believed to be caused by the ac ageing.

Careful comparison of samples S4, S5 and S6 indicates that the time for packet charge formation is dependent on the ac ageing conditions. From figure 3, packet charge only appear in sample S3 after 24 hours of ageing while it only took 12 hours in the case of sample S5 and 4 hours for sample S6. It is noteworthy that after it initiates, the packet charge tends to move towards the cathode with ageing time as indicated by the arrows in figure 3.

According to the findings reported in [7], positive charge packet can be observed only when the positive charge is the dominate carriers. Similar conclusion can be drawn by looking at figure 3, which shows that samples S4 to S6 are dominated by positive charge. A quick look at figure 4, which shows the space charge profiles of all the samples with the applied voltage removed after the 24 hours of ageing, further confirms this.

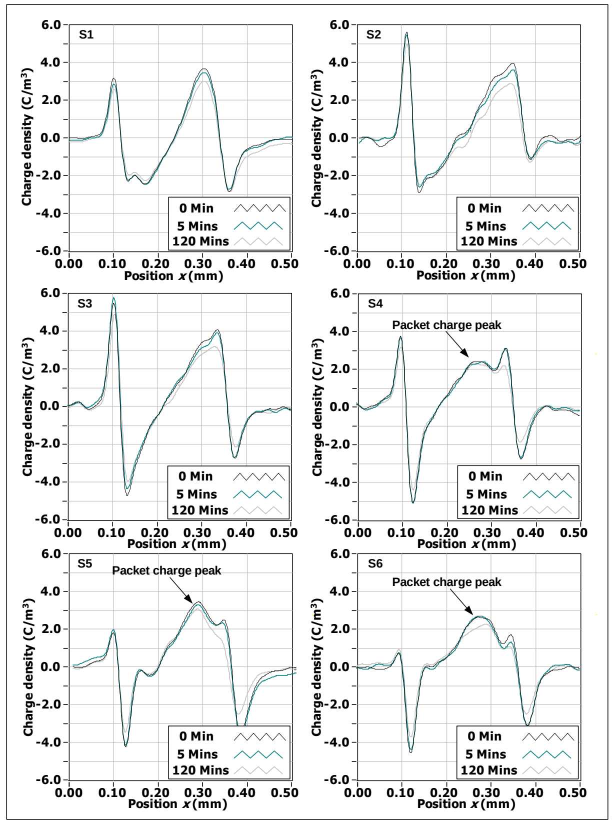

Figure 4. Space charge profiles of samples S1 to S6 after ageing ageing

The amount of positive and negative charges trapped in sample S1 are almost equal as seen in figure 4. In the case of sample S2, positive charge appears to be more dominant, moving more towards the cathode. This effect is even more profound in samples S3 and S4. This is probably due to the difference in frequencies of the pre-ageing ac stress they were subjected.

One way to explain this is at 1Hz, sample S2 was subjected to 10 and 50 times less cycles of polarity reversal as compared to samples S3 and S4 respectively. Therefore the effect of ac ageing experienced by S2 can be viewed as much lesser comparatively.

Increasing the ac stress level seems to enhance the effects exhibited in samples S2 to S4. This is can be clearly seen in the space charge profiles of samples S5 and S6 in figures 3 and 4.

The space charge distributions of samples S4 to S6 shown in figure 4 indicate two peaks in the positive charge trapped in the bulk. This is not seen in samples S1 to S3. The second peak as indicated by the arrow appears to correspond to the packet charge seen in figure 3.

The packet charge peak tends to be positioned closer to cathode when the pre-ageing ac stress is higher.

This can be clearly seen by comparing the space charge of samples S4 to S6 in figure 4.

The mechanism of which the packet charge forms and move is believed to the same as reported in [7]. To summarise, positive charge injected from the anode moves towards the cathode under the influence of the effective stress, $E_e(x)$, given which can be described as:

$$E_e(x) \quad = \quad E_a + E_c(x) \qquad (1)$$

where E_a = the applied stress and
$E_c(x)$ = the stress from space charge distribution

As more positive charge is injected into the bulk, the interfacial stress of the anode reduces and hence the rate of charge injection also reduces. The positive charge then moves towards the cathode under the influence of the effect stress. This probably explains why the positive packet charge in sample S6 is smaller and penetrates deeper into bulk.

Reduction of positive charge can be seen in samples S1 to S3 after the voltage was removed for 5 minutes. On the other hand, insignificant reduction in positive charge was observed in sample S4 to S6 after voltage removal for the same duration. This suggest that charges are trapped more deeply in samples S4 to S6 as compared to S1 to S3. Hence it is believed that ac ageing result in the formation of deep traps. This is consistent with the observation in LDPE after ac ageing [8].

It is also noted that the reduction of negative trapped charge is relatively less as compared to that of positive charge. This may imply that ac ageing causes the formation of traps that are more stable for negative charge.

Conclusion

The effects of ac ageing on space charge evolution in XLPE have been reported. Samples tested were pre-aged under different ac frequencies and stress.

Results of the ramp rate experiment shows no space charge formation in all the samples up to a stress of 30 kV_{dc}/mm. This suggests that the threshold voltage at which space charge initiates is not affected by the ac pre-ageing conditioned that were considered in this study. However, this only holds true for stress of 30 kV_{dc}/mm or below.

Positive charge becomes more dominant after the samples were pre-aged under ac stress. The higher the frequency and/or stress of the ac pre-ageing condition the more dominant positive charge over negative charge.

As positive charge becomes more and more dominant, positive packet charge was formed. These were observed in samples that were pre-aged under 50 Hz ac. The formation and dynamics of the packet charge were explained.

Charge accumulated during dc stress period was allowed to decay for two hours. It seems that ac ageing results in the formation of deeper traps, particularly for negative charge carriers.

In conclusion, the frequency and the stress level of the ac ageing greatly affect the dynamics and trapping characteristics of space charge in the material.

Acknowledgement

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