Return to Session

EFFECT OF SEMICON-INSULATION INTERFACE ON SPACE CHARGE FORMATION IN HVDC POLYMERIC CABLES

Davide FABIANI, DIE-LIMAT University of Bologna, Bologna (Italy), davide.fabiani@unibo.it
Gian Carlo MONTANARI, DIE-LIMAT University of Bologna, Bologna (Italy), giancarlo.montanari@unibo.it
Leonard A. DISSADO, Dept. of Engineering - University of Leicester, Leicester (UK), lad4@leicester.ac.uk
Christian LAURENT, Université Paul Sabatier - Laplace, Toulouse (France), christian.laurent@laplace.univ-tlse.fr
Gilbert TEYSSEDRE, Université Paul Sabatier - Laplace, Toulouse (France), gilbert.teyssedre@laplace.univ-tlse.fr
Peter H. F. MORSHUIS, Delft University of Technology, Delft (The Netherlands), p.h.f.morshuis@its.tudelt.nl
Riccardo BODEGA[1], Delft University of Technology, Delft (The Netherlands), riccardo.bodega@prysmian.com
Alfred CAMPUS, Borealis AB, Wire & Cable BU, Stenungsund (Sweden), alfred.campus@borealisgroup.com
Ulf H. NILSSON, Borealis AB, Wire & Cable BU, Stenungsund (Sweden), ulf.nilsson@borealisgroup.com

ABSTRACT

This paper deals with the analysis of the insulation/semicon interface as regards space charge injection and accumulation in the insulation bulk. Comparing space charge characteristics, originating from experimental measurements and relevant to different semicon/insulation combinations, it can be observed that the semicon may play an increasing role in charge injection as temperature rises, with an extent depending on the kind of semicon used. In addition, the type of insulation affects also the space charge accumulation, depending on trap distribution.

KEYWORDS

HVDC, polyethylene, semiconducting material, insulating material, charge injection, space charge accumulation threshold.

INTRODUCTION

Much effort has been spent to expand the use of polymeric cables (usually limited to HVAC) to HVDC power links [1]. This would provide tangible environmental and economic benefits with respect to mass-impregnated cables traditionally used in HVDC applications. Polymeric cables, however, seem to be greatly affected by space charge build-up, particularly when DC voltage is applied [2-4]. Space charge accumulation is considered, indeed, to be one of the main factors responsible for ageing acceleration in cable insulation, due to local electric field enhancement produced by accumulated charge, particularly in the presence of voltage polarity inversions.

Space charge build up is a complex mechanism that is yet to be fully explained. Generally, if the electric field is larger than a given threshold, i.e. the threshold for space charge accumulation, charge injection from the electrodes, promoted by field and temperature, may prevail over charge extraction/recombination [4]. This causes accumulation of space charge in traps located in the insulation bulk that hold the excess charge injected by the electrodes for times depending on trap depth which, in turn, may be associated with chemical/morphological structure of the insulating material. It has been observed that the amount of charge injection and accumulation may depend significantly on the contact between electrode and insulation. In particular, since a semiconductive layer is interposed between metal electrodes and insulation of a polymeric cable, the interface between semicon and insulation is thought to have a significant effect on space charge build-up in insulation.
Experimental tests were performed on mini-cable specimens having different combinations of insulation (INS1, INS2) and semiconductive materials (SC1, SC2), with the aim of investigating the way the semicon-insulation interface affects space charge accumulation. In particular, space charge measurements were carried out on these specimens at different electric field and temperature values, to obtain the characteristics of charge accumulation as a function of field and temperature.

TEST PROCEDURES

In order to measure space charge accumulation characteristics for each insulation system, space charge measurements were performed by means of the Pulsed Electro Acoustic (PEA) technique on mini-cable and plaque specimens [5]. Before testing, a thermal treatment was applied to cable models and plaques for 5 days at 80°C and for 3 days at 70°C, respectively, with the aim of expelling in principle all crosslinking by-products [6].

Two kinds of specimens, made by insulating/semi-conducting materials were considered for testing:

1) Press-moulded plaques, consisting of a two-layer sandwiches, one insulating layer, 0.5 mm thick, and one semiconducting layer, 0.5 mm thick.
2) Cable models, reproducing HV cables on a reduced-scale (mini-cables), consisting of three layers: inner semicon (0.7 mm thick), insulation layer (1.5mm thick) and outer semicon (0.15 mm thick). The conductor diameter is 2.8 mm (Fig. 1).

Two different XLPE-based insulating materials (INS1 and INS2) and semiconducting materials (SC1 and SC2) were evaluated, giving rise to insulation systems with different permutations of semicon/insulating materials. In particular, the combinations INS1-SC1, INS2-SC1, INS2-SC2 for the plaques and INS1-SC1, INS2-SC1, INS1-SC2, INS2-SC2 for the mini-cables were used for experimental testing.

[1] Now with Prysmian Cables and Systems, The Netherlands

Return to Session

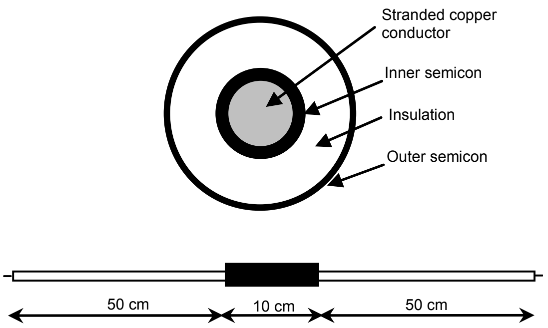

Figure 1: Mini-cable specimen. Conductor diameter = 2.8 mm; Inner semicon = 0.7 mm; Insulation thickness = 1.5 mm; Outer semicon = 0.15 mm.

Space charge tests were performed by poling both kinds of specimens at electric fields ranging from 2 to 40 kV/mm (average field) for 10000s and at different temperatures from 25°C to 70°C, under isothermal conditions, i.e., through heating uniformly the specimens inside an oven. Isothermal conditions were needed in order to avoid the formation of a temperature gradient across cable insulation, which may have an effect on space charge accumulation [7]. Depolarisation for at least 3600 s followed after polarisation. A quantity associated with the space charge accumulation in the insulation bulk is the medium absolute charge density, Q_{med}, which can be calculated directly from the space charge profiles by means of following equation [4]:

$$Q_{med} = \frac{1}{x_2 - x_1} \int_{x_1}^{x_2} |\rho(x)| dx \qquad (1)$$

where ρ(x) is the space charge density detected at the beginning of the depolarisation phase (conventionally, after 2s from voltage removal), x_1 and x_2 are the electrode radial positions.

EXPERIMENTAL RESULTS

Space charge patterns reported in Figs. 2-5 represent a 3-dimensional plot where the extent of charge amount, as a function of time, is characterized by a colour scale (positive charge = warm colours and negative charge = cold colours). The white colour stands for saturation of colour scale (> 10 C/m^3), thus indicating an out-of-scale amount of space charge (as can occur, for example, for electrode charge). Anode and cathode are the inner and the outer semicon electrodes, respectively, while the horizontal and vertical axis represent time and position in the insulation bulk.

Figure 2 shows the space charge patterns relevant to tests at average poling field of 13 kV/mm on INS1-SC1 mini-cables at 25 °C (Fig. 2A) and 70°C (Fig. 2B). As can be seen, a small amount of positive charge can be observed in the insulation bulk at room temperature (Fig. 2A), because the average field is not too far from the threshold for space charge accumulation (7 kV/mm). As temperature increases, the accumulated charge density rises and, moreover, an homocharge distribution close to the cathode builds up (Fig. 2B).

Increasing the average field to 40 kV/mm, space charge patterns on INS1-SC1 mini-cables show more and more accumulated charge (Fig. 3). At room temperature (Fig. 3A) negative fast charge packets, i.e., injected charge travelling from the cathode to the anode, are observable in the insulation bulk, eventually accumulating as heterocharge close to the anode. At the same time, positive charge packets bring charge accumulation near the cathode. At 70°C (Fig. 3B), a more evident distribution of heterocharge close to both electrodes can be seen already from the start of the polarisation phase.

Figures 4 and 5 report results obtained on flat specimens (plaques) of INS1-SC1, at 20 and 40 kV/mm, respectively, for temperature levels, 25 °C (A) and 70°C (B). The semiconductive layer acts as cathode while an Al foil is used as anode.

As for mini-cables, Figs. 4 and 5 show that the extent of space charge accumulation in the insulation bulk increases on rising electric field and/or temperature. At room temperature homocharge can be seen close to both electrodes in steady state. At 70°C, heterocharge accumulates close to the cathode and homocharge near the anode. The next section will try to provide an explanation of the behaviour regarding space charge accumulation showed by mini-cables and plaques.

Similar observations can be made from space charge patterns of different combinations of semicon/insulating materials. For the sake of brevity, these patterns, reported elsewhere [8], are omitted in this paper. However, a summary of all the tests performed on all the combinations of insulation systems is provided by the values of medium charge density, Q_{med}, calculated by eq. (1) and plotted in Fig. 6 as a function of average geometric electric field, obtaining the so-called threshold characteristics.

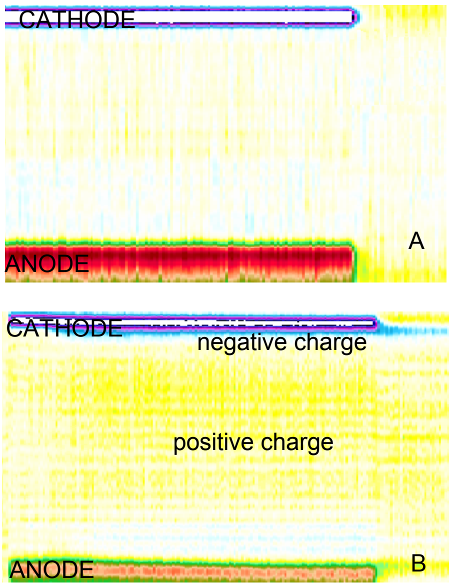

Figure 2: Space charge patterns on INS1-SC1 mini-cables at 13kV/mm (average field). Test temperature: 25°C (A) and 70°C (B).

Return to Session

It can be noted that at 25°C INS2-SC1 shows the smallest amount of charge, i.e., the largest threshold, followed by INS1-SC1, INS2-SC2 and INS1-SC2, which seem to have similar characteristics at room temperature (Fig. 6A). An increased space charge accumulation can be observed at 70°C (Fig. 6B) for all the insulation systems. This time, INS2-SC2 is the insulation system accumulating the lower amount of charge, followed by INS1-SC2, INS1-SC1 and finally INS2-SC1.

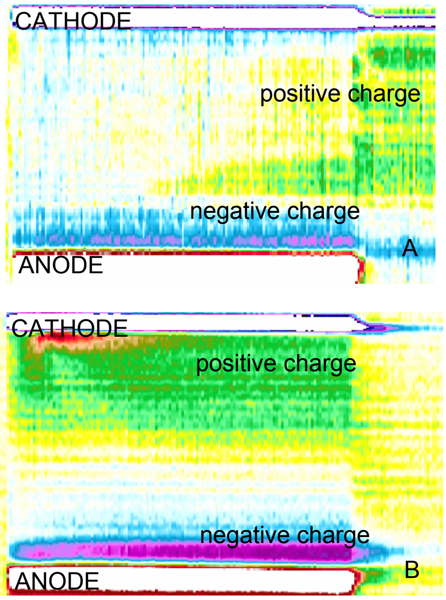

Figure 3: Space charge patterns on INS1-SC1 mini-cables at 40kV/mm (average field). Test temperature: 25°C (A) and 70°C (B).

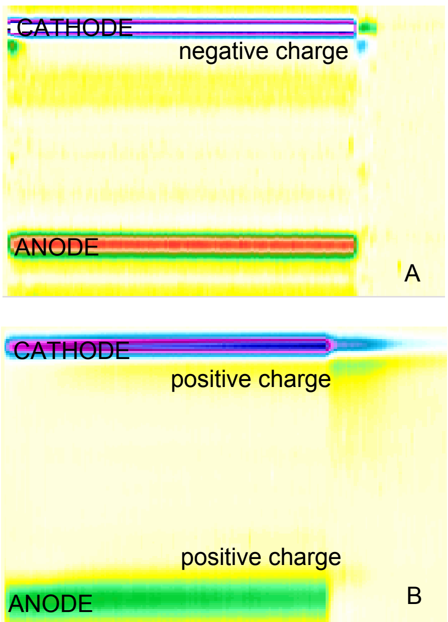

Figure 4: Space charge patterns on INS1-SC1 plaques at uniform field of 20kV/mm. Test temperature: 25°C (A) and 70°C (B).

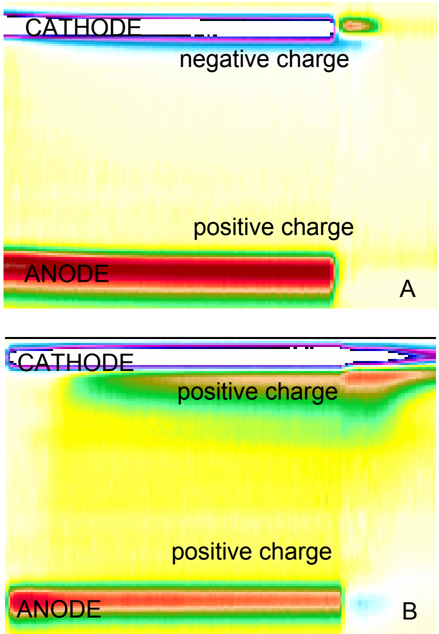

Figure 5: Space charge patterns on INS1-SC1 plaques at uniform field of 40kV/mm. Test temperature: 25°C (A) and 70°C (B).

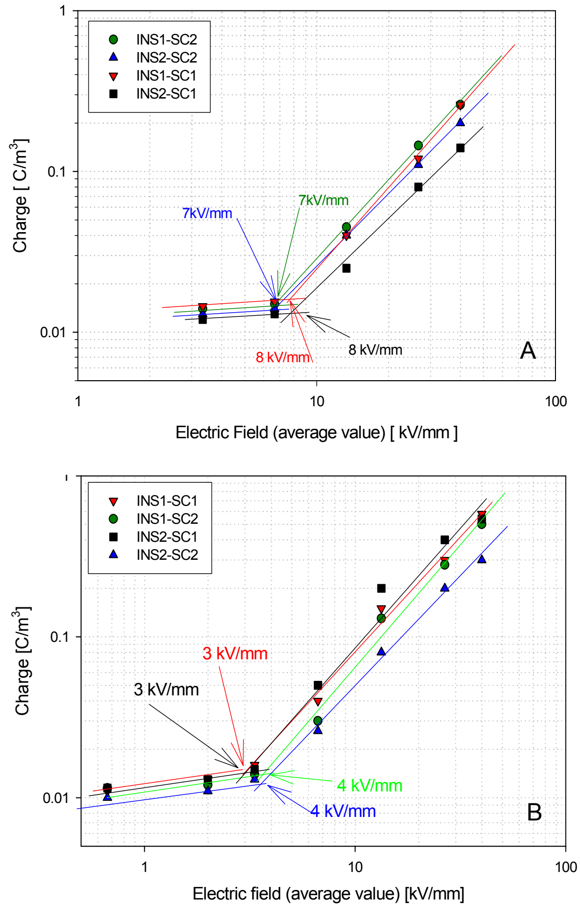

Figure 6: Space charge characteristics for mini-cables at 25°C (A) and 70 °C (B). The thresholds for space charge accumulation are indicated by arrows.

It is noteworthy that, as expected, the threshold for space charge accumulation (indicated by arrows in Fig. 6) diminishes as temperature increases owing to injection of excess charge from electrodes favoured by temperature increase. In particular, the values of threshold are halved for all the tested combinations passing from 25°C to 70 °C. It should be pointed out, moreover, that the largest thresholds at 25°C and 70°C is shown by INS2-SC1 (8 kV/mm, average field) and INS2-SC2 (4 kV/mm, average field), respectively. From these results, specimens constituted by SC2 seem to accumulate less charge than SC1 at high temperature, while the opposite occurs at room temperature. The role of the semiconducting layer regarding charge accumulation as a function of temperature, thus, needs to be better analyzed. This will be done in the next Section.

DISCUSSION

First of all we discuss the heterocharge build-up seen in mini-cable specimens at both electrodes and in plaques at the cathode. Evidence of relatively fast charge packets traveling in the insulation bulk can be observed, particularly at high fields (see, e.g., Fig. 3). Since mobility of this charge increases significantly with temperature, charge packets can be detected precisely only by employing an ultra-fast acquisition system (see [9]). The presence of fast charge packets gives rise to heterocharge formation close to the electrodes, just a few instants after voltage application. The charge injected from one semicon electrode, in fact, travels through the insulation bulk and remains trapped at the other semicon interface, acting as a partially-blocking electrode. This could explain why heterocharge accumulates symmetrically at both electrodes in mini-cables, but not in plaques, where heterocharge is observed only at the cathode. In mini-cables, in fact, both electrodes have a semicon interface, while plaques have only one semicon layer close to the cathode. It should be emphasized that the heterocharge extent increases with temperature, as expected, since temperature gives rise to injection and, thus, to charge packets accumulating close to the opposite electrode (see Fig. 3).

Referring to space charge amount and comparing space charge characteristics of the different combinations of semicon/insulation reported in Fig. 6, it could be concluded that the best insulation system at room temperature (Fig. 6A) might be that involving INS2 and SC1, since the combination INS2-SC1 shows very good space charge features (i.e., high threshold field, 8 kV/mm, and small trapped charge as the applied field exceeds threshold). The worst combination, on the contrary, is INS1-SC2, showing a significantly larger amount of charge and a smaller threshold than INS2-SC1.

As temperature increases (see Fig. 6B), semicon materials seem to behave differently. The best combination in terms of accumulated space charge contains always INS2 material, but SC2 in place of SC1. The second best combination involves again SC2 (INS1-SC2), while the largest amount of accumulated space charge can be associated with SC1 (INS2-SC1).

Summarizing, experimental results showed that even if the insulating material INS2 accumulates less charge than INS1, at high temperature the nature of the semiconducting material seems to govern space charge accumulation. All the combinations including SC1 and SC2 show, in fact, the larger and the smaller charge amount, respectively, independently of the insulating material. This could be explained considering that semiconducting materials may show a different temperature dependence regarding charge injection. Material SC1, in fact, is more easily injecting than SC2 at high temperatures, while the opposite occurs at room temperature. Since the behaviour of SC2 seems to depend less on temperature (in terms of space charge accumulation) HVDC cables designed with the combination INS2-SC2 would be subjected to an electric field profile less dependent on temperature, thereby improving cable reliability.

CONCLUSIONS

The experimental results here reported show that the nature of semiconducting material have an important role on space charge accumulation in the insulation bulk, affecting injection and extraction of charges at the electrode/semicon/insulation interface. These results can be successfully exploited for HVDC polymeric cable manufacturing. Comparing different semicon-insulation candidates, in fact, space charge measurements can provide fundamental information for improving cable design by choosing the best combination of semicon-insulation, i.e., the one showing the smallest amount of charge combined with the mildest dependence of accumulated charge on temperature, as well as for optimizing cable manufacturing by developing improved technological processes.

Acknowledgments

This research was performed within the European Project (of the 5th Framework-program) HVDC, "*Benefits of HVDC Links in the European Power Electrical System and Improved HVDC Technology*".

REFERENCES

[1] A. Campus, R. N. Hampton, U. H. Nilsson, M. Bergkvis, A. Farkas, M. Jeroense, 2003, "Material solutions for extruded HVDC Cables", Proc. JICABLE'03, Paris, France, pp. 753-758.

[2] Y. Zhang, J. Lewiner, C. Alquie and N. Hampton, 1997, "*Evidence of strong correlation between space charge buildup and breakdown in cable insulation*", IEEE Trans. Dielectr. Electr. Insul., Vol. 4, pp. 778-783.

[3] L. A. Dissado, G. Mazzanti and G. C. Montanari, 1997, "*The role of trapped space charges in the electrical ageing of insulation materials*", IEEE Trans. Dielectr. Electr. Insul., Vol. 4, pp. 496-506.

[4] G.C. Montanari, 2000, "*The electrical degradation threshold of polyethylene investigated by space charge*

Return to Session

and conduction current measurements", IEEE Trans. Dielectr. Electr. Insul., Vol. 7, pp. 309-315.

[5] G. C. Montanari, G. Mazzanti, E. Boni, G. De Robertis, 2000, "Investigating ac space charge accumulation in polymers by PEA measurements" Proc. IEEE CEIDP, Victoria, Canada, pp. 113-116.

[6] U. H. Nilsson, A. Campus, G. C. Montanari, P.H.F. Morshuis, 2007, "The use of model cables for evaluation of dc properties of polymeric cable materials", Proc. JICABLE, Versailles, France.

[7] D. Fabiani, G. C. Montanari, R. Bodega, P. H. F. Morshuis, C. Laurent, L. A. Dissado, 2006, The Effect of Temperature Gradient on Space Charge and Electric Field Distribution of HVDC Cable Models, Proc. IEEE ICPADM, Bali, Indonesia, pp. 65-68.

[8] D. Fabiani, G. C. Montanari, C. Laurent, G. Teyssedre, P.H.F. Morshuis, R. Bodega, L. A. Dissado, A. Campus, U. Nilsson, 2007, "*Polymeric HVDC cable design and space charge accumulation. Part 1: Effect of semicon/insulation interface*", submitted to IEEE Electrical Insulation Magazine.

[9] S. Delpino, D. Fabiani, G. C. Montanari, L.A. Dissado, C. Laurent, G. Teyssedre, 2007, "Fast charge packet dynamics in XLPE insulated cable models" to be presented at IEEE CEIDP.