"Mirror Image" Space Charge Distribution in XLPE Power Cable under Opposite Stressing Voltage Polarity

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Abstract: The paper presents the research on space charge distribution under different polarities in full size cross-linked polyethylene power cables using the pulsed electro-acoustic technique. Under both positive and negative voltage space charge distributions possess about the same profiles but opposite polarities. Similar phenomenon had been reported previously in plaque samples and was termed as "mirror image effect". By comparing the results among the cables treated (degassing) under different conditions, the paper concludes that the "mirror image" charge distribution is mainly attributed to bulk effect within the volume of the insulation, whilst the electron transfer by tunnelling through an electrode/insulator interface contribute to the generation of homo "mirror image" at the vicinity of the electrode.
Key Words: "Mirror Image" charge; Space charge; XLPE cable; Voltage polarity reversal.

INTRODUCTION

The excellent electrical properties of cross-linked polyethylene (XLPE) in combination with its good physical properties have attracted many manufacturers worldwide to look at its application for high voltage direct current (HVDC) underground power cables development. However, the low charge carrier mobility and charge trapping within this type insulating material can give rise to space charge, resulting in localised electric stress enhancement which may lead to premature failure of the cable well below the anticipated and designed values. In particular, in the case of space charge presence in DC power cable insulation, the manoeuvre of polarity reversal may create extremely high electric stress in some specific region [1, 2]. This could pose a foremost threat to the cable insulation in service. As described by enormous of literature, these charge may be supplied from the electrode injection and the ionisation of impurities and then trapped within the bulk material [3-7]

The aim of studying space charge in polymer insulation in electrical apparatus (e.g. extruded polymeric power cables) is to acquire better understanding of space charge behaviour in practical structure. In particular, in an on-going project to develop cross-linked polyethylene (XLPE) insulated direct current (DC) power cable, space charge measurement on a full sized cable sample can give insight into the effects of a number of factors, particularly including semiconductive layers, XLPE insulating materials actually being made in the manufacturing process, and the divergent distribution of electric field along cable radius on space charge generation and accumulation. It would also be convenient and realistic method to investigate the effect of a temperature gradient throughout the insulation on space charge when the cable is loaded in service.

The paper presents the research on space charge distribution in polymer (e.g. XLPE) insulated power cables under opposite voltage polarities and its response to voltage polarity reversal. It was noticed that at positive and negative voltage polarity space charge distributions possess almost the same shape but with opposite charge polarities. Same phenomenon has been reported by Bambery [8] and Wang [9] in the plaque XLPE samples and cable geometry respectively, and was termed as "mirror image effect". The reasons attributed to this "mirror image" charge have been discussed on the basis of the results of different space charge profiles from different cables.

EXPERIMENT

PEA for cable samples and experiment procedures

Space charge distribution throughout cable insulation was measured in a modified PEA, as show in Fig. 1, in which the use of a flat ground electrode makes the system easy to be used to cables with different radii [1]. A current transformer was set up in the testing rig to generate a temperature gradient across the cable insulation using induct-heating (joule heating I^2R) method. To allow sufficient clear distance from voltage applying terminal to ground electrode the outer semi-conductive screens at the two ends of the cable were stripped back, and the remaining section worked as outer-earthed electrode. Stress relief rings were also built at the screen cuts to reduce the possibility of flashover along the insulation surface.

The research was carried out on two types of commercial XLPE AC power cables with different insulation thicknesses. Each cable sample was stressed with positive or negative voltage at central conductor separately, or with opposite voltages at central conductor consequently. Space charge profile was measured at different time over the whole stressing term. To discriminate the existence of homocharge some measurements were also taken with external voltage removal. In order to examine the space charge response to voltage polarity change, a real common operating manner in HVDC transmission system, the space charge was closely observed in the process of polarity reversing and voltage ramping up. In this test positive voltage (80kV) was initially applied at the centre conductor, after the space charge reached its saturation the external voltage switched off and the polarity reversed, and then ramped up to desired values (-80kV). The whole voltage reversing process took about 90 seconds.

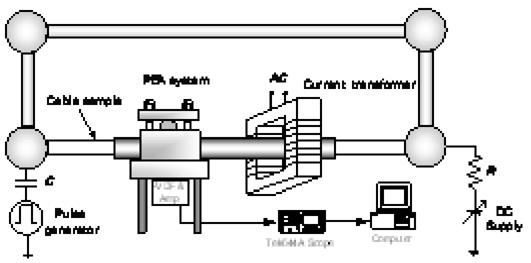


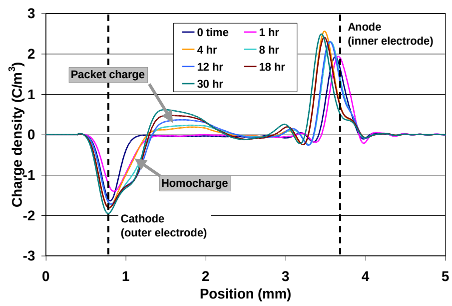
Fig. 1 Schematic diagram of PEA system for coaxial cable samples

Experiment results

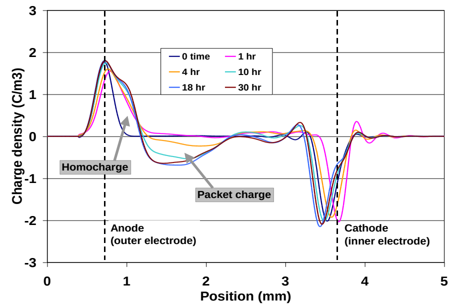
<u>Experiment under opposite voltages</u>

Fig. 2 (a) and (b) show the space charge development in XLPE cable insulation over a stressing time up to 30 hours. In the experiment, the central conductor was respectively energised with positive and negative voltages. In each situation with positive or negative voltage, it is noticed that a packet homocharge gradually accumulates in the region adjacent to the outer electrode, simultaneously with another bulk of charge neighbouring to it. It is also interesting to see that the space charges under each voltage polarity have almost the same shapes (distributions) but the opposite polarities. They are even of the same space charge building up rate. The same phenomenon had been reported in the literatures [8, 9] and was defined as “mirror image effect” charge by Bambery [8]. It has to be pointed out that due to two different semiconductive materials being used at inner and outer screen layers, space charge at these two areas possess different distributions and generating tendency.

Another significant characteristic of space charge accumulated in this cable sample is its high stability, which is clearly illustrated in Fig. 3 (a) and (b) of space charge decay. After stressing at each voltage polarity, the central conductor and outer sheath of cable sample was short circuited for as long as 48 hours and space charge decay was measured. However, space charge decline over this period of time is hardly visible.

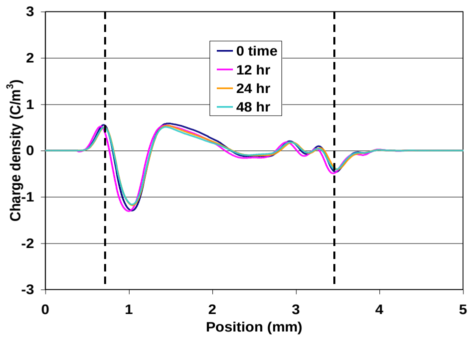


(a) Positive voltage at central conductor

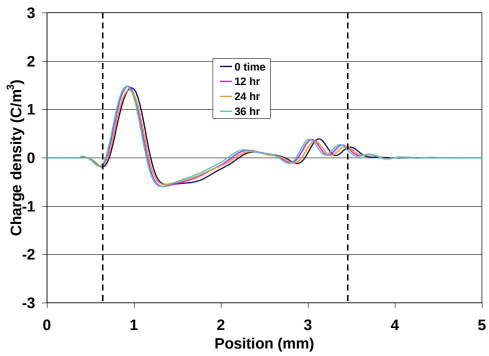


(b) Negative voltage at central conductor

Fig. 2 Space charge distributions in XLPE cables with opposite voltages applied at central conductors



(a) Charge decay after positive voltage stressing



(b) Charge decay after negative voltage stressing

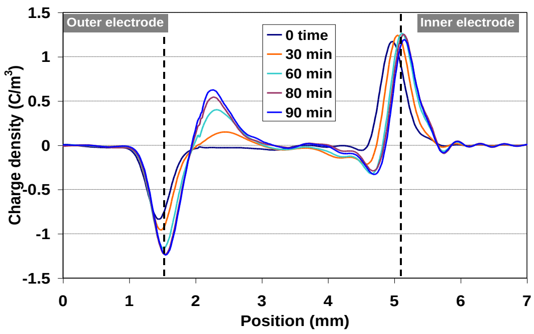
Fig. 3 Space charge decay profiles in XLPE cables after opposite voltages applied at central conductors

Experiment under voltage polarity reversal

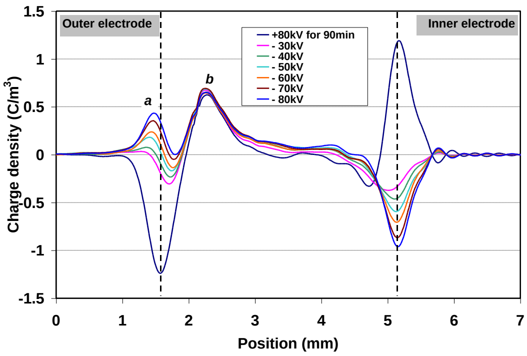
Fig. 4 (a), (b) and (c) shows space charge accumulation and evolution with a positive voltage application to central conductor first and then reversed to negative in another XLPE cable sample. In the first case with positive voltage, heterocharge gradually accumulates in volume immediately adjacent to inner and outer electrodes and reaches a stable distribution in about 90 minutes.

During the voltage polarity reversing and voltage amplitude ramping up, previously formed charge (positive near the outer sheath, indicated in ***b***) remains almost unchanged. The induced charge at the outer electrode (peak ***a***) increases linearly with the external voltage, which may suggest no fast charge is developed over this voltage ramping process.

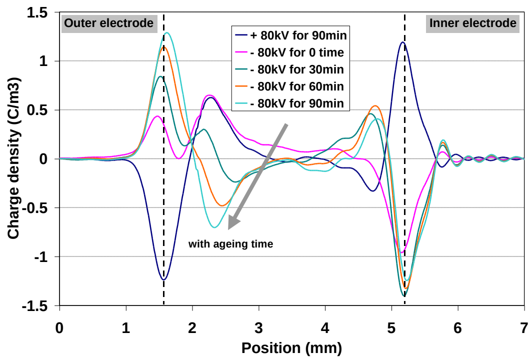
After the voltage reached –80kV, the heterocharge began to accumulate in the bulk of the insulation again, as shown Fig. 4 (c). The previously accumulated heterocharge (positive) near the outer electrode was gradually neutralised by the newly formed heterocharge (negative) at the same position, and resulted in the reduction of positive charge. The final result of the neutralisation was the accumulation of the new heterocharge (negative) and the induced surface charge at the outer electrode/insulation interface increase. It is of interest to note that space charge under negative voltage took another 90 minutes to reach equilibrium, rather than taking longer time for previously formed charge neutralization [2]. It is surprise again to that final space charges at the two opposite stressing polarities are of “mirror image” distributions.



(a) Space charge accumulation with +80kV at central conductor



(b) Space charge response to reversed voltage amplitude



(c) Space charge re-distribute with reversed voltage application

Fig. 4 Space charge development over external voltage reversing

DISCUSSION ON “MIRROR IMAGE EFFECT” CHARGE DISTRIBUTION

Heterocharge and volume charge in bulk insulation

The tendency of space charge generation in polymer insulating material has been well acknowledged if it’s subjected to an adequate high electric field. The mechanism of charge generation and accumulation is generally considered to be the result of electron injection or extraction at the electrode/insulation interface, and/or the ionization of impurities in the bulk material by ion separation [10].

In the case of cable insulations being stressed with a positive and negative voltages at central conductor respectively, like the samples in Fig. 2 (a) and (b), if the electric field is adequately high to fulfil electron/or hole injection at a specific electrode/insulator, electrons and holes injection at outer cable semi-conductive sheath has let to homocharge build up. Simultaneously, due to remainders of cross-linking by-products, the ionization of these tiny molecules has led to a large packet of heterocharge (referring to outer electrode) accumulation within insulation bulk under two opposite stressing polarities at the central conductor respectively [10,11].

The initiation of "mirror image effect" charge in the bulk insulation due to ionization is more explicable in comparison with homocharge adjacent to electrode/XLPE interface. The samples tested in the research were commercial XLPE power cable and but not fully conditioned (degassed) after manufacture, hence it was supposed to have high residue content of cross-linking by-products and additives. Electric filed assisted dissociation of these small chemical species will occur throughout the thickness of cable insulation when external voltage is applied. It is therefore seemingly to give a "mirror image" distribution when an opposite external field is applied.

The same argument could also be made to the situation in which opposite fields is applied consequently, like the results shown in Fig. 4 (a)~(c), where heterocharges are observed at both electrode/insulator interfaces. It is generally believed that charge carrier generated by ionisation have a negligible mobility, which is clearly evidenced in the Fig. 4(b) when the voltage polarity is reversed and ramps up from –30kV to –80kV, see the charge labelled by letter *b*. During following period of stressing time with reversed field, a negative bulk charge is gradually building up around the central part of insulation and the position of its peak steadily shifts towards outer sheath of the cable owing to the cancellation between this newly formed negative charge and previously formed positive charge, as indicated by the arrow in Fig. 4 (c). After certain length of stressing time the same space charge distribution both on position and magnitude will present in the regions with same impurity concentration. The justification of alignment of the small molecular dipoles of the impurities along the external electric field is, however, questionable because the fraction of this sort of charge due to polarization is negligible in the case of figure 2 with homocharge adjacent to electrode/insulator interface, and the location of charge is not consistent with the situation shown in Fig. 4 (c). This judgment may also be supported by the factor of very slow decay rate displayed in Fig. 3(a) and (b) when external voltage was removed.

Homocharge

The sample for the measurement of Fig. 2 and 3 has different semi-conducting materials at inner and outer electrodes, and a large homocharge appears next to outer electrode/XLPE interface at both field polarities. These results imply the combination of outer semi-conductive material and XLPE is of higher electron injection than the interface presenting at inner electrode if outer sheath is cathode. However, one may easily ask if this combination will be of high hole injection (or electron extraction) ability when the electric field is at reversal.

According to Lewis [12], electron transfer by tunnelling through an electrode/insulator interface, no matter the direction, will involve only a narrow "window" of combined donor and acceptor states in the insulation, centred on the Fermi level and the states within the same energy range in the electrode. For a given electrode (same material), the equilibrium barrier heights and widths for electron extraction and injection must be equal.

The interface injection effect in this situation will finally arrive at equilibrium due to the decline of the interfacial stress as the homocharge is formed at the outer electrode. Since the height and the width of a given barrier depends on the local electric stress, in the present case the equal amount of negative and positive charge close to a given electrode will be obtained under two opposite voltage polarities. This leads to the same but opposite charges being generated near the outer electrode at two opposite stressing polarities.

CONCLUSIONS

Space charge measurements throughout XLPE insulation of two commercial power cables have been carried out with opposite external voltage applied respectively or consequently. The following conclusions may be drawn from these results and relevant discussion.

1) The "mirror image effect" space charge distribution along cable insulation thickness is likely to be a common phenomenon under two opposite stressing voltage polarities. This type of charge distribution may be found in bulk insulation or in the immediate vicinity of electrode and insulator interface.

2) The bulk charge within the cable insulating material or heterocharge neighbouring the electrodes are generated by the ionization of impurities and, which are generally assumed to have negligible mobility. Under the opposite voltage being of same stressing strength, this sort of field-aided ionisation is therefore reckoned to give the "mirror image" distribution at same region.

3) Sample giving the results of Fig. 2 (a) and (b) have different semiconducting materials at inner and outer screening sheath, while the one used at outer screen shows both a higher electron and hole injection when electrode is cathode and anode respectively in comparison with inner semiconducting layer. This electron and hole injection for homo- "mirror image effect" charge may be explained by electron tunnelling.

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