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IEEE Recommended Practice for Space Charge Measurements on High-Voltage Direct-Current Extruded Cables for Rated Voltages up to 550 kV

IEEE Dielectrics and Electrical Insulation Society

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IEEE Std 1732™-2017

IEEE Recommended Practice for Space Charge Measurements on High-Voltage Direct-Current Extruded Cables for Rated Voltages up to 550 kV

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Abstract: The aim of this recommended practice is establishing a protocol for the measurement of space charges in high-voltage direct-current (HVDC) extruded cables having rated voltage up to 550 kV. Such measurements are prescribed to be carried out at the beginning and at the end of load cycle qualification tests (either the long-duration voltage test of prequalification tests or the load cycle test of type tests). The various steps of the protocol for the measurement of space charges in such cables are carefully described. Details are given about the procedure for applying and switching off the voltage, the preparation and conditioning of specimens, the measurement times during poling and depolarization, and the calculations for checking electric field stabilization. The ultimate goal of this recommended practice is not verifying the compliance with any maximum acceptable limit of either space charge or electric field, but rather assessing the variation of the electric field profile in the cable insulation wall during load cycle qualification tests.

Keywords: HVDC extruded insulation, IEEE 1732™, power cables, power cable testing, space charge measurements

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When the IEEE-SA Standards Board approved this recommended practice on 23 March 2017, it had the following membership:

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Introduction

This introduction is not part of IEEE Std 1732-2017, IEEE Recommended Practice for Space Charge Measurements on High-Voltage Direct-Current Extruded Cables for Rated Voltages up to 550 kV.

Recently many high-voltage direct-current (HVDC) cable systems with extruded insulation have been installed all over the world (Mazzanti and Marzinotto [B13]). Since extruded insulation for HVDC cables is strongly affected by trapped space charge, several space charge measurement methods have been developed since the mid-1980s. So far, space charge measurements have mostly been made using thin, small-size plaques and mini-cables. Much less effort has been devoted to cables of size and design comparable or equal to the full-size cables installed in the field. On the other hand, space charge measurements on full-size cables are of great interest for practical cable systems, as such measurements enable actual service conditions of power cables to be evaluated.

Inherent difficulties mainly related to thick insulation make measuring space charge on full-size cables difficult. However, since the 1990s, satisfactory space charge measurements on large HVDC extruded cables have been described in the literature. Furthermore, space charge measurements on full-size HVDC extruded cable loops have been, and are being, used worldwide in qualification tests for HVDC extruded cable link projects. These measurements are based on project-dependent agreements between cable manufacturers and the customers, as there is no agreed standard procedure.

Aiming to fill this gap, in 2015 a position paper prepared by the IEEE DEIS HVDC Cable Systems Technical Committee was published (Mazzanti, et al. [B12]). The paper illustrates a protocol for the measurement of space charge on full-size HVDC extruded cables during load cycle qualification tests (either the long-duration voltage test of prequalification tests or the load cycle test of type tests). The protocol incorporates experience gained in the above-mentioned space charge measurements for HVDC extruded cable system projects.

This recommended practice aims at improving this protocol and establishing it as a reference IEEE best practice for the measurement of space charge on full-size HVDC extruded cables. At the time of writing of this document, the maximum rated voltage of HVDC extruded cable systems commissioned worldwide is 320 kV, but systems with rated voltage up to 525 kV are being qualified. Moreover, in 2012 CIGRÉ issued the Technical Brochure 496 entitled “Recommendations for Testing DC Extruded Cable Systems for Power Transmission at a Rated Voltage up to 500 kV” (see Clause 2). Aiming at accounting for these recent and/or ongoing developments, an upper limit of 550 kV has been selected for the rated voltage of HVDC extruded cables to which the present recommended practice is applicable.

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IEEE Recommended Practice for Space Charge Measurements on High-Voltage Direct-Current Extruded Cables for Rated Voltages up to 550 kV

1. Overview

1.1 Scope

This standard recommends best practices for the measurement of space charge on high-voltage direct-current (HVDC) extruded cables having rated voltage up to 550 kV. Focus is on poling time, depolarization time, heating and cooling of specimens. Particular reference is made to space charge measurements to be carried out during load cycle qualification tests (either prequalification or type test load cycles). The ultimate goal of this standard is not checking the compliance with any maximum acceptable limit of either space charge or electric field; rather, assessing the variation of the electric field profile in the cable insulation wall during load cycle qualification tests.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

CIGRÉ Technical Brochure 288:2006, Guide for Space Charge Measurement in Dielectrics and Insulating Materials—PEA, PWP (PIPWP & LIPP) and TSM Methods.

CIGRÉ Technical Brochure 496:2012, Recommendations for Testing DC Extruded Cable Systems for Power Transmission at a Rated Voltage up to 500 kV.

IEC 60060-1:2010, High-Voltage Test Techniques—Part 1: General Definitions and Test Requirements.[1]

[1] IEC publications are available from the International Electrotechnical Commission (http://www.iec.ch/). IEC publications are also available in the United States from the American National Standards Institute (http://www.ansi.org/).

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3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.[2]

cable loop: *See:* **test loop**.

cable system: Cables with installed accessories. Cable accessories are typically joints and terminations. There may be other types of accessories associated with a cable system (e.g., measuring devices or fixtures). These need only to be incorporated in the test objects to the extent that they are deemed to have an impact on the operational characteristics of the cable system (adapted from CIGRÉ Technical Brochure [TB] 496:2012, page 6, 1.5.1).

compensation cable: Cable that serves for compensating the polarization and conduction currents of the measured cable subjected to space charge measurements with the thermal step method and has identical capacitance to the measured cable (for more details, see Annex B).

compensation cable loop: Compensation cable arranged in a cable loop with two terminations.

depolarization time: Time starting—after voltage removal—as soon as the cable conductor has been short-circuited and grounded.

full-size cables: Cables of the same size, design, and rated voltage as the power cables installed in the field.

load cycle test: Part of the electrical type tests for dc extruded cable systems for power transmission at a rated voltage up to 550 kV (adapted from CIGRÉ TB 496:2012, page 19, 4.4.2). (Equivalent to the heating cycle voltage test after IEC 62067:2011, 12.2.4, for ac cables.)

long-duration voltage test: Part of the prequalification test for dc extruded cable systems for power transmission at a rated voltage up to 550 kV (adapted from CIGRÉ TB 496:2012, page 14, 3.4). (Equivalent to the heating cycle voltage test after IEC 62067:2011, 13.2.4, for ac cables.)

measured cable: Cable subjected to space charge measurements with the thermal step method where the thermal diffuser is installed (for more details, see Annex B).

measured cable loop: Measured cable arranged in a cable loop with two terminations (for more details, see Annex B).

negative voltage depolarization time: Depolarization time following the application of a voltage of negative polarity between the cable conductor and the grounded cable metal sheath.

negative voltage poling time: Poling time in case that the polarity of the voltage applied between the cable conductor and the grounded cable metal sheath is negative.

poling time: Time starting as soon as the voltage applied between the cable conductor and the grounded cable metal sheath reaches the rated voltage U_0 of the tested cable system—as defined in CIGRÉ TB 496:2012, page 8, 1.5.3.

positive voltage depolarization time: Depolarization time following the application of a voltage of positive polarity between the grounded cable conductor and the cable metal sheath.

[2] *IEEE Standards Dictionary Online* subscription is available at: http://www.ieee.org/portal/innovate/products/standard/standards_dictionary.html.

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positive voltage poling time: Poling time in case that the polarity of the voltage applied between the cable conductor and the grounded cable metal sheath is positive.

prequalification test: Test made before supplying, on a general commercial basis, a type of dc extruded cable system for power transmission at a rated voltage up to 550 kV in order to demonstrate satisfactory long-term performance of the complete cable system (adapted from CIGRÉ TB 496:2012, page 5, 1.4). The prequalification test consists of (see CIGRÉ TB 496:2012, page 14, 3.2):

a) Long-duration voltage test (see CIGRÉ TB 496:2012, page 14, 3.4)

b) Superimposed impulse voltage test (see CIGRÉ TB 496:2012, page 15, 3.5)

c) Examination (see CIGRÉ TB 496:2012, page 16, 3.6)

space charge: Electric charge locally present within the insulation wall that modifies the internal, radial electric field.

space charge measurement: Measurement of the radial electrical space charge distribution, through the extruded cable insulation, detected using calibrated electro-acoustic or thermal pulses.

test loop: A combination of series connected test objects (consisting of cable lengths and accessories) simultaneously under test, as defined in CIGRÉ TB 496:2012, page 6, 1.5.1, and page 7, 1.5.2.

type tests: Tests made before supplying on a general commercial basis a type of cable system in order to demonstrate satisfactory performance characteristics to meet the intended application (adapted from CIGRÉ TB 496:2012, page 5, 1.4).

volt-off measurement: Space charge measurement performed during depolarization time.

volt-on measurement: Space charge measurement performed during poling time.

3.2 Acronyms and abbreviations

HV	high voltage
HVDC	high voltage direct current
IHT	inner heating technique
OCT	outer cooling technique
PEA	pulsed electro-acoustic
PQ	prequalification
PVDF	polyvinylidene fluoride
TB	technical brochure
TS	thermal step
TSM	thermal step method
TT	type test

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4. Recommended space charge measurement methods

The space charge measurement methods recommended for space charge measurements on high-voltage direct-current (HVDC) extruded cables for rated voltages up to 550 kV are the following:

a) The pulsed electro-acoustic (PEA) method

b) The thermal step method (TSM)

For details about the PEA method, reference shall be made to CIGRÉ Technical Brochure (TB) 288:2006. For more details about the usage of the PEA method in the case of cable geometry, see Annex A.

For details about the TSM, reference shall be made to CIGRÉ TB 288:2006. For more details about the usage of the TSM in the case of cable geometry, see Annex B.

5. Space charge measurements during the prequalification test

5.1 Introduction

Given the importance to space charge formation of cross-linking byproducts associated with the crosslinking agent dicumyl peroxide, and of anti-oxidants and molecular voltage stabilizers, and the effect of humidity (water) and the relatively rapid transmission of water through extruded insulation (in particular polyethylene and ethylene-propylene rubber), considerable care shall be exercised in performing PEA or TSM space charge measurements on HVDC extruded cables. Exposure to humid environments shall be minimized and limited strictly to the measurement duration. Constant and predefined values of cable conductor temperature, temperature gradient across insulation wall, and humidity of the surrounding environment shall be maintained during such measurements, to every extent possible. Ambient conditions during PEA or TSM measurements shall be recorded and included in the space charge measurement report.

5.2 Measurements by means of the PEA method

5.2.1 Measurement times

During the long-duration voltage test of the prequalification (PQ) test (described in CIGRÉ TB 496:2012, page 14, 3.4) two sequences of space charge measurements by means of the PEA method shall be carried out at the following times:

a) Before starting the long-duration voltage test of the PQ test: This first sequence of space charge measurements shall be carried out on a virgin (unaged) cable sample identical to the cable employed in the PQ test loop (see CIGRÉ TB 496:2012, subclauses 1.5.2, 3.3, and 3.4); this will serve as a reference for calibrating the PEA measurement set-up.

b) After the completion of the long-duration voltage test of the PQ test: This second sequence of space charge measurements shall be performed on an aged cable sample identical to the cable employed in the PQ test loop and subjected to the same long-duration voltage test as the PQ test loop.

5.2.2 Preparation of cable sample for space charge measurement with the PEA method

For each sequence of space charge measurements with the PEA method at the times established in 5.2.1, the cable sample shall be arranged in a cable loop consisting at least of:

— A cable of length sufficient to perform the space charge measurements by means of the PEA method satisfactorily.

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— Two terminations. Laboratory terminations are acceptable provided that they do not give rise to any flashover during both the space charge measurements and the whole PQ test.

The two sequences of space charge measurements with the PEA method at the times established in 5.2.1 shall not be performed on the same cable loop. Indeed, the PEA method requires that the outer shielding layer of the cable is removed and the outer semiconductive layer of the cable is exposed; this modifies the de-gassing rate and the effect of humidity on the cable loop subjected to space charge measurements compared to an unmeasured PQ test loop. The two different cable loops for the two sequences of space charge measurements at the times established in 5.2.1 shall be obtained according to one of the two following alternative procedures:

a) The two cable loops shall be both obtained from the PQ test loop—provided that its initial overall length is sufficient—as follows:

   1) The first sequence of space charge measurements with the PEA method at the first time established in 5.2.1 shall be performed at a location of the PQ test loop where the PEA set-up can be properly installed.

   2) After this first sequence of space charge measurements, the cable section where the PEA measurement cell is located shall be cut and removed. A joint shall be installed between the remaining cable ends, thereby preventing further degassing and humidity penetration in the cable insulation during the whole PQ test.[3]

   3) The long-duration voltage test of the PQ test shall be carried out.

   4) The second sequence of space charge measurements with the PEA method at the second time established in 5.2.1 shall be performed at a location of the PQ test loop where the PEA set-up can be properly installed.

b) The cable loop for the first sequence of space charge measurements—made of a virgin cable identical to the cable employed in the PQ test loop [as prescribed in 5.2.1, item a)] and of length sufficient for the PEA set-up to be properly installed (as described in 5.2.2)—shall be different from the PQ test loop. The cable loop for the second sequence of measurements shall be the PQ test loop and the space charge measurements shall be performed at a location of the PQ test loop where the PEA set-up can be properly installed.

NOTE—It is permitted to let the *first* cable loop undergo the whole PQ test leaving the PEA measurement cell on it to monitor space charge evolution during the PQ test and to compare it with the measurements carried out on the *second* cable loop after the completion of the PQ test.[4]

5.2.3 Sequence of space charge measurements with the PEA method

Before each sequence of space charge measurements at the times established in 5.2.1, an adequate section of the outer semicon of the cable sample for space charge measurement with the PEA method (see 5.2.2) shall be exposed. The PEA measurement cell shall be installed at the exposed section of the outer semicon. The measurements shall be made at ambient atmospheric conditions without extraneous precipitation or pollution (dry tests, see IEC 60060-1:2010, 4.2). The temperature and the humidity in the vicinity of the PEA measurement cell shall be monitored and recorded in the test report. All the required power and signal connections shall be set up by considering the safety of personnel and testing equipment. The sequence of space charge measurements shall then be accomplished according to the following steps:

a) The cable sample for space charge measurement with the PEA method shall be heated, and the cable conductor kept for at least 24 h at a value $T_{cond,max}$ (maximum temperature at which the cable

[3] This joint can be one of the joints that are to be qualified via the prequalification test.
[4] Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

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conductor is designed to operate) with a temperature gradient ΔT_{max} (maximum temperature difference over the cable insulation in steady state at which the cable is designed to operate) across cable insulation—$T_{cond,max}$ and ΔT_{max} are defined in CIGRÉ TB 496:2012, page 10, 1.5.4—before the space charge measurements start. Thereafter, the cable conductor temperature $T_{cond,max}$ and the temperature gradient ΔT_{max} across cable insulation shall be maintained for the whole duration of the space charge measurements. To ensure that $T_{cond,max}$ and ΔT_{max} have not been changed by exposing the semicon where the PEA test cell is located, this cable section shall be covered with appropriate thermal insulation throughout all the measurements.

b) By means of a dc voltage source, the rated voltage U_0 of the tested cable system—as defined in CIGRÉ TB 496:2012, page 8, 1.5.3—shall be applied with *positive polarity* to the cable conductor with respect to the cable metal sheath. The cable metal sheath shall be solidly and effectively grounded. As soon as a voltage $+U_0$ is attained between the cable conductor and the metal sheath, the positive voltage poling time, $t_{P,ON}$, will start.

c) Immediately after the positive voltage poling time $t_{P,ON}$ has started, at a time $t_{P,ON}(0) = 0$ h a first volt-on measurement shall be performed. This first volt-on measurement shall represent the reference at the start of the positive polarity measurements.

d) With the space charge measurement at time $t_{P,ON}(0) = 0$ h, a first series of volt-on measurements shall start, to be performed once every 60 min, until a time equal to 3 h has passed since $t_{P,ON}(0)$. Thus, the first series of volt-on measurements shall be performed at the following measurement times:

   1) $t_{P,ON}(0) = 0$ h[5]

   2) $t_{P,ON}(1) = 1$ h

   3) $t_{P,ON}(2) = 2$ h

   4) $t_{P,ON}(3) = 3$ h. This latter measurement time $t_{P,ON}(3)$ shall be referred to as $t_{P,C}(1)$ for calculation purposes according to Equation (1) through Equation (12).

   The relevant space charge and electric field profiles within the cable insulation wall shall be recorded and plotted[6].

e) The maximum absolute percent variation between the electric field profile at $t_{P,ON}(0) = 0$ and at $t_{P,ON}(3) = t_{P,C}(1) = 3$ h, namely $\Delta E_{max}[t_{P,ON}(0), t_{P,C}(1)]$, shall be calculated according to the following Equation (1):

$$\Delta E_{\max}(t_{P,ON}(0), t_{P,C}(1)) = \max\left\{100 \times \left|\frac{E(t_{P,ON}(0), r_k) - E(t_{P,C}(1), r_k)}{E(t_{P,ON}(0), r_k)}\right|\right\}, \quad k = 1,.., N \quad (1)$$

where

$E\left(t_{P,ON}(0), r_k\right)$ is the k^{th} point of the electric field profile at measurement time $t_{P,ON}(0)$

$E\left(t_{P,C}(1), r_k\right)$ is the k^{th} point of the electric field profile at measurement time $t_{P,C}(1)$

N is the total number of points in the field profile

$r_k \in [r_i, r_o]$ is the radial coordinate within the cable insulation wall of the k^{th} point of the electric field profile

r_i is inner insulation radius

r_o is outer insulation radius

[5]For engineering purposes, intermediate measurements at times 1 min, 5 min, 10 min, 15 min between $t_{P,ON}(0)$ and $t_{P,ON}(1)$ can be performed, so as to capture faster transient changes that may take place, e.g., associated with charge polarization.
[6]All recorded, calculated, and plotted quantities shall be recorded in this and subsequent test reports.

The stabilization of the measured electric field is assumed as having occurred at $t_{P,C}(1)$ if the condition expressed by the following Equation (2) is matched:

$$\Delta E_{\max}\left(t_{P,ON}(0),t_{P,C}(1)\right)\leq 10\% \tag{2}$$

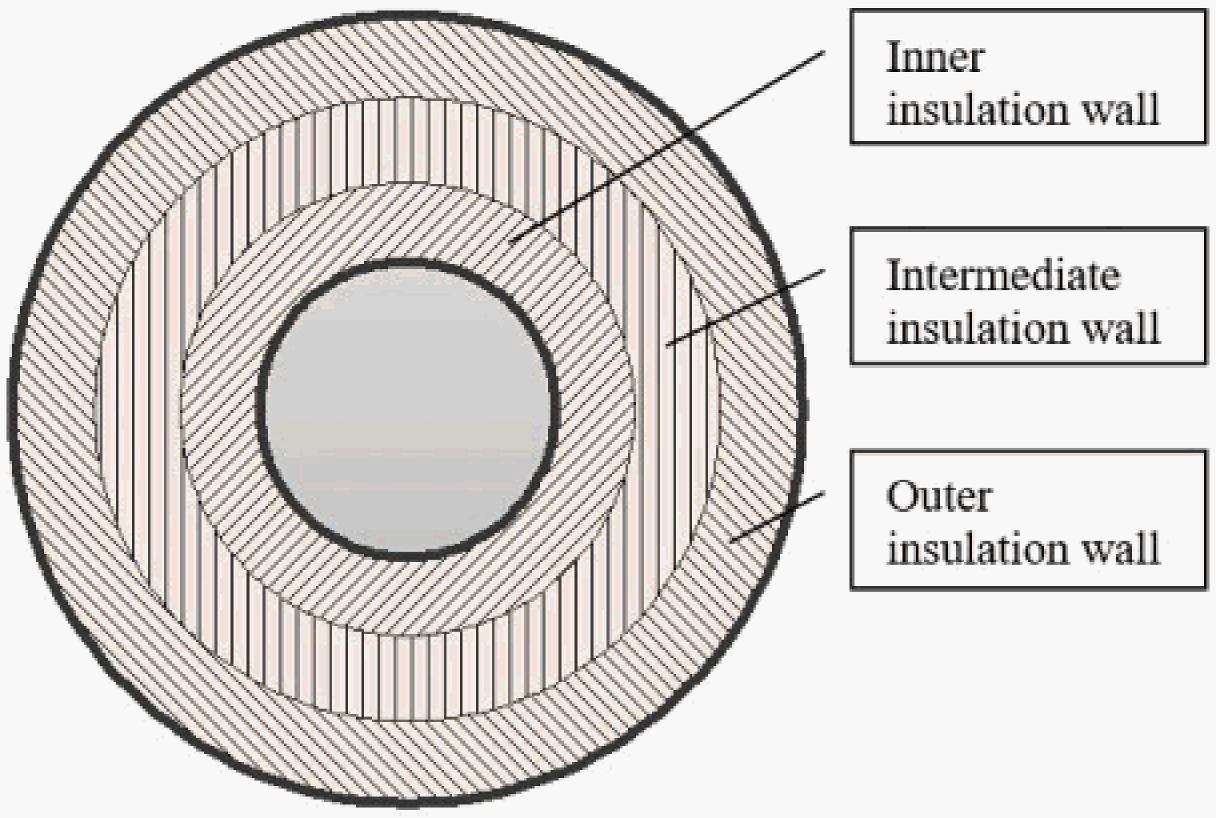

Figure 1—Schematic of cable with the insulation wall divided into three parts of thickness *d*/3 each: inner insulation wall, intermediate insulation wall, outer insulation wall

Furthermore, as shown in Figure 1, the whole cable insulation wall, of thickness $d = r_o - r_i$, shall be regarded as divided into three parts of thickness $d/3$ each, as follows:

1) Inner insulation wall, located between inner insulation radius r_i and radial coordinate $r_i + d/3$
2) Intermediate insulation wall, located between radial coordinate $r_i + d/3$ and radial coordinate $r_i + 2d/3$
3) Outer insulation wall, located between radial coordinate $r_i + 2d/3$ and outer insulation radius r_o

The location, r_{inner}, and the value, $E[t_{P,C}(1),r_{inner}]$, of the maximum field at $t_{P,C}(1)$ in the inner insulation wall shall be recorded. The electric field value at the same location r_{inner} at $t_{P,ON}(0)$, $E[t_{P,ON}(0),r_{inner}]$, shall be resumed and the absolute percent variation $\Delta E_{inner}[t_{P,ON}(0),t_{P,C}(1)]$ between $E[t_{P,ON}(0),r_{inner}]$ and $E[t_{P,C}(1),r_{inner}]$ shall be calculated for engineering purposes according to the following Equation (3):

$$\Delta E_{inner}\left(t_{P,ON}(0),t_{P,C}(1)\right)=100\times\left|\frac{E\left(t_{P,ON}(0),r_{inner}\right)-E\left(t_{P,C}(1),r_{inner}\right)}{E\left(t_{P,ON}(0),r_{inner}\right)}\right| \tag{3}$$

Similarly, the location, r_{outer}, and the value, $E[t_{P,C}(1),r_{outer}]$, of the maximum field at $t_{P,C}(1)$ in the outer insulation wall shall be recorded. The electric field value at the same location r_{outer} at $t_{P,ON}(0)$, $E[t_{P,ON}(0),r_{outer}]$, shall be resumed and the absolute percent variation $\Delta E_{outer}[t_{P,ON}(0),t_{P,C}(1)]$ between $E[t_{P,ON}(0),r_{outer}]$ and $E[t_{P,C}(1),r_{outer}]$ shall be calculated for engineering purposes according to the following Equation (4):

$$\Delta E_{outer}\left(t_{P,ON}(0),t_{P,C}(1)\right)=100\times\left|\frac{E\left(t_{P,ON}(0),r_{outer}\right)-E\left(t_{P,C}(1),r_{outer}\right)}{E\left(t_{P,ON}(0),r_{outer}\right)}\right| \tag{4}$$

f) Once electric field stabilization has been achieved—i.e., the matching of the inequality expressed by Equation (2)—and can be proved in real time, go directly to step j). Otherwise, a second series of volt-on measurements shall start, to be performed once every 60 min, until an overall time equal to 6

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h has passed since $t_{P,ON}(0)$. Thus, the second series of volt-on measurements shall be performed at the following measurement times:

1) $t_{P,ON}(4) = 4$ h

2) $t_{P,ON}(5) = 5$ h

3) $t_{P,ON}(6) = 6$ h. This latter measurement time $t_{P,ON}(6)$ shall be referred to as $t_{P,C}(2)$ for calculation purposes according to Equation (1) through Equation (12).

The relevant space charge and electric field profiles within the cable insulation wall shall be recorded and plotted.

g) The maximum absolute percent variation between the electric field profile at $t_{P,ON}(3) = t_{P,C}(1) = 3$ h and $t_{P,ON}(6) = t_{P,C}(2) = 6$ h, shall be calculated according to the following Equation (5):

$$\Delta E_{\max}\left(t_{P,C}(1), t_{P,C}(2)\right) = \max\left\{100 \times \left|\frac{E\left(t_{P,C}(1), r_k\right) - E\left(t_{P,C}(2), r_k\right)}{E\left(t_{P,C}(1), r_k\right)}\right|\right\}, k = 1,.., N \tag{5}$$

where all symbols have the same meaning as in Equation (1) except that:

$E\left(t_{P,C}(2), r_k\right)$ is the k^{th} point of electric field profile at measurement time $t_{P,C}(2) = 6$ h

The stabilization of the measured electric field is assumed as having occurred at $t_{P,C}(2)$ if the condition expressed by the following Equation (6) is achieved:

$$\Delta E_{\max}(t_{P,C}(1), t_{P,C}(2)) \le 10\% \tag{6}$$

Furthermore, the location, r_{inner}, and the value, $E[t_{P,C}(2), r_{inner}]$, of the maximum field at $t_{P,C}(2)$ in the inner insulation wall shall be recorded. The electric field value at the same location r_{inner} at $t_{P,C}(1)$, $E[t_{P,C}(1), r_{inner}]$, shall be resumed and the absolute percent variation $\Delta E_{inner}[t_{P,ON}(1), t_{P,C}(2)]$ between $E[t_{P,ON}(1), r_{inner}]$ and $E[t_{P,C}(2), r_{inner}]$ shall be calculated for engineering purposes according to the following Equation (7):

$$\Delta E_{inner}(t_{P,C}(1), t_{P,C}(2)) = 100 \times \left|\frac{E(t_{P,C}(1), r_{inner}) - E(t_{P,C}(2), r_{inner})}{E(t_{P,C}(1), r_{inner})}\right| \tag{7}$$

Similarly, the location, r_{outer}, and the value, $E[t_{P,C}(2), r_{outer}]$, of the maximum field at $t_{P,C}(2)$ in the outer insulation wall shall be recorded. The electric field value at the same location r_{outer} at $t_{P,C}(1)$, $E[t_{P,C}(1), r_{outer}]$, shall be resumed and the absolute percent variation $\Delta E_{outer}[t_{P,C}(1), t_{P,C}(2)]$ between $E[t_{P,C}(1), r_{outer}]$ and $E[t_{P,C}(2), r_{outer}]$ shall be calculated for engineering purposes according to the following Equation (8):

$$\Delta E_{outer}\left(t_{P,C}(1), t_{P,C}(2)\right) = 100 \times \left|\frac{E\left(t_{P,C}(1), r_{outer}\right) - E\left(t_{P,C}(2), r_{outer}\right)}{E\left(t_{P,C}(1), r_{outer}\right)}\right| \tag{8}$$

h) Once electric field stabilization has been achieved—i.e., the matching of the inequality expressed by Equation (6)—and can be proved in real time, go directly to step j). Otherwise, a third series of volt-on measurements shall start, to be performed once every 60 min, until an overall time equal to 9 h has passed since $t_{P,ON}(0)$. Thus, the third series of volt-on measurements shall be performed at the following measurement times:

1) $t_{P,ON}(7) = 7$ h

2) $t_{P,ON}(8) = 8$ h

3) $t_{P,ON}(9) = 9$ h. This latter measurement time shall be referred to as $t_{P,C}(3)$ for calculation purposes according to Equation (1) through Equation (12).

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The relevant space charge and electric field profiles within the cable insulation wall shall be recorded and plotted.

i) The maximum absolute percent variation between the electric field profile at $t_{P,ON}(6) = t_{P,C}(2) = 6$ h and at $t_{P,ON}(9) = t_{P,C}(3) = 9$ h, shall be calculated according to the following Equation (9):

$$\Delta E_{\max}\left(t_{P,C}(2), t_{P,C}(3)\right) = \max\left\{100 \times \left|\frac{E\left(t_{P,C}(2), r_k\right) - E\left(t_{P,C}(3), r_k\right)}{E\left(t_{P,C}(2), r_k\right)}\right|\right\}, k = 1,.., N \quad (9)$$

where all symbols have the same meaning as in Equation (5) except that:

$E\left(t_{P,C}(3), r_k\right)$ is the k^{th} point of electric field profile at measurement time $t_{P,C}(3) = 9$ h

The stabilization of the measured electric field is assumed as having occurred at $t_{P,C}(3)$ if the condition expressed by the following Equation (10) is achieved:

$$\Delta E_{\max}\left(t_{P,C}(2), t_{P,C}(3)\right) \le 10\% \quad (10)$$

Furthermore, the location, r_{inner}, and the value, $E[t_{P,C}(3),r_{inner}]$, of the maximum field at $t_{P,C}(3)$ in the inner insulation wall shall be recorded. The electric field value at the same location r_{inner} at $t_{P,C}(2)$, $E[t_{P,C}(2),r_{inner}]$, shall be resumed and the absolute percent variation $\Delta E_{inner}[t_{P,C}(2),t_{P,C}(3)]$ between $E[t_{P,C}(2),r_{inner}]$ and $E[t_{P,C}(3),r_{inner}]$ shall be calculated for engineering purposes according to the following Equation (11):

$$\Delta E_{inner}\left(t_{P,C}(2), t_{P,C}(3)\right) = 100 \times \left|\frac{E\left(t_{P,C}(2), r_{inner}\right) - E\left(t_{P,C}(3), r_{inner}\right)}{E\left(t_{P,C}(2), r_{inner}\right)}\right| \quad (11)$$

Similarly, the location, r_{outer}, and the value, $E[t_{P,C}(3),r_{outer}]$, of the maximum field at $t_{P,C}(3)$ in the outer insulation wall shall be recorded. The electric field value at the same location r_{outer} at $t_{P,C}(2)$, $E[t_{P,C}(2),r_{outer}]$, shall be resumed and the absolute percent variation $\Delta E_{outer}[t_{P,C}(2),t_{P,C}(3)]$ between $E[t_{P,C}(2),r_{outer}]$ and $E[t_{P,C}(3),r_{outer}]$ shall be calculated for engineering purposes according to the following Equation (12):

$$\Delta E_{outer}\left(t_{P,C}(2), t_{P,C}(3)\right) = 100 \times \left|\frac{E\left(t_{P,C}(2), r_{outer}\right) - E\left(t_{P,C}(3) r_{outer}\right)}{E\left(t_{P,ON}(2), r_{outer}\right)}\right| \quad (12)$$

j) The applied voltage shall be removed. Next, the cable conductor shall be short-circuited and grounded. Voltage removal and grounding shall be performed within a time no longer than 5 min. Both the cable conductor and the high-voltage (HV) electrode of the dc source employed in the test shall be solidly and effectively grounded, without interposed resistances, and kept grounded throughout the volt-off measurements (see steps k) through m) below) until the volt-on measurements with negative polarity start (see step n) below). As soon as the cable conductor has been short-circuited and grounded, the positive voltage depolarization time, $t_{P,OFF}$, will start.

k) Immediately after the positive voltage depolarization time $t_{P,OFF}$ has started, at a time $t_{P,OFF}(0) = 0$ h, a first volt-off measurement shall be performed. This first volt-off measurement shall represent the reference at the start of depolarization after poling the cable loop for space charge measurement with positive polarity.

l) With the space charge measurement at time $t_{P,OFF}(0) = 0$ h, a series of volt-off measurements shall start, to be performed once every 60 min, until a time of 3 h has passed since $t_{P,OFF}(0)$. Thus, the series of volt-off measurements shall be performed at the following measurement times:

1) $t_{P,OFF}(0) = 0$ h

2) $t_{P,OFF}(1) = 1$ h

3) $t_{P,OFF}(2) = 2$ h

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4) $t_{P,OFF}(3) = 3$ h

The relevant space charge and electric field profiles within the cable insulation wall shall be recorded and plotted.

m) The cable shall be left grounded for at least 24 h while the temperature and temperature gradient are kept constant.

n) Following the completion of step m), by means of a dc voltage source, the rated voltage U_0 of the tested cable system shall be applied with *negative polarity* between the cable conductor and the cable metal sheath. The cable metal sheath shall be solidly and effectively grounded. As soon as a voltage $-U_0$ is attained between the cable conductor and the metal sheath, the negative voltage poling time, $t_{N,ON}$, will start.

o) The previous steps from c) to m) shall be repeated in the same sequence as above. All space charge measurements shall be performed at the same times as in the previous steps from c) to m), but measurement times shall be denoted as follows:

1) $t_{N,ON}(j)$ (j = 0,1,..,9) instead of $t_{P,ON}(j)$ and $t_{N,C}(l)$ (l = 1,2,3) instead of $t_{P,C}(l)$ during poling time, since a negative polarity voltage $-U_0$ will be applied between the cable conductor and the metal sheath.

2) $t_{N,OFF}(j)$ (j = 0,1,2,3) instead of $t_{P,OFF}(j)$ during depolarization time, since depolarization time will follow the application of a negative polarity voltage $-U_0$ between the cable conductor and the metal sheath.

5.3 Measurements by means of the TSM

5.3.1 Measurement times

During the long-duration voltage test of the prequalification (PQ) test (described in CIGRÉ TB 496:2012, page 14, 3.4), two sequences of space charge measurements by means of the TSM shall be carried out at the following times:

a) Before starting the long-duration voltage test of the PQ test: This first sequence of space charge measurements shall be carried out on a virgin (unaged) cable sample identical to the cable employed in the PQ test loop (see CIGRÉ TB 496:2012, subclauses 1.5.2, 3.3, and 3.4), and will serve as a reference for calibrating the TSM measurement set-up.

b) After the completion of the long-duration voltage test of the PQ test: This second sequence of space charge measurements shall be performed on an aged cable sample identical to the cable employed in the PQ test loop and subjected to the same long-duration voltage test as the PQ test loop.

5.3.2 Preparation of cable sample for space charge measurement with the TSM

For each sequence of space charge measurements with the TSM at the times established in 5.3.1, the cable sample shall consist of two cable lengths:

— The measured cable

— The compensation cable

Both the measured cable and the compensation cable shall be:

— Identical to the cable in the PQ loop.

— Of length sufficient to perform the space charge measurements by means of the TSM satisfactorily.

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— Arranged in a cable loop with two terminations. Laboratory terminations are acceptable provided that they do not give rise to any flashover during both the space charge measurements and the whole PQ test.

The space charge measurements with the TSM shall be carried out on the measured cable loop and the compensation cable loop connected to each other in such a way that the electric field and space charges can be measured using the TSM–double capacitor, outer cooling procedure. For details about the TSM–double capacitor, outer cooling procedure, see Annex B.

The two sequences of space charge measurements with the TSM at the times established in 5.3.1 shall not be performed on the same measured cable loop. Indeed, the TSM requires that the outer shielding layer of the measured cable is removed and the outer semiconductive layer of the measured cable is exposed; this modifies the de-gassing rate on the measured cable loop compared to an unmeasured PQ test loop. The two different measured cable loops for the two sequences of space charge measurements at the times established in 5.3.1 shall be as follows:

a) A first measured cable loop, whose cable section shall be made of an unaged cable sample identical to the cable employed in the PQ test loop. On this measured cable loop—arranged with the compensation cable loop according to the TSM–double capacitor configuration—the first sequence of space charge measurements with the TSM shall be performed at the first time established in 5.3.1.

b) A second measured cable loop, made of an aged cable sample identical to the cable employed in the PQ test loop and subjected to the same long-duration voltage test as the PQ test loop. On this second measured cable loop—arranged with the compensation cable loop according to the TSM–double capacitor configuration—the second sequence of space charge measurements with the TSM shall be performed at the second time established in 5.3.1.

NOTE—For engineering purposes, it is permitted to let the *first* measured cable loop undergo the whole PQ test leaving the TSM measuring apparatus on it to monitor space charge evolution during the PQ test and to compare it with the measurements carried out on the *second* measured cable loop after the completion of the PQ test.

5.3.3 Sequence of space charge measurements with the TSM

Before each sequence of space charge measurements at the times established in 5.3.1, an adequate section of the outer semicon of the measured cable for space charge measurement with the TSM (see 5.3.2) shall be exposed. The TSM measuring apparatus—including the thermal diffuser (see Annex B)—shall be installed at the exposed section of the outer semicon. The measurements shall be made at ambient atmospheric conditions without extraneous precipitation or pollution (dry tests, see IEC 60060-1:2010, 4.2). The temperature and the humidity in the vicinity of the TSM measuring apparatus shall be monitored and recorded in the test report. All the required power and signal connections shall be set up by considering the safety of personnel and testing equipment. The sequence of space charge measurements shall then be accomplished according to the following steps.

a) The measured cable loop and the compensation cable loop for space charge measurement with the TSM shall be heated, and the cable conductor kept for at least 24 h at a value $T_{cond,max}$, with a temperature gradient ΔT across cable insulation—where $T_{cond,max}$ and ΔT are the values defined in CIGRÉ TB 496:2012, page 10, 1.5.4—before the space charge measurements start. Thereafter, the cable conductor temperature $T_{cond,max}$ and the temperature gradient ΔT across cable insulation shall be maintained for the whole duration of the space charge measurements. To ensure that $T_{cond,max}$ and ΔT_{max} have not been changed by exposing the semicon where the TSM test cell is located, this cable section shall be covered with appropriate thermal insulation throughout all the measurements.

b) By means of a dc voltage source, the rated voltage U_0 of the tested cable system—as defined in CIGRÉ TB 496:2012, page 8, 1.5.3—shall be applied with *positive polarity* to the cable conductor with respect

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to the cable metal sheath. The cable metal sheath shall be solidly and effectively grounded. As soon as a voltage $+U_0$ is attained between the cable conductor and the metal sheath, the positive voltage poling time, $t_{P,ON}$, will start.

c) Immediately after the positive voltage poling time $t_{P,ON}$ has started, at a time $t_{P,ON}(0) = 0$ h, a first volt-on measurement shall be performed. This first volt-on measurement shall represent the reference at the start of the positive polarity measurements.

d) With the space charge measurement at time $t_{P,ON}(0) = 0$ h, a first series of volt-on measurements shall start, to be performed once every 90 min, until a time equal to 3 h has passed since $t_{P,ON}(0)$. Thus, the first series of volt-on measurements shall be performed at the following measurement times:

1) $t_{P,ON}(0) = 0$ h

2) $t_{P,ON}(1) = 1.5$ h

3) $t_{P,ON}(2) = 3$ h. This latter measurement time shall be referred to as $t_{P,C}(1)$ for calculation purposes according to Equation (1) through Equation (12) in 5.2.3.

The relevant space charge and electric field profiles within the cable insulation wall shall be recorded and plotted.

e) The maximum absolute percent variation between the electric field profile at $t_{P,ON}(0) = 0$ and at $t_{P,ON}(2) = t_{P,C}(1) = 3$ h, namely $\Delta E_{max}[t_{P,ON}(0),t_{P,C}(1)]$, shall be calculated according to Equation (1). The stabilization of the measured electric field is assumed as having occurred at $t_{P,C}(1)$ if the condition expressed by Equation (2) is matched.

Furthermore, the whole cable insulation wall, of thickness $d = r_o - r_i$, shall be regarded as divided into three parts of thickness $d/3$ each, as follows (see Figure 1):

1) Inner insulation wall, located between inner insulation radius r_i and radial coordinate $r_i + d/3$

2) Intermediate insulation wall, located between radial coordinate $r_i + d/3$ and radial coordinate $r_i + 2d/3$

3) Outer insulation wall, located between radial coordinate $r_i + 2d/3$ and outer insulation radius r_o

The location, r_{inner}, and the value, $E[t_{P,C}(1),r_{inner}]$, of the maximum field at $t_{P,C}(1)$ in the inner insulation wall shall be recorded. The electric field value at the same location r_{inner} at $t_{P,ON}(0)$, $E[t_{P,ON}(0),r_{inner}]$, shall be resumed and the absolute percent variation $\Delta E_{inner}[t_{P,ON}(0),t_{P,C}(1)]$ between $E[t_{P,ON}(0),r_{inner}]$ and $E[t_{P,C}(1),r_{inner}]$ shall be calculated for engineering purposes according to Equation (3).

Similarly, the location, r_{outer}, and the value, $E[t_{P,C}(1),r_{outer}]$, of the maximum field at $t_{P,C}(1)$ in the outer insulation wall shall be recorded. The electric field value at the same location r_{outer} at $t_{P,ON}(0)$, $E[t_{P,ON}(0),r_{outer}]$, shall be resumed and the absolute percent variation $\Delta E_{outer}[t_{P,ON}(0),t_{P,C}(1)]$ between $E[t_{P,ON}(0),r_{outer}]$ and $E[t_{P,C}(1),r_{outer}]$ shall be calculated for engineering purposes according to Equation (4).

f) Once electric field stabilization has been achieved—i.e., the matching of the inequality expressed by Equation (2)—and can be proved in real time, go directly to step j). Otherwise, a second series of volt-on measurements shall start, to be performed once every 90 min, until an overall time equal to 6 h has passed since $t_{P,ON}(0)$. Thus, the second series of volt-on measurements shall be performed at the following measurement times:

1) $t_{P,ON}(3) = 4.5$ h

2) $t_{P,ON}(4) = 6$ h. This latter measurement time shall be referred to as $t_{P,C}(2)$ for calculation purposes according to Equation (1) through Equation (12).

The relevant space charge and electric field profiles within the cable insulation wall shall be recorded and plotted.

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g) The maximum absolute percent variation between the electric field profile at $t_{P,ON}(2) = t_{P,C}(1) = 3$ h and $t_{P,ON}(4) = t_{P,C}(2) = 6$ h, shall be calculated according to Equation (5). The stabilization of the measured electric field is assumed as having occurred at $t_{P,C}(2)$ if the condition expressed by Equation (6) is achieved.

Furthermore, the location, r_{inner}, and the value, $E[t_{P,C}(2),r_{inner}]$, of the maximum field at $t_{P,C}(2)$ in the inner insulation wall shall be recorded. The electric field value at the same location r_{inner} at $t_{P,C}(1)$, $E[t_{P,C}(1),r_{inner}]$, shall be resumed and the absolute percent variation $\Delta E_{inner}[t_{P,ON}(1),t_{P,C}(2)]$ between $E[t_{P,ON}(1),r_{inner}]$ and $E[t_{P,C}(2),r_{inner}]$ shall be calculated for engineering purposes according to Equation (7).

Similarly, the location, r_{outer}, and the value, $E[t_{P,C}(2), r_{outer}]$, of the maximum field at $t_{P,C}(2)$ in the outer insulation wall shall be recorded. The electric field value at the same location r_{outer} at $t_{P,C}(1)$, $E[t_{P,C}(1),r_{outer}]$, shall be resumed and the absolute percent variation $\Delta E_{outer}[t_{P,C}(1),t_{P,C}(2)]$ between $E[t_{P,C}(1),r_{outer}]$ and $E[t_{P,C}(2),r_{outer}]$ shall be calculated for engineering purposes according to the Equation (8).

h) Once electric field stabilization has been achieved—i.e., the matching of the inequality expressed by Equation (6)—and can be proved in real time, go directly to step j). Otherwise, a third series of volt-on measurements shall start, to be performed once every 90 min, until an overall time equal to 9 h has passed since $t_{P,ON}(0)$. Thus, the third series of volt-on measurements shall be performed at the following measurement times:

1) $t_{P,ON}(5) = 7.5$ h

2) $t_{P,ON}(6) = 9$ h. This latter measurement time shall be referred to as $t_{P,C}(3)$ for calculation purposes according to Equation (1) through Equation (12).

The relevant space charge and electric field profiles within the cable insulation wall shall be recorded and plotted.

i) The maximum absolute percent variation between the electric field profile at $t_{P,ON}(4) = t_{P,C}(2) = 6$ h and at $t_{P,ON}(6) = t_{P,C}(3) = 9$ h, shall be calculated according to Equation (9).

The stabilization of the measured electric field is assumed as having occurred at $t_{P,C}(3)$ if the condition expressed by Equation (10) is achieved.

Furthermore, the location, r_{inner}, and the value, $E[t_{P,C}(3),r_{inner}]$, of the maximum field at $t_{P,C}(3)$ in the inner insulation wall shall be recorded. The electric field value at the same location r_{inner} at $t_{P,C}(2)$, $E[t_{P,C}(2),r_{inner}]$, shall be resumed and the absolute percent variation $\Delta E_{inner}[t_{P,C}(2),t_{P,C}(3)]$ between $E[t_{P,C}(2),r_{inner}]$ and $E[t_{P,C}(3),r_{inner}]$ shall be calculated for engineering purposes according to Equation (11).

Similarly, the location, r_{outer}, and the value, $E[t_{P,C}(3),r_{outer}]$, of the maximum field at $t_{P,C}(3)$ in the outer insulation wall shall be recorded. The electric field value at the same location r_{outer} at $t_{P,C}(2)$, $E[t_{P,C}(2),r_{outer}]$, shall be resumed and the absolute percent variation $\Delta E_{outer}[t_{P,C}(2),t_{P,C}(3)]$ between $E[t_{P,C}(2),r_{outer}]$ and $E[t_{P,C}(3),r_{outer}]$ shall be calculated for engineering purposes according to Equation (12).[7]

j) The applied voltage shall be removed. Next, the cable conductor shall be short-circuited and grounded. Voltage removal and grounding shall be performed within a time no longer than 5 min. Both the cable conductor and the HV electrode of the dc source employed in the test shall be solidly and effectively grounded, without interposed resistances, and kept grounded throughout the volt-off measurements (see steps k) through m) below) until the volt-on measurements with negative polarity start (see step n) below). As soon as the cable conductor has been short-circuited and grounded, the positive voltage depolarization time, $t_{P,OFF}$, will start.

[7]In this way the whole poling time (9 h at worst) and the 3 stabilization check-times (3 h, 6 h, and 9 h) are the same for PEA and TSM.

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k) Immediately after the positive voltage depolarization time $t_{P,OFF}$ has started, at a time $t_{P,OFF}(0) = 0$ h, a first volt-off measurement shall be performed. This first volt-off measurement shall represent the reference at the start of depolarization after poling the cable loop for space charge measurement with positive polarity.

l) With the space charge measurement at time $t_{P,OFF}(0) = 0$ h, a series of volt-off measurements shall start, to be performed once every 90 min, until a time of 3 h has passed since $t_{P,OFF}(0)$. Thus, the series of volt-off measurements shall be performed at the following measurement times:

   1) $t_{P,OFF}(0) = 0$ h

   2) $t_{P,OFF}(1) = 1.5$ h

   3) $t_{P,OFF}(2) = 3$ h[8]

   The relevant space charge profiles and electric field profiles within the cable insulation wall shall be recorded and plotted.

m) The cable shall be left grounded for at least 24 h.

n) Following the completion of step m), by means of a dc voltage source, the rated voltage U_0 of the tested cable system shall be applied with *negative polarity* to the cable conductor with respect to the cable metal sheath. The cable metal sheath shall be solidly and effectively grounded. As soon as a voltage $-U_0$ is attained between the cable conductor and the metal sheath, the negative voltage poling time, $t_{N,ON}$, will start.

o) The previous steps from c) to m) shall be repeated in the same sequence as above. All space charge measurements shall be performed at the same times as in the previous steps from c) to m), but measurement times shall be denoted as follows:

   1) $t_{N,ON}(j)$ ($j = 0,1,..,6$) instead of $t_{P,ON}(j)$ and $t_{N,C}(l)$ ($l = 1,2,3$) instead of $t_{P,C}(l)$ during poling time, since a negative polarity voltage $-U_0$ will be applied between the cable conductor and the metal sheath.

   2) $t_{N,OFF}(j)$ ($j = 0,1,2$) instead of $t_{P,OFF}(j)$ during depolarization time, since depolarization time will follow the application of a negative polarity voltage $-U_0$ between the cable conductor and the metal sheath.

6. Space charge measurements during the type tests

6.1 Measurements by means of the PEA method

6.1.1 Measurement times

During the load cycle test of type tests (TT) (described in CIGRÉ TB 496:2012, page 19, 4.4.2), two sequences of space charge measurements by means of the PEA method shall be carried out at the following times:

a) Before starting the load cycle test of the TT. This first sequence of space charge measurements shall be carried out on a virgin (unaged) cable sample identical to the cable employed in the TT loop (see CIGRÉ TB 496:2012, page 18, 4.2), and will serve as a reference for calibrating the PEA measurement set-up.

b) After the completion of the load cycle test of the TT. This second sequence of space charge measurements shall be performed on an aged cable sample identical to the cable employed in the TT loop and subjected to the same load cycle test as the TT loop.

[8] In this way the whole volt-off time (3 h) is the same for PEA and TSM, and two common time instants exist: 0 h, 3 h. The overall measurement time is 12 h at worst.

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6.1.2 Preparation of cable sample for space charge measurement with the PEA method

For each sequence of space charge measurements with the PEA method at the times established in 6.1.1, the cable sample shall be arranged in a cable loop consisting at least of:

— A cable identical to the cable in the TT loop. The cable shall be of length sufficient in order to perform the space charge measurements by means of the PEA method satisfactorily.

— Two terminations. Laboratory terminations are acceptable provided that they do not give rise to any flashover during both the space charge measurements and the whole load cycle test of the TT.

The two sequences of space charge measurements with the PEA method at the times established in 6.1.1 shall not be performed on the same cable loop. Indeed, the PEA method requires that the outer shielding layer of the cable is removed and the outer semiconductive layer of the cable is exposed; this modifies the de-gassing rate and the effect of humidity on the cable loop subjected to space charge measurements compared to an unmeasured TT loop. The two different cable loops for the two sequences of space charge measurements at the times established in 6.1.1 shall be obtained according to one of the two following alternative procedures:

a) The two cable loops shall be both obtained from the TT test loop—provided that its initial overall length is sufficient—as follows:

   1) The first sequence of space charge measurements with the PEA method at the first time established in 6.1.1 shall be performed at a location of the TT loop where the PEA set-up can be properly installed.

   2) After this first sequence of space charge measurements, the cable section where the PEA measurement cell is located shall be cut and removed. A joint shall be installed between the remaining cable ends, thereby preventing further degassing and humidity penetration in the cable insulation during the whole TT.[9]

   3) The load cycle test of the TT shall be carried out.

   4) The second sequence of space charge measurements with the PEA method at the second time established in 6.1.1 shall be performed at a location of the TT loop where the PEA set-up can be properly installed.

b) The cable loop for the first sequence of space charge measurements—made of a virgin cable identical to the cable employed in the TT loop [as prescribed in 6.1.1, item a)] and of length sufficient for the PEA set-up to be properly installed (as prescribed in 6.1.2)—shall be different from the TT loop. The cable loop for the second sequence of measurements shall be the TT loop and the space charge measurements shall be performed at a location of the TT loop where the PEA set-up can be properly installed.

NOTE—It is permitted to let the *first* cable loop undergo the whole TT leaving the PEA measurement cell on it to monitor space charge evolution during the TT and to compare it with the measurements carried out on the *second* cable loop after the completion of the TT.

6.1.3 Sequence of space charge measurements with the PEA method

Before each sequence of space charge measurements at the times established in 6.1.1, an adequate section of the outer semicon of the cable sample for space charge measurement with the PEA method (see 6.1.2) shall be exposed. The PEA measurement cell shall be installed at such exposed section of the outer semicon. The measurements shall be made at ambient atmospheric conditions without extraneous precipitation or pollution (dry tests, see IEC 60060-1:2010, 4.2). The temperature and the humidity in the vicinity of the PEA measurement cell shall be monitored and recorded in the test report. All the required power and signal

[9] This joint can be one of the joints that are to be qualified via the type tests.

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connections shall be set up by considering the safety of personnel and testing equipment. Then, the sequence of space charge measurements shall be accomplished according to the same steps a) through o) as in 5.2.3.

6.2 Measurements by means of the TSM

6.2.1 Measurement times

During the load cycle test of type tests (TT) (described in CIGRÉ TB 496:2012, page 19, 4.4.2), two sequences of space charge measurements by means of the TSM shall be carried out at the following times:

a) Before starting the load cycle test of the TT: This first sequence of space charge measurements shall be carried out on a virgin (unaged) cable sample identical to the cable employed in the TT loop (see CIGRÉ TB 496:2012, page 18, 4.2), and will serve as a reference for calibrating the PEA measurement set-up.

b) After the completion of load cycle test of the TT: This second sequence of space charge measurements shall be performed on an aged cable sample identical to the cable employed in the TT loop and subjected to the same load cycle test as the TT loop.

6.2.2 Preparation of cable sample for space charge measurement with the TSM

For each sequence of space charge measurements with the TSM at the times established in 6.2.1, the cable sample shall consist of two cable lengths:

— The measured cable

— The compensation cable

Both the measured cable and the compensation cable shall be:

— Identical to the cable in the TT loop.

— Of length sufficient in order to perform the space charge measurements by means of the TSM satisfactorily.

— Arranged in a cable loop with two terminations. Laboratory terminations are acceptable provided that they do not give rise to any flashover during both the space charge measurements and the whole load cycle test of the TT.

The space charge measurements with the TSM shall be carried out on the measured cable loop and the compensation cable loop connected to each other in such a way that the electric field and space charges can be measured using the TSM–double capacitor, outer cooling procedure. For details about the TSM–double capacitor, outer cooling procedure, see Annex B.

The two sequences of space charge measurements with the TSM at the times established in 6.2.1 shall not be performed on the same measured cable loop. Indeed, the TSM requires that the outer shielding layer of the measured cable is removed and the outer semiconductive layer of the measured cable is exposed; this modifies the de-gassing rate on the measured cable loop compared to an unmeasured TT loop. The two different measured cable loops for the two sequences of space charge measurements at the times established in 6.2.1 shall be as follows:

a) A first measured cable loop, whose cable section shall be made of an unaged cable sample identical to the cable employed in the TT loop. On this measured cable loop—arranged with the compensation

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cable loop according to the TSM–double capacitor configuration—the first sequence of space charge measurements with the TSM shall be performed at the first time established in 6.2.1.

b) A second measured cable loop, made of an aged cable sample identical to the cable employed in the TT loop and subjected to the same load cycle test as the TT loop. On this second measured cable loop—arranged with the compensation cable loop according to the TSM–double capacitor configuration—the second sequence of space charge measurements with the TSM shall be performed at the second time established in 6.2.1.

NOTE—It is permitted to let the *first* measured cable loop undergo the whole TT leaving the TSM measuring apparatus on it to monitor space charge evolution during the TT and to compare it with the measurements carried out on the *second* measured cable loop after the completion of the TT.

6.2.3 Sequence of space charge measurements with the TSM

Before each sequence of space charge measurements at the times established in 6.2.1, an adequate section of the outer semicon of the measured cable for space charge measurement with the TSM (see 6.2.2) shall be exposed. The TSM measuring apparatus—including the thermal diffuser (see Annex B)—shall be installed at such exposed section of the outer semicon. The measurements shall be made at ambient atmospheric conditions without extraneous precipitation or pollution (dry tests, see IEC 60060-1:2010, 4.2). The temperature and the humidity in the vicinity of the TSM measuring apparatus shall be monitored and recorded in the test report. All the required power and signal connections shall be set up by considering the safety of personnel and testing equipment. Then, the sequence of space charge measurements shall be accomplished according to the same steps a) through o) as in 5.3.3.

Annex A

(informative)

The PEA method for space charge measurements on cables

The pulsed electro-acoustic (PEA) method was initially developed for space charge measurements on thin samples between plane parallel electrodes. A description of the PEA method applied to a sheet sample can be found in CIGRÉ Technical Brochure 288:2006, 2.1.

Thereafter the PEA method was extended successfully to the coaxial cable geometry (Fukunaga, Miyata, Sugimori, and Takada [B8]) using the system shown in Figure A.1 (after Liu [B10]), where

a	is the inner radius of the insulation wall
b	is the outer radius of the insulation wall
$\rho(r)$	is the volume space charge density at radial coordinate r within the insulation wall
s	is the thickness of the outer semicon
l	is the distance between the outer semicon and the piezo device or piezoelectric transducer
c	is the position of the piezo device—normally a polyvinylidene fluoride (PVDF) film
R	is the resistance of the PEA measurement system
C	is the capacitance of the PEA measurement system
V	is the voltage of the dc source
$v_p(t)$	is the time-dependent applied voltage pulse
$v_s(t)$	is the voltage signal from the piezo device, whereby $\rho(r)$ is derived

As made clear by Figure A.1, the cable sample electrode has coaxial structure, thereby enabling a close contact between the cable and the electrode; the PVDF film is carefully positioned between the detecting electrode and the absorber avoiding any air gaps to prevent acoustic wave reflection at the interface between electrode and transducer (Liu [B10], Takada [B16]). The detecting electrode also acts as an acoustic delay line to enable the small piezoelectric signal to be distinguished from the electrical noise induced by the voltage pulse.

For large size high-voltage direct-current (HVDC) cables, if the pulse voltage were applied to the high-voltage (HV) terminations, it would travel along the cable and—considering the characteristic impedance of the large cable—it would be distorted and/or reflected. Thus, the signal at the measuring point would not be a single pulse (Takada [B16]). In Hozumi, et al. [B9] a measurement set-up is proposed for solving these problems (see Figure A.2, after Takeda, et al. [B17]): the voltage pulses are applied between the measuring point (at the center of an exposed section of the outer semicon) and ground. If the characteristic impedance of the cable is much lower than the impedance of the capacitance at the measuring point—in the frequency range of the voltage pulses—most of the voltage pulse is applied at that point (see Figure A.3, after Takada [B16]). Typically, voltage pulses are a few kV in amplitude and some tens ns in duration, and the PVDF film is ≈100 μm thick. The signal is amplified within a shielded box that is electrically isolated (a HV pulse is applied there) and is eventually transferred to a digital oscilloscope with a high sampling frequency via an optical fiber (Hozumi, et al. [B9], Takada [B16], Takeda, et al. [B17], Terashima, Suzuki, Hara, and Watanabe [B18]).

The PEA system with curved ground electrode, transducer, and acoustic absorber block—implemented and used by various R&D teams in the world—has shown excellent performances on cable models of various sizes, even in the presence of multiple interfaces (Bodega, et al. [B1], Delpino, et al. 2008 [B4], Fabiani, et al. 2008 [B5], Fabiani, et al. 2007 [B6], Olsson and Jeroense [B15]). Others have successfully used a modified version of the PEA cell with curved ground electrode, transducer, and absorber, with slightly different electrical connections from the HV pulse source to the outer semicon and the metallic shield of the cable (more details are omitted here, they can be found in Mori, Niinobe, and Yagi [B14]). However, a different configuration with a flat ground electrode—that can be easily applied to cables of different diameters—has also been proposed and employed satisfactorily for cable models with insulation thickness up to ~6 mm (Choo, Chen, and Swingler [B3], Fu, Dissado, Chen, and Fothergill [B7]).

Further details about the PEA measurement set-up for a full-size cable are outside the scope of this recommendation. They can be found, e.g., in Liu [B10], Maruyama, et al. [B11], Mori, Niinobe, and Yagi [B14], Takada [B16], Takeda, et al. [B17], Terashima, Suzuki, Hara, and Watanabe [B18], Yamanaka, Maruyama, and Tanaka, [B19].

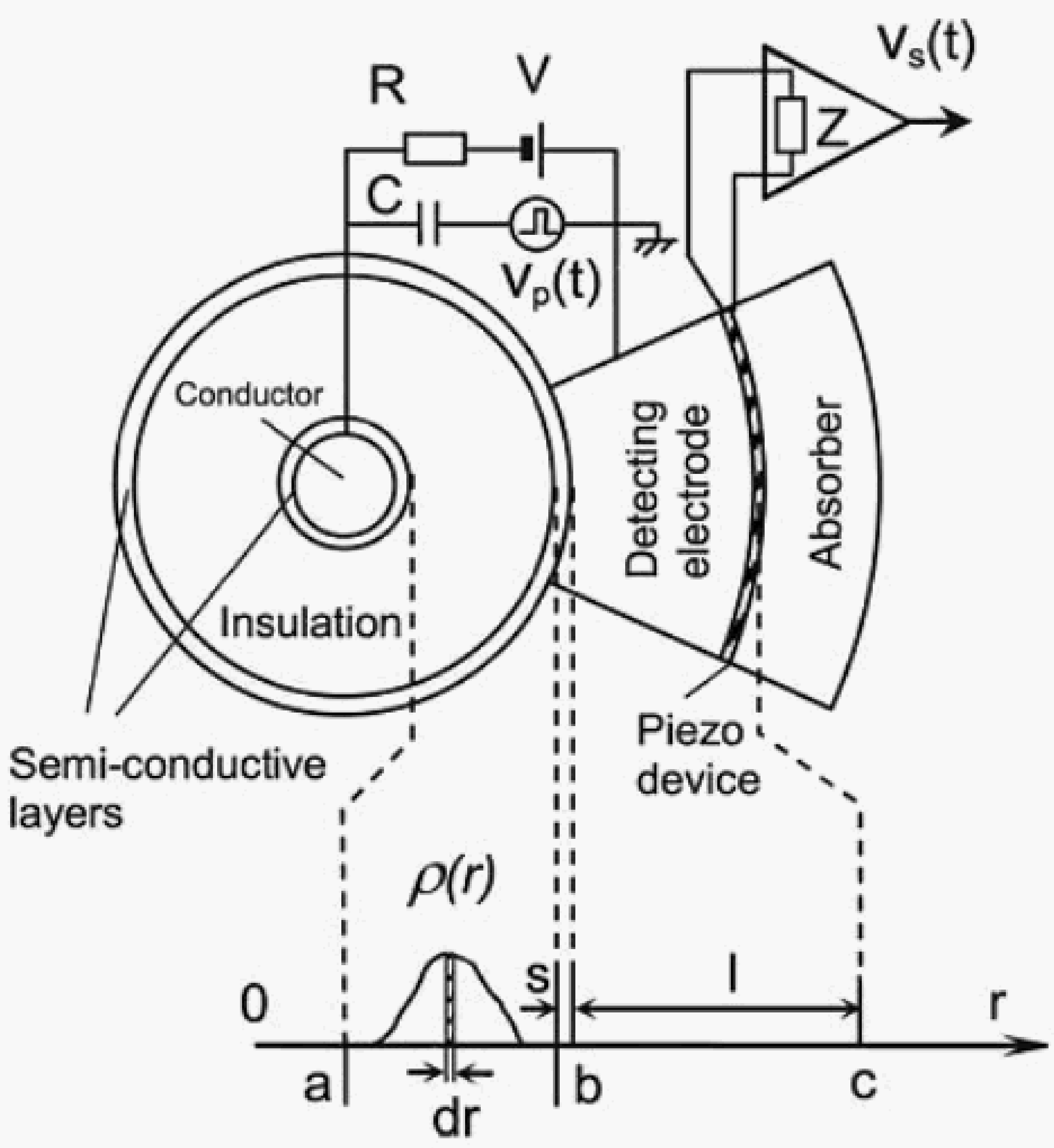

Figure A.1—Principle of the PEA method for the measurement of space charge on cylindrical geometry (after Mazzanti, et al. [B12], © 2015 IEEE, and Liu [B10], © 2013 IEEE)

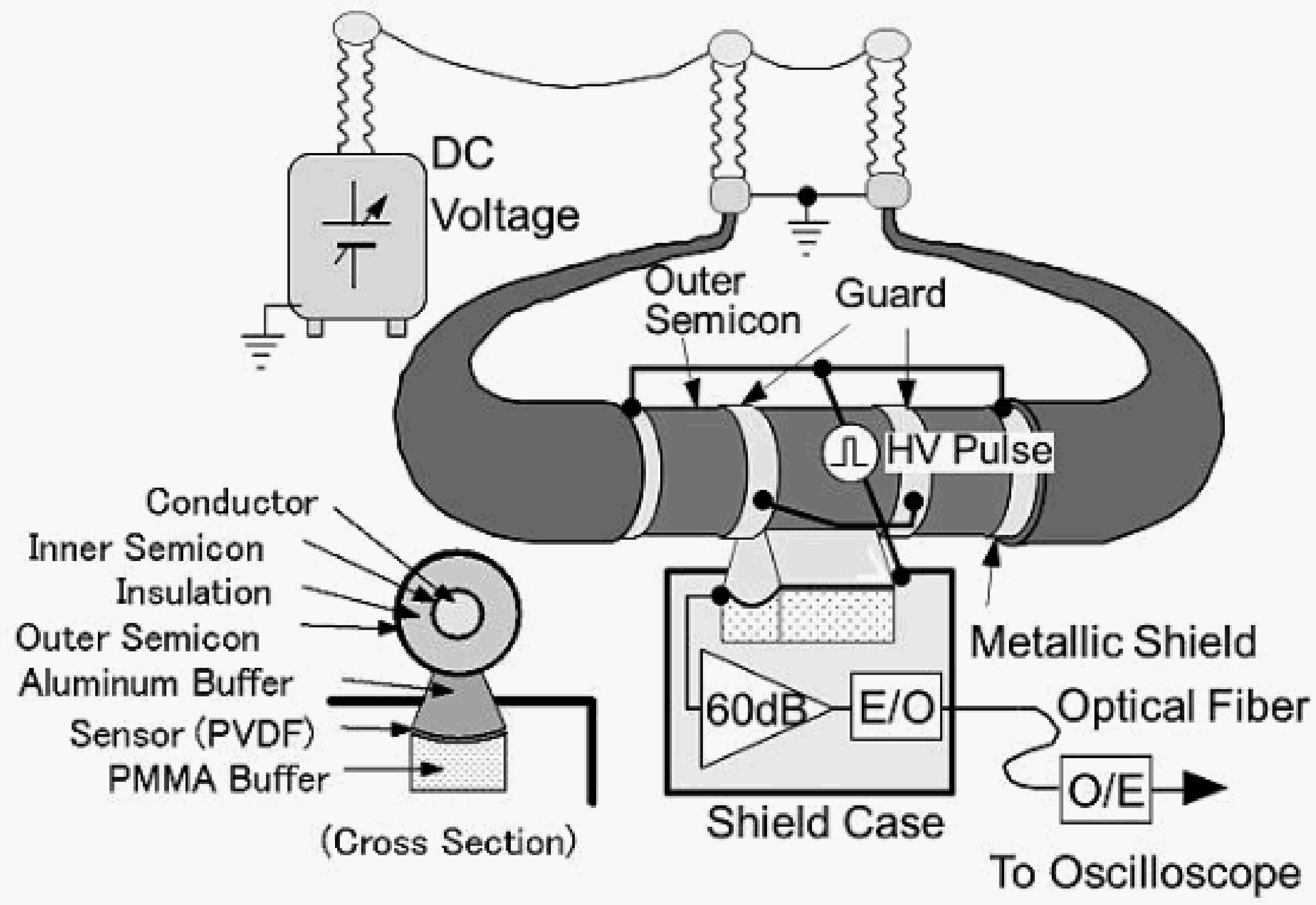

Figure A.2—Experimental setup for space charge measurement for a long cable with the PEA method (after Mazzanti, et al. [B12], © 2015 IEEE, and Takeda, et al. [B17], © 1998 IEEE)

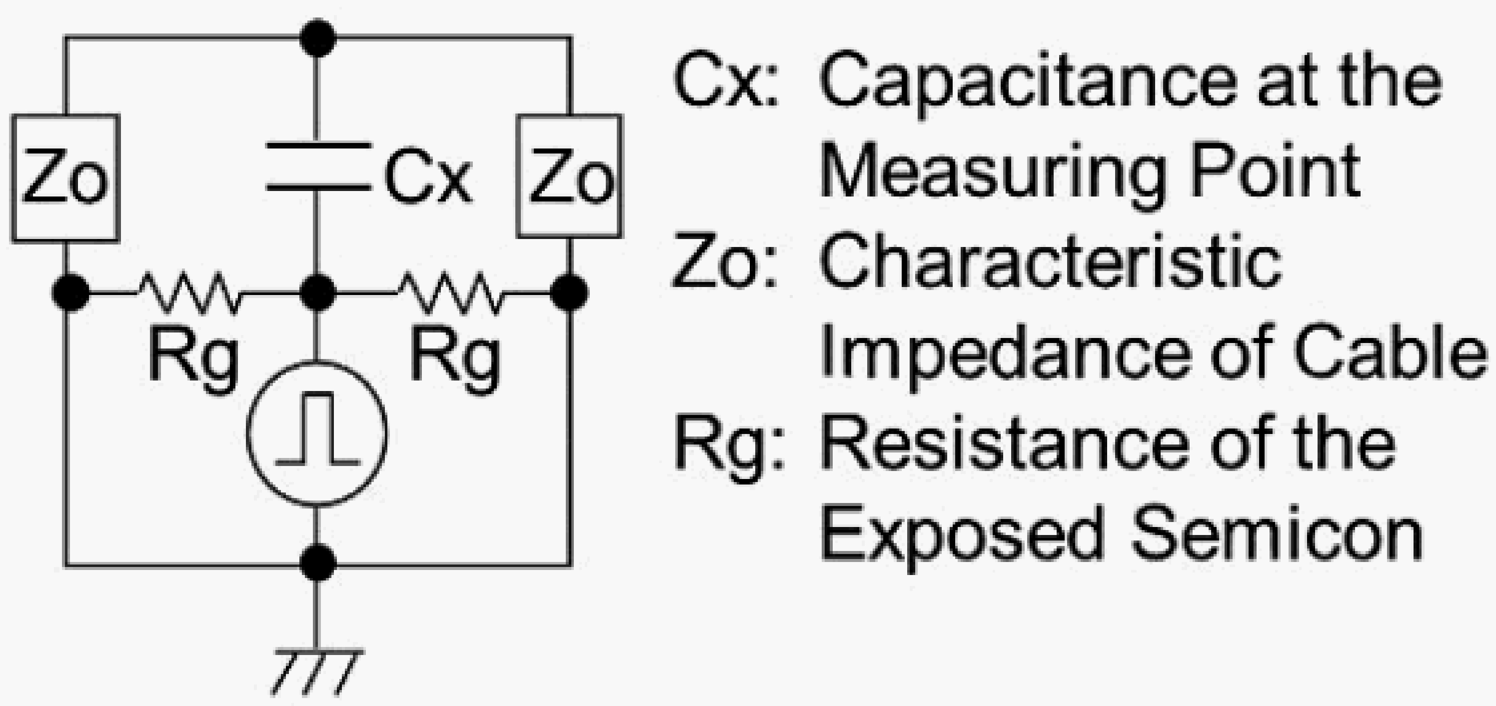

Figure A.3—Equivalent circuit (after Mazzanti, et al. [B12], © 2015 IEEE, and Takada [B16], © 1999 IEEE)

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Annex B

(informative)

The TSM for space charge measurements in cables

The thermal step method (TSM) is a technique that was initially developed for space charge measurements on samples between plane parallel electrodes. An extensive description of the TSM applied to flat specimens between plane parallel electrodes can be found in CIGRÉ Technical Brochure 288: 2006, 2.2.

The TSM was extended to the coaxial cable geometry. The TSM relies in the successful application of a positive or negative thermal stimulus, the so-called "thermal step" (TS) which can be created by two alternative techniques, namely (Castellon, et al. [B2]):

— The inner heating technique (IHT), whereby the TS is generated through a strong current (several kA) circulating in the cable conductor. The conductor in short circuit works as the single-turn secondary of a heating transformer. After several seconds of heating, the conductor and the outer semi conductive layer are short circuited through a current amplifier. The IHT aims at following the evolution of the mean electrical state of the whole length of the cable insulation and does not require any specific preparation before measurements.

— The outer cooling technique (OCT), whereby the TS is created through a cold liquid circulating within a thermal diffuser surrounding the sample (Figure B.1 after Castellon, et al. [B2]). The OCT aims at a local analysis of the cable over small lengths (~20 cm to 60 cm). In the proposed protocol this technique is chosen.

  For measurements under dc voltage, the setup of Figure B.1 has two main drawbacks:

  1) The current amplifier must not be in contact with the high voltage (HV).
  2) If the current amplifier is placed between the sample subjected to HV and ground, the conduction and the polarization currents may mask the TS current.

  For this reason, the TSM in "double capacitor" configuration is used in practice, whereby a "compensation cable" with identical capacitance to the cable under measurement is inserted in parallel. The external semicon of the compensation cable is connected to a current amplifier and its conductor to the cable under measurement, i.e., the cable the TS is applied to. Thus, the space charge measurement via the TSM in "double capacitor" configuration consists of two steps, as shown in Figure B.2 after Castellon, et al. [B2]:

  1) During conditioning by pre-heating the cable under measurement, the dc voltage is applied to the cable conductor and the current amplifier is short-circuited. In this way the two cables constitute two identical capacitances in parallel with respect to the high-voltage direct-current (HVDC) source (Figure B.2.a).
  2) During the measurement, the HVDC generator is disconnected (and ideally switched off to minimize electrical noise) to prevent the leakage of induced charges at the electrodes via the high voltage (HV) source rather than via the current amplifier (Figure B.2.b). The TS is applied to the cable under measurement via the thermal diffuser creating a displacement of charges as the thermal wave diffuses through the insulation wall, generating the TS current. The duration of the application of the TS depends on the insulation wall thickness. The TS current is measured from the compensation cable where the current amplifier is connected. This time, the two cables are in series with each other and with the current amplifier, and the short-circuit condition required by the TSM is matched.

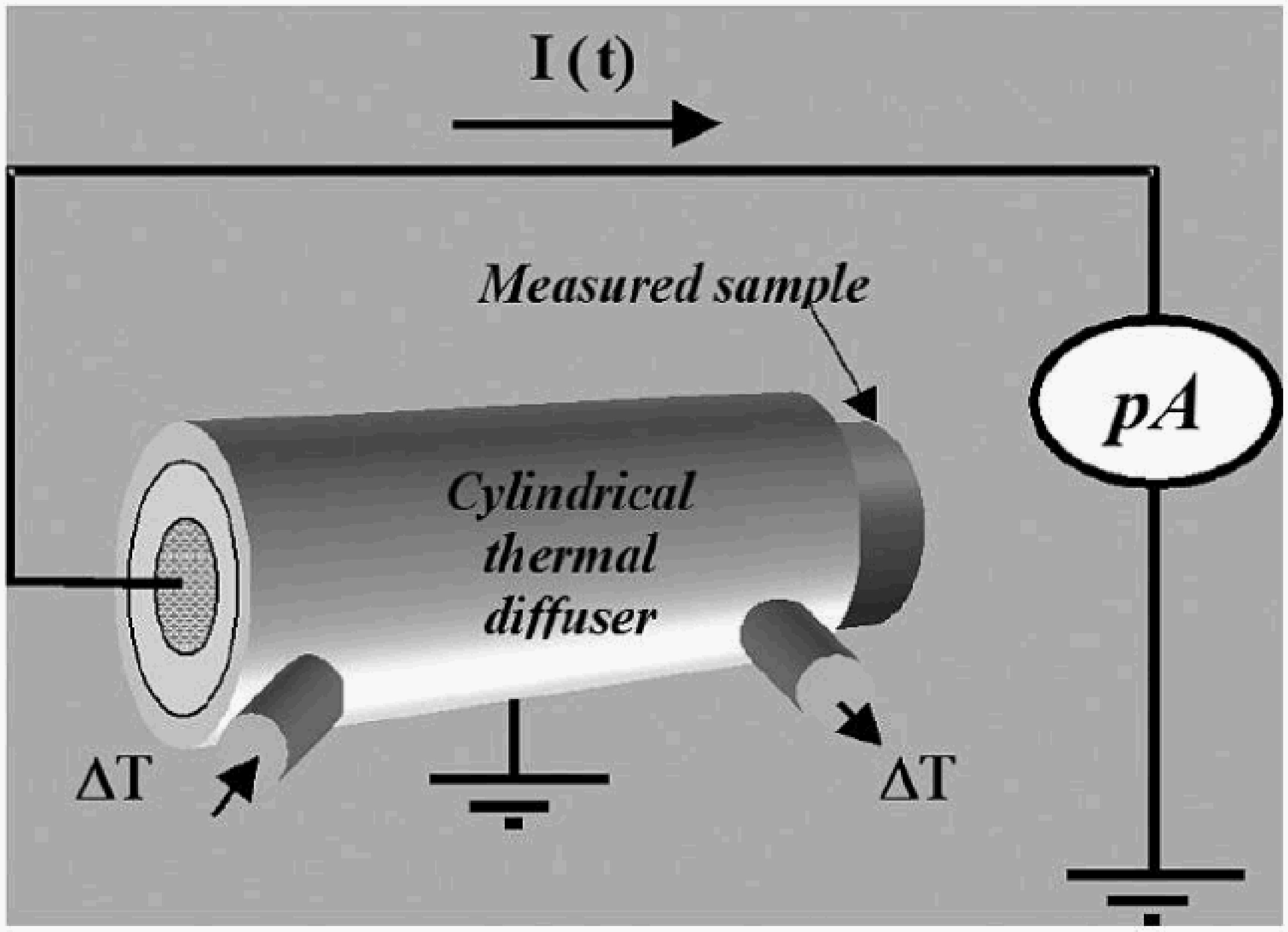

Figure B.1—Principle of the TSM applied to a cable using the outer cooling technique in short-circuit conditions (after Mazzanti, et al. [B12], © 2015 IEEE, and Castellon, et al. [B2], © 2009 IEEE)

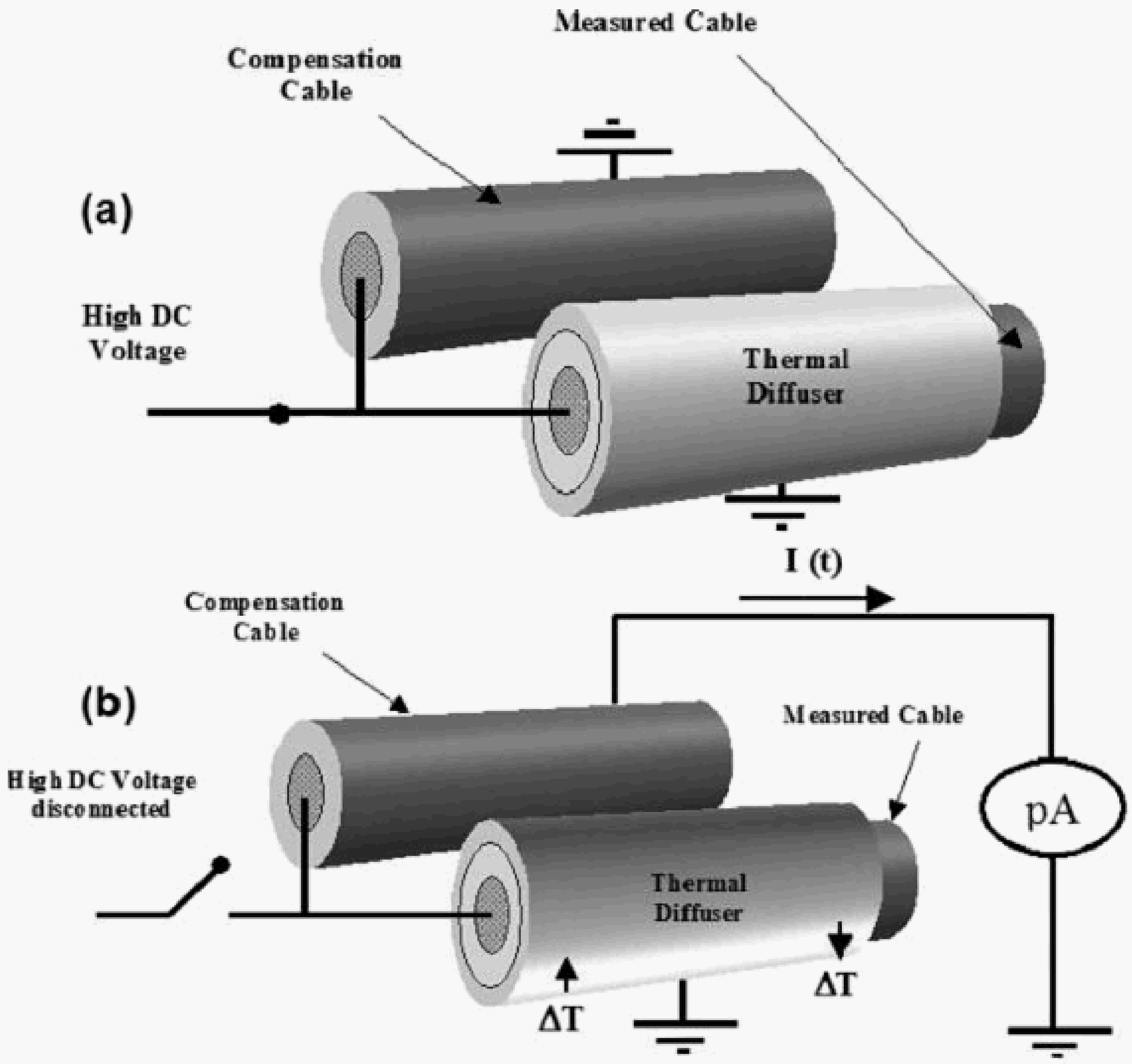

Figure B.2—Undervoltage TSM measurements on cables in double capacitor configuration: (a) the dc voltage is applied prior to the measurement, (b) the measurement is performed on the measured cable after disconnecting the dc source (after Mazzanti, et al. [B12], © 2015 IEEE, and Castellon, et al. [B2], © 2009 IEEE)

Annex C

(informative)

Calibration

Introduction

The calibration procedure followed for space charge measurements for both the pulsed electro-acoustic (PEA) method and thermal step method (TSM) can vary subject to cable specification and environmental conditions. However, the calibration procedure that is followed to obtain space charge density distribution and electric field profiles shall be described in detail in the measurement report. Details of the calibration and measurement parameters to be included in the space charge measurement report are given in this annex.

C.2 Calibration parameters for the PEA method

As pointed out in 5.2.1 and 6.1.1, two sequences of space charge measurements by means of the PEA method shall be carried out: the first sequence (before load cycle qualification tests) will serve as a reference for calibrating the PEA set-up; the second sequence (after load cycle qualification tests) will serve for assessing the variation of the electric field profile in the cable insulation wall during load cycle qualification tests. The space charge measurement report should include a detailed description of the calibration parameters used in the first sequence of measurements to process the second sequence of measurements. Ideally, the report should include the following detailed information:

a) Positive and negative voltage levels
b) Cable conductor temperature $T_{cond,max}$ and temperature gradient ΔT across cable insulation. They shall be identical to the values of $T_{cond,max}$ and ΔT in the second sequence of space charge measurements
c) Calibration poling time
d) High-voltage (HV) pulse amplitude
e) HV pulse width
f) HV pulse shape
g) Thickness of the polyvinylidene fluoride (PVDF) sensor
h) Area of the PVDF sensor (optional)
i) Attenuation parameters (optional)
j) Dispersion parameters (optional)
k) Acoustic signal velocity (optional)
l) Signal processing filter used (optional)
m) The unprocessed calibration profile
n) The processed calibration profile as charge density or electric field distribution
o) Background noise signal with the HV pulse applied, but no voltage applied at the conductor
p) Resolution achieved (optional)
q) DC offset correction applied (optional)
r) Slope correction applied (optional)

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Points d), e), and f)—i.e., HV pulse amplitude, width, and shape—should be reported also in the report of the second sequence of space charge measurements. Alternatively, the calibration profiles m) and n) should be reported also in the report of the second sequence of space charge measurements.

A final calibration check should be made by double integration of the charge profile. This should obey the boundary conditions for the applied voltage.

A.1 Calibration parameters for the TSM

As pointed out in 5.3.1 and 6.2.1, two sequences of space charge measurements by means of the TSM shall be carried out: the first sequence (before load cycle qualification tests) will serve as a reference for calibrating the TSM set-up; the second sequence (after load cycle qualification tests) will serve for assessing the variation of the electric field profile in the cable insulation wall during load cycle qualification tests. The space charge measurement report should include a detailed description of the calibration parameters used in the first sequence of measurements to process the second sequence of measurements. Ideally, the report should include the following detailed information:

a) Positive and negative voltage levels whereby the thermal step (TS) calibration currents were obtained
b) Cable conductor temperature $T_{cond,max}$ and temperature gradient ΔT across cable insulation, both for the measured cable and for the compensation cable. They shall be identical to the values of $T_{cond,max}$ and ΔT in the second sequence of space charge measurements.
c) Conditioning, pre-heating temperature
d) Conditioning, pre-heating duration
e) TS temperature
f) TS temperature profile
g) Differential current measurement profile
h) TS current measurement duration
i) Re-heating time duration
j) Filter applied
k) Sampling time
l) Electrical potential profile of the conductor as the TS current is obtained
m) Current suppress correction used
n) The unprocessed TS current profile
o) The processed TS current profile as charge density or electric field distribution

Points e) and f)—i.e., TS temperature and TS temperature profile—shall be reported also in the report of the second sequence of space charge measurements. Alternatively, the TS current calibration profiles n) and o) shall be reported also in the report of the second sequence of space charge measurements.

A final calibration check should be made by double integration of the charge profile. This should obey the boundary conditions for the applied voltage.

Annex D

(informative)

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