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***Abstract*—The assessment of insulating materials regarding space charge features is one important aspect of HVDC cable development. Whereas most of space charge characterization is achieved under relatively short stressing time, it is important to understand if there is an evolution of materials behavior during long time under stresses, including service stresses such as combination of electrical and thermal stresses along with polarity reversal. Our purpose in this communication is to present the implementation of long term ageing tests on crosslinked polyethylene materials in such a way that relevant and valuable information can be gained as a function of stressing time. The designed stress cycle on model cables encompasses maximum fields up to 90 kV/mm at the inner semiconductor and temperature up to 100°C with repetitive grounding or polarity reversal. The stressing time is up to 18 months. The electrical and physicochemical characterizations techniques as well as the first ageing results are presented.**

Keywords— XLPE; HVDC; Ageing; Space charge; cables; Conductivity; Polarity reversal

I. INTRODUCTION

One important property in the development of polymer-insulated cables for HVDC energy transmission is space charge build-up in the material that can potentially induce substantial field redistribution into the insulation and alter long-term performance or reliability [1]. Accordingly, one of the main properties probed when developing insulating materials and related processes is the propensity of materials to accumulate charges. However, most of published space charge studies on insulating materials involve relatively short stressing times. The approach does not necessarily account for the possible evolution of material properties during long time stressing, especially if thermal and electrical stresses are combined. Besides space charge accumulation, it is also important that the electrical conductivity of the material remains at a low and controlled level during service. In addition, the polymer structure should also remain stable in service conditions. The purpose of this paper is to present the long term ageing tests performed on crosslinked polyethylene (XLPE) materials in such a way that relevant and valuable information can be gained as a function of time and repetitive variations of the DC stress.

II. SAMPLES AND PROTOCOLS

The samples used for ageing are model cables (Fig. 1), produced by triple extrusion using crosslinked polyethylene insulation and semiconductive shield using grades developed for the currently most demanding commercial HVDC applications. The main advantage of this type of samples compared to plaques is the cylindrical geometry. Accordingly, the tests to be applied have to be adapted to this geometry. The thermal and electrical ageing conditions were designed in order to study the effect of isothermal ageing up to 100°C, thermal gradient, and the effects of grounding and polarity reversal. Ageing is planned for up to 18 months and at electrical stresses up to 90 kV/mm at the interface between the insulation and the inner semiconductive shield. Given the geometry of the cable, when applying 90 kV to the conductor, the field at the inner semiconductive shield is 90 kV/mm, at the outer semiconductive shield 45 kV/mm and the average field E_{av} is 60 kV/mm. For each condition, electro-thermal ageing is compared to thermal ageing alone in order to distinguish the effects. As electrical characterization, space charge measurements, either on-line during ageing or off-line on aged samples, and DC conductivity are performed. Physical and chemical analyses are planned on samples taken at intermediate times in order to monitor the potential change of the properties of the XLPE during ageing.

A. Ageing protocol

After extrusion, model cables were degassed for 10 days at

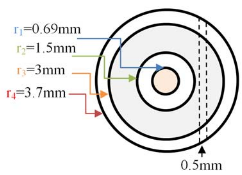

Fig. 1. Model cable geometry and sampling for physicochemical analyses.

70°C to remove XLPE crosslinking decomposition products [2]. Two ageing bench set-ups are run in parallel. In bench 1, relatively short ageing times are used, typically 42 days, in which a thermal gradient (TG) is applied to the cables and either grounding (G) or polarity inversion (IP), are applied periodically. Space charge profiles are measured periodically during the ageing. Samples are aged under different stresses with grounding or polarity reversal at E_{av} = 60 kV/mm or 45 kV/mm. The temperature T_{in} at the conductor is 90°C or 70°C, the corresponding calculated temperature difference between inner and outer semiconductive shields are ΔT = 5.7°C and 4.3°C, respectively. Fig. 2 shows an example of polarity inversion procedure.

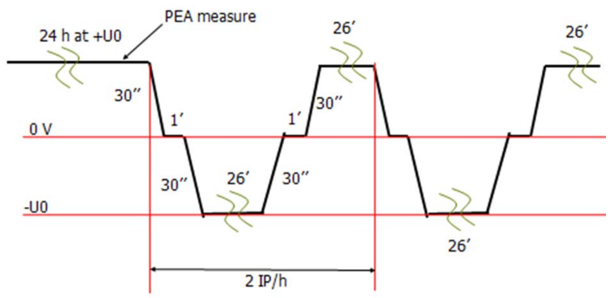

Fig. 2. Schematic of polarity inversion cycle (+U_0 during 24h and 2 IP/hour during 24h = 48IP)

Fig. 3 shows the part for the PEA measurement on test bench 1. The voltage is applied using two high voltage power supplies of inverse polarity, both connected to a high voltage switch for polarity reversal. The temperature gradient is applied using Joule effect in the cable conductor through a current transformer. Three cables are installed in parallel: i/ cable 1 for on-line space charge measurement during electro-thermal ageing; ii/ cable 2 for sampling for offline electrical and physicochemical characterization during electro-thermal ageing; iii/ cable 3 same as cable 2 for thermal aging only.

In parallel to the ageing performed in bench 1, a cable is aged for 18 months in bench 2 at a constant average stress of 60 kV/mm and under isothermal condition (T=100°C) in an oven. A reference cable is also aged in parallel but only under thermal stress at T=100°C. A sampling is made every 42 days for space charge, conductivity, and physicochemical off-line measurements.

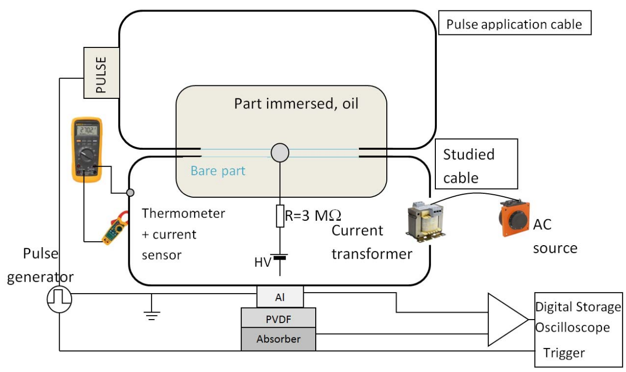

Fig. 3. Schematic of PEA test bench for space charge measurements on model cables.

B. *Space charge measurements*

Space charge measurements are realized by means of pulsed electro-acoustic (PEA) method. The average applied field is 60 kV/mm in the first results presented. Measurements are recorded under thermal gradient. It is also important to note that the cable 1 in the PEA test cell has a substantially lower temperature compared to the cable part outside the cell due to the fact that it acts as a thermal sink. Therefore 'online' PEA profiles for cable 1 are measured at the same electrical stress and same ΔT = 5.7°C but at different average temperature (T_{av} = 36°C) compared to cable 2 (T_{av} = 83°C). Each space charge measurement sequence lasts for 24 h in which records are realized every 100 s under constant voltage. For off-line measurements (on samples aged in bench 2), the average field is 45 kV/mm, with a temperature gradient of 4.3°C. Each polarization and depolarization step lasts for 4 h. The pulse is generated with a frequency of 5 kHz and an amplitude of 1.5 kV on a separated cable (pulse cable), cf. Fig. 3.

C. *Current measurement*

Current measurement is carried out on cable sample of 90 cm long. The outer semiconductive material is stripped at both ends of the cable over 30 cm. Guard electrodes of 1 cm width are set close to the section on which the current is measured, which is about 30 cm. Measurements are performed under average DC electric field from 5 to 20 kV/mm in isothermal conditions at T = 70°C in an oven. The voltage is applied to the conductor. Current values are recorded every 2 s during the polarization/depolarization steps which last for 4 h each.

D. *Physicochemical measurement*

Besides electrical characteristics, different techniques are implemented to evaluate the physical and mechanical properties of the insulation material under aging. Dynamic Mechanical Thermal Analysis (DMTA) is used to follow the evolution of the mechanical properties of XLPE (real E', and imaginary E" moduli and damping tanδ [3]). Specimens of dimension $L \times l \times e = 50 \times 7 \times 0.5\ \mathrm{mm}^3$ are cut parallel to the axis of the cable (see Fig. 1) using a slicing machine. DMTA measurements are made in traction mode at a constant frequency of 1 Hz, in the temperature range from 25 to 120°C. Thermogravimetric analysis (TGA) and Differential Scanning Calorimetry (DSC) are used respectively to detect potential changes in the degradation kinetics and in the crystallinity degree and melting point as a function of ageing conditions (temperature ramp=10°C/min from 25°C to 180°C). Finally Fourier Transform Infrared Spectroscopy (FTIR) is used to evaluate the effects of aging on the macromolecular structure of the studied insulation. The main chemical modification is the formation of carbonyl groups by oxidation of the polymer [4]. The samples for FTIR measurements are the same as for DMTA. Those for TGA and DSC are prepared in the same way as for DMTA, i.e. in the form of specimens and then cut again into adequate shape.

III. BENCHMARK

The properties of XLPE, before ageing, on cables have been carefully determined as they are the baseline for the entire study. From DSC data, the degree of crystallinity is 44% and the melting temperature is 107.8 °C.

A. Space charge results

The measurement is carried out over a period of 4 h of polarization and 4 h of depolarization for each average field of 30, 50, and 60 kV/mm. The charging and discharging steps at the different fields were applied in series on the same sample. The space charge patterns are shown in Fig. 4. For an average field of 30 kV/mm (Fig. 4a), charges are difficult to observe during polarization. However, positive charges are visible during short-circuit in the first half of the insulator. This indicates that these charges have been generated during polarization at the inner semiconductive shield and have moved towards the outer electrode. The absence of negative charges in the vicinity of the outer semiconductive shield is also noticeable. The density of injected charges is greater as the electric field is increased. Under 50 kV/mm, the positive space charge region occupies nearly all the insulation. No negative charges are observed. The resorption of positive charges during the depolarization phase is clear in Fig. 4. For stresses of 50 and 60 kV/mm, the charge amount appears higher close to the outer semiconductive shield.

Under thermal gradient, the gradient in electrical conductivity produces a field redistribution given under steady state conditions by equation 1 [5]:

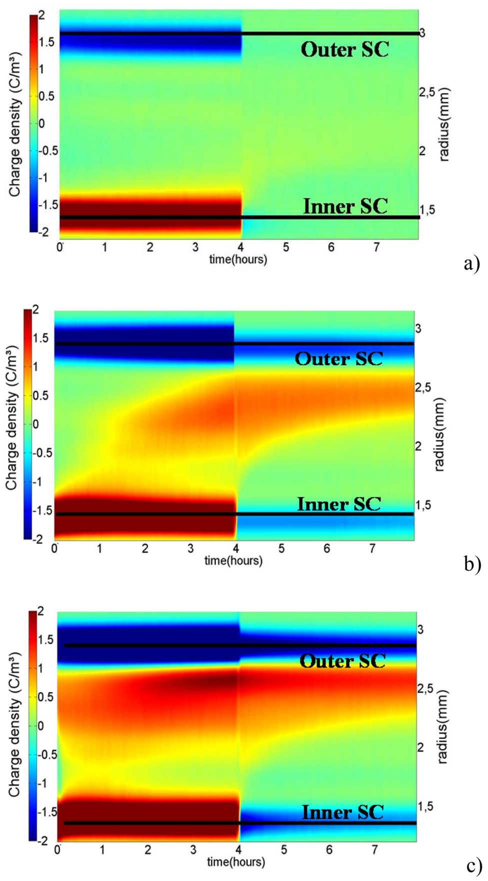

Fig. 4. Space charge mapping for a 4h / 4h polarization / depolarization protocol of the insulator under thermal gradient of ΔT=4.3°C for average fields of a) 30 kV/mm, b) 50 kV/mm; c) 60 kV/mm.

$$E(r) = E_c \frac{r_c \sigma_c}{r\sigma(r)} \quad (1)$$

where E_c and σ_c are the electric field and the conductivity at the reference position r_c. The corresponding 'geometrical' space charge distribution is of the form:

$$\rho_g(r) = div(\varepsilon \cdot E) = -E(r)\frac{\varepsilon}{\sigma(r)}\frac{\partial \sigma(r)}{dr} \quad (2)$$

where ε is the dielectric permittivity. For a positive voltage applied to the conductor, and supposing that σ(r) decreases with r, the space charge is positive as is actually measured. However the accumulation of charges close to the outer semiconductive shield is not predicted by the expression.

B. Experimental results on conductivity

Fig. 5 shows experimental results of polarization current vs. time at 70°C for different stresses. The current has been normalized based on the current value at 70°C and 5 kV/mm, after 4 h of polarization. The steady state conduction is approached after 4 h of charging for the highest constraints. The transient current for 5 kV/mm has a different shape presumably because of the thermal history.

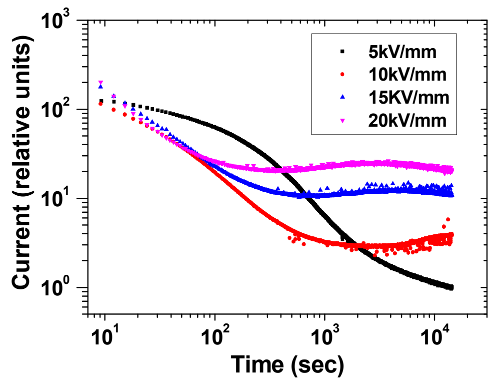

Fig. 5. Polarization currents under different stresses at 70°C.

The conductivity was estimated from current taken after 4 h of polarization. At 70°C, the DC conductivity is relatively low and increases substantially with the field. So the field in the cable will be redistributed according to the temperature and field dependencies of the conductivity, besides potential space charge accumulation.

TABLE I. RELATIVE CONDUCTIVITY AS FONCTION OF THE AVERAGE FIELD AND TEMPERATURE

Field (kV/mm)	**5**	**10**	**15**	**20**
	Conductivity (relative units)[a]			
T=25°C	0.122	0.139	0.134	0.135
T=70°C	1	2.08	3.83	5.43

[a]Normalized based on conductivity value at 70°C and 5 kV/mm.

IV. AGEING RESULTS

A. Space charge results after ageing

These results arise from the test bench 2, where the ageing is performed under isothermal conditions (100°C, and an average field of 60 kV/mm). During the space charge characterization, i.e. 4 h polarization at 45 kV/mm and 70°C,

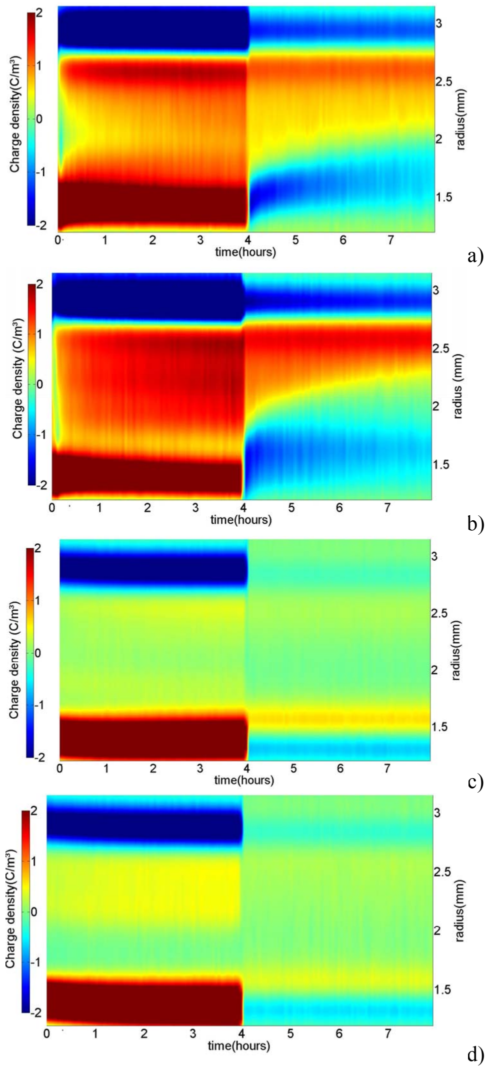

Fig. 6. Mapping of the charge density for the thermal cable (100°C) for a) 42 days, b) 84 days, and for the electro-thermal cable (100°C, 60 kV/mm) during c) 42 days, d) 84 days.

we observed in Fig. 6a and 6b, for the thermal cable, positive charges in the bulk. The charge density intensifies near the outer semiconductive shield with ageing time. For the electrothermal cable (Fig. 6c and 6d), a small positive heterocharge is detected at the vicinity of the outer SC. This density seems to increase with ageing time, but remains very low compared to the thermal cable.

B. Experimental results on conductivity after ageing

Fig. 7 shows the relative conductivity as a function of applied average field for different ageing times with a thermal gradient or under isothermal conditions. The relative conductivity is calculated based on the conductivity of the benchmark measured at 70°C and 5 kV/mm. Data from the benchmark and obtained for sample aged under thermal stress alone are added for comparison. We observe that the trend for the conductivity is a decrease with ageing time for the 4 cases tested. The effect is more important with the thermal stress than with electro-thermal stresses. Cables aged under thermal stress alone, being under thermal gradient or isothermal conditions, have a conductivity of a decade higher compared to the ones aged under electrothermal stress. So the material acts as if the electric field was driving charges outside the sample during stressing. It would be consistent with the relative decrease in charge amount obtained in Fig. 6 compared to Fig 4c (though the temperature was not 90°C in space charge data).

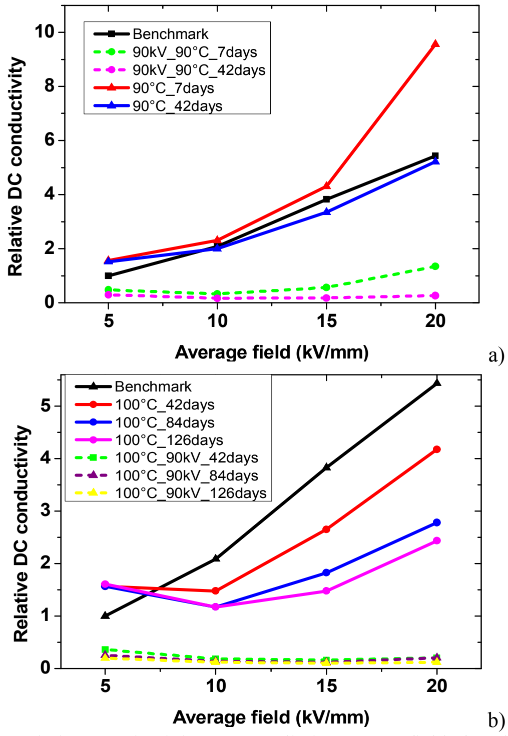

Fig. 7. Relative conductivity vs. applied average field for different stresses and ageing times: a) ageing with thermal gradient; b) ageing in isothermal conditions.

V. CONCLUSION

The methodology settled for evaluating thermoelectric ageing in model cables has been described. On-line space charge measurements are achieved during ageing but not in conditions of nominal thermal stress. The implemented means provide information on space charge behavior, conductivity and physicochemical parameters. Preliminary results with stressing under relatively severe conditions in terms of field indicate a substantial decrease in conductivity under thermoelectric stress compared to thermal stresses. The space charge patterns are different considering thermal and electro thermal stress. In the forthcoming steps the impact of polarity inversion ageing on space charge will be investigated comparatively to grounding ageing.

REFERENCES

[1] G.C. Montanari, IEEE Trans. Dielectr. Electr. Insul., vol. 18, pp. 339-364, 2011.

[2] T. Andrew, R.N. Hampton, A. Smedberg, D.A. Wald, V. Waschk and W. Weissenberg, IEEE Electr. Insul. Mag., vol. 22, pp. 5-16, 2006.

[3] J.L. Parpal, C. Guddemi and L. Lamarre, Proc. IEEE. Internat. Symp. Electr. Insul. (ISEI), pp. 171-174, 1996.

[4] J.V. Gulmine and L. Akcelrud, Polymer Testing, vol. 25, pp. 932-942, 2006.

[5] N. Adi, T.T.N. Vu, G. Teyssèdre and N. Sinisuka, Technologies, vol. 5, 46 (10p), 2017.