ELECTRIC FIELD REQUIREMENTS FOR CHARGE PACKET GENERATION AND MOVEMENT IN XLPE

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INTRODUCTION

The advent of experimental techniques capable of directly measuring the density of space charge in insulators under voltage in a non-destructive manner [1-4] has revealed the existence of charge packet formation at high DC fields. In these circumstances space charge is observed to cross the insulation in the form of a packet rather than through the steady advance of a charge front. Such packets have been observed both in cable insulation [5,6], and in thin films [7,8,9]. Since they occur at high fields before an electric failure occurs they are of interest as a possible pre-breakdown phenomenon. For this reason there is an interest in understanding the phenomena. Currently there are three models that are capable of giving charge packet formation. In one case [6] the packet is formed by injected charges and moves across the sample as a packet of excess charge carriers. Usually these packets are small in magnitude and spread out as the packet moves so that the packet loses its identity as it crosses the sample. This type of packet can only be re-created a few times. A different model for packet generation proposes field-induced dissociation as a source of carriers [5]. The packet is still, however, a region of slow moving charge carriers, and will also spread out during its passage. In an alternative model [8], field-assisted generation of carriers produces a depletion front in the form of a solitary wave. The packet does not spread out and can be recreated indefinitely as each packet approaches the counter-electrode. The charge density in these packets is much higher. Evidence exists for the formation of each type of packet, however, the details of the packet formation is still unclear. Hozumi et al [5] has shown that heat treatment of XLPE samples containing acetophenone and anti-oxidant play a role in packet formation. In the experiments reported here we explore the electrical conditions required for the initiation of very slow moving charge packets in XLPE.

EXPERIMENTAL INVESTIGATIONS

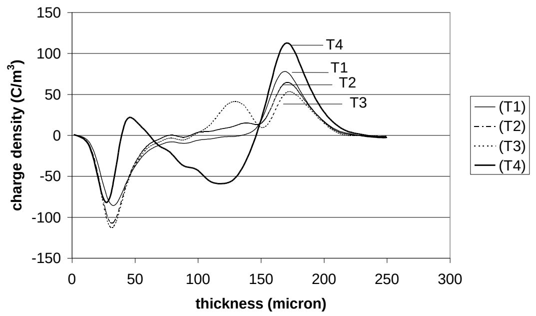
Sample preparation

The measurements were performed on tapes cut from unaged cross-linked polyethylene (XLPE) cables produced specifically for the project [10], by turning them on a lathe equipped with a specially designed cutting tool. The tapes had a width of 80mm and mean thickness 150 μm. Before testing, specimens were cut from tapes from insulation located 3 ± 1mm from the inner screen. Specimens were pretreated in an oven for 48 ± 1 hours at 50 ± 2 °C, atmospheric condition in order to expel most of the cross-linking by-products. Space charge observations were made by the pulsed electro-acoustic technique (PEA) at various constant dc-voltage levels systematically varied corresponding to applied fields between 80 kV/mm and 120 kV/mm. The apparatus set-up can be found in [12]. Description of this technique can be found in [11,13]. The samples were not coated with electrodes but were clamped between two electrodes. The cathode was a solid aluminium electrode. The anode was constructed from 0.75 ± 0.03mm thick piece of semicon from a commercial XLPE cable that was coated with a 1 ± 0.2 μm thick layer of 99.9% pure aluminium. The anode was in contact with the smooth face of the specimen. A thin (~0.2μm) film of silicon oil was used in all experiments on both the top and bottom electrodes to aid acoustic transmission. All measurements were made in air at atmospheric pressure.

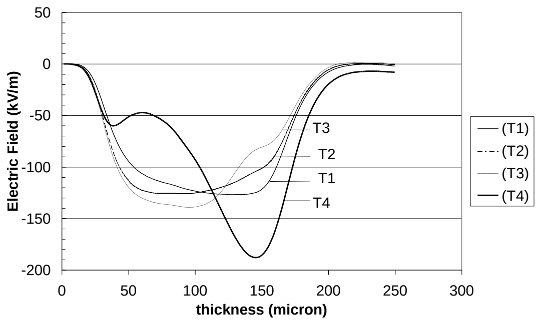
Measurement protocols

Two different measurement protocols were used. Both experiments were conducted at a temperature of 20 ± 0.1 °C. Prior to measurements, the XLPE sheet specimens were cleaned with isopropyl alcohol and allowed to dry. The first measurement procedure was to apply a constant dc electric field at 120 kV/mm for a period of 48 hours. PEA measurements were taken at 6-second intervals for the first 10 minutes and subsequently every 15 minutes. The second measurement procedure was aimed at determining the onset/threshold for charge packet generation. The sheet specimen was subjected to an applied field of 120 kV/mm for duration of 1 hour until a charge packet was initiated. The applied electric field was then reduced to 90 kV/mm for 30 minutes and then further reduced to 80 kV/mm for an hour. At this point the applied field was increased to 90 kV/mm for another 1 hour and finally to 120 kV/mm for another 1 hour. Throughout the second experiment the PEA measurements were taken at intervals of 6s for about 10 minutes and then changed to 3 minutes intervals at each of the voltage levels applied.

RESULTS



(a)



(b)

Fig. 1(a) and (b) shows space charge and the internal electric field profiles respectively when the applied electric field was at 120kV/mm. The duration of stress was for 48 hours. Time T1 is at 588s, T2 at 12342s, T3 at 14142s and T4 at 15942s.

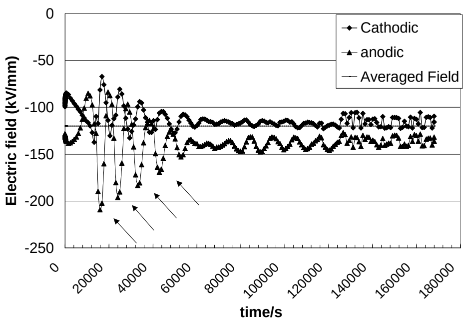


Fig. 2 Comparison of the temporal change of local internal electric fields at the anode and cathode sides. Average applied electric field at 120kV/mm

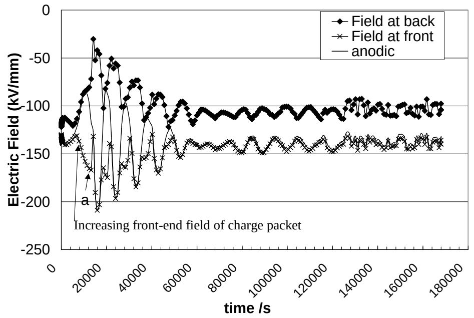
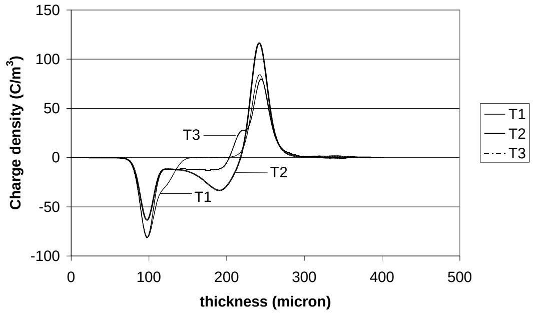
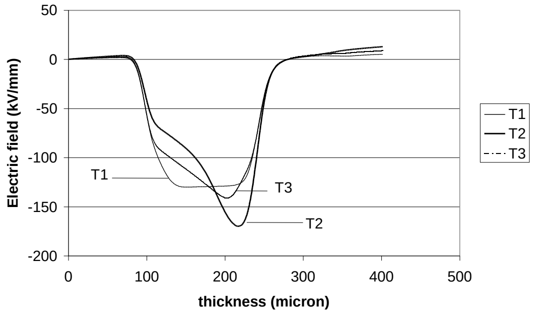


Fig. 3 Temporal change of local internal electric fields at the front, at the rear of the charge packets together with the anodic field. Applied electric field at 120kV/mm.

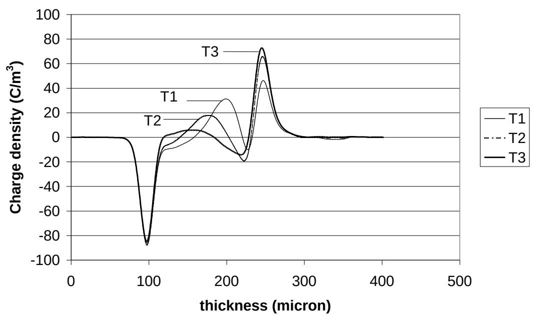


(a)

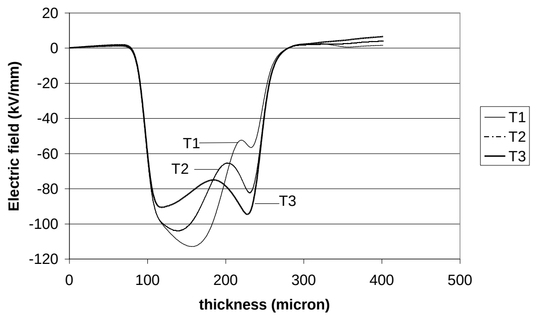


(b)

Fig. 4(a) and (b) shows space charge and the internal electric field profiles respectively when the applied electric field was 120kV/mm. The duration of electrical stress was for 1 hour. Time T1 is at 41s, T2 at 1435s and T3 at 3321s.

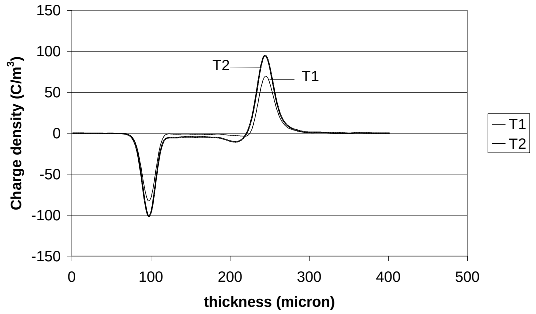


(a)

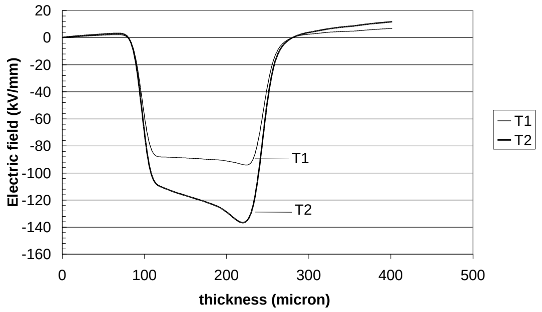


(b)

Fig. 5(a) and (b) shows space charge and the internal electric field profiles respectively when the applied electric field was reduced to 90kV/mm. The duration of electrical stress was for 0.5 hour. Time T1 is at 81s, T2 at 810s and T3 at 1620s.



(a)



(b)

Fig. 6(a) and (b) shows space charge and the internal electric field profiles respectively when the applied electric field was re-increased to 90kV/mm for 1 hour and later to 120kV/mm for the last 1 hour.

DISCUSSION

The results presented clearly demonstrate the need for an onset or threshold field if the charge packets are to be initiated. In this work the charge packets are triggered by the formation of a hetero-charge (negative space charge) field at the anode. In the first experiment it was shown that packets were continually generated as long as the anode field reached ~140 kV/mm. The threshold field is the minimum packet onset field obtained over experiment lasting up to 48 hours during which the onset field (see figure 2) steadily declined from a high of 210 kV/mm down to 140 kV/mm. The second experiment showed that a packet could not be initiated when the anode field only reached ~135 kV/mm on re-application of an applied field of 120 kV/mm. If the packet is caused by ionic dissociation and transport of one of the ionic species to the cathode where it is neutralised it could be argued that the failure to initiate a packet might be due to exhaustion of the dissociable species in the region of the anode. In the first experiment, however, several charge packets were initiated with a magnitude decreasing from 50 to 25 Cm^{-3}, but only one packet of magnitude 35 Cm^{-3} in the second experiment. Exhaustion of the positive charge reservoir is therefore unlikely to be the explanation for the failure to generate further packets. Hence there must be a packet initiation field lying between 135 kV/mm and 140 kV/mm for the type of packets observed here. This result is consistent with all three current theories. In [6] a threshold field was required for a switch to a high injection current, in [5] it is required to initiate carrier generation and in [8] it is required to create trapped carriers some fraction of which become mobile. There is also the question as to the nature of the charge carriers. The samples used had undergone a 48-hour heat treatment at 50 °C prior to use. This thermal conditioning treatment removes much of the volatile material and certainly reduces the acetophenone concentration [10]. It does not, however, remove it completely, and as pointed out in [5] the treatment may well have caused a reaction with anti-oxidant in the material leading to a dissociable chemical species. It may be possible that this species is responsible for the charge generation observed here as the transit times are similar to those found in [5]. A clearer idea of their nature will depend on a spectral analysis of the electro-luminescence produced during charge packet transit. The above considerations lead us to suggest that the charge packets formed during the first phase of the process (i.e. up to about 68000s are produced by field ionisation of an unknown chemical species. The onset field is required to both ionise the species and to displace the mobile negative charge and hence prevent recombination without packet formation. The packet advances as a progressive field ionisation revealed by displacement of the negative charge to the rear of the packet where it recombines. At times longer than 68000s, a nearly steady state of packet generation occurs. The period of the field oscillations remains the same, so it seems that this also involves packet formation and transit of the sample, although their magnitude is much reduced. Beyond 128000s there is intermittent fluctuations in the local field that appear to be associated with charge displacement, but we have insufficient resolution to say whether or not this involves packets of charge.

CONCLUSIONS

A critical onset field is required before the generation of charge packets that in the present case has a value of ~140 kV/mm, which can take a long time to develop. Once initiated long sequences of packet formation are possible. As it moves through the sample, each packet in the sequence maintains a field at its front that is sufficient to maintain movement. Reduction of the applied field from 120kV/mm to 90kV/mm allowed the field necessary to maintain packet movement to be determined. Even though the field at the packet front was less than that achieved at the higher applied fields the packet continued moving at the same speed but with reduced amplitude. A return to 120kV/mm verified the existence of a critical onset field.

The positive charge packets are formed at or near the anode because they rely on the build-up of a negative hetero-charge field to reach the required onset field.

The first charge packet at least is caused by a moving front of field ionisation as shown by the equivalent increase in negative hetero-charge at the anode [14]. The inability of the negative charge to exit quickly at the anode, unlike the situation considered in [8] prevents the exact repetition of the process for succeeding packets. The subsequent generation of packets is governed by the anode field as determined by the balance of negative charge extraction/positive charge injection processes and field ionisation. Consequently the amplitudes of successive packets reduce, to the point at which a nearly exact repetition can be achieved. The packet can continue to travel at fields down to 100 kV/mm albeit at a lower magnitude until eventually it disappears.

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