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Implementation of space charge measurement using the Pulsed Electro-Acoustic method during ageing of HVDC model cable

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SUMMARY

Due to high dielectric performances, cross-linked polyethylene (XLPE) is one of the preferred materials for the insulation of HVDC cables. However, polymeric insulating materials tend to store electric charges, which disturb the electric field within the material and may eventually lead to a structural modification of the polymer thus promoting its ageing. This degradation of the insulation may induce a decrease in the life expectancy of the cables.

Nowadays many studies are carried out to bring knowledge on the degradation mechanisms in polyethylene. Indeed, an improved understanding of the behaviour of charges makes it possible to better correlate the measurements with the ageing of the material. However, it is often not possible to measure the dielectric characteristics (current, space charge) during ageing, and most generally this has to be done a posteriori. The objective of this research is to measure the variations of the dielectric properties of the polyethylene insulation in a model cable, either during ageing conditions, i.e. when a thermo-electric stress is applied to the cable, or a posteriori. To do so, two approaches have been developed and put into practice.

The first approach is based on the adaptation of the Pulsed Electro-Acoustic (PEA) measurement method to an already charged model cable having undergone thermo-electric ageing. In this case, the PEA measurement is not performed online, but on samples taken regularly from a long cable length under thermo-electric stress. Hence, for each measurement, a different piece of cable, already charged when received, is under study. The PEA method requires a calibration step, normally performed on a non-charged sample to obtain the response of the system. We have developed a calibration procedure on an already charged cable without removing the possible charges that are present in the insulation. In this way crucial information on the state of charge before any further electrical stressing can be analysed. The treatment of the PEA signal has been revised, and it is now possible to quantify the charge present on an already stressed cable sample prior to any measurement. The improvement of the PEA signal conditioning will be presented in the paper. Moreover, the results of space charge measurements at different ageing times will be discussed.

The second approach is focused on an online space charge measurement at laboratory scale, using the PEA method on model cables over long periods of time. One of the difficulties when measuring during a long time, all the more when the set-up is not at room temperature, is the possible drift of the system configuration, as the mechanical pressure inside the PEA cell for example may vary even slightly. It may lead to changes in the transfer function of the whole system and possibly to some mistakes on the space charge profiles. The dedicated test bench has been developed with realizing periodic calibration using the procedure described below. It allows measuring space charge during long periods of time, and moreover during grounding and during polarity inversion cycles. Space charge profiles will be presented for long measurement times (several days) where the polarity is reversed each 30 min, for a mean applied field of 60 kV/mm and under thermal gradient.

KEYWORDS

Space charge, cable aging, HVDC, pulsed electro-acoustic (PEA) method, polarity reversal

INTRODUCTION

The worldwide increasing demand for renewable energy sources to supply electricity is a new challenge to face for power networks. HVDC technology is now increasingly used to transmit electricity from offshore windfarms, for interconnection of asynchronous networks, or simply for long distance transmission. Developments have been made on the insulating material used in HVDC cables, and cross-linked polyethylene (XLPE) has several advantages over oil-impregnated paper [1]. However, one drawback when using XLPE under DC stress is the possibility for the material to store charge for a long time, disturbing the electric field distribution. This behaviour needs to be deeply understood for insulating materials able to sustain ever increasing voltage levels over 40 years or more. Ageing studies have been performed on XLPE materials, under AC [2, 3] and DC, but mostly over short ageing periods and for temperatures above the melting temperature with no electric stress [4] or relatively low electric stress. Some aging studies under HVDC and high temperatures have been proposed on plane parallel samples [5, 6]. In this paper, ageing has been performed on model cables, in two different ways:

- A long term ageing over 18 months has been developed at relatively high constant temperature (100°C) but below the melting temperature [7], and at average stress of 60 kV/mm, higher than the highest electric field required during short term qualification tests for 640 kV DC cables ([8], extrapolated for 640 kV), and also higher than the average electric field calculated for long term qualification tests for 640 kV DC cables with polarity inversions ($1.45 U_{DC}$).
- An accelerated ageing is proposed over shorter periods (several weeks), but with a temperature gradient along the insulation radius and with regular grounding (GR) or polarity reversal (PR) periods, as polarity reversals are thought to shorten the cable lifetime [9].

We present in this paper the challenges overcome during the method development and space charge measurements for each ageing type, the evolutions of the space charge measurement test bench and the signal treatment. We also present for the first time space charge measurement performed during 24h of polarity reversal.

MATERIALS

Model cables are used for this project, as they have the advantage to be more representative of the real full-size cable configuration than plaques, i.e.:

- a cylindrical geometry where electric field and temperature are not homogeneous over the insulation thickness, and
- the presence of semiconducting screens (SC) on each side of the XLPE insulation, which can have a role on the thermal and electrical behaviour.

The model cable consists of a copper core and a three layers (SC/XLPE/SC) insulation system (Figure 1). It has been extruded on a laboratory CCV (Continuous Catenary Vulcanization) line using the material grade developed for the currently most demanding HVDC applications. Model cables were degassed for 10 days at 70°C after extrusion to remove XLPE peroxide decomposition products [10].

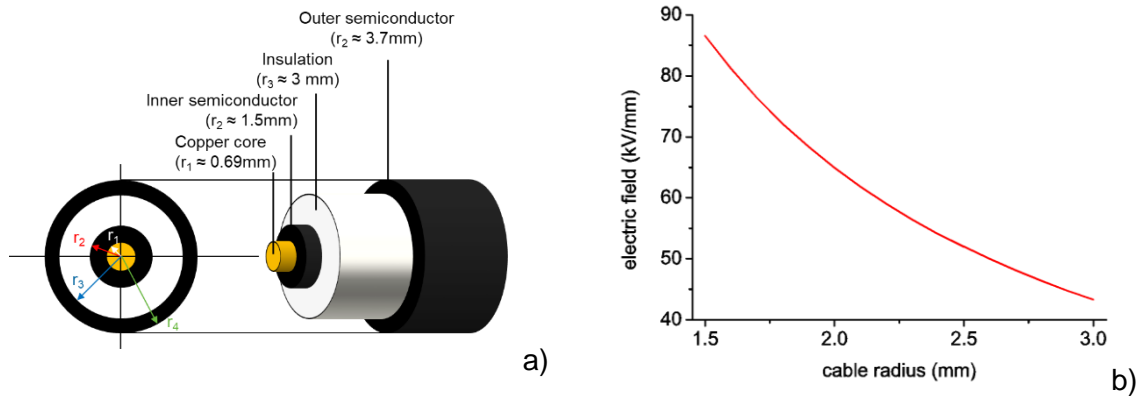


Figure 1. a) Model cable geometry, b) electric field distribution for the model cable when the applied voltage is 90kV.

AGEING SET-UP

Figure 2 presents the test bench used for accelerated ageing with a thermal gradient and under periodic grounding or polarity reversal conditions (the study also included a separate setup for long-term ageing under isothermal conditions, which is presented in [11]). Space charge measurements are performed online, while under voltage, and during grounding and/or polarity reversal periods. As no power supply with embedded polarity reversal function is available commercially, the voltage is applied with two high voltage power supplies of opposite polarity (+ and – 100 kV), being connected to a high voltage switch. To apply a temperature gradient within the cable insulation, an AC current is injected in the cable loop using a current transformer. The control of the thermal gradient is presented in the following paragraph. The maximal applied average electric stress is 60 kV/mm (i.e. 90 kV voltage to the cable), which corresponds to a geometric electric field of around 90 kV/mm at the inner SC and around 45 kV/mm at the outer SC, following the equation:

$$E(r) = \frac{V}{r \cdot \ln \frac{r_3}{r_2}} \quad (1)$$

where V is the applied voltage, and r is the insulation radius at which the electric field is calculated (r_2 and r_3 are defined in Figure 1a). The electric field distribution across the insulation is given in Figure 1b).

The maximal temperature at the conductor is 90°C, with a thermal gradient of 5.7 °C between the inner and the outer SC. For this short term ageing test bench, three cables are installed in parallel:

- Cable "Pulse" for applying the voltage pulse for space charge measurement by PEA;
- Cable 1 for on line space charge measurements while under voltage, during grounding and PR (thermo-electric ageing). The length of this cable is 3m.
- Cable 2 for sampling and off-line characterizing of the physico-chemical behaviour of the insulation (thermo-electric ageing). The length of the cable is 25m at the beginning of

ageing, and decreases of 3m each 7 days, due to sampling. Note that a second cable of 25m is aged with thermal stress only and is sampled every 7 days like for cable 2.

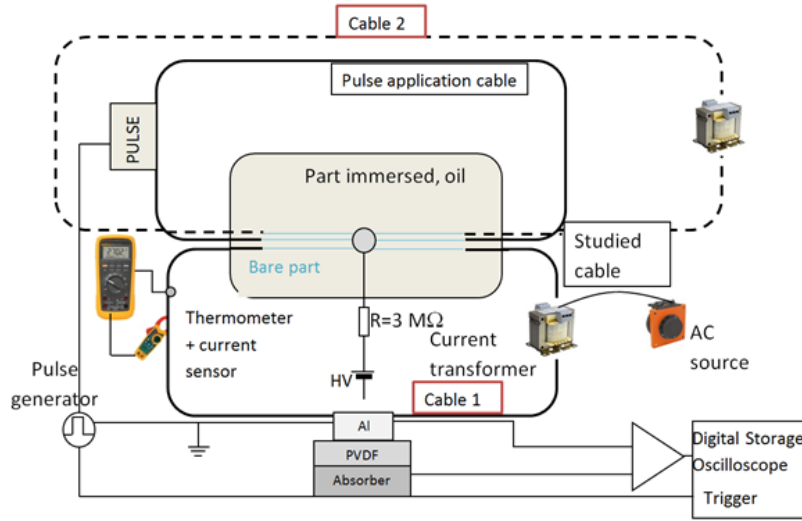


Figure 2 : Schematics of space charge measurement using the PEA method on model cables

All three cables are connected to the high slot sphere immersed in an insulating oil bath. For each cable termination, the outer SC has been removed on a length of 30 cm, kept in oil bath, to manage sufficient creepage distance between conductor end and SC screen end. The quality of cable stripping is of utmost importance, as the ending point of the SC represents a weak point for breakdown. Sampling on cable 2 for physico-chemical measurements implies to prepare a new cable termination every 7 days.

Cable “Pulse” is dedicated to PEA pulse application. In the literature, different PEA set-ups designed for cables are available, applying the PEA pulse either via the PEA cell electrode [12], via the cable conductor [13, 14], or via the outer screen [15, 16]. For the last case, the external SC needs to be removed over a certain length within the cable loop to form a decoupling capacitor. As the cable stripping is a sensitive operation, we decided to dedicate a specific cable loop for pulse application.

SETTING THERMAL GRADIENT

As stated before, a thermal gradient is generated in the cable insulation by Joule effect in the conductor. In steady state condition, the temperature gradient can be calculated if the temperatures at the cable core and at the outer SC are known (i.e. measured) [17]. The temperature at the outer SC is relatively easy to measure, but for the one at the conductor, a dummy loop is needed.

We have estimated the temperature T_C at the conductor core from the resistance per unit length of the conductor R_{CT} :

$$R_{CT} = R_{C20}(1 + \lambda_{20}(T_C - 20^\circ C)) \quad (2)$$

where R_{C20} is the resistance per unit length of the cable at $20^\circ C$, and λ_{20} is a coefficient characterizing the temperature dependence of the resistivity of copper, and is taken as $3.9 \cdot 10^{-3} K^{-1}$. R_{C20} is related to the electrical resistivity of copper ρ_{Cu} ($1.7 \cdot 10^{-8} Ohm.m$ at $20^\circ C$):

$$R_{C20} = \frac{\rho_{Cu}}{S} \quad (3)$$

where S is the conductor section. R_{C20} is theoretically $0.0117 \Omega/m$. This value has been determined experimentally and the mean of this value over four measurements is $0.01168 \pm 10^{-4} \Omega/m$, which is in good agreement with the theoretical data.

R_{CT} can be determined on a dummy loop of length $L=3m$ by measuring the current (I_S) and voltage (V_S) in the model cable forming the secondary winding of the current transformer:

$$R_{CT} = \frac{1 V_S}{L I_S} = \frac{1 V_P}{L m. I_S} \quad (4)$$

I_S is measured using a contactless sensor. V_S is not measured directly on the model cable, but is deduced from the voltage (V_P) at the primary winding and the transformer ratio (m) which is 98.5. Measuring I_S and V_P allows obtaining R_{CT} and then T_C . It is then possible to calculate the temperature everywhere inside the model cable, using:

$$T(r') = T(r) - \frac{W_c}{2\pi\alpha} \ln\left(\frac{r'}{r}\right) \quad (5)$$

where $T(r')$ is the temperature at radius r' , $T(r)$ the temperature at radius r , α is the thermal conductivity of the medium, being 0.34 W/m/K for XLPE and 0.45 W/m/K for the SC. These thermal conductivity values have been measured separately.

In equation (5), W_c is the heat flow per unit length (W/m), which is equal to:

$$W_c = \frac{\rho_{Cu} I_S^2}{S} \quad (6)$$

Using equation (5), one can obtain the temperature everywhere inside the cable system, composed of three layers (SC/XLPE/SC), and particularly at each interface. The thermal gradient across the insulation is given by:

$$\Delta T_{INS} = T(r_2) - T(r_3) = \frac{W_c}{2\pi\alpha_{ins}} \ln\left(\frac{r_3}{r_2}\right) \quad (7)$$

Table 1 summarises the values used in order to have a temperature at the conductor of 90°C (fixed for the ageing protocol) and of 70°C (fixed for the model cable characterization in post-ageing). Temperature measurements achieved at the outer SC to check the procedure were in good agreement with those calculated, for the given injected current. However, temperature measurements performed on the surface of the outer SC inside the PEA cell were much lower than outside the cell being of the order of 30°C and 33°C respectively for a desired temperature at cable core of 70°C and 90°C . This is due to the fact that the PEA cell acts as a heat sink compared to the cable installed in air. Neglecting axial heat transfer and temperature dependence of the electrical resistivity of copper, Eq. 7 shows that the thermal gradient is unchanged in spite of different limit conditions for thermal exchange. It is therefore considered that the thermal gradient is the same inside and outside the PEA cell.

Table 1 – Relation between interface temperatures and injected current in model cables. See Figure 1 for cable geometry.

V_P (V)	V_S (V)	I_S (A)	R_{CT} (Ω/m)	$T(r_1)$ ($^\circ\text{C}$)	$T(r_2)$ ($^\circ\text{C}$)	$T(r_3)$ ($^\circ\text{C}$)	$T(r_4)$ ($^\circ\text{C}$)	ΔT_{INS} ($^\circ\text{C}$)
164.5	1.76	39.4	0.0149	88.4	83.6	77.9	76.6	5.7
140.6	1.42	34.2	0.0140	69.9	66.2	61.9	60.9	4.3

EXAMPLE OF PEA MEASUREMENT ON MODEL CABLES WITH A THERMAL GRADIENT

Before ageing, a benchmark was performed on model cables without thermal gradient, and with different thermal gradients, to characterise the unaged system. Figure 3 presents the space charge measurements for an average applied electric field of 60 kV/mm

- for 4h under voltage, and 4h without voltage,
- with no thermal gradient at room temperature (Figure 3a), and with a thermal gradient of 4.3°C (Figure 3b).

As stated in the previous paragraph, the temperature at the core at the measurement point is of 34.3°C for Figure 3b. The anode is the inner electrode (conductor).

When no thermal gradient is applied (Figure 3a), there is first a front of negative charges, coming from the outer electrode, with an apparent transit time of around 2 hours. Once these charges have reached the inner electrode, there is an injection of positive charges from the inner electrode. These positive charges completely mask the previous negative charges. During short-circuit, only positive charges are measured, with the same position as at the end of the phase under voltage.

When a thermal gradient is present (Figure 3b), the negative charge front tends to disappear. It is only visible in the first minutes of the measurement. Positive charges are rapidly dominating the space charge pattern. This is not surprising as the thermal gradient drives the charges from the inner electrode to the outer electrode [18]. However, the accumulation of positive charges at the outer electrode is not predicted by the thermal gradient, and is due to other physical processes. Negative charges seem however present, during short-circuit, they seem to appear next to the inner electrode. Imposing a thermal gradient has a significant impact on the space charge pattern. This shows the interest of using a thermal gradient when ageing the material.

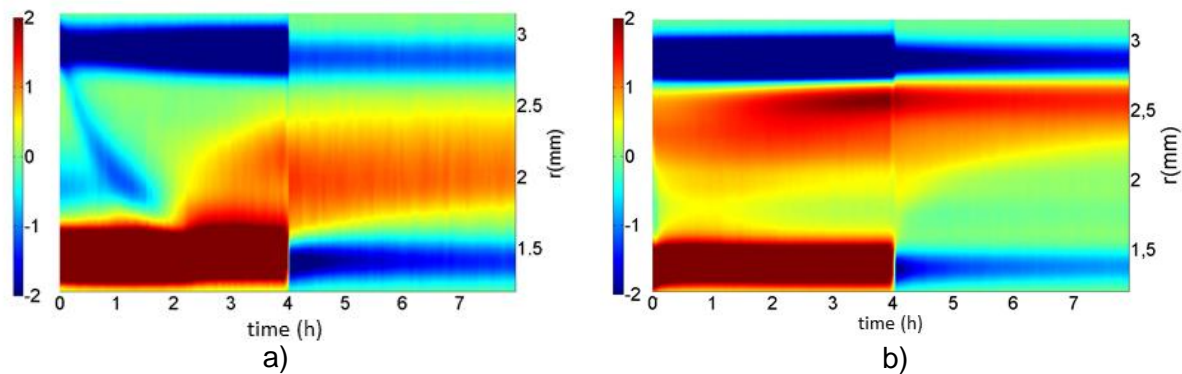


Figure 3. Space charge cartography on a model cable stressed at an average electric field of 60 kV/mm, where a) there is no thermal gradient, $T=25^{\circ}\text{C}$, and b) the thermal gradient across the insulation is 4.3°C . The colour scale refers to charge density, in C/m^3 .

SETTING POLARITY REVERSALS

Polarity reversals have been proposed in the ageing protocols, as they are thought to have an adverse effect on the lifetime, compared to continuous DC application or periodic grounding [9, 19]: the higher the frequency of inversion, the shorter the lifetime. Accelerating the ageing of model cable using PR or GR implies setting several parameters related to the ageing protocol. In this paragraph, only PR will be presented, as the GR protocol is based on the PR one.

The thermal and electrical constraints have already been discussed previously. The methodology proposed for ageing under PR consists of applying cycles of 24hours each with the following sequence: $+U_0$, PR, $-U_0$, PR (Figure 4a). This sequence is repeated during several weeks, with a sampling each week for current measurement, and physico-chemical characterizations. Polarity reversal takes 2 min, following the CIGRE recommendation TB496

[8]. During each PR, a waiting time of 1 min at 0V is applied. Hence, for an inversion from positive to negative applied voltage, the voltage decrease from 90 kV to 0V takes 30s, and the decrease to -90 kV also takes 30s. The frequency of PR is set to two per hour (Figure 4b).

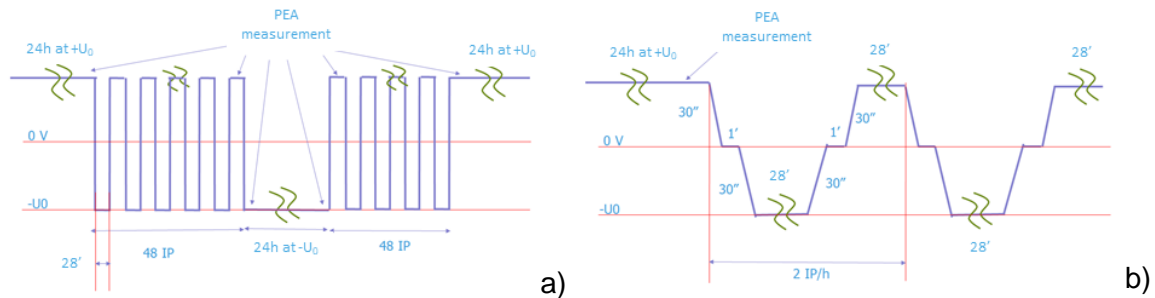


Figure 4. Schematic representation of a) the sequences of applied voltage and polarity reversal, and b) detail of voltage variation during two periods of PR.

During this accelerated ageing, PEA measurements are performed online, with the possibility to probe the space charge behaviour during PR. Figure 5 shows a cartography of charges measured on a model cable during short term ageing, at $E_{\text{average}} = 60 \text{ kV/mm}$, and $\Delta T = 5.7^\circ\text{C}$, after 24 hours of DC polarization at +90 kV. We observe clearly the repetition of negative charges injection at the inner SC, and phases during the ageing where the charge density in the bulk is higher. These patterns will require a more detailed analysis. However, the purpose here is mainly to show the feasibility of achieving on-line measurement during PR.

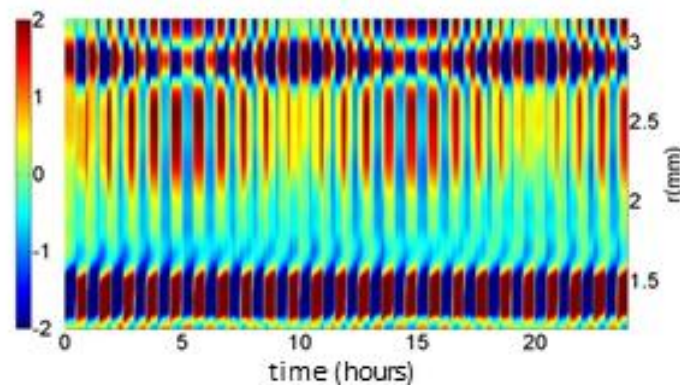


Figure 5. Space charge cartography measured on a model cable stressed during 24 hours with PR. The colour scale refers to charge density, in C/m^3 .

PEA MEASUREMENTS ON AGED CABLES

Space charge measurement by the PEA method requires a calibration step necessary to identify the transfer function of the PEA cell. This step consists of applying a relatively low electric field in order not to inject charges into the cable and to consider that the output signal of PEA cell is the response of capacitive charges at the interfaces between the insulation and the internal and external SC. In the case of a pre-stressed cable, the presence of space charge within the insulation makes the hypothesis of the sole presence of capacitive charges invalid, and the calibration step must be adapted accordingly.

In order to identify the transfer function of the PEA cell for aged cables, two measurements are performed (Figure 6a) as proposed previously in the case of flat samples [20]:

- A first measurement without applying voltage in order to measure the signal coming only from the internal space charge and the corresponding image charges;
- A second measurement where a DC voltage is applied to measure a composite signal due to the internal space charge, the image charges and the capacitive charges.

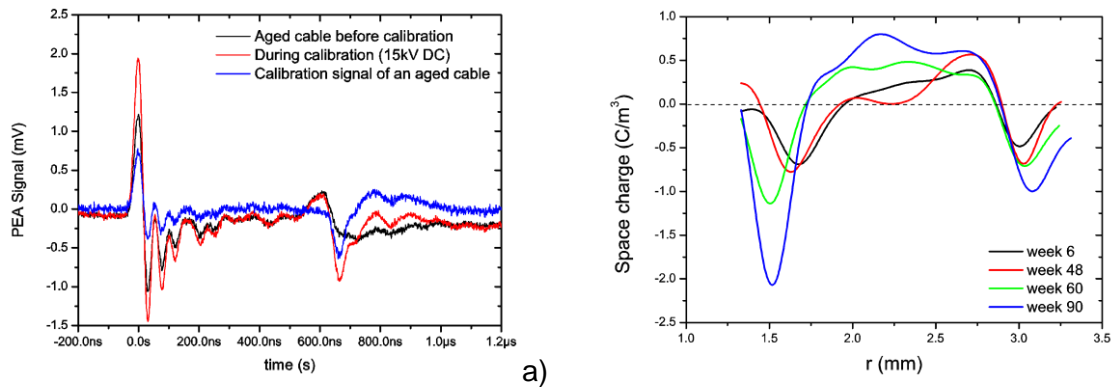


Figure 6: a) PEA signal of an aged cable: before calibration, during calibration (with 15kV applied DC voltage), and calibration signal of an aged cable used for identification of the cell transfer function; The peak to the left corresponds to the response at the outer screen/XLPE interface. b) Measured charge density profiles on as received aged cables at different ageing times.

A first treatment consists of making the difference between the two measurements in order to obtain the signal only related to capacitive charges, which will then be used to identify the transfer function of the system.

The second treatment is the classic deconvolution used to identify the transfer function of the system constituted by the PEA cell and the cable in a cylindrical geometry [21]:

- Identification of the response of the measuring cell from the response of capacitive charges on the external electrode
- Identification of the cable transfer function taking into account the attenuation and dispersion of acoustic waves from the responses of capacitive charges on the internal and external electrodes.

The synoptic of the signal conditioning scheme is shown in Figure 7 [22]; details of the mathematical treatment are given in [21]. Note that in the present treatment, we do not account for the gradient in acoustic properties along the cable radius.

Once the overall frequency response $H_{sys}(f)$ of the PEA cell and cable is identified, the electric field and the space charge density distribution in a previously charged cable and the evolution when a protocol is applied can be obtained. Figure 6b shows the residual space charge profiles corresponding to pre-charged cables during the long term ageing protocol, for different ageing times. The amount of stored charge increases with ageing time and the charge is positive, as was the polarity of the conductor [11]. During ageing, for sampling, the cable was cooled to room temperature with the voltage still applied, in a way that the accumulated space charges were “frozen”.

LONG-TERM ON-LINE MEASUREMENTS BY PEA

An advantage of the test bench developed above is the possibility to measure space charges all along the ageing, in principle for days. Aside from the question of available data storage space that should be resolved (the frequency of data acquisition is 1 profile every 3 minutes), the main difficulty that came is a slow change in the shape of the acoustic signals being recorded which is not due solely to the evolution of the space charge density. After deconvolution, an overestimate of the charge density was obtained. This drift in the acoustic response resulted from different sources:

- The mechanical pressure imposed to the cable for acoustic signal detection could evolve in time at the scale of days due to mechanical creeping of the material. This may also result in a change in cable shape.

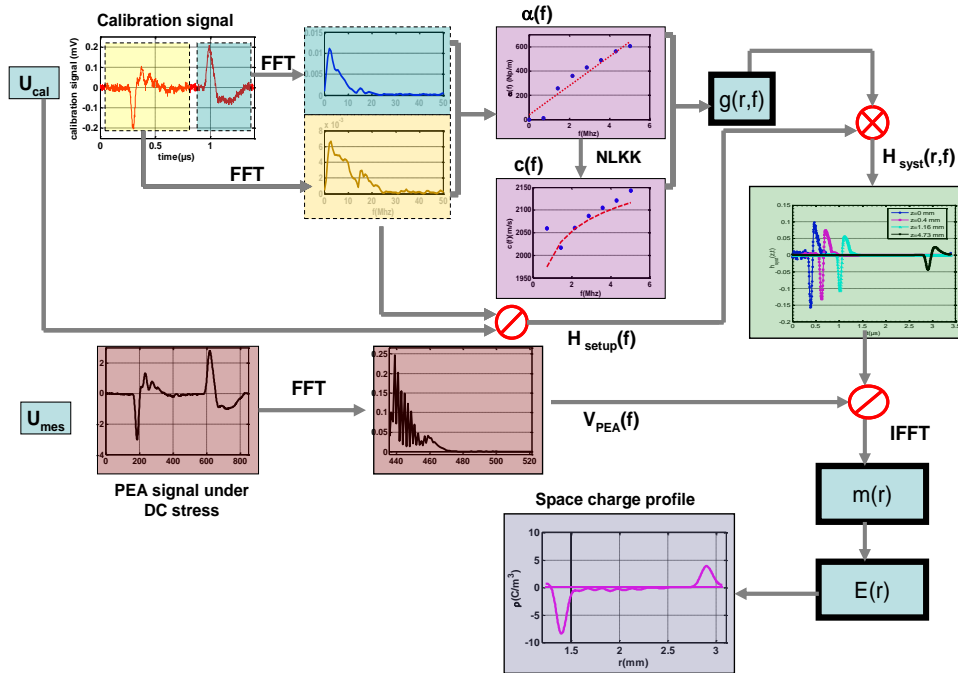


Figure 7: Synoptic of deconvolution method on PEA signal from cable [22].

- The temperature of the test cell could evolve slightly.
- The periodic (weekly) sampling of the cable imposed to stop application of high voltage, and reducing the length of one cable (for sampling and preparing terminations) changed the capacitance of the load viewed by the pulse generator.
- In the event of breakdown or incident on the test bench, the cable heating had to be stopped which could change the thermo-mechanical stress on the sample.

All these possibilities produce a drift in the transfer function of the system and prevent reliable analysis of the data over a long period. Figure 8 shows examples of rough calibration signals obtained at the beginning of the ageing protocol with PR, and after 7 weeks of ageing. The position of the peaks has evolved along with the delay between the responses from the two interfaces.

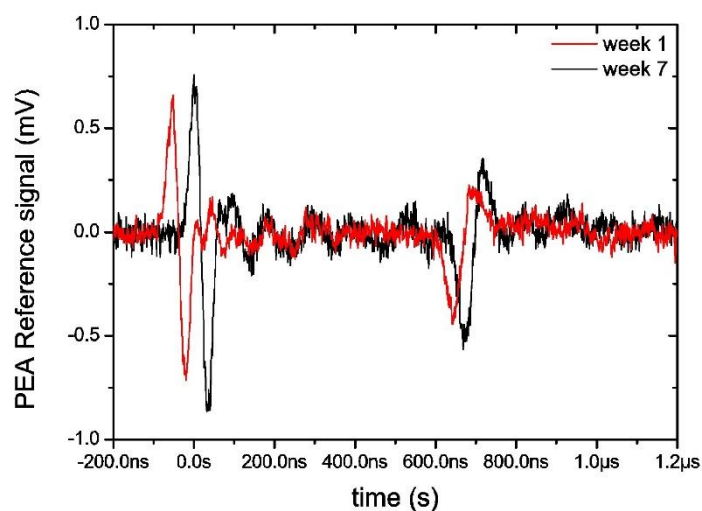


Figure 8: Rough PEA (calibration) signals obtained with 15kV DC voltage, at the beginning of the ageing under PR and after 7 weeks.

In order to fix this issue, the only possibility consists of repeating the calibration step periodically, and processing the data as for the pre-charged cables (because of the charge

accumulated during the ageing). As an indication, PEA measurements can be reasonably done for a few days without calibration – but this may depend on the temperature. Tighter control of the geometry of the cable, of pressure exerted on it and keeping the environment unchanged are ways to improve the reliability of the long term measurements.

CONCLUSION

We have presented the implementation of a test bench for simultaneous ageing and space charge characterization of model cables for HVDC applications, the ageing cycle combining voltage application, grounding, and/or polarity reversal steps. This short-term ageing is achieved with a thermal gradient applied to the cable. We have shown the feasibility of realizing continuous measurement of space charges during ageing for several weeks using the pulsed electroacoustic method. The temperature gradient in the aged cable loop is controlled by the AC current injected in the conductor through a current transformer and by the surface temperature. Custom DC voltage cycles up to +/-100kV can be defined and applied using two HVDC supplies and a high voltage switch. The PEA hardware is the one developed for model cables where the pulse is applied through a separate cable loop. In this way, higher fields could be applied as the weak points in cable samples were moved to cable terminations.

Two main bottlenecks were encountered. The first one is the temperature gradient control at the measurement point for space charge. As the PEA cell acts as a heat sink, the temperature is lower than it is in the rest of the cable loop outside of the cell. A way to fix this while keeping online space charge monitoring, could be to control temperature of the PEA cell by means of a heating system.

The second challenge resorts to the drift of the transfer function of the PEA test cell as a function of ageing time. This drift can be due to an evolution of the test object and / or of the mechanical stress. A procedure for calibration of the PEA on a pre-charged cable was implemented. An update of the calibration then becomes possible during the ageing, limiting the impact of the transfer function drift. Using the same test bench, it is possible to probe space charges in cable sections aged under thermoelectric stress in separate conditions, the procedure for calibration on pre-charged cable sections being necessary for such case.

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