A METHODOLOGY FOR THE ASSESSMENT OF HVDC-XLPE CABLE INSULATION

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ABSTRACT

The purpose of this work is to present and to discuss a methodology for the assessment of materials intended to HVDC-XLPE cables, particularly as regards the evaluation of the effects of material formulation on space charge accumulation within the insulation. Sample design, testing method and protocol and criteria used for the material evaluation are specifically considered.

It will be shown through several examples that criteria such as the Field Enhancement Factor (FEF) and the space-averaged charge density (Q_M) are indeed sensitive to material formulation.

The question of the representativeness of tests performed on flat specimens vs. model or full cables will be discussed.

KEYWORDS

HVDC, XLPE cable, material formulation, space charge, field enhancement factor, pulsed electro-acoustic method.

INTRODUCTION

From economic and environmental points of view, polymeric cables are more advantageous than mass-impregnated cables. If the use of synthetic material in AC has been a success, attempts made for adapting them to DC face a challenge mainly due to space charge build-up under constant electrical stress. The mechanisms behind space charge accumulation have been widely investigated during these last decades and it is admitted that the amount of charges trapped in the insulation bulk depends significantly on the nature of the contact between electrode and insulating material as it controls charge injection and extraction efficiency.

Space charges measurement in dielectrics has become rather common practice for investigating charge accumulation processes under electrical stress. A wealth of measurement system exists with their respective merit in terms of sensibility, sample geometry, measurement dynamics, etc. They represent interesting tools in the perspective of optimizing semicon / insulation materials formulation intended to HVDC cables provided adequate criteria are identified.

The aim of the present work is to present a methodology for cable materials screening, including:

- Manufacturing of plaque samples;
- Field and Temperature testing conditions;
- Measurement technique;
- Criteria for materials assessing;

The question of the representativeness of testing planar samples vs. model cables will also be addressed.

ISSUES IN SELECTING MATERIALS FOR HVDC APPLICATIONS

Correlation between insulation life and space charge

● Without polarity reversal

When the cable is intended to work with Voltage Source Converters - VSC system, the inversion of power flux is achieved by changing the current direction without inverting the voltage polarity. In that case, the insulation life is generally estimated through the well-known Inverse Power Law - a semi-empirical relationship giving the time to breakdown as a function of the maximum stress level through the insulation:

$$L = C.\left(\frac{1}{F_{\max}}\right)^N$$

where F_{max} accounts for the maximum electrical stress through the insulating material, N is the aging parameter also known as the Voltage Endurance Coefficient (VEC) and C is a constant.

Space charge accumulation under DC stress leads to local field enhancement within the insulating material hence decreasing the time to breakdown. Furthermore, it has been pointed out that space charge is likely to take part in the aging process (through the modification of the material structure **[1]**) and may act to increase the VEC. Considering a value of VEC of 10, in accordance with the *Cigré* recommendations for HV extruded cables **[2]**, a field enhancement of 10% of the Laplacian field leads a life reduction by a factor about 3 applying the Inverse Power Law model. For non-optimized insulation, the amount of space charge (and thus the field enhancement) mostly increases with the applied voltage. In order to keep an acceptable cable life, the design stress has then to be limited reducing thereby the power transmission efficiency (power per unit of the cable weight).

● With polarity reversal

Line Commutated Converters -LCC cable system requires voltage polarity reversals for changing the power flux. Hence cables have to be designed to withstand such kind of stress. In that case, It has been demonstrated **[3]** through accelerated life tests coupled to space charge measurements that the insulation life depends not only on the electrical stress level but also on different parameters related to the charge accumulation among which the amplitude of charge (Q_M) obtained after a polarization procedure under an applied field F_{app}, the charge depletion rate during depolarization (s) and the frequency of polarity inversion (f). According to the model proposed by *Cavallini et al.* **[4]**, the ratio between life with and without voltage inversion is given by:

$$\frac{L_I}{L} = \frac{1}{1+K.s^{-a_1}Q_M(F_{app}).f^{a_2}}$$

where K, a_1 and a_2 are known as correlation coefficients.

According to the above relationship, it can be emphasized that the insulation life decreases with the frequency of inversion and the amount of trapped charge (Q_M). For polymeric materials, Q_M is generally assumed to evolve as a power function of the applied field F_{app} **[3-4]** for electrical stresses above the ohmic regime namely $Q_M = F_{app}^b$, with b corresponding to the charge accumulation rate versus the applied stress.

It is worth mentioning that the insulation life in the presence of inversions (L_I) decreases inversely with the charge depletion rate. It means that in the presence of inversion, the material should be able to expel trapped charges as fast as possible during short-circuit. As a consequence, the presence of deep traps within the insulating material introduced by chemical additives may be harmful with regard to the material endurance.

Need for short term methodology

According to the model presented above, qualification of additives relevant to crosslinked materials (antioxidants, crosslinking agents, etc.) may be performed by deriving relevant parameters from space charge measurements. For a given case study (i.e. XLPE), it can be assumed that the correlation coefficients (K, a_1 and a_2) involved in the expression of the insulation life (L_I) are not modified by changing the nature of additives and only the parameters related to space charges that are the field reinforcement, the trapped charges density and the depletion rate during volt-off are modified. These parameters may be derived using short term testing under proper conditions of electrical stress and temperature. Moreover, when several formulations are investigated, quality comparison could be done on the basis of space charge parameters assuming that the best formulation is the one which exhibits an optimized set of parameters, say the lowest amount of space charge (implying in general weak field amplification) and a high rate of charge release during volt-off.

MATERIALS SCREENING ON SHORT TERM TESTS BASIS

Space charge measuring technique

● Advantages of the Pulsed Electro-acoustic technique

In this work, we have selected the pulsed electro-acoustic –PEA- method for space charge measurement **[5]** first because of its simplicity of use and second because of its flexibility insofar as a wide range of material thicknesses can be measured, typically from hundred of micrometers to several millimetres for XLPE materials. This can be achieved by adapting the device characteristics such as the pulse width or the piezoelectric sensor thickness. Another advantage of the PEA method is that measurements are easy to perform both in Volt-on and Volt-off because of the nature of the excitation (electrical pulse) and though the use of decoupling capacitor. The PEA system also provides an excellent time resolution (typically 1 profile/s for plaque specimen) and therefore enables to detect fast time-varying phenomena such as the so-called fast charge packets **[6]**.

● Measurements on cable samples

The method can also be adapted to coaxial geometry which is advantageous for taking into account the thermal gradient existing in cable. However, signal processing is somewhat trickier due to the impact of thermal gradient and the need to account for the cylindrical geometry and the attenuation of the acoustic waves in the deconvolution of raw PEA signal.

Sample preparation

● Co-reticulation of semiconducting electrode/XLPE

Rough products were LDPE –low density polyethylene – and semiconducting materials- SC, in the form of granules, both being cross-linkable, i.e. containing peroxide. Plaques of LDPE and SC materials were processed by press-moulding at 120°C. Then, disks of SC material, 12 mm in diameter, were cut. The final samples were obtained, with structure described in Figure 1, by cross-linking the 3 layers altogether at 180°C for 15 min under a press. The upper semiconducting electrode (in contact with the PEA electrode to which voltage is applied) is chosen thicker (typically 600 µm) than the lower one (in contact with the PEA electrode connected to the acoustic sensor) to attenuate possible reflection of the acoustic waves that may occur at the interfaces between the sample and the metallic electrodes of the PEA cell due to acoustic impedance mismatching between these materials. The lower semiconducting electrode is chosen as thin as possible (typically 200 µm) to keep a reasonable spatial resolution. The insulation layer was limited to 500 µm for the purpose of reaching high level of electrical stress (up to 40 kV/mm) taking into account the voltage max than can stand the PEA cell (30 kV). This is also advantageous because it reduces attenuation and dispersion of the acoustic waves. The picture of Figure 2 shows an example of cross-section of such samples (showing distinctly the three different layers). Typical sample geometry is 200 µm/500 µm/600 µm.

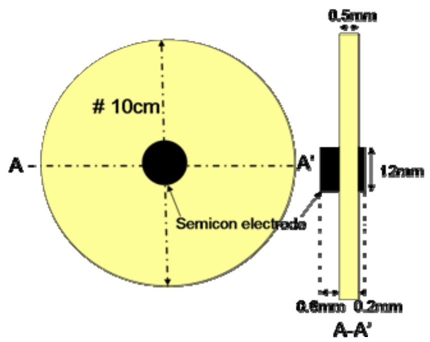

Figure 1: Typical geometry of plaque samples.

Figure 2: Cross-section of SC/XLPE/SC sandwiches. Scale: x30.

● Gold electrodes

For evaluating the impact of insulating material formulation (base resin, antioxidants or different cross-linking agents), gold electrodes may be used instead of semicon. In that case, gold electrodes are deposited onto the XLPE samples by sputtering of a gold target. Deposited gold layers have to be thick enough (typically thicker than 30 nm) to avoid possible influence of the electrodes of the PEA cell.

● Outgassing issues

Cross-linking by-products are known to promote space charge formation under DC field especially heterocharge build-up i.e. charge of polarity opposite to that of the adjacent electrode. This phenomenon is generally attributed to charge mobility enhancement due to the presence of by-products (mainly cumyl alcohol, acetophenone and alpha-methyl styrene when using dicumyl peroxide as a cross-linking agent) and the blocking nature of electrodes. Heterocharges enhance electric stress in the vicinity of the electrodes leading to a premature failure of the specimen according to the Inverse Power Law. The amount of heterocharges can be reduced by degassing the sample **[7]**. Actually, fully degassing a real cable may require long time and considerable energy, becoming economically unsustainable. For this reason, cables are partially degassed for the purpose of eliminating low boiling point species such as methane and ethane.
To be as closed as possible to the real condition in cables, by-products concentration in plaque samples should be adjusted to the one contained in real cable. However, in general plaque samples exhibit a very high rate of degassing due to their shape and thickness making it difficult to control the amount of by-products. For that reason, all samples were degassed, at 50°C for 2 days to constitute a baseline for comparison of material formulation.

Protocols and measurements

● Field and Temperature

For plaque specimens, the typical test procedure is depicted in Figure 3, consisting in polarization/depolarization at -10, -20, -30 kV/mm, each step lasting 3h up to -40 kV/mm step followed by polarity inversion to +40kV/mm lasting for 3h, and finally depolarization measurement for 3h. Applied field ramps-up and ramps-down were 1kV/mm/s. Cycles of 3h/3h polarization/depolarization were chosen as a compromise between a quasi-steady state behaviour and reasonable measurement time.

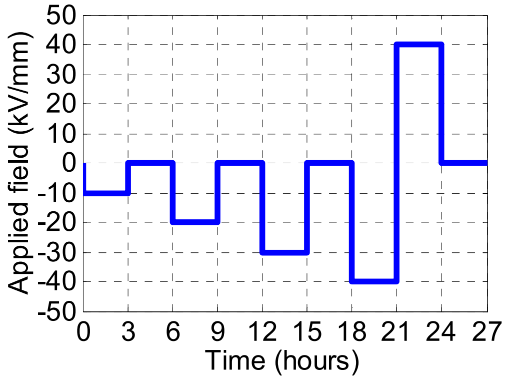

Figure 3: Stress cycle applied for space charge measurements on flat specimens.

Ideally, plaque sample should be stressed with temperature gradient as in cable. This requires setting two different temperatures at each face of the plaque. Given the thickness of sample and the PEA cell configuration, such heating system is practically impossible to set up. Hence measurements were carried out in isothermal conditions in the range of 25 to 50°C as the maximum allowable temperature is limited to 70°C by the electronic part of the measuring system.

Space charge profiles were acquired all along the cycle at a frequency of 1 profile/s.

● Direct observation of space charge

Spatio-temporal evolution of space charge can be pictured by means of a cartography using a colour code for representing the net charge density. This representation enables to identify the global behaviour of the material regarding space charge accumulation under different level of field. From the observation of the cartography, one can also make a first idea about charge depletion rate during volt-off. Furthermore, such representation is suitable to identify particular phenomena such as charge injection or heterocharges build-up. Hence, cartography of space charge can be used as a starting point for comparison between different formulations.

An example of charge pattern for gold-metalized commercial HVAC-XLPE is given in Figure 4. The measurement is done at 40°C using the protocol of Figure 3. The time is given on X-axis (each step lasts 3h); the thickness is along the vertical axis (anode is to the top, cathode to the bottom before the polarity reversal) and colour scales represent charge density, negative and positive polarity being represented by cool (blue) and warm (yellow) colours respectively.

For -10 kV/mm, charges are injected at both anode and cathode forming homocharges adjacent to the electrodes. A high proportion of these charges still remains after 3 h in volt-off, suggesting the presence of deep traps within the bulk of the material.

For higher stress level (from -20 to -40kV/mm), the bulk of the insulation is mainly dominated by negative charges injected from the cathode and transported into the bulk.

Negative charges enhance the field at the anode triggering an injection of positive charges as it can be seen at the beginning of the volt-on at -40 kV/mm. This phenomenon is even more spectacular after polarity reversal where positive charges are injected from the anode.

One has to realize here that the PEA technique as well as the other methods for space charge measurements is only sensitive to the net space charge density. A domain appearing as negatively charged (conversely positive) is a domain where the negative density (conversely positive) dominates over the positive one. One therefore has to think in terms of majority vs. minority carriers.

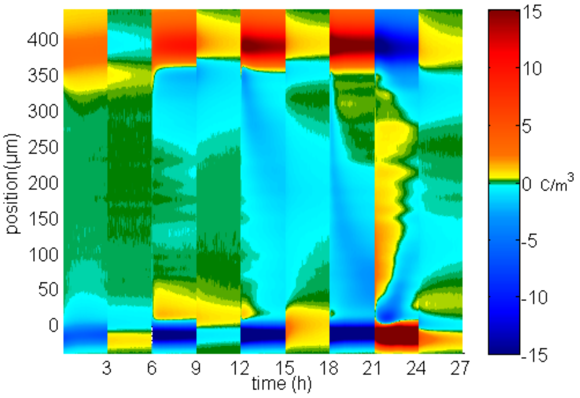

Figure 4: Space charge pattern for a gold-metalized HVAC-XLPE sample obtained using the protocol of Figure 3.

● Spatio-temporal evolution of the Field Enhancement Factor

The Field enhancement factor (FEF) is defined as the ratio between the internal field and the Laplacian field. The FEF is rigorously equal to 1 along the sample thickness if no space charge is present. If charges accumulate in the dielectric, the FEF takes necessarily a value higher than the unity somewhere within the dielectric (and, conversely, a value lower than the unity somewhere else). Hence, it seems relevant to consider the evolution in time of the position where the FEF is at maximum. Also its position during a polarization step could bring interesting information. As an example, a maximum FEF in the vicinity of an electrode could be attributed to a possible presence of charges of opposite polarity to that electrode. Similarly, a maximum FEF located in the bulk is mostly due to homocharges.

Figure 5 portrays the evolutions vs. time of the FEF_{max} for different electrical stresses in the case of the HVAC-XLPE sample. The evolution of its position is also represented on the right column. For -10 kV/mm, the highest value of the field is located in the bulk (closer to the anode) as a consequence of homocharges. For higher stress (-20 and -30 kV/mm), maximum enhancements of about 1.2 are reached after 3 h of polarization and are located to the anode due to negative charges in the bulk. The injection of positive charges occurring at -40 kV/mm leads to a displacement of the maximum stress from the anode to the bulk of the insulation.

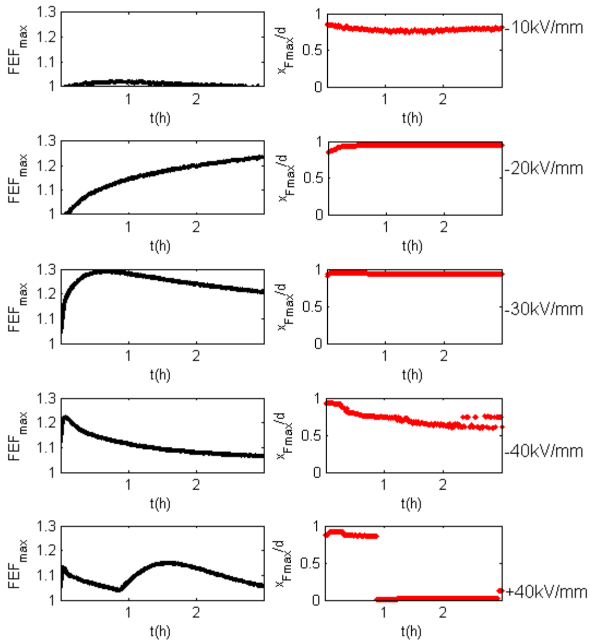

Figure 5: Evolution of the FEF_{max} and its position vs. time under various fields for the gold-metalized HVAC-XLPE sample. x=0 (d) for anode (cathode).

● Dynamic of trapped charge relaxation

The total amount of trapped charges cannot be fully quantified by the FEF value. Consider, for example, successive layers of negative and positive charges. In this case the FEF can take a small value throughout the bulk of insulation whereas the amount of charge could be relatively high and may accelerate the material aging through the storage of electromechanical energy **[1]**. A more relevant way to quantify the amount of trapped charge is to compute the average along the sample depth (Q_M). The value estimated immediately after grounding (in volt-off) could be considered as the amount of accumulated charges during the volt-on procedure.

Moreover, the temporal evolution of $Q_M(t)$ is directly related to charge detrapping. Using a proper detrapping model **[8]**, relevant parameters related to the traps (density, apparent depth in energy) can be extracted from such curves, as well (results not shown for sake of space saving).

Figure 6 shows the different curves of $Q_M(t)$ obtained during depolarization in the case of the HVAC-XLPE sample. One can notice that before the polarity reversal, the amount of charges (at the beginning of depolarization) increases with the applied field. However, the value of Q_M(t=0, +40 kV/mm) after polarity reversal falls below the one obtained after -30 kV/mm. This is due to the complex reorganization of space charges controlled by the voltage inversion, e.g. recombination between the bulk negative majority carriers and the injected positive charges following the polarity reversal (see Figure 4).

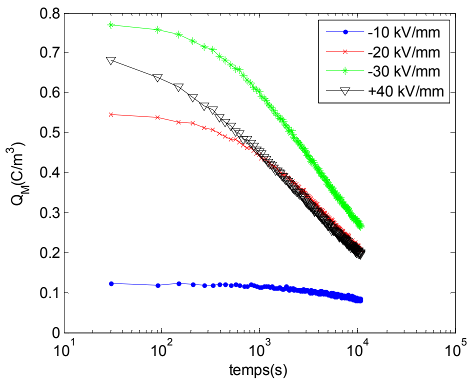

Figure 6: Evolution of Q_M obtained after different polarization steps.

Selectivity of the protocol to material formulation

Two different composites obtained with different association of semi-conducting layers and XLPE (denoted F_1 and F_2) are compared on the basis of the presented methodology. SC/XLPE/SC sandwiches have been assembled and degassed for 2 days at 50°C to expel volatile by-products. The samples have been stressed under electrical field ranging from -10 to -40 kV/mm according to the protocol of Figure 3 and space charge measurements have been performed at 50°C. For sake of brevity, only the results obtained at -25 kV/mm will be discussed.

As it can be seen from the space charge profile recorded during the depolarization procedure (Figure 7), F_1 accumulates positive charges at both electrodes leading to maximum field at the cathode. For F_2, homocharges are observed at both electrodes which set the position of the highest electric field into the bulk of the insulation. The maximum values of the FEF after 3 h of polarization are estimated to about 1.3 and 1.1 for F_1 and F_2 respectively. Moreover, the value of Q_M at the beginning of the depolarization is about 3 times higher for F_1 compared to F_2. For both insulations, charge relaxation can be considered as relatively slow as it can be seen from the evolution of the profiles during depolarization (Figure 7) where a high proportion of the initial amount of charges still remains trapped in the insulation after 3 hours of grounding. From these results, one may expect a better performance with F_2 compared to F_1.

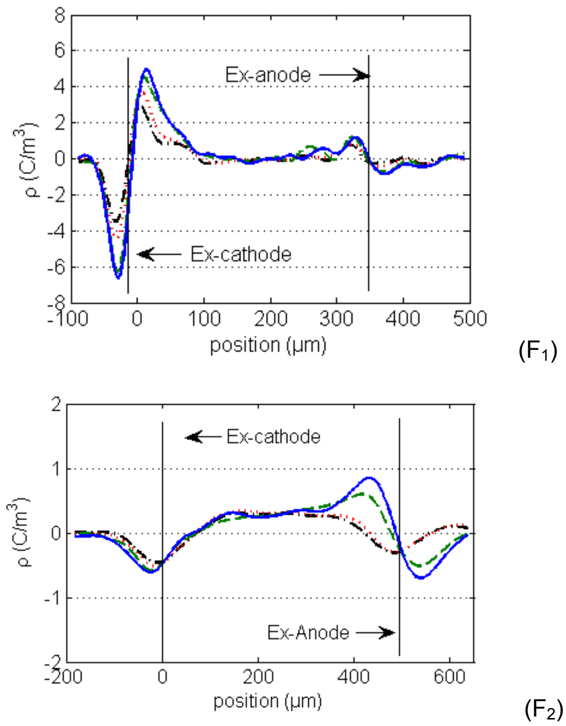

Figure 7: Evolution (at different time: -t=0, -- t=2 min, .. t=90 min, .- t=180 min) of space charge density during volt-off after 3h under a poling field of -25 kV/mm for 2 different formulations (F_1 and F_2).

REPRESENTATIVENESS: PLAQUE SAMPLES VS. CABLE GEOMETRY

Need for a suitable deconvolution method for model cables

In the purpose of checking the representativeness of plaque samples vs. real cables, a PEA cable system has been used. Regarding cable geometry, the primary guide was the limit of cable diameter admissible by the PEA test bench. In this work, model (medium voltage) cables have been used with the following dimensions:

- Conductor (Copper): ∅ 8.2 mm;
- Inner and Outer SC : ≈ 1 mm thickness;
- Insulation: ≈ 4.5 mm thickness.

With this geometry, the Laplacian field at the inner SC/XLPE interface is about twice that at the outer interface.

Space charge measurements have been performed with and without thermal gradient. For the latter, a current transformer has been used to heat the internal conductor of the cable, the external semiconducting surface being left in ambient environment. A temperature gradient of 10°C across the XLPE (55/65°C at outer/inner SC interface) is obtained when the cable is loaded with a current of ≈250 A. Cable loops (for heating) used for space charge measurements are about 3 meters in diameter.

A deconvolution algorithm has been developed for the purpose of correcting the effects of set-up (high pass-filter) and material (cylindrical propagation, attenuation and dispersion of acoustic waves) on the PEA signals. The developed method has the advantage of showing the same space charge resolution throughout the cable insulation thickness **[9]**.

PEA measurements have been carried out on model cables at ambient temperature (without gradient) in order to make qualitative comparison with results on plaque samples. Note that the cables have been subjected to ambient degassing. For the measurements, the cable has been stressed at -80 kV for 90 min (the outer semicon being connected to the ground). Such a stress corresponds to a Laplacian field of about -25 kV/mm at the internal semicon. The evolution of space charge during the poling procedure is shown in Figure 8. The profiles essentially reveal heterocharges build-up at both electrodes with a higher amount adjacent to the outer semicon. This gives rise to an inversion of the stress distribution (the outer stress being higher than the inner one) compared to the initial stress (Laplacian field). Heterocharges build-up has also been observed in fresh plaque samples and is generally attributed to the effect of by-products. However, the amount of charges, also their impact on the field enhancement, has not been quantitatively compared to those in plaque samples. The difficulty comes from the non-homogeneity of the electric field along the cable radius (due to the geometry).

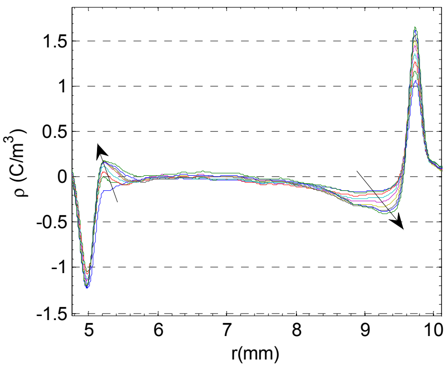

Figure 8:Evolution of space charge density during poling at -80 kV for 90 min in the case of a full HVDC commercial formulation XLPE model cable.

Thermal gradient issues

Temperature gradient has also a strong impact on the field distortion in cables due to the dependence of conductivity with the temperature and field. For low level of stress, typically under 5 kV/mm (for which the insulation exhibits an ohmic behaviour), field distortion can be computed from the activation energy of the conductivity (which is generally derived though conduction current measurements performed at different temperatures). In our case, assuming an activation energy of 1 eV, a field inversion is expected to occur for a temperature gradient of 10°C across the insulating material. For higher stress level however, it becomes difficult to dissociate the effect of the thermal gradient from those produced by injected charges as these processes seem to be interdependent.

CONCLUSION

A methodology has been given for the purpose of comparing different candidate formulations (SC/XLPE) intended to HVDC cable. The use of a sample representative of the cable structure is of great importance because space charge depends on interface characteristics as well as sample formulation through charge injection and internal dissociation. Also, the condition of measurement should be chosen on the basis of a compromise between the conditions encountered by the cable during service and the maximum stresses allowed by the measuring system. The electrical field protocol implemented here enables to investigate materials behaviour regarding space charge accumulation at different levels of field in the range 10 to 40 kV/mm. On the basis of existing life model, the maximum FEF during volt-on and the magnitude of trapped charge $Q_M(t)$ during volt-off have been used as critical parameters to select materials. These criteria have been applied to compare different formulations.

PEA measurements have been also performed on model cables, first to check the representativeness of planar samples (vs. cables) and second to investigate the effect of temperature gradient on space charge accumulation. Similar trends have been indeed observed for both (non-degassed) model cables and plaques.

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