Ageing study of XLPE submitted to long-term thermo-electrical DC stress for HVDC cables

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ABSTRACT

The electrical behaviour of cross-linked polyethylene (XLPE) used as electrical insulation for extruded power cables is investigated. The aim is to better understand the influences of electrical and thermal stresses on the insulation material, in order to provide useful information for designing HVDC cables. This study is carried out on Rogowski samples made of XLPE insulation with semi-conductive electrodes, aged during more than 3 years (1245 days) at three different temperatures (70°C, 80°C and 90°C) under two DC electric fields (30 kV/mm and 60 kV/mm). Dielectric loss factor, volume resistivity and space charge accumulation have been measured. Results are analysed and cross-correlated.

KEYWORDS

XLPE, HVDC, cables, ageing, space charge, electric field, dielectric spectroscopy

INTRODUCTION

Cross-linked polyethylene (XLPE) is widely used as an electrical insulation in extruded power cables. In particular, it has been used over the last 40 years as an insulation material for HVAC cables and more recently, for HVDC cables (> 15 years). Extruded XLPE has since long been the preferred insulation material due to its high dielectric strength and electrical resistivity, as well as with its good thermal and mechanical properties [1-2]. The electrical properties of the insulating material have been widely studied under AC stress, however its behavior under high DC stress is less known and needs thorough investigation. The electrical behavior of XLPE under DC conditions is completely different compared to AC stress. The dielectric behavior in AC is mainly determined by permittivity, which varies only slightly with field and temperature, while the DC behavior is determined by conduction process. Moreover, the local electric field due to the presence of space charges in the insulation affects locally the electric field distribution. The increased local stress generated by space charge accumulation is likely to accelerate ageing and may lead to premature electrical breakdown of insulation material [3-5].

Understanding the effects of space charge accumulation on the insulation is very important in order to provide manufacturers, utilities and TSO's information useful for designing HVDC cables and to ensure the reliability of cable systems.

This paper describes the long-term performance that can be affected by the electrical and thermal stresses during cable operation. This work investigates the evolution of the electrical state of the XLPE during ageing tests. Several dielectric properties of the material, such as electrical capacitance, dielectric loss factor (tan δ), volume resistivity and space charge accumulation were monitored.

SAMPLES

Rogowski XLPE samples have been made using Borealis commercial HVDC materials qualified for voltage up to 320 kV. The insulation material is first compression moulded at 120°C in order to form the Rogowski shape. Thereafter, thin semi-conductive plaques are added on both sides to the pre-moulded Rogowski shape and all layers are cross-linked together at 180°C. Finally samples are conditioned during 72 hours at 70°C. The sample profile is thicker on the edge than in the center in order to provide uniform electric field in the center of the sample and to reduce field enhancement at the edges of the electrodes. The dimensions of the active area are 50 mm in diameter with insulation thickness of 0.5 mm or 1 mm. All the samples used for the study had the profile shown in Figs.1-2.

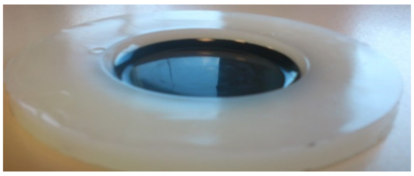

Fig. 1. XLPE Rogowski sample with semi-conductive

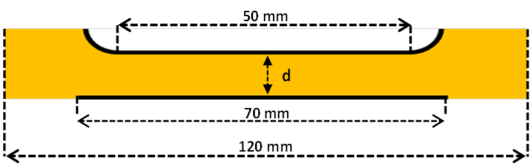

Fig. 2: Profile of XLPE Rogowski sample

EXPERIMENTAL SET UP

Ageing test set up

Rogowski samples have been aged during 1245 days in ovens at 70, 80 and 90°C under normal atmospheric conditions. For each temperature, an oven has been used to test 20 samples (10 having 0.5 mm insulation thickness and 10 having 1 mm thickness). A high voltage DC power supply was connected to each oven in order to apply

30 kV to the samples. Thus, 0.5 and 1 mm samples have been submitted to 60 and 30 kV/mm, respectively. It must be noted that 8/9 samples submitted to ageing under 90°C-60 kV/mm have undergone an electrical breakdown after different ageing times. The last one was removed from the oven for physical and chemical measurements.

Fig. 3. Ageing test set-up with 0.5 mm samples (up) and 1 mm samples (down)

MEASUREMENT TECHNIQUES

In order to acquire information about the evolution of the electric properties when the material is aged at different temperatures and electric fields, the samples have been periodically removed from the ageing test ovens for dielectric spectroscopy measurements and space charge characterizations. After measurements, samples were put back in ovens and the ageing test was continued. The characterization techniques and measurement conditions used in this study are briefly described hereafter.

Dielectric spectroscopy

Electrical capacitance and dielectric loss factor were determined by dielectric spectroscopy under an RMS AC voltage of 2 V. Measurements were carried out at room temperature for a frequency range of 10^5 Hz to 10^{-1} Hz. For each point, the reported value is presented as the average value of 4 consecutive measurements.

Volume resistivity

The electrical volume resistivity evolution of the material has been monitored during the ageing tests under low and high electric field (2 and 30 kV/mm) at 70°C. Quasi-steady state currents have been obtained after 100 minutes. The details of this measurement are given in [6-7].

Space charge measurements

The evolution of the space charge accumulated during ageing has been monitored by using a non-destructive technique: the thermal step method (TSM) [*8*]. The measurements have been made in short-circuit conditions, with a thermal step of -30 K (25°C to -5°C).

RESULTS AND DISCUSSION

Dielectric spectroscopy

Dielectric spectroscopy has been widely used in the investigation of polarization and conduction processes in electrical insulating materials when subjected to different constraints like temperature and electric field [9-10]. While, the dielectric properties were measured in the range of 10^5 Hz to 10^{-1} Hz, only 3 frequency values have been deeply investigated, corresponding to frequency domains where different behaviors with respect to dielectric losses have been observed during the initial characterization of the material [6]: 10^4 Hz (high), 10^2 Hz (medium) and 10^{-1} Hz (low).

Electrical capacitance and dielectric loss factor tan δ measured for ageing tests under 60 kV/mm and 30 kV/mm at 90°C, as a function of ageing time, are given in Figs.4-5.

Tan δ measurements do not show any significant variation with ageing time for all ageing test conditions except for 90°C and 30 kV/mm where tan δ tends to increase during ageing test at 10^2 Hz after 600 days of ageing. In the literature, it has been reported that this increase, observed at 10^2 Hz, could be linked to the semicon-insulation interface [11].

The electrical capacitance for ageing at 70°C and 80°C for both applied electric field, does not show any significant variation, while an increase can be observed at 90°C under 30 and 60 kV/mm after 700 days. In this last case, two dielectric breakdowns occurred after 625 days and 817 days of ageing test.

The increase of both tan δ and capacitance occur for sample aged at 90°C and 30 kV/mm but this was not observed for the ageing under 60 kV/mm, since the electrical capacitance increases while the dielectric loss factor remains constant. This latter could not be considered as a HVDC ageing marker. However, it must be recalled that tan δ has been measured under low voltage (2 V); a possible evolution of this parameter could be observed using higher voltages.

Volume resistivity

Electrical volume resistivity did not show any significant evolution as function of ageing time, for all temperatures and electric fields studied [7].

Space charge

In order to determine the evolution of trapped charges during DC ageing, the samples have been assessed by the TSM. An example of the evolution of the thermal step current measured during ageing at 90°C - 30 KV/mm is presented in Fig.6.

The change of the sign of the signal during the ageing test suggests a transition of the dominant charge within the material.

As all the currents have similar shapes, it is possible to compare their amplitudes for obtaining an insight of the space charge evolution during ageing. In this context, the maximum values (positive and negative) of the currents obtained after different ageing time are represented in Figs. 7-8. These graphs show a change in dominant sign of the TSM current during ageing test (from positive to negative). In addition, it can be observed that the current increases with ageing time at 70°C and 80°C under 30 and 60 kV/mm. For ageing at 90°C under 30 and 60 kV/mm, the current increases and reaches a maximum value at 759 days, after a stabilization it tends to decrease. These representations allow following-up the evolution of space charge current during ageing, but they give no information about space charge nature and the electric field evolution.

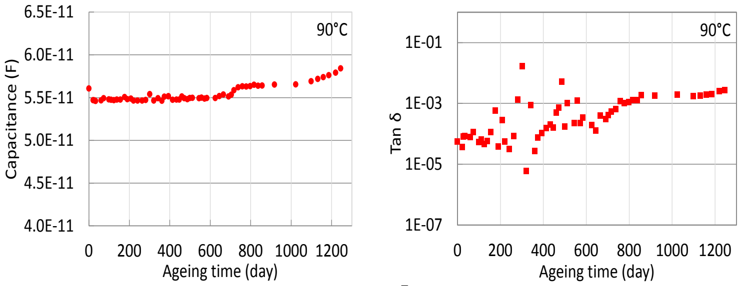

Fig.4: Capacitance and tan δ measured at 10^2 Hz on samples aged at 90°C - 30 kV/mm

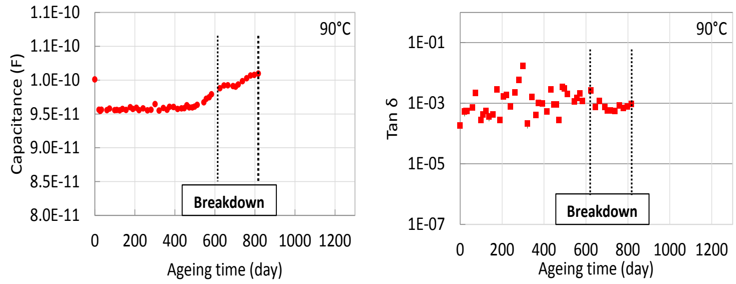

Fig. 5: Capacitance and tan δ measured at 10^2 Hz on samples aged at 90°C - 60 kV/mm

The TSM signals have been mathematically analyzed in order to investigate the evolution of space charge density and the electric field due to space charge. Results of internal electric field induced by space charge and space charge density are given in Figs. 9-14.

DC ageing under 30 kV/mm

The analysis of the charge density distribution after ageing under 30 kV/mm, given in Fig.9, shows an inversion of the dominant charge during all the ageing tests: the dominant charge at electrodes, initially controlled by homocharge, becomes heterocharge from different ageing time: 472 days (70°C-30 kV/mm), 208 days (80°C-30 kV/mm) and 156 days (90°C-30 kV/mm). Then, dominant heterocharge increases for all ageing conditions. This increase was followed by a decrease and a stabilization of heterocharge, for the sample aged at 90°C under 30 kV/mm.

It has been shown in the literature that the presence of heterocharge could be detrimental for the insulation as this heterocharge increases the field at the electrode polymer interface [12]. The evolution of the electric field due to space charges is presented in Fig.10.

An inversion of the residual field is observed for all ageing test conditions after different ageing time. Then a steep augmentation appears for all the ageing conditions, indicating an increase of the amount of trapped charges.

The space charge monitoring shows an increase of heterocharge in the samples. This could mean that conduction phenomenon is dominant compared to injection.

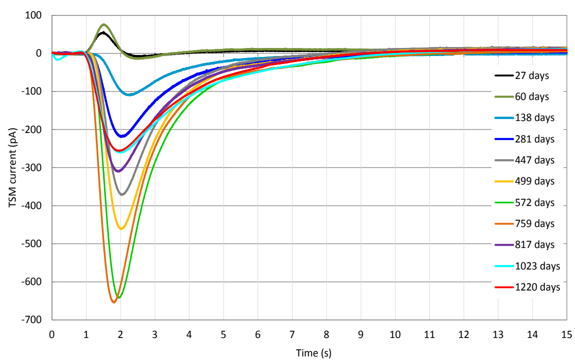

Fig. 6: Evolution of raw TSM signals for XLPE sample aged at 90°C - 30 kV/mm

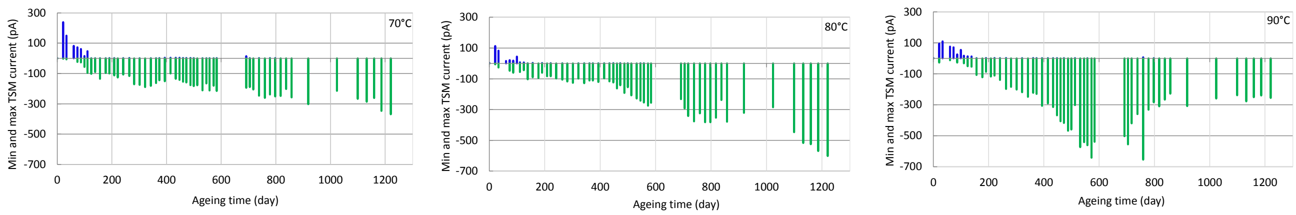

Fig. 7: Minimum and maximum values of TSM signals for samples aged under 30 kV/mm at 70°C, 80°C and 90°C

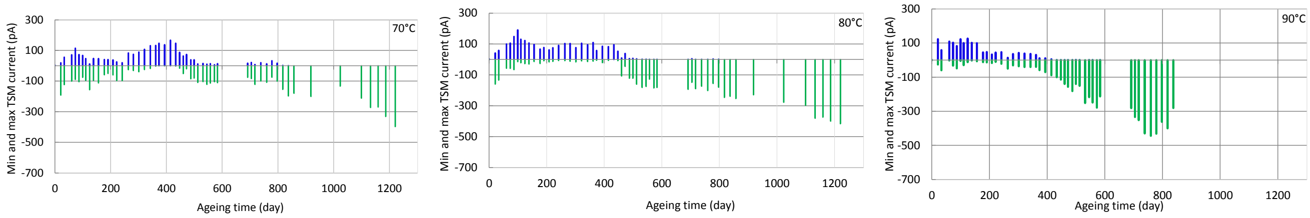

Fig. 8: Minimum and maximum values of TSM signals for samples aged under 60 kV/mm at 70°C, 80°C and 90°C

The increase of internal electric field was followed by a decrease and a stabilization for samples aged at 90°C and 30 kV/mm. The levels of the internal steady fields reached 200% of the applied field for ageing under 30 kV/mm at 90 and 80°C and 106% (70°C - 30 kV/mm). This demonstrates the effect of space charge on the distortion of the electric field within the insulation.

In order to simplify the analysis of the results and to quantify and localize the electric field enhancement across the samples, we can consider the value and the location of the maximum amplification of the electric field called "Field Enhancement Factor" (FEF). This factor is defined as the ratio of the maximum of total electric field (E_T) within the material to the applied electric field stress E_A (equation 1). Evolutions of this factor during the different ageing tests under 30 kV/mm and the location of the maximum of total electric field in the thickness of the insulation are presented in Fig.11.

$$FEF=\frac{E_T}{E_A} \qquad [1]$$

An increase of the FEF appears for all the temperatures with different levels and times of occurrence. The FEF increases earlier at 90°C than at 80°C and 70°C. It reached a maximum value of 3.1 for both 90°C and 80°C, after 759 days and 1186 days, respectively. This means that the total electric field withstood by the insulation was 3.1 times the applied electric field. Then, a decrease of the FEF followed by a stabilization can be observed at 90°C. For the ageing test under 70°C - 30 kV/mm, the FEF reached a value of 2.1 after 1220 days of ageing.

If we consider the position in the insulation where an enhancement of the electric field is observed, it is located at the centre of the sample at the beginning of the ageing, then it moves to the electrodes for all ageing conditions. The time where these changes occurs is in accordance with those corresponding to the inversion of dominant charges.

DC ageing under 60 kV/mm

Results of space charge density for ageing under 60 kV/mm show a change from dominant homocharge to dominant heterocharge near the electrodes, from 817 days (70°C - 60 kV/mm), 545 days (80°C - 60 kV/mm) and 447 days (90°C - 60 kV/mm) (Fig.12). As it was shown for ageing under 30 kV/mm, an increase of heterocharge appears indicating that conduction phenomenon dominates over injection. After, heterocharge decreases and tends to stabilize for ageing at 90°C

Changes observed in the electrical field correlates with space charge density evolution. In fact, after an inversion of the electric field, an increase is observed for all ageing tests. The residual electric field due to space charge accumulation reached a maximum of 54 kV/mm at 70°C, 49 kV/mm at 80°C and 55 kV/mm at 90°C which represents around 90%, 82% and 92% of the applied field, respectively (Fig.13). Then, the internal electric field decreases for the ageing at 90°C until 817 days. For this latter case, the results were not presented after 817 days, because all samples have undergone an electrical breakdown, except one sample kept for physical and chemical characterizations.

The FEF and the location of the maximum electric field are represented in Fig.14. For the ageing at 90°C, the FEF increases with ageing time. It reaches the twice of the applied field after 759 days, then it decreases. At the beginning of the ageing test, the position of the maximum electric field was located at the centre of the sample indicating the presence of dominant homocharge, and then it moves to the cathode. For ageing under 80°C and 70°C, the FEF increases and reaches a maximum value of only 1.9 and 1.8 after 1220 days of ageing test.

Overall discussion

When analyzing the internal electric field and the charge density evolution, three periods with different durations, corresponding to different charge and electric field behaviors, have been identified:

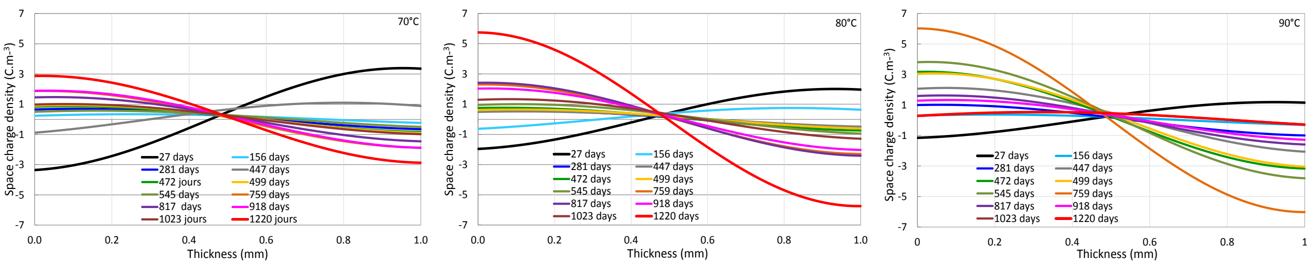

Fig. 9: Space charge density evolution for samples aged under 30 kV/mm at 70°C, 80°C and 90°C

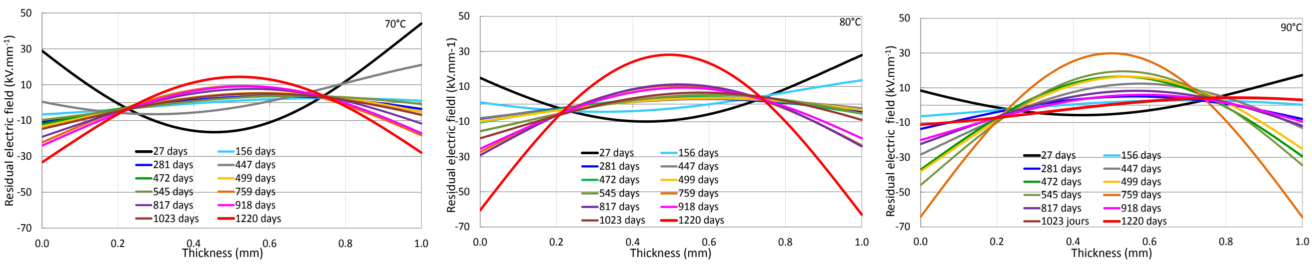

Fig. 10: Residual electric field evolution for samples aged under 30 kV/mm at 70°C, 80°C and 90°C

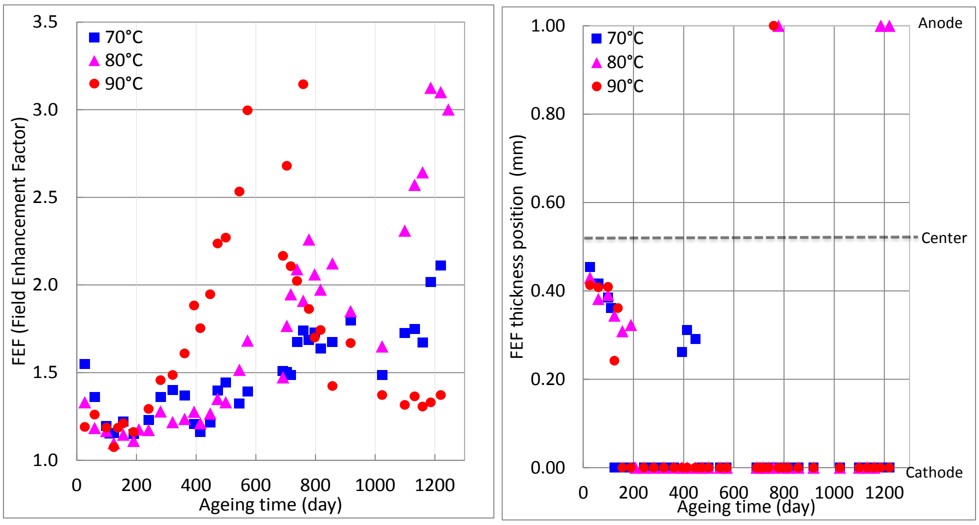

Fig. 11: Field enhancement factor (FEF) and location of the maximum field for a sample aged under 30 kV/mm

- Period 1: Change from dominant homocharge to dominant heterocharge and inversion of the internal electric field.
- Period 2: Increase in dominant heterocharge and in internal electric field.
- Period 3: Decrease in space charge density and residual electric field, followed by a possible stabilization.

At this stage of the ageing test, the three periods appear for ageing at 90°C under 30 and 60 kV/mm, while only the two first periods appear at 70 and 80°C.

According to the ageing test conditions, the electrical state of the samples does not follow the same dynamics of evolution. Nevertheless, the same kinematic of space charge evolution seems to exist for all these ageing conditions. Moreover, we can note a shift of the location of the electrical field enhancement from the bulk to the insulation-semi conductive interfaces, corresponding to the change of dominant charges (homocharges to heterocharges). Consequently, whatever the location of the field enhancement, the sample is locally overstressed (in the bulk in presence of homocharge and near the electrode interfaces when heterocharge is dominant).

Independently the applied field (30 or 60 kV/mm), the increase of the FEF appears earlier for higher temperatures with respect to ageing time. For a given temperature, this increase appears earlier for lower applied electric fields.

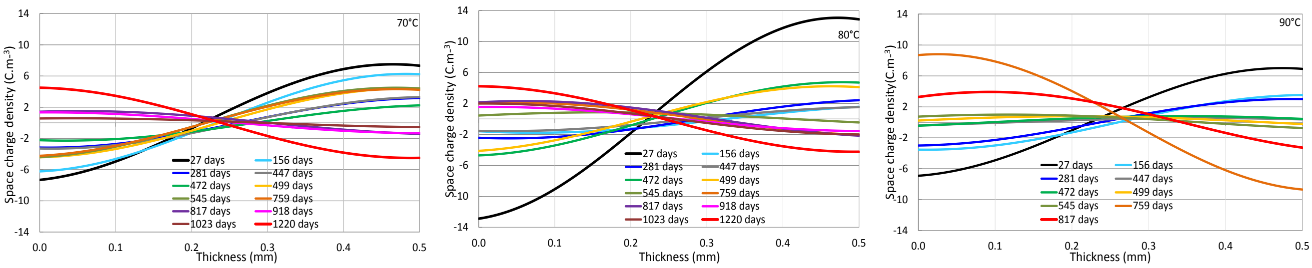

Fig. 12: Space charge density evolution for samples aged under 60 kV/mm at 70°C, 80°C and 90°C

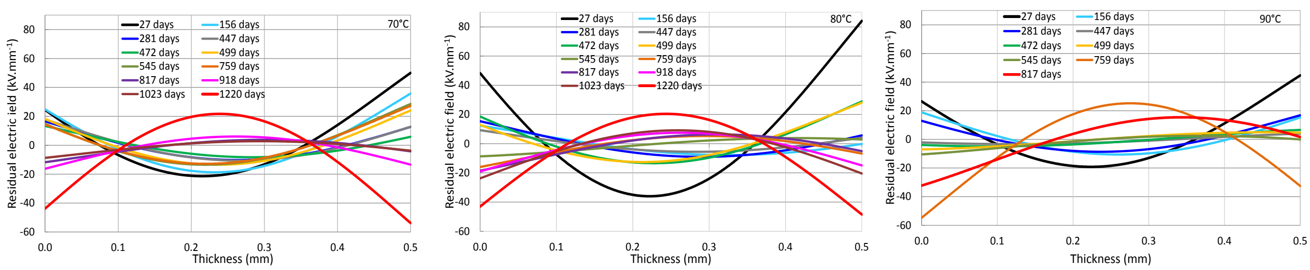

Fig. 13: Residual electric field evolution for samples aged under 60 kV/mm at 70°C, 80°C and 90°C

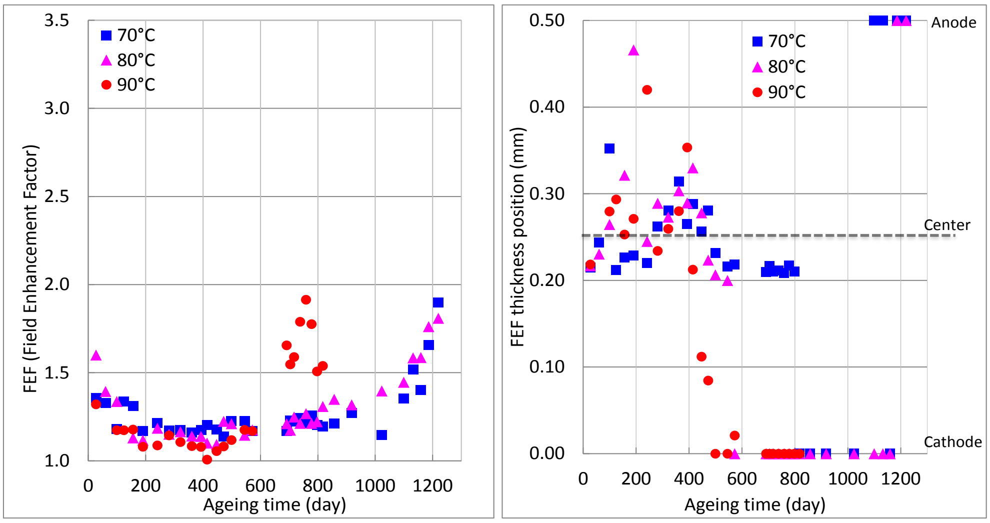

Fig. 14: Field enhancement factor (FEF) and location of the maximum field in sample aged under 60 kV/mm

CONCLUSION

This study has highlighted the effect of combined thermal and electrical stresses on HVDC XLPE material. Ageing tests have been performed during 1245 days on Rogowski XLPE samples submitted to DC electric fields of 30 kV/mm and 60 kV/mm, at temperatures of 70°C, 80°C and 90°C. Selected electrical properties, such as capacitance, tan δ, volume resistivity and space charge accumulation, have been followed during these ageing tests, in order to identify potential ageing markers and to establish a lifetime model by using these ageing markers.

It is important to note that all the potential ageing markers, selected at the beginning of this study, did not show significant evolution during the ageing tests; in particular the volume electric resistivity which is a key electrical properties for HVDC materials.

Analysis of the dielectric spectra has put into evidence an increase of the capacitance for ageing at 90°C under 30 and 60 kV/mm. Tan δ Increases for ageing under 90°C - 30 kV/mm, but did not show any variation for the other ageing conditions.

Analysis of space charge accumulation in the insulating material showed the same kinematic of space charge evolution for all the ageing tests but with different dynamics during ageing. The evolution of space charge density and of the electric field appears faster for the lowest applied electric field and the highest ageing test temperature. Thus, the effect of temperature seems to be preponderant compare to the electric field.

The Field Enhancement Factor increases for all the ageing tests with different times of occurrence and levels. This FEF factor reached a maximum value of 3, corresponding to an enhancement of 300% in two ageing test conditions (90°C - 30 kV/mm, 80°C – 30 kV/mm). This maximum seems to be followed by a period of stabilization/fluctuation, preceding a period of decrease.

We can note that breakdown occurred for samples aged under 90°C – 60 kV/mm, within the period where the FEF decreases. This confirms that breakdown could not be caused only by an increase of the FEF.

Ageing test will be continued in order to confirm the observation recorded so far and eventually conclude on the choice of a possible ageing marker. Moreover, physico-chemical measurements on the samples have been performed in order to better understand changes occurred during ageing.

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