Space Charge Measurements in Cable Insulating Materials: from Research Laboratory to Industrial Application

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ABSTRACT

In this paper, after presenting the non-destructive technique developed these last years at the University of Montpellier (the thermal step method - TSM), we present some examples of research led on power cable specimens, and finally recent applications and technology transfers in industry. The TSM presents the advantage of measuring the electric field distribution both in short circuit conditions and directly under DC voltage stress. Originally developed for academic studies in research laboratory, the technique has been adapted, in recent years, to be install in industrial environments, in order to measure the space charge in the insulation of HVDC cables submitted to high electric fields in industrial facilities.

KEYWORDS

Space charge; Electric field; Polyethylene; Insulating materials; Power cable; Thermal Step Method.

1 - INTRODUCTION

Measuring electric charge in insulating materials has been an important research field for the last decades. Indeed, various studies during the 1960's and 1970's, which investigated the mechanism and applications of electric charge accumulation and transport, have brought in focus the need for techniques allowing to quantify and localize the charge in materials and structures used in electrical engineering. This encouraged the development of several charge characterization techniques, which can be classified in "destructive" and "non-destructive". The "destructive" techniques, such as the thermally stimulated current technique [1], are so called because they change the electrical state of the sample by evacuating the charge or modifying the charge amount. "Non destructive" techniques do not evacuate the charges trapped within the material and allow determining their distribution across the sample [2]. They present the advantage of allowing time monitoring of the charge. The effect of space charge accumulation in an insulating material can be highly detrimental, going from premature ageing to dielectric breakdown. The measurement of the real distribution of the electric field is therefore of considerable importance for an optimal design of the systems insulation.

For polymer-insulated HVDC cables, a major challenge to insure a good level of reliability is controlling the amount of space charge that accumulates in the dielectric under the effect of electrical stress and thermal gradient. It is now recognized that, although studies on space charge are absolutely necessary to understand the charge accumulation and relaxation phenomena, direct measurements on power cables (model and full size) are required to measure and anticipate the local distortions of the electric field under thermal gradient.

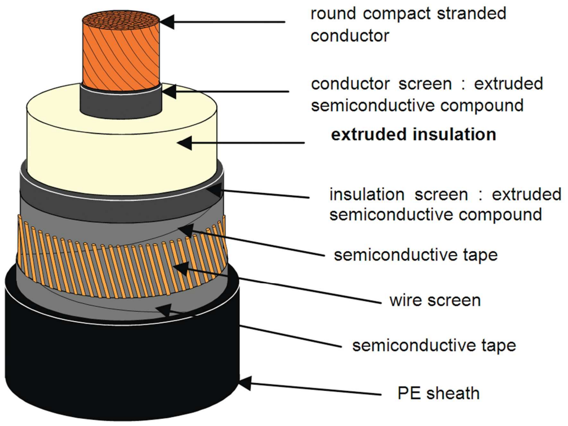

Fig. 1: High Voltage cable

The University of Montpellier has developed a Non-destructive technique, called the Thermal Step Method (TSM), based on the measurement of space charge accumulation in insulating materials and components. Originally developed for academic studies in research laboratory, the technique has been, in recent years, adapted to be install in industrial environments. This method presents the advantage of measuring the electric field distribution both in short circuit conditions and directly under DC voltage stress. The thermal step can be generated by circulation of a "cold" or "hot" liquid in a thermal diffuser adjusted to the geometry of the cable (technique called "outer cooling" and allowing a localized analysis of the insulating part of the cable wrapped up by the diffuser). The thermal step can also be generated by the passage of a "strong" current in the central core of the cable (temperature rise generated by Joule effect – technique called "inner heating" and allowing a global analysis of the insulation on the cable length).

In this paper, after detailing the principle of the TSM applied to power cable, we present some examples of research led on power cable specimens, and finally recent applications and technology transfers in industry to measure space charge (or electric field distribution) in HVDC cable insulation.

2 - THE THERMAL STEP METHOD (TSM) APPLIED TO POWER CABLE: BASIS

The TSM can be applied to flat specimens [3], short pieces of cable or cable loops of several meters long [4]. In this paper, we focus only on the application of the technique to power cables.

Let us consider a power cable of length *l*, insulated by a homogeneous dielectric containing trapped charges and permanent dipoles. The insulator has a cylindrical structure, of internal radius R_i and external radius R_e. We assume that all the points placed on the external surface of a cylinder of radius $R_i<r<Re$ are in the same electrical state. On this surface, the density of the trapped charge $\rho_t(r)$ and the permanent polarization are therefore considered as constants. A non uniform radial polarization *P* can still exist, and it will be the equivalent of a charge density $\rho_P(r)$ = -div(*P*) = -[(*P*/*r*)+(d*P*/d*r*)]. The total charge will then be $\rho(r) = \rho_t(r) + \rho_P(r)$. Initially, the entire cable is in short circuit condition at a temperature T_0 (the outer semicon and the cable core are connected through a conducting wire). The system consisting of the cable, the outer semicon electrode, the core and the conducting wire is then electrostatically equilibrated; consequently, the space charge within the cable insulator will induce influence charges on the internal and external semicon layers (Fig. 2).

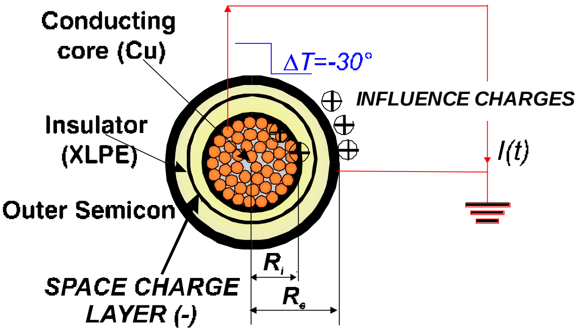

Fig. 2: Principle of the Thermal step method

If the thermal balance of the cable is affected by a thermal step $\Delta T = T_0 - T_1$ applied on the outer or inner semicon, the electrostatic balance of the system is changed. This is due to the contraction (or expansion) of the cable's insulator, which causes a slight and reversible movement of the space charge within the sample, and to the slight variation of the electric permittivity of the insulating material with the temperature. As the system tends to rebalance, the influence charges on the electrodes are redistributed. Hence, charge transport occurs from an electrode to the other in the external circuit. This corresponds to an external current, given by [5]:

$$I(t) = -\alpha C \int_{R_e}^{R_i} E(r) \frac{\partial \Delta T(r,t)}{\partial t} dr \qquad [1]$$

where α is a constant of material related to the sample's contraction (or expansion) and to the variation of its permittivity with the temperature, *C* is the electrical capacitance of the cable, *E*(*r*) is the radial electric field distribution, and $\Delta T(r,t)$ is the relative temperature distribution in the cable : $\Delta T(r,t) = T(r,t) - T_0$.

The thermal step current *I*(*t*) is measured experimentally. After calculating $\Delta T(r,t)$ by solving the heat equation, the field distribution can be extracted from equation [1]. Equation [1] is also valid if the cable is submitted to a DC voltage *V* during the measurement [6].

Two techniques for generating the thermal perturbation can be used: the "outer cooling" technique (OCT) and the "inner heating" technique (ICT). The "outer cooling" technique consists of using a ring-shaped radiator adjoined to the outer semicon of the cable, in which the temperature step is produced by the arrival of a cold liquid (Fig. 3). This allows analysing the part of insulator placed below the radiator. By moving the radiator along the cable, cartography of the space charge can be achieved.

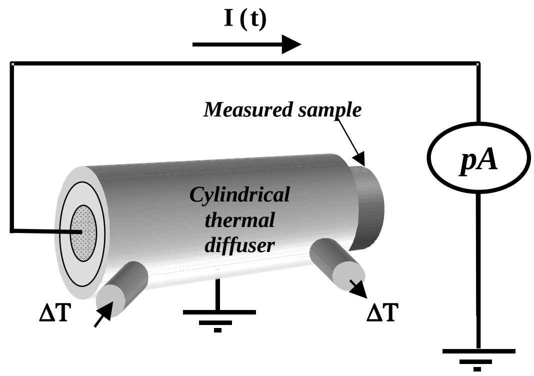

Fig. 3: TSM – Principle of Outer Cooling Technique "OCT"

The "inner heating" (Fig. 4) is based on the Joule effect provoked by a strong current circulating through the cable core to generate the thermal wave, and gives a global evaluation of the charging state of the entire insulation.

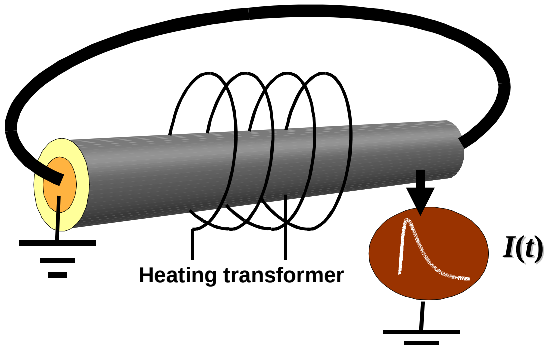

Fig. 4: TSM – Principle of Inner Heating Technique "IHT"

3 – APPLICATION OF THE TECHNIQUE IN RESEARCH LABORATORY

Conduct laboratory studies on insulating material in plate configuration can be sometimes interesting to evaluate some properties of the material; nevertheless, to fit as close as possible with the real system configuration (cable insulated with extruded materials giving a radial repartition of the applied electric field), it is preferable to directly characterize power cables.

We present hereafter some results obtained on power cable insulation by the TSM.

Evaluation of insulating systems quality for HVDC power cable design toward space charge criterion [7] - In this part, we have studied the dielectric properties of polymer materials developed by NEXANS. The study has been carried out on miniature cables (Fig. 5), called here "model cables". Different cables, with different couples insulation/semicon materials, have been analysed. Each cable length (model cable) has been split into three parts (3 samples) and measured by the TSM,

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using the OCT, without applying thermal and electrical stress. These measurements (not shown here) were used as references. The samples were then submitted to thermal and electrical constraints (20 kV DC, 70℃, 4 hours) and then characterized to assess their ability to accumulate or evacuate space charge.

Fig. 5: Cable length for TSM measurements

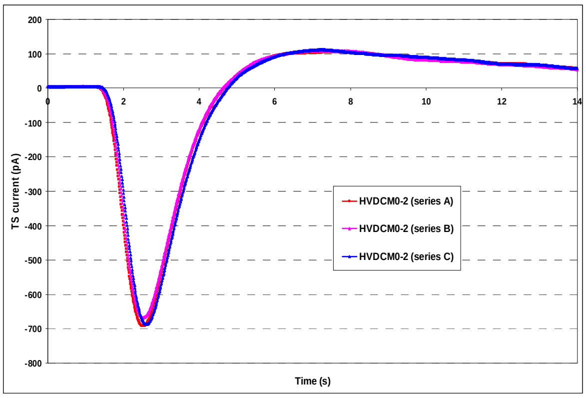

Fig. 6: TS currents measured on 3 samples from the same cable length (model cable HVDCM0-2)

Fig. 6 confirms a good longitudinal homogeneity of the model cable called HVDCM0-2; the signals waveforms and amplitudes recorded for each sample are very similar.

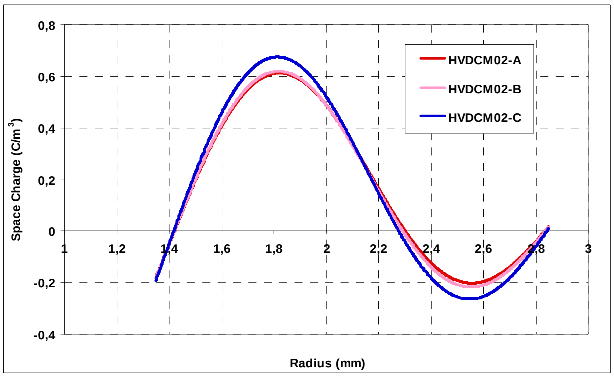

Fig. 7: Space charge distribution in 3 samples from the same cable length (model cable HVDCM0-2)

The space charge results obtained on these 3 samples taken from the same model cable (Fig. 7) confirm this good longitudinal homogeneity too. On the other hand, another cable length (model cable HVDCM0-4, with another couple insulation/semicon) appeared less homogeneous and has presented some highest level of space charge accumulation (see Fig. 8).

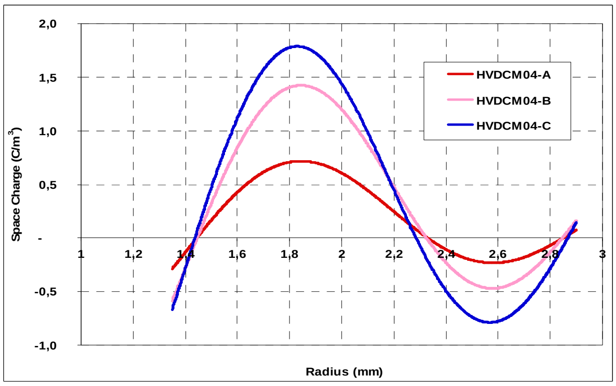

Fig. 8: Space charge distribution in 3 samples from the same cable length (model cable HVDCM0-4)

This kind of work, using the space charge accumulation criterion can thus be done in laboratory to evaluate the quality of each insulation/semicon system.

Space charge measurements in power cable length [4] - In this work, carried out on 3-meter long cable, we have shown the complementary use of the two thermal-based techniques (OCT and IHT) for space charge measurements in power cable length.

The sample tested in this work is a 3 m-long piece coming from a commercially available 12/20 kV cable (aluminum core section of 95 mm^2). 25 cm of the external semicon layer were removed on each cable extremity for allowing the application of the electrical stress. The two extremities have then been connected to constitute a single turn secondary of a heating transformer. The heating core has 2 functions: it generates the strong current needed for the inner heating measurement by TSM, and it is used to establish in the cable a current close to the nominal value (~ 0,2 kA) during the electrical conditioning. Three thermal diffusers have been placed at different positions to control the homogeneity of the insulation dielectric behavior (Fig. 9 and 10).

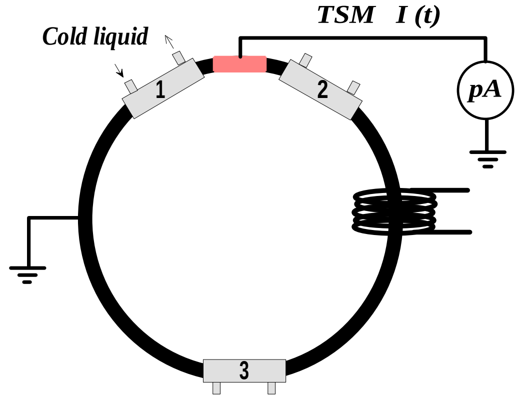

Fig. 9: Space charge measurement by OCT

Examples of TS currents are given Fig. 11 and 12, after conditioning the cable under 40 kV DC on the core during 12 h with a thermal gradient of 40℃ between the ca ble core and the outer semicon layer.

If we approximate the radial diffusion of the temperature in a cable by a law of the form:

$$\Delta T(r,t) = \Delta T \cdot f(r,t) \qquad [2]$$

where ΔT is the amplitude of the thermal step, the equation of the TS current (1) may be written as:

$$I(t) = -\alpha C \Delta T \int_{R_i}^{R_e} E(r) \frac{\partial f(r,t)}{\partial t} dr \qquad [3]$$

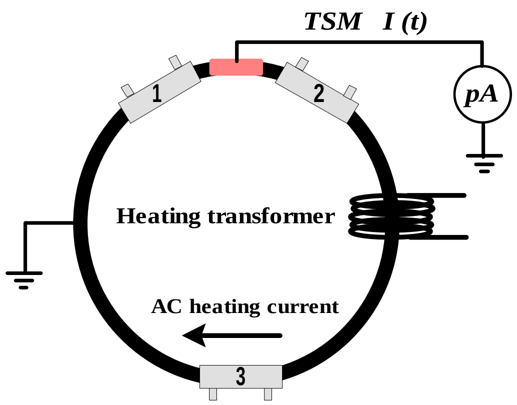

Fig. 10: Space charge measurement by IHT

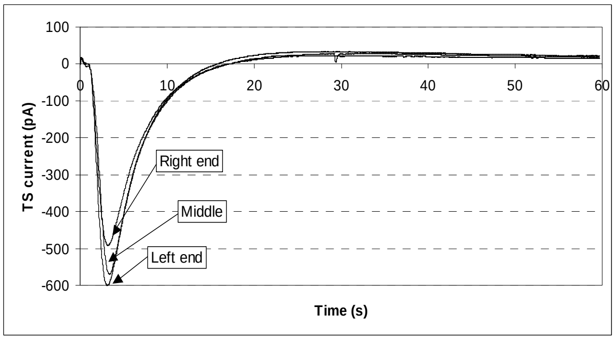

Fig. 11: TS currents obtained by OCT after DC conditioning under thermal gradient

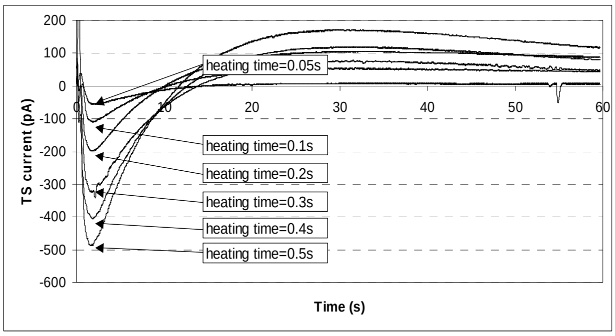

Fig. 12: TS currents obtained by IHT after DC conditioning under thermal gradient

For an equivalent residual field *E*(*r*), the ratio between the currents obtained by IHT and OCT is:

$$R = \frac{I_{heating}(t)}{I_{cooling}(t)} = \frac{C_h \cdot \Delta T_h}{C_c \cdot \Delta T_c} = R_C \cdot R_{\Delta T} \qquad [4]$$

where R_C and $R_{\Delta T}$ are the ratios of the capacitances, and, respectively, of the temperature steps for the two cases.

By calculating the capacitances corresponding to the cable lengths measured by the 2 techniques, and the maximum temperature steps ratio, we get for the *R* ratio the following value:

$$R = R_C \cdot R_{\Delta T} = 12.14 \cdot 0.123 = 1.42 \qquad [5]$$

The experimental ratio R_{exp}, calculated using the measured TS currents maxima is:

$$R_{\exp} = \frac{I_{h\max 0.5s}}{I_{c\max}}$$, between 0.8 and 0.98.

The difference between the experimental and the theoretical value is due to the fact that, in the case of OCT, we produce a real thermal step on the outer semicon layer, whilst in the case of IHT, the cable core temperature decreases slowly after the transient heating, thus the approximation made above for the temperature propagation may not be enough accurate.

However, the quasi-equivalent values obtained for the TS currents show that the sample's capacitance, significantly greater in the case of IHT, compensates easily the low temperature raise. It seems therefore possible to obtain exploitable results on significant lengths of cable with only a very low transient inner heating (<1℃).

Recent developments - Portable installation for space charge measurements on Full-size HV cable [8] - The aim of this recent development is to set up a portable installation to be used for TSM space charge measurements on long cable loops (> 100 m) and high conductor sections (> 2500 mm^2). Its principle is based on a transient heating of the cable core or of the outer conducting screen by Joule effect for generating a thermal pulse of several degrees (Fig. 14-15). This requires the ability to obtain and control a high current (> 12 kA) during a given duration. The use of AC current heating requiring significant apparent power can hardly be used for such a goal. We have recently propose a set-up based on a coupled inductor parallel multicellular power buck converter, with a topology especially designed for generating and controlling high currents during short durations (Fig. 13).

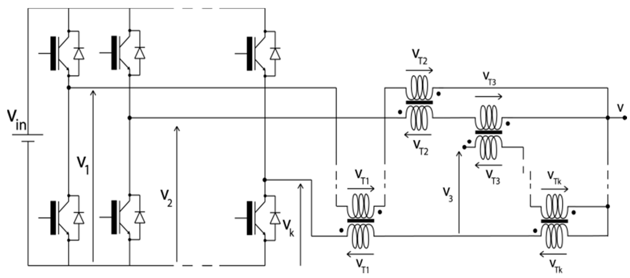

Fig. 13: 12-phase parallel multicellular converter using ICT - equivalent electrical circuit

Recently, a 1200 A DC elementary cell using a 4-phases DC/DC power converter, with an ultra capacitor module (165 F – 48 V), has been tested and validated. The presented results have demonstrated the capabilities of the proposed type of DC/DC cells for setting up of a high current portable bench for space charge measurements on long cable loops with high conductor sections. This should allow setting up a 12000 A converter easy to be handled and displaced, allowing on-site measurements.

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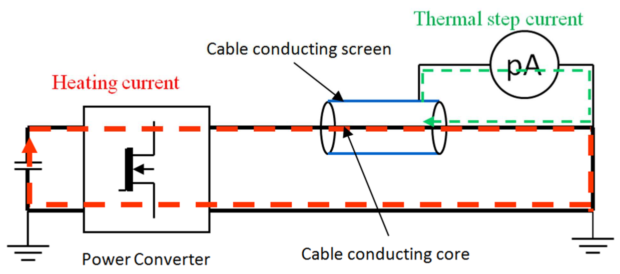

Fig. 14: Heating current in the cable core provided by the controlled discharge of the ultra capacitor

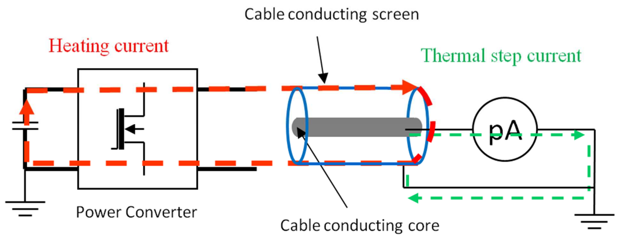

Fig. 15: Heating current in the cable screen provided by the controlled discharge of the ultra capacitor

4 – TSM IN INDUSTRIAL ENVIRONMENT – TECHNOLOGY TRANSFERS

Electric field monitoring within HVDC cable insulation in service conditions can represent an essential stage to assess a long-term behavior of the cable. Measuring space charge under applied electric field is based upon TSM in a double capacitor configuration [4]. The experiment requires the use of 2 identical cables (same electrical capacitance and dimensions) whose external electrodes are insulated from one another (Fig. 16).

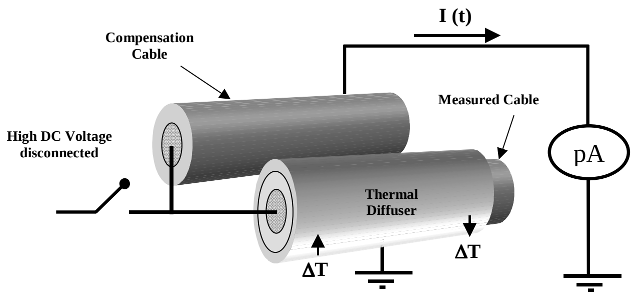

Fig. 16: Under field TSM measurements on cables in double capacitor configuration. Outer Cooling Technique on the measured cable after disconnecting the DC source

Industrial set-up - The under field measurement technique has been installed in the NEXANS-France site of Calais in 2000. An overview of the HV laboratory dedicated to TSM measurements is given in Fig. 17.

First, the 20 m-long cables are submitted to an electric field via an HV relay, the current amplifier is in short circuit. The second stage consists, in the case of the outer cooling technique (OCT) (see principle in Fig. 16), in measuring a current due to the application of a thermal step generated on a thermal diffuser (from 10 to about 100 cm long) wrapping up a part of the measured cable. The thermal diffuser is placed on the test cable; the measurement is performed with a current amplifier placed between the external semi conductor of the compensation cable and the ground.

Fig. 17: Experimental equipment for measurements on cables under electric and thermal gradient – A: measurement cable - B: compensation cable - 1: HV DC source - 2: HV relay - 3: current amplifier - 4: heating - 5: thermal sources - 6: thermal diffuser - 7: computer - 10: command desk

In the case of the inner heating technique (IHT), a strong current circulating in the central core of the cable generates the thermal step; the measurement is made on the compensation cable (Fig. 18). As for OCT, during the Thermal Step current measurement, the voltage source must be disconnected because the system must imperatively remain insulated during the acquisition of the signal. This imposes the use of a remote high voltage relay, controllable from the command desk.

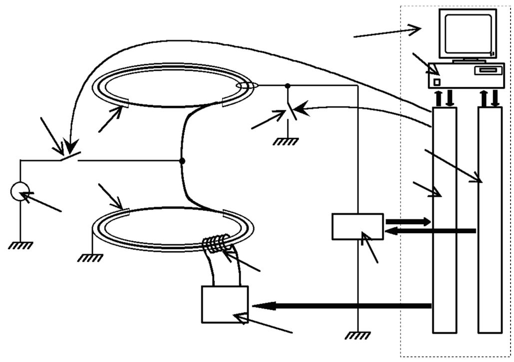

Fig. 18 : Inner Heating Technique on cable length

Monitoring of the internal electric field of a cable submitted to electrical and thermal stress (voltage-on measurements) [9] - In this example, a 2600 h ageing campaign was carried out on a model cable (insulation thickness 4.6 mm, core 95 mm^2) under -150 kV and 80℃ on core. Measurements were regularly performed to follow-up internal field evolutions. This results in maximum field distortion after 15 days, followed by a smoothening of the electric field distribution up to 105 days under stress (Fig. 19). Field distribution may tend toward the purely resistive distribution, but this is far from being obvious even after 105 days testing.

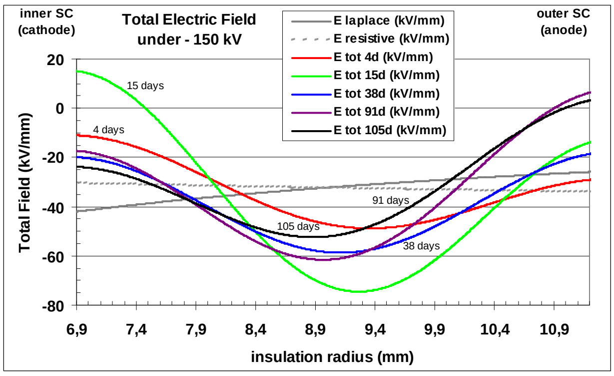

Fig. 19: Total electric field distribution in a model cable under applied voltage and thermal gradient.

Monitoring of the residual space charge during aging (voltage-off measurements) [9] - Here after, another ageing campaign on a model cable (insulation thickness 4.9 mm, core 95 mm^2) is presented. Since voltage-on measurements cannot be performed on such a cable because of a strong potential decay during the TS measurement, build-up of steady residual space charge was only studied by means of voltage-off measurements. The negative injected charge close to the inner semiconductor is getting lower whereas a positive charge is expanding from the anode to the bulk. We must keep in mind that "conduction space charges" are not involved in the distributions of Fig. 20 purely related to the steadily trapped ones (voltage-off measurements).

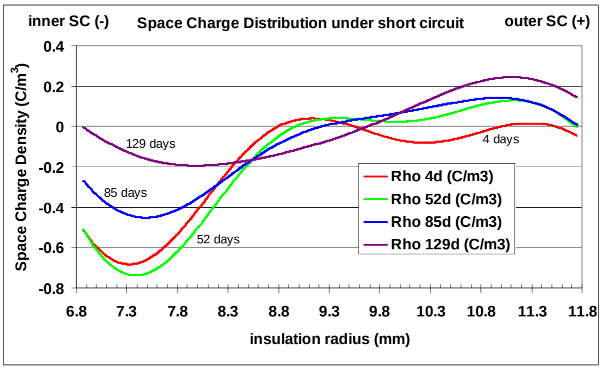

Fig. 20: Evolution of residual space charge (voltage-off) in a model cable as a function of ageing duration

HVDC cables during a long-term ageing program [10].- To get a good understanding of HVDC cable operation, loading management and long term performance of its insulation under DC voltage, ALSTOM Grid teamed up with university research laboratories and partnerships from cable like NEXANS France has been devoting on developing a world first ever HVDC cable long term ageing evaluation facility, which combines online measurement probes to characterize the electrical properties of full-size 200 kV cables undergoing a program of ageing similar to the CIGRÉ prequalification test [11]. To do this, the TSM is currently deployed on-line to monitor space charge phenomena and possible material variation caused by electric and thermal stress.

5 – CONCLUSION

The Thermal step Method for measuring space charge in insulating materials has been invented in 1986. Since then, the technique has not stopped evolving and the different studies and researches led for the last few years have made it a renowned non-destructive technique, both by the academic community and industry.

In this paper, we have presented both the principle of the TSM applied to power cables and the different possibilities of applying the technique on cable length. Several studies performed on power cable insulation have been discussed. Some of them were conducted in university research laboratory and other in industrial environments.

During these last years, the progress achieved and the industrial collaborations have thus allowed resulting in technology transfers of the method in industry. The use of this type of measuring technique in real conditions should allow, in the future, better understanding the processes leading to the ageing of cable insulating materials, when submitted to thermal and electrical gradients.

Acknowledgments

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