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

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Abstract: The paper presents space charge distributions under opposite voltage polarities in full size cross-linked polyethylene power cables using the pulsed electro-acoustic technique. Under both positive and negative polarities, space charge distributions possess similar profiles but opposite polarities. A similar phenomenon had been reported previously in plaque samples and was termed the "mirror image effect". By comparing the results between cables treated by degassing under different conditions, the paper concludes that the "mirror image" charge distribution is mainly attributed to a bulk effect within the volume of the insulation, whilst electron transfer by tunneling through an electrode/insulator interface contributes to the generation of homo "mirror image" close to the electrodes.

Key Words: "Mirror Image effect" 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 consider its application for high voltage direct current (HVDC) underground power cables. However, the low charge carrier mobility and charge trapping within this insulating material can give rise to space charge, resulting in localized electric stress enhancement, which may lead to premature failure of the cable. In particular, the operation of polarity reversal in DC transmission system may create extremely high electric stresses in certain parts of the insulation when space charge is present in cable insulation [1, 2]. This could pose a considerable threat to such cable insulation in service. As described by a large body of scientific literature, these space charges may be supplied through electrode injection or through the ionization of impurities that are 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 a better understanding of space charge behavior in practical structures. In particular, in an on-going project to develop a 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, in particular, the semiconductive layers, the XLPE insulating materials actually being made in the manufacturing process, and the divergent distribution of electric field along the cable radius on space charge generation and accumulation. This is also a 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.

This paper presents research on the space charge distribution in 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. A similar phenomenon has been reported by Bambery [8] and Wang [9] in XLPE plaque samples and cable geometries respectively, and was termed the "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 system, as shown in Fig. 1, in which the use of a flat ground electrode makes the system easy to use with cables of different radii [1]. For the investigation into the effect of temperature gradient across cable insulation on space charge, a current transformer was set up in the testing rig to heat the cable by induction-heating (Joule heat, I^2R). To allow sufficient clear distance between the high voltage terminal and the ground electrode, the outer semi-conductive screens at the two ends of the cable were stripped back, and the remaining section used as an 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 the central conductor separately, or with opposite voltages at central conductor one after the other. The space charge profile was measured at different times over the whole stressing term. To ascertain the existence of homocharges, some measurements were also taken with external voltage removed (i.e. open circuit conditions).

In order to examine the space charge response to voltage polarity change, a common operation in an HVDC transmission system, the space charge was closely observed during the process of polarity reversal and voltage ramping up. In this test, a positive voltage (+80kV) was initially applied at the centre conductor, after the space charge reached its saturation the external voltage was switched off and the polarity reversed, and then ramped up to desired values (-80kV). The whole voltage reversing process took about 90 seconds.

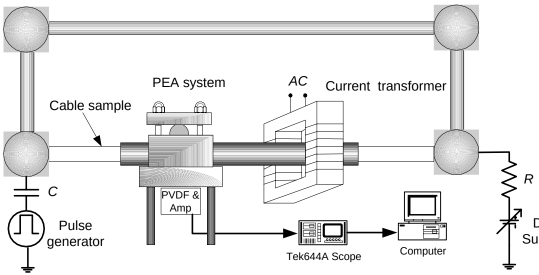


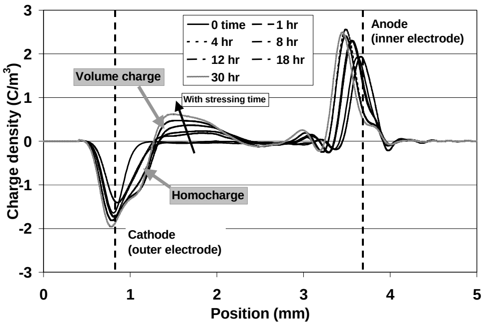
Fig. 1 Schematic diagram of PEA system for coaxial cable samples

Experiment results

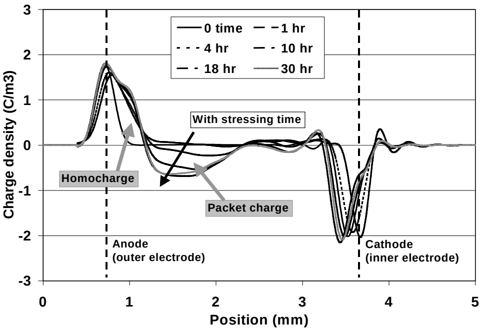
Experiment under opposite voltages

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 energized with positive and negative voltages. In each situation, with positive or negative voltage, it is noticed that homocharge gradually accumulates in the region adjacent to the outer electrode, simultaneously with another bulk of charge adjacent to it. These homocharges adjacent to outer electrodes (sheathes) are clearly presented in Fig. 3 (a) and (b), the space charge decay results when the induced surface charge due to external voltage are absent. It is interesting to see that the space charges under each voltage polarity have almost the same shapes (distributions) but the opposite polarities. They even have the same rate of build-up. Bambery *et al* [8] has described the same phenomenon in their research as “mirror image effect”. It has to be pointed out that due to two different semiconductive materials being used at inner and outer screen layers in the specimen, space charge at these two areas possess different distributions and ease of generation.

Another significant feature of space charge accumulated in the experiment is its high stability in the subsequent discharging experiment. After space charge got equilibrium at each polarity, the external voltage was removed to carry out space charge decay test with the outer sheath and the central conductor short-circuited. Fig. 3 (a) and (b) show the space charge profile as the function of time after stressing voltages removal. The stable distribution of space charge is clearly revealed by these space charge decay results, as charge decline over this period of time (as long as 48 hours) is hardly visible.

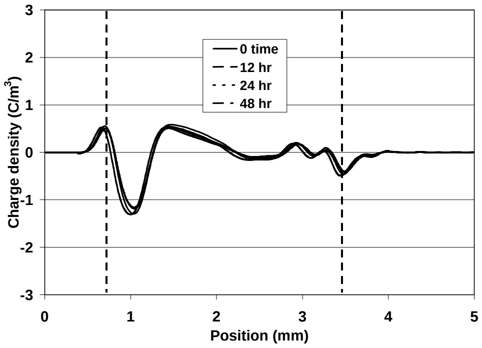


(a) Positive voltage at central conductor

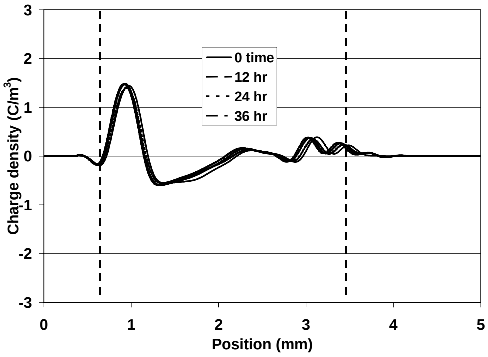


(b) Negative voltage at central conductor

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



(a) Charge decay after positive voltage stressing



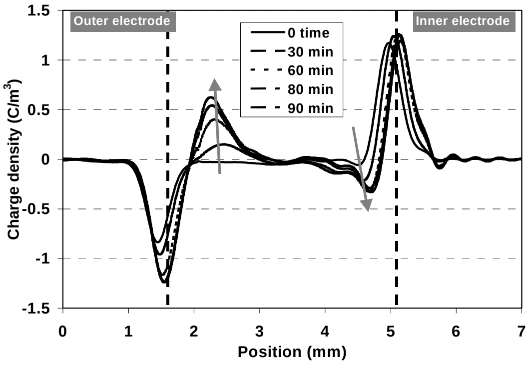
(b) Charge decay after negative voltage stressing

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

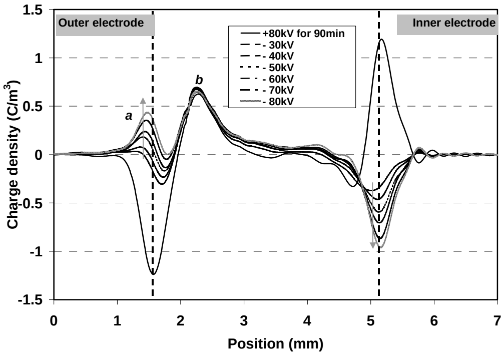
Experiment under voltage polarity reversal

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, like the results shown in Fig. 4 (a), heterocharges gradually accumulate in volume immediately adjacent to inner and outer electrodes but with a higher density at outer electrode and reaches their stable distributions in about 90 minutes. In the following voltage polarity reversing and voltage amplitude ramping up process, in Fig.4 (b), previously formed charge (positive near the outer sheath, indicated in ***b***) remains almost unchanged. The induced charge at the outer electrode (peak ***a***, anode) increases linearly with the external voltage but shows a low magnitude because of stable positive charge ***b*** alongside, which may suggest no fast charge is developed over this voltage ramping process.

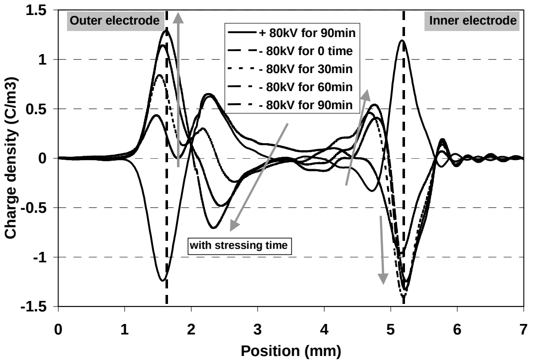
As a function of stressing time at –80kV, the heterocharge (negative) began to accumulate in the bulk of the insulation, where the highest electric field may exist because of the positive charge formed under previous voltage polarity. From Fig. 4 (c), it is noticed that previously accumulated heterocharge (positive) near the outer electrode was gradually neutralized by the newly formed negative charge from the central part of insulation, and resulted in the reduction of positive charge. As a result of above mentioned neutralization, one can see that the peak position of the newly formed charge (negative) shifting from the centre of insulation towards the outer sheath. The final result was the accumulation of the new heterocharge (negative at outer electrode and positive at inner electrode) and the increase of the induced surface charge at the outer electrode/insulation interface. It is interesting to note that space charge under negative voltage took another 90 minutes to reach equilibrium, rather than taking longer time as generally expected to cancel out the previously formed charge (neutralization) and then reach a new redistribution [2]. Again the final space charges at the two opposite stressing polarities are of "mirror image effect" distributions.



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



(b) Space charge response to reversed voltage amplitude



(c) Redistribution of space charge under opposite polarity

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 for space charge to form in polymeric insulating materials under sufficient electric fields is well known. 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, as in the samples in Fig. 2 (a) and (b), if the electric field is sufficiently high to fulfill electron/or hole injection at a specific electrode/insulator, injection of electrons and holes at the outer cable semi-conductive sheath allows homocharge to build up. Simultaneously, the ionization of residual cross-linking by-products leads to a large region of heterocharge (referring to the outer electrode) accumulation within the insulation bulk irrespective of the polarity of the central conductor [10, 11].

The initiation of "mirror image effect" 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 cables 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 chemical species may occur throughout the thickness of cable insulation when an external voltage is applied. This therefore appears 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 are applied one after another, as in the results shown in Fig. 4 (a)~(c), where heterocharges are observed at both electrode/insulator interfaces. It is generally believed that charge carriers generated by residual impurities ionization have a negligible mobility, which has been clearly evidenced in the Fig. 4 (b) when the voltage polarity is reversed and ramps up from –30kV to –80kV, see the charge labeled as letter *b*. During the 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 a certain length of stressing time, the same space charge distribution both in position and magnitude will present in the regions with the 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 under 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 under reversal as same homocharge profiles has been observed under two opposite voltages.

According to Lewis [12], electron transfer by tunneling through an electrode/insulator interface, no matter the direction, will involve only a narrow “window” of combined donor and acceptor states in the insulation, centered 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 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 neighboring the electrodes are generated by the ionization of impurities, which are generally assumed to have negligible mobility. Under the opposite voltage, being of same stressing strength, this sort of field-aided ionization is therefore reckoned to give the “mirror image” distribution at same region.

3) Samples 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 tunneling.

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