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Space charge and associated electroluminescence processes in XLPE cable peelings

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Abstract

The intent of this paper is to correlate the information obtained by space charge profile analysis and electroluminescence detection in cross-linked polyethylene samples under DC\fields, with the objective to make a link between space charge phenomenon and energy release as revealed by detection of visible photons. Space charge measurements carried out at different electrical fields by the pulsed electro-acoustic method. show the presence of a low-field threshold, close to 15-20 kV/mm, above which space charges begins to accumulate considerably in the insulation. Charges are seen to cross the insulation thickness through a packet-like behavior at higher fields, starting at about 60-70 kV/mm. Electroluminescence measurements show the existence of two distinct thresholds, one related to the excitation of electroluminescence under voltage, the other upon specimen short-circuit. The former occurs at values of fields corresponding to space charge packet formation, and the latter to space charge accumulation. The two techniques give therefore consistent information on space charge phenomenology and associated energy release in the optical EM spectrum.

Introduction

Measurements of electrical properties useful for insulation characterization and for aging diagnosis were carried out by different research groups in the framework of the European project “ARTEMIS” (Aging and Reliability Testing and Monitoring of Power Cables : Diagnosis for Insulation Systems), with the aim to investigate the degradation mechanisms and to evaluate reliability of high voltage cross-linked polyethylene (XLPE) cables. Among these properties, space charge, charging-discharging current, polarization loss and electroluminescence (EL) measurements are associated with the mechanism of charge injection and transport.

There is a general agreement among researchers that electrical aging of synthetic insulation used in high voltage cables could be started by space charge accumulation. However, there is no clear picture of the nature of the degradation reaction that would be involved at a microscopic level. Electroluminescence emission enables a link to be made between space charge phenomenology and the release of energy due, for example, to radiative charge recombination. It is therefore of importance to be able to define levels of fields and associated space charge profiles that are liable to give rise to luminescence excitation since EL is the evidence of the existence of highly reactive excited states in the insulation that could promote accelerated aging [1]. This paper presents and discusses the results obtained from space charge and EL measurements, focusing on the limits of electrical field (thresholds) which promote space charge formation and luminescence excitation.

Experimental procedures

Measurements were performed on peels cut from unaged cross-linked polyethylene (XLPE) cables produced specifically for the project [2], width 80 mm and mean thickness 150 µm. Before testing, specimens were pretreated in an oven for 48 h at 50°C in order to expel cross-linking by-products.

Space charge observations were made by the pulsed electroacoustic technique (PEA) at various constant DC voltage levels from 1 - 150 kV/mm. The poling scheme consisted in a poling time (10^4 s) and a depolarization (volt-off) time when the specimen is short-circuited (lasting 2000 s). Electrodes were made of semicon (high voltage, anode) and aluminium (cathode). Tests with gold electrodes prepared by cold sputtering were also performed [3, 4].

Electroluminescence was detected through a photomultiplier (PM) working in photon counting mode, using specimens metallized on both surfaces with semi-transparent layers of gold deposited by cold sputtering. EL measurements were carried out during polarization and depolarization at various DC poling fields. The procedure adopted for measuring EL under DC consisted in increasing the voltage in constant steps up to a maximum voltage, and then decreasing the voltage with the same step. EL is recorded at constant voltage both in the increasing and decreasing cycle. The duration of each step is relatively short (300 s upon increase, 150 s upon decrease), the steady state value of the current is therefore not reached. As no evidence of EL transient was detected, the values have been averaged over the whole time range at each step. A sampling time of one second was adopted for these measurements. Two voltage cycles were applied consecutively on the same sample:

- 0/120/0 kV/mm, with steps of 4.0 kV/mm
- 0/150/0 kV/mm, with steps of 5.3 kV/mm.

The procedure adopted to measure EL during depolarization was slightly different. We have already reported that under short-circuit conditions, the EL is a transient process occurring immediately after grounding the sample [4]. The analysis of the EL decay necessitates a shorter sampling time which has been chosen at 10 ms. Voltage was applied to the specimen by using a high voltage switch which can be used to ground the sample after the polarization time. The length of the polarization time was 3600 , which allows sufficient space charge accumulation in the sample. The length of the depolarization time is also 3600 . The voltage is further increased and the same experiment is repeated. Measurements were carried out starting from 10 kV/mm up to 90 kV/mm, with steps of 5 kV/mm.

Experimental results and discussion

Fig. 1 shows the EL versus DC field characteristics obtained for the two voltage cycles. The EL during the decreasing part of the voltage cycle (Figure 1a) is slightly lower at the same field than that during the increasing part which means that charge accumulation is the controlling factor in EL excitation. Experiments performed on different samples have shown a good reproducibility of the EL versus field characteristics. A threshold for EL detection (E_{PP}) can be defined at field 60-70 kV/mm as seen in Figure 1b.

The results obtained from depolarization measurements are summarized in Figure 2. The integrated EL counts recorded after electrode short-circuit and grounding are reported as a function of the poling field in Figure 2a. A threshold below which the EL emission is lower than the measuring system sensitivity and above which the EL signal is steeply increasing in magnitude is clearly detectable close to 20 kV/mm. The time dependence of the luminescence after short-circuit is also shown in Figure 2b at a field level of 80 kV/mm.

It is noteworthy that the threshold value detected by means of EL observations under short-circuit is significantly lower than the previously inferred permanent EL threshold estimates that were carried out under field. Indeed the above-described experimental procedure allows, through the EL measurements carried out during depolarization, the detection of signals coming from charge recombination forced by the short-circuit condition, that occur at fields much lower than those required for permanent EL detection. In other words, this procedure is able to provide early and sensitive indications of the presence of space charges, and thus of the electrical field above which space charge is accumulated in the material under test.

Turning now to the excitation mechanism of the EL, it is noteworthy that in the last stage of the process, light would always be generated upon annihilation of a pair of positive and negative charges, either trapped at different sites, or bounded to the same center. As always in the EL process, the quest is to find the mechanism of generation of the pair. When both kinds of carriers are involved in charge transport, there is a strong probability that the light comes from recombination of the two kinds of charged particles if they are able to interact, i.e. one has to observe positively and negatively charged regions with frontiers in between. If only one kind of carrier is contributing to the transport mechanism, the EL should be excited when these carriers reach a kinetic energy able to generate the pair by impact excitation or impact-ionization (hot carrier effects). Correlating the space charge profiles with the two different EL regimes is of interest and is reported here.

Consideration of the emission spectra of the EL can also give a first indication. Although it has not been possible to record the EL emission spectrum under DC stress, we have analyzed it under AC (previous studies have shown that for a given material, EL spectra have similar spectral features under DC and AC [5]). The AC spectrum is shown in Figure 3, where it is compared with the spectrum of the light emitted by the same XLPE material during the recombination of positive and negative charges, in the absence of an applied field (i.e. the excitation mechanism cannot be due to hot carriers)[6]. Even if all the spectral features of the EL spectrum cannot be fully interpreted on the basis of the so-called recombination-spectrum, it is clear that the latter is a component of the former. Other indications that cannot be discussed in this paper point towards an EL controlled by the recombination of charges in the presence of two types of carriers (i.e. without the mediation of hot electrons). Further indications come from the space charge distribution.

The PEA measurements show that below fields of the order of 15-20 kV/mm, the space charge magnitude is at the sensitivity limit of the system, close to 0.1 C/m^3. Above 20 kV/mm charge begins to accumulate considerably as function of applied field. Qualitative examples of this behavior are given by the space charge profiles reported in Figure 4. They were obtained after 10^4 s of poling at 15 and 35 kV/mm, respectively. As can be seen, while no charge can be detected at 15 kV/mm, a small but appreciable amount of heterocharge appears at 35 kV/mm.

A quantitative evaluation of the field value above which charge accumulates can be obtained resorting to the calculation of Q_M, called the total stored charge, and defined as the integral of the absolute value of the charge profile, at a given depolarization time, e.g. 10 s, excluding the image charges on the electrodes [3]. Once the obtained value of Q_M is plotted as function of poling (Laplacian) field, E, the plot of Figure 5 is obtained. From this plot (hereafter called the threshold characteristic), the threshold above which space charges begins to accumulate in insulation can be easily determined, i.e. above 20 kV/mm from Figure 5. It is noteworthy that this value is close to the one obtained for EL measurements (Figure 2) and that it does not change significantly for gold-coated or uncoated specimens.

The good correspondence between the threshold estimates obtained by space charge and EL techniques shows that each technique provides consistent information regarding the space-charge formation phenomenon, thus space-charge accumulation observed by PEA and electroluminescence produced by trapped charges during depolarization constitute different aspects of the same process.

In order to investigate the recombination phenomena giving rise to the permanent EL threshold, E_{PP}, the 3D space-charge patterns providing space charge evolution with time should be considered. Figures 6 and 7 show space charge patterns obtained during polarization and depolarization at 60 and 90 kV/mm. The intensity of the charge is associated with the darkest tone of gray (with the exception of the electrodes, where the maximum intensity, saturating the tones to the white color, is achieved). As can be seen, at 60 kV/mm and, more clearly, at 90 kV/mm, positive and negative charge packets tend to leave electrodes and cross insulation. When the fronts of the packets meet each other, charges recombine and only one packet prevails, reaching the opposite electrode. This interpretation is not straightforward on the basis of space charge observation, since PEA (as the other techniques for space charge measurements) provides information on the net charge, independently of real charge recombination. However, if the EL observations are considered, it comes out that above 60-70 kV/mm charge recombination becomes significant, constituting the threshold for permanent EL.

Figure 8 shows the space charge profiles during poling, in steady conditions, at 60 and 90 kV/mm. Comparing with Figure 4, it can be seen that while at 30 kV/mm heterocharges are located only close to the electrodes, at 60 kV/mm and, more, at 90 kV/mm charges begin to penetrate into specimen thickness, so that charges of opposite sign are faced in the insulation bulk. This would support the appearance of recombination phenomena.

Conclusions

Both space charge and electroluminescence (EL) measurements can provide significant information about the processes of space charge formation and transport. A threshold for space charge formation can be detected through the threshold characteristics obtained from space charge magnitude vs. field and EL intensity vs. field measurements, once the latter experiments are carried out in the way indicated in this paper, i.e. measuring EL during depolarization. At higher fields, space charges occupy insulation bulk and would tend to cross insulation thickness through charge packets. The information coming from space charge observations is, again, in agreement with that given by EL measurements, which provide a threshold for permanent electroluminescence at the fields at which space charges tend to cross insulation. Electroluminescence spectra, moreover, complement space-charge measurement information indicating that the occurrence of packet charges is associated with recombination phenomena.

Acknowledgements

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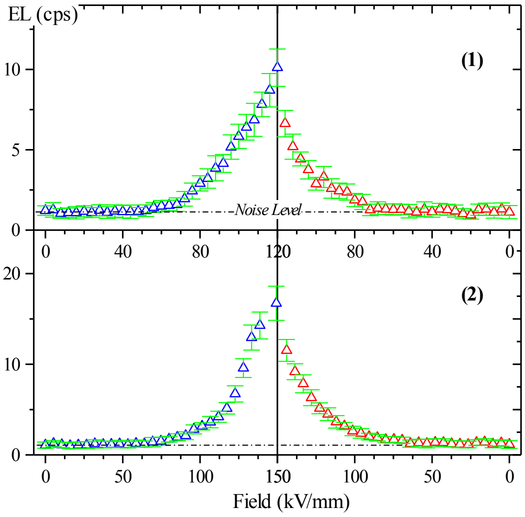

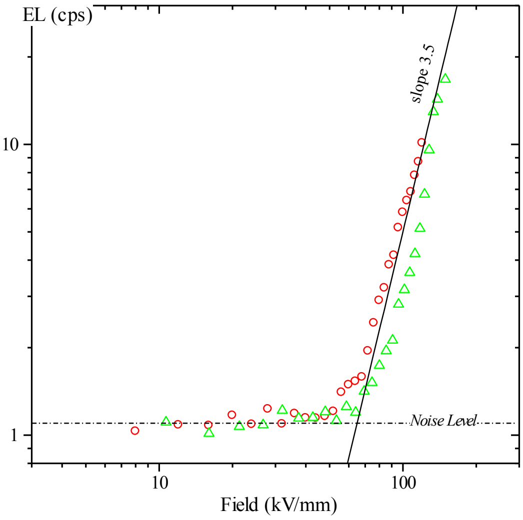

Fig. 1(b): EL versus DC field characteristics obtained during voltage increases for the two cycles

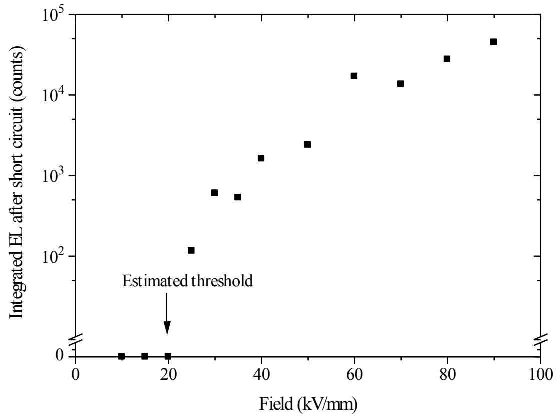

Figure 2(a): :EL at the short-circuit after one hour of DC polarization. Integrated electroluminescence versus field level. (Data corrected for the PM background noise)

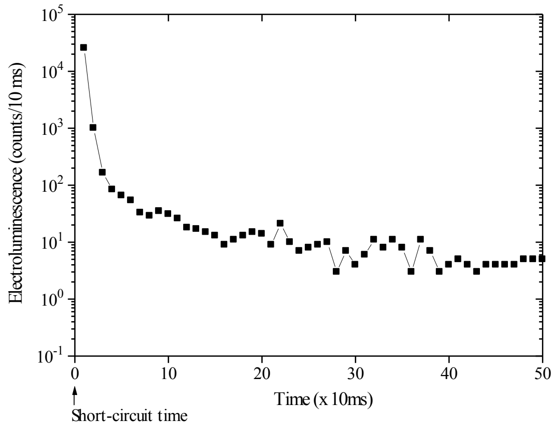

Figure 2(b): :EL at the short-circuit after one hour of DC polarization. Time dependence of the EL at the short circuit for a poling field of 80 kV/mm. (Data corrected for the PM background noise

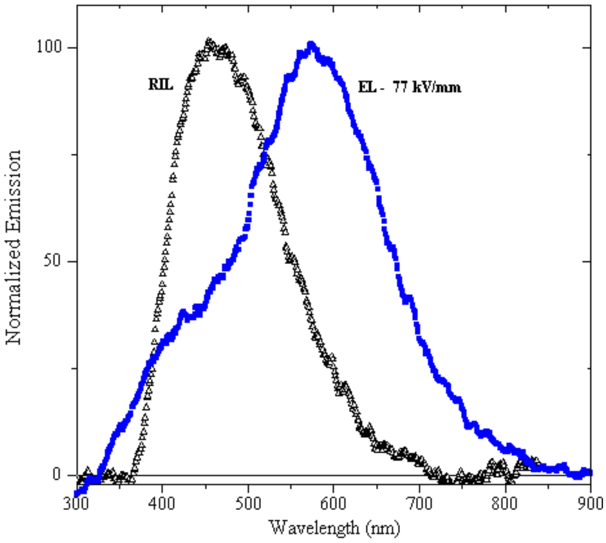

Figure 3: EL spectrum under AC compared to the luminescence spectrum due to charge recombination (RIL)

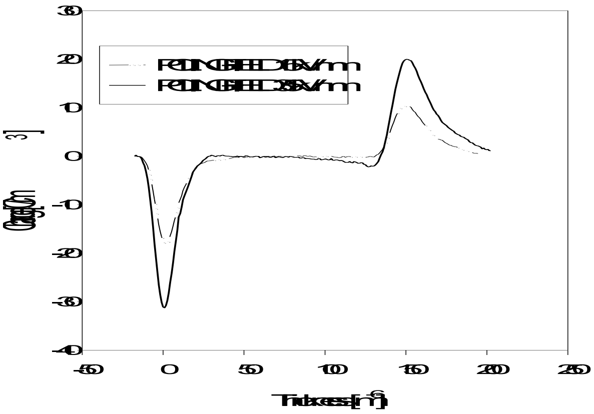

Figure 4: Space charge profiles after 10000 s of polarization. Poling fields 15 and 35 kV/mm

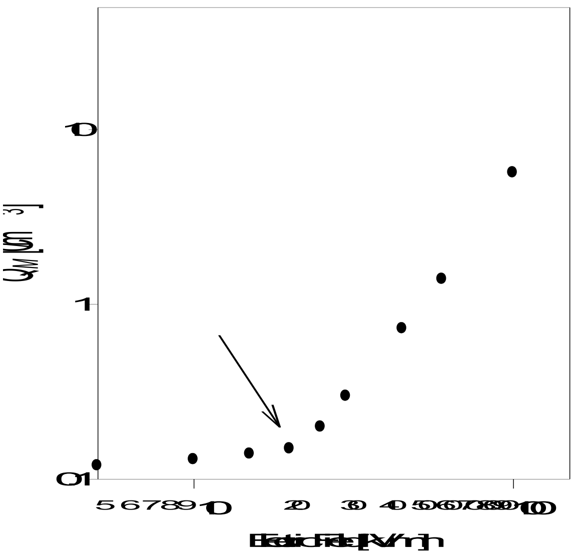

Figure 5: Threshold caracteristic (total stored charge versus poling field) obtained from space charge measurements. The estimated threshold is indicated by a arrow.

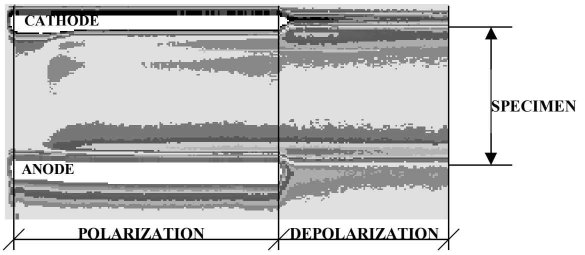

Figure. 6: Space charge 3D patterns obtained during polarization and depolarization at 60 kV/mm. The intensity of the charge is associated with the darkest tone of gray (the white color, however, is used for the electrodes, where the charge intensity is maximum).

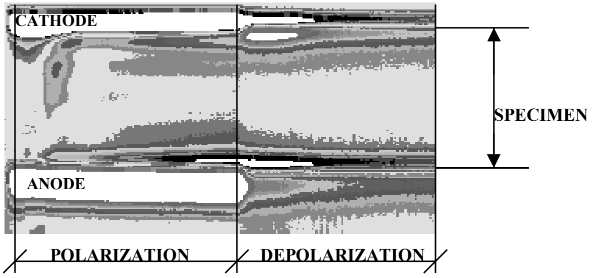

Figure 7: Space charge 3D patterns obtained during polarization and depolarization at 90 kV/mm.

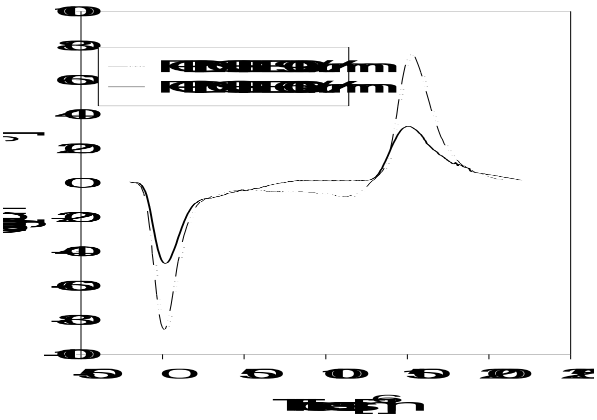

Figure 8: Space charge profiles after 1000 s of poling at 60 and 90 kV/mm.