Return to Session

EVOLUTION OF SPACE CHARGE AND INTERNAL ELECTRIC FIELD DISTRIBUTIONS IN HVDC CABLE UNDER LONG TERM TESTING

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ABSTRACT

In spite of significant advances within the R&D community of HV cable technology, the definition of a suitable insulation design for extruded HVDC cables remains quite a challenge. It is widely agreed that the electric field distortions resulting from long-lasting space charge build-up over the insulation thickness govern the cable performance and its life expectancy. But because it is difficult to allow for unavoidable space charge build-up through comprehensible insulation design rules, the most pragmatic approach opening the way to space charge dynamics understanding is to measure them directly on cables subjected to long term DC testing. This has been achieved by means of an industrial facility based on the Thermal Step Method set up in a Nexans HV Competence Centre in close cooperation with the Electrical Engineering Lab of the University of Montpellier.

The aim of this contribution is to present the evolution of the electric field and/or space charge distributions as a function of time in HVDC trial cables under long term testing. Two aspects of the Thermal Step Method have been considered :

- *Measurements under high applied DC field to reach the actual internal field distribution under service conditions,*
- *Measurements under short-circuit condition to record the build-up and evolution of the steady residual space charge.*

The outcome of these experimental campaigns was found to be of great interest and led to decisive orientations for insulation selection and design.

KEYWORDS

Space charge – Electric field measurements – HVDC cables

INTRODUCTION

The design of HVDC extruded cables is one of the most challenging issues in the cable industry. It is today well established that the electric field distribution over the insulation thickness is strongly affected by space charges which somehow control the cable behavior and its life expectancy. Fortunately, some tractable calculations of the field and space charge distributions in steady state have been treated in many publications, e.g. [1-2]. Such approaches assume an intrinsic resistivity depending on both temperature and field through a Poole-Frenkel type mechanism. These considerations are commonly used by engineers to design HVDC cables under loaded condition. However, from a R&D standpoint, one cannot be satisfied by such a restricted understanding, mainly for two reasons. The first one is that the conduction mechanisms involved in the insulation under service conditions are considerably more complex and governed by charge trapping/de-trapping and injection through semi-conductive screens. The second one is that a measurement facility is required to assess or not considered hypotheses directly on cables under test. This alternative has been exhaustively examined by manufacturers and researchers, e.g. [3-5], and is currently the most reliable alternative to determine the capability of an insulation system to withstand HVDC application throughout its lifetime.

This paper relates Nexans approach to study their developed HVDC cable insulation. The space charge dynamics over long testing durations has been investigated through electric field measurements on cable by means of an industrial facility based on the Thermal Step Method.

EXPERIMENTAL FACILITY

Theoretical background

The technique is based upon the Thermal Step Method (TSM) in double capacitor configuration, exhaustively described in [6]. Compared with the classical TSM – carried out on a single short-circuited cable sample – the double capacitor technique consists of using a “compensation cable”, placed oppositely to the "cable under test" (both cables are assumed to be identical). By connecting one side of the compensation sample to a current amplifier and the other one to the measured specimen via an electrode, a “double capacitor” is obtained. A voltage can then be applied to the cable core, and a thermal step to the measured sample. The TSM current will be recorded via the “compensation sample” (see on Figure 1). By the “outer cooling technique” the TSM current is given by the expression :

$$I_{TSM}(t) = -\alpha \frac{C}{2} \int_{R_E}^{R_I} E(r) \frac{\partial \Delta T(r,t)}{\partial t} dr \qquad (1)$$

where $\alpha = \frac{1}{r}\frac{dr}{dT} - \frac{1}{\varepsilon}\frac{d\varepsilon}{dT}$ is a constant of the material, C is the electrical capacitance of the cables, R_I and R_E the inner and outer radii of insulation layer, $E(r)$ is the radial electric field distribution, and $\Delta T(r,t)$ is the relative temperature distribution in the area of the cable subjected to the thermal step : $\Delta T(r,t) = T(r,t) - T_0$.

Using two identical cables offers the considerable advantage of compensating the polarization and conduction currents which can flow across the insulation under high DC field. Theoretically, the measured current is solely due to the internal field of the measured sample. In practice, a slight imbalance between both cable samples always exists and a differential conduction and/or polarization current component is superimposed to the TSM signal (see on Figure 2). Of course, the higher the applied field and temperature, the more sensitive the effect. To get rid of that, the experimental session is divided into two parts [7]. Firstly, a measurement is taken as usual by applying a thermal step. Secondly, after having restored initial conditions, a second measurement is recorded without any application of a thermal step. In this way the "differential current" is determined. The "actual" TSM current I_{TSM} is then derived considering :

$$I_{TSM} = I_{TSM\ measured} - I_{differential} \qquad (2)$$

Note that in the worst case, a significant potential decay can prevent acquisition of the TSM current since it is performed keeping the HV electrode floating. To check stability of the applied voltage during the measurement, a potential monitoring device shall be used.

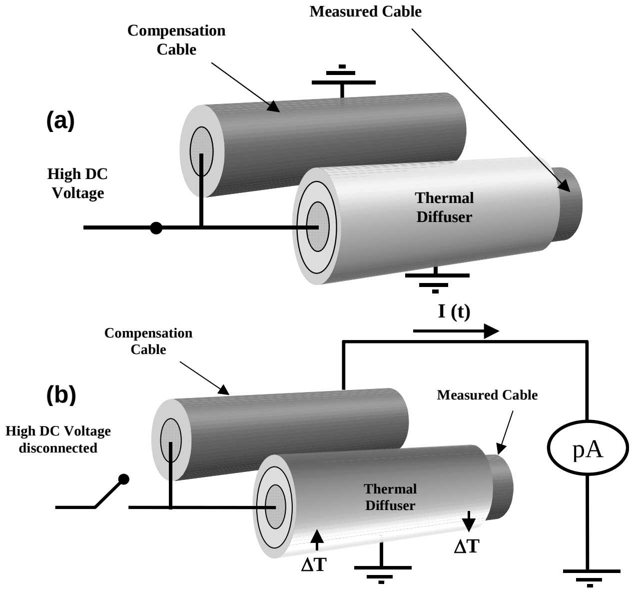

Figure 1 : "Under field" TSM measurements on cables in double capacitor configuration. (a) : the DC field is applied prior to the measurement. (b) : the measurement is performed on the "measured cable" after disconnecting the DC source.

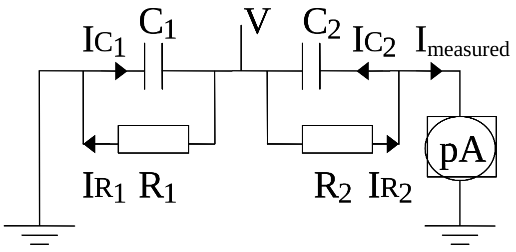

Figure 2 : The slight discrepancy between the two cables under test gives rise to a component of the measured current superimposed to the TSM signal.

Industrial set-up

An overall view of the HV lab dedicated to TSM measurements is given in Figure 3. The thermal step is generated by means of a cold liquid (the so-called "Outer Cooling Technique") circulating within a cylindrical thermal diffuser into contact with the outer semiconductive layer of the cable (Figure 4). To achieve that, the semiconductive tapes, the copper wire screen and the outer HDPE sheath have been locally removed. The screen of the compensation cable is connected through a Keithley 428 current amplifier which acquires the TSM current during the several minutes of thermal step application.

During measurement, the floating HV potential applied on cable cores is recorded by means of a judiciously arranged field mill (John Chubb JCI 111) as displayed in Figure 3.

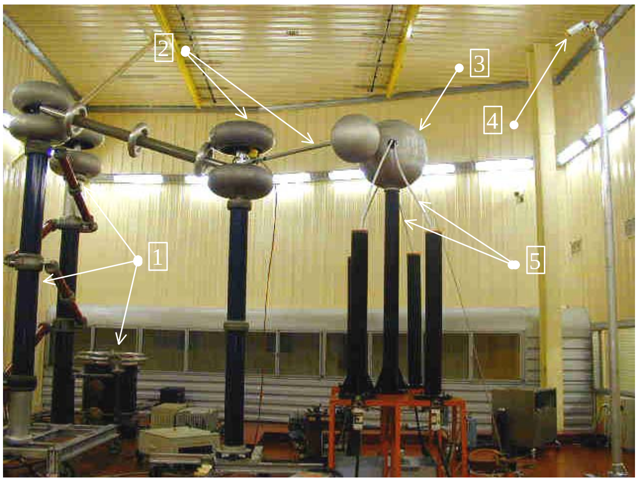

Figure 3 : Experimental set-up for TSM measurements of cables under applied field and temperature. 1: HVDC Supply; 2: Voltage divider and HV switch; 3: cables junction sphere; 4: HV monitoring device (field mill); 5: Cables under test ("measurement" and "compensation") fitted with oil-filled lab terminals.

Figure 4 : The thermal diffuser (400 mm long) used to generate the thermal step from the outer screen.

Cables under test

To evaluate the electrical performance of Nexans solution for HVDC extruded insulation, small scale trial cables (Figure 5 and Table 1) have been manufactured using up-to-date technology for VHV (vertical extrusion line, triple crosshead).

Both insulation and semi-conductive materials have been developed by Nexans with regard to their capability to manage space charge build-up under high DC field and temperature [8]. The insulating materials consist of an alloy of thermoplastic polymers, the base matrix being polyethylene. Two of them, among the most promising, have been selected for long term DC testing. The two materials only differ in the base matrix.

The basic dielectric features of these materials lies in the fact that their resistivity is highly field dependant but weakly temperature dependant. These properties were found to favour space charge evacuation on small scale [8].

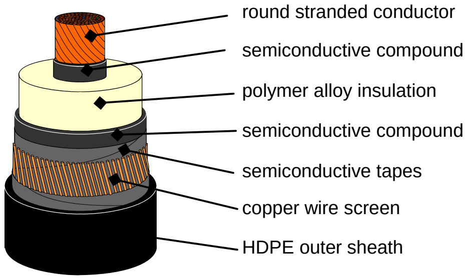

Figure 5 : HVDC trial cables for TSM investigations

Cable	Insulation	Ins. thickness	Core
1	polymer alloy 1	4.6 mm	95 mm^2
2	polymer alloy 2	4.9 mm	95 mm^2

Table 1 : Main features of studied trial cables

Considering the usual exponential resistivity law (3), it is well known the higher β and the lower α, the smoother the “resistive” field distribution within the cable under load conditions as deduced from resistivity in steady state [1-2] :

$$\rho = \rho_0 \exp\left[-\alpha T - \beta E\right] \qquad (3)$$

Resistivity coefficients for both materials are summed-up in Table 2. They were used to calculate the theoretical resistive field distributions under the different testing conditions.

Insulation	α (°C^{-1})	β (mm/kV)	ρ_0 (Ω.m)
polymer alloy 1	0.065	7.3 10^{-2}	3.5 10^{18}
polymer alloy 2	0.058	8.2 10^{-2}	2.3 10^{18}

Table 2 : Resistivity coefficients of insulating alloys

Experimental conditions

The aim of the study was to determine the field distortions which can be expected in the insulations as a result of space charge build-up over long test durations (more than 2500 hours). At the start, we wondered if outstanding charge mobility observed during tests on material samples led to electric field enhancement or, on the contrary, if charge release was initiated as a function of elapsed time under stress.

TSM measurements under live conditions; i.e. with applied voltage and thermal gradient, were aimed for. However, given the conduction features of “polymer alloy 2” (see on Table 2), measurements under applied field and temperature were impossible to carry out due to strong differential currents and potential decay phenomena occurring during measurement. Consequently, it was decided to measure the cable 2 with voltage off ($V = 0$ volt at the HV electrode), the insulation layer being isothermal and at room temperature. This configuration amounts to measure under short-circuit conditions (conventional TSM), but on the series capacitance $C/2$ as a result of the “double capacitor” experimental arrangement (refer to Figure 1 and Figure 2). This way, the steadily trapped space charge and its time evolution is reached. Ageing conditions for tests on both cable 1 and 2 are given in Table 3. Note that room temperature was 18°C.

Cable	I (A)	T_{core} (°C)	ΔT (°C)	V (kV)	Applied field on core (kV/mm)
1	480	80	14	- 150	43
2	476	80	15	- 230	63

Table 3 : Ageing conditions for long term tests

Taking into account the different ageing conditions (thermal drop across insulation, applied voltage), theoretical field distributions on cables under test are reported on Figure 6. All measurement conditions are given in Table 4. In case of voltage-off measurements (cable 2), cable samples were grounded and cooled down during 3 hours prior to.

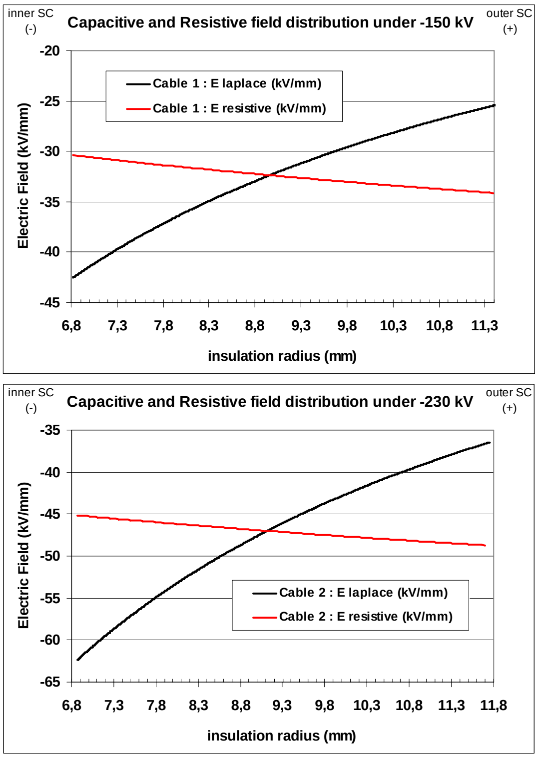

Figure 6 : Calculated field distributions based on theoritical Laplace and ”Resistive” field distributions for the defined ageing conditions for both cables

Cable	T_{core} (°C)	T_{screen} (°C)	T cold liquid (°C)	Thermal Step (°C)	$V_{measurement}$ (kV)
1	80	60	30	- 30	- 150
2	20	20	-10	- 30	0

Table 4 : Measurement conditions on each cable

Return to Session

STUDY OF CABLE 1 : UNDER-FIELD MEASUREMENTS

A 2600 h ageing campaign was carried out on Cable 1 under –150 kV (negative HV) and 80°C on core. TSM measurements were regularly performed to follow-up internal field evolutions. Each time, the "TSM signal" and the "Differential current" were recorded (Figure 7) and the "actual TSM current" component extracted from (Figure 8).

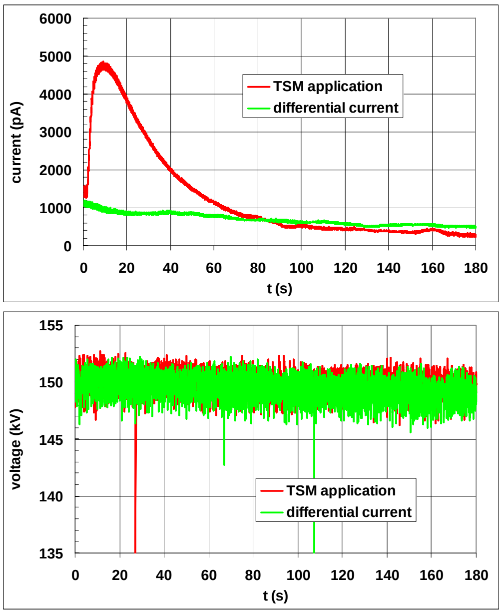

Figure 7 : The two steps measurement session after 91 days ageing. 1 (red curves) : acquisition of thermal step current. 2 (green curves) : acquisition of differential current. Stability of applied voltage is verified in both cases.

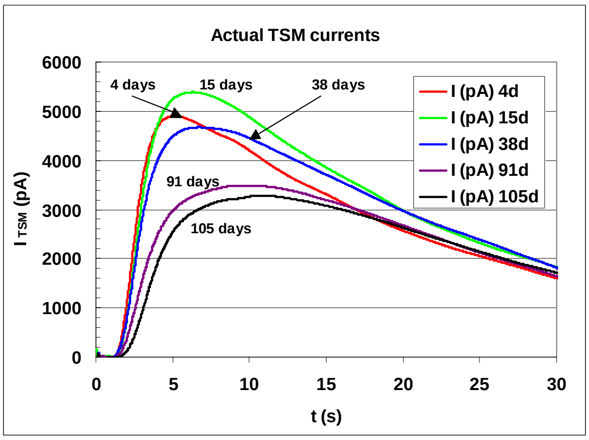

Figure 8 : "Actual" TSM currents as deduced from signal acquisitions with and then without application of the thermal step on the outer semiconductor.

At first sight, an increase of the TSM current was observed up to 15 days followed by a continuous decrease of the signal. This results in maximum field distortion after 15 days followed by a smoothening of the electric field distribution up to 105 days under stress (Figure 9). Field distribution may tend toward the purely resistive distribution but it is far from being obvious even after 105 days testing. Double charge injection at contacts seems to be prevalent over the ageing campaign even if negative charge build-up is fading whereas positive charges are progressing toward the bulk of the insulation (Figure 10).

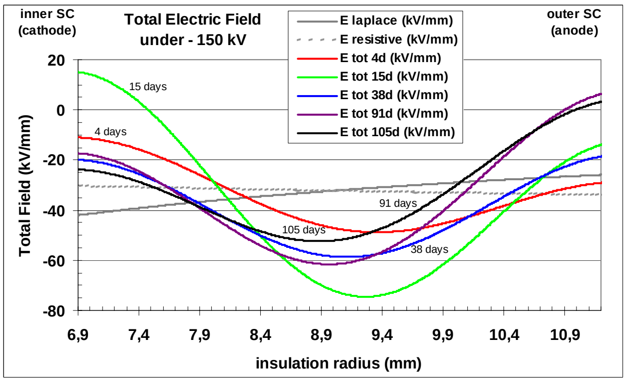

Figure 9 : Total electric field distributions of cable 1 under applied voltage and thermal gradient. Capacitive and resistive (steady state) distributions have been included for comparison.

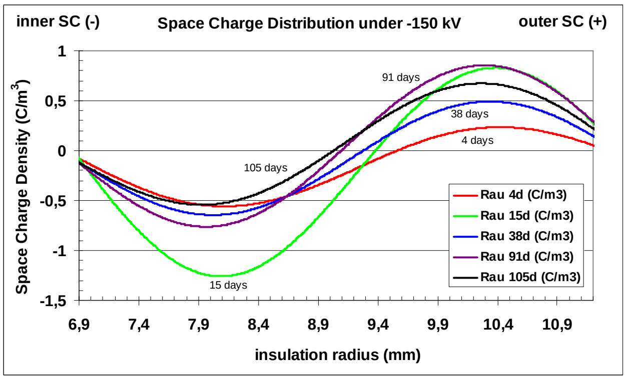

Figure 10 : Space charge distributions of cable 1 under applied voltage and thermal gradient.

STUDY OF CABLE 2 : VOLTAGE-OFF MEASUREMENTS

After the investigation on Cable 1, another ageing campaign was undertaken on Cable 2 under an applied field 50% higher than for Cable 1. Since voltage-on measurements cannot be performed on such a cable, build-up of steady residual space charge was only studied by means of voltage-off measurements. At the date this paper was issued to the Jicable committee, the ageing campaign had continued without interruption for 2950 hours under –230 kV (negative HV) and 80°C on cable core.

During the whole campaign, TSM currents still evolved the same way. A decrease of the signal even followed by an inversion of the signal at the start display the continuous evolution of the residual field and so the space charge distribution as a function of time (Figure 11).

Return to Session

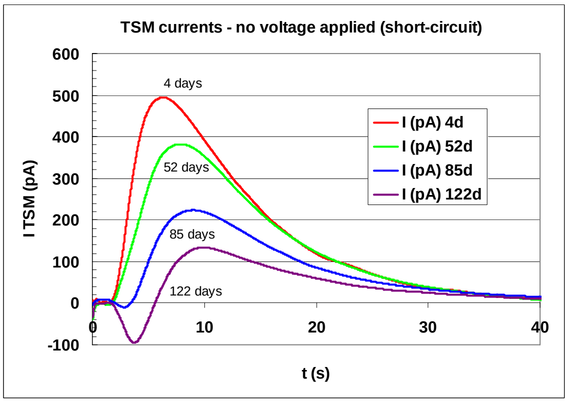

Figure 11 : Evolution of TSM currents (voltage-off) for cable 2 as a function of ageing duration.

The negative residual field decreases at the anode to become positive as it goes along, and regularly loses its strength at the cathode (Figure 12). Consequently, the negative injected charge close to the inner semiconductor is getting lower whereas a positive charge is expanding from the anode to the bulk (Figure 13). One notices space charge levels are limited with respect to the ones measured on Cable 1 under a lower applied field (Figure 10). However, we must keep in mind that “conduction space charges” are not involved in the distributions of Figure 13 purely related to the steadily trapped ones (voltage-off measurements).

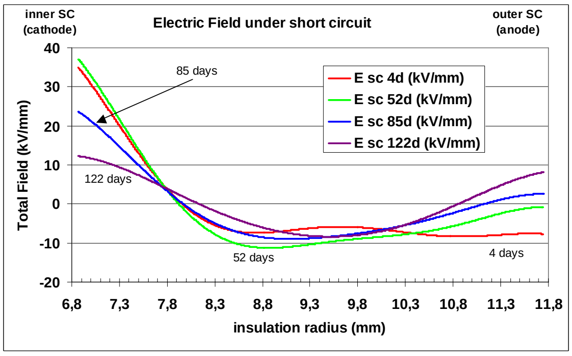

Figure 12 : Evolution of residual field (voltage-off) for cable 2 as a function of ageing duration.

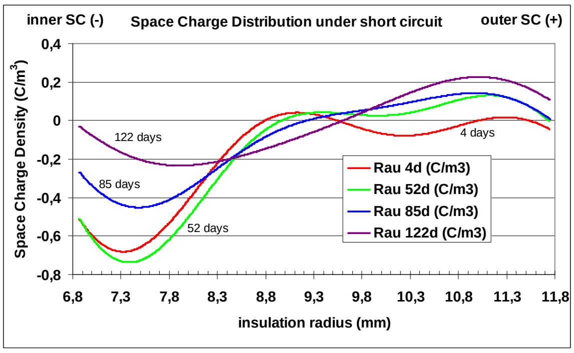

Figure 13 : Evolution of residual space charge (voltage-off) for cable 2 as a function of ageing duration.

OUTCOME OF THE ANALYSIS

Under field measurements – Cable 1

Among key results of this investigation, maximum field distortions and space charge levels are observed after 10-15 days ageing. Beyond this duration, the distortions are getting weaker : negative charges start to be evacuated or recombined and positive ones are building-up. In fact, the net balance of charges shifts from a negative to a positive value as displayed in Figure 14 (charge quantities have been calculated by integration over the volume of the measured area of the cable). The role of positive carriers seems to be essential in space charge dynamics.

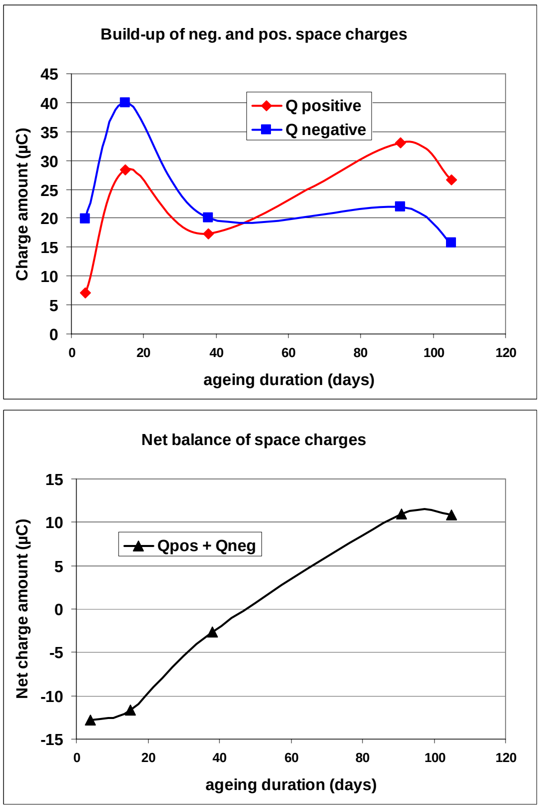

Figure 14 : Build-up of positive space charges vs. negative ones and net balance for Cable 1 (voltage-on measurements under thermal gradient)

Voltage-off measurements – Cable 2

Phenomena occurring in Cable 2 seem to be highly similar to ones involved in Cable 1, despite the differences in applied field and measurement protocol. Finally, negative charge content is decaying whereas positive charges are spreading across the insulation. After integration, the evolution of the net balance of charge amounts is edifying : it is moving closer to nought (see on Figure 15). Charge evacuation by compensation of negative space charges by positive ones may take place as a result of the dielectric properties of the insulation material. Because space charge management over long durations under stress is required for the HVDC application, this insulation system is particularly interesting in this respect.

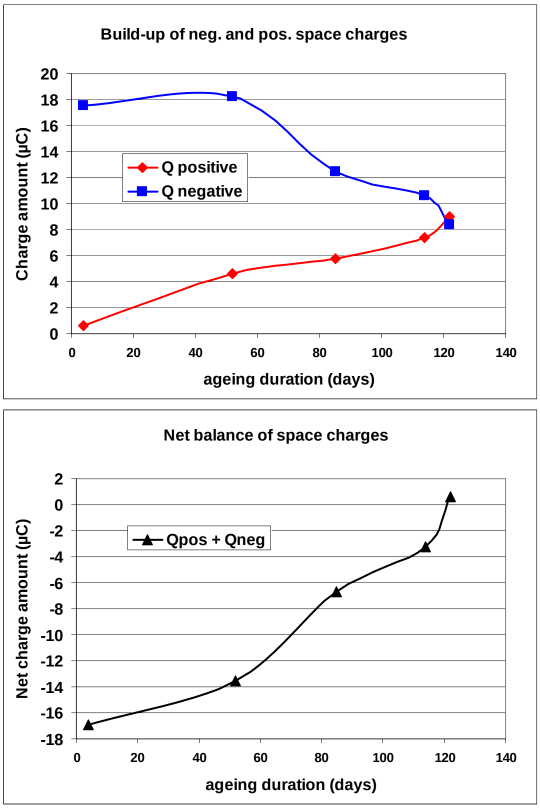

Figure 15 : Build-up of positive space charges vs. negative ones and net balance for Cable 2 (voltage-off measurements, isothermal insulation)

Since same trends have been pointed out on comparable insulating materials using voltage-on and voltage-off measurements, we could consider voltage-off configuration to be an attractive alternative for assessment of field distortions under service conditions. For instance, this has been done for Cable 2 in Figure 16 superposing a capacitive, or better a resistive field distribution, to the residual space charge field.

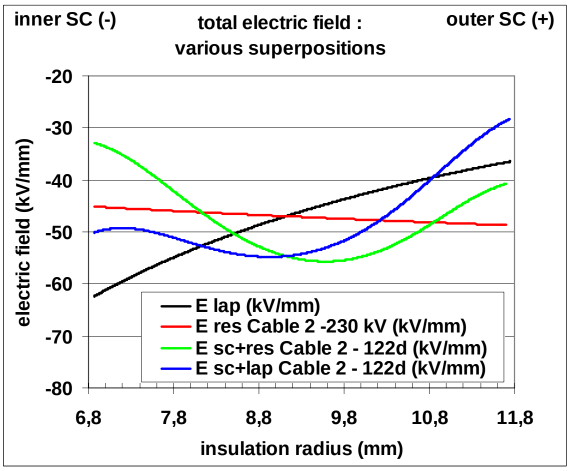

Figure 16 : Various assumptions for field distortions after 122 days ageing on Cable2. Superposition of Laplace field and residual field (blue curve), superposition of resistive field and residual field (green curve).

At last, we conclude on the outstanding performance of the "Polymer alloy 2" used in Cable 2. Space charge build-up remains limited and then field distortions acceptable with respect to the high level of applied field and temperature.

CONCLUSION

Nexans is equipped with a facility based on the Thermal Step Method (TSM) which allows the study of electric field distortions within extruded HVDC cable insulations during long term testing.

Materials were developed and selected on the basis of specific dielectric properties for the HVDC cable application. These materials have been assessed using this measurement set-up. The promising behaviour of these materials was displayed during various investigations for which space charge build-up was found to be limited owing to well identified mechanisms in space charge dynamics.

The role of positive carriers was shown to be essential to balance negative charge build-up. Ageing campaigns with cables under positive applied voltage would be of high interest to draw definite conclusions.

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GLOSSARY

HVDC: High Voltage Direct Current
TSM: Thermal Step Method