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Measurement of internal electric field in insulating materials - Pressure wave propagation method

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National foreword

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The UK participation in its preparation was entrusted to Technical Committee GEL/112, Evaluation and qualification of electrical insulating materials and systems.

A list of organizations represented on this committee can be obtained on request to its secretary.

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Measurement of internal electric field in insulating materials – Pressure wave propagation method

INTERNATIONAL ELECTROTECHNICAL COMMISSION

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CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

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MEASUREMENT OF INTERNAL ELECTRIC FIELD IN INSULATING MATERIALS – PRESSURE WAVE PROPAGATION METHOD

FOREWORD

The main task of IEC technical committees is to prepare International Standards. However, a technical committee may propose the publication of a technical report when it has collected data of a different kind from that which is normally published as an International Standard, for example "state of the art".

IEC/TR 63836, which is a technical report, has been prepared by IEC technical committee 112: Evaluation and qualification of electrical insulating materials and systems.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
112/258/DTR	112/263/RVC

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

INTRODUCTION

High-voltage insulating cables, especially high-voltage d.c. cables, are subject to charge accumulation and thus to electrical breakdown if the electric field produced by the charges exceeds the electrical breakdown threshold. With the trend to multiply power plants, especially green power plants such as wind or solar generators, more cables will be used for connecting these power plants to the grid and share the electric energy between countries. Therefore the materials for the cables, and even the structure of these cables when considering electrodes or the junction between cables, need a standardized procedure for testing how the internal electric field can be characterized. The measurement of the internal electric field would give a tool for comparing materials and help to establish thresholds on the internal electric field for high voltage applications in order to limit as much as possible breakdown risks. The pressure wave propagation (PWP) method has been used by several researchers to measure the space charge distribution and the internal electric field distribution in insulators. However, since experimental equipment, with slight differences, is developed independently by researchers over the world, it is difficult to compare the measuring results between the different researchers.

The procedure outlined in this technical report would give a reliable point of comparison between different test results carried out by different laboratories and avoid interpretation errors. The IEC has established a project team to develop a procedure to evaluate PWP measurement. The method will be verified in a Round Robin test. Once, having received reliable experience, this report is intended later to be upgraded to a technical specification in order to establish a specified way to estimate fairly the performance of a PWP measurement.

MEASUREMENT OF INTERNAL ELECTRIC FIELD IN INSULATING MATERIALS – PRESSURE WAVE PROPAGATION METHOD

1 Scope

IEC/TR 62836, which is a technical report, contains an efficient and reliable procedure to test the internal electric field in the insulating materials used for high-voltage applications using the pressure wave propagation (PWP) method. It is suitable for a sample with homogeneous insulating materials and an electric field higher than 1 kV/mm, but it is also depended on the thickness of sample and the pressure wave generator.

2 Terms, definitions and abbreviations

For the purposes of this document, the following terms, definitions and abbreviations apply.

2.1 Terms and definitions

2.1.1
pressure wave propagation
PWP
propagation of wave generated by the action of a pressure pulse

2.2 Abbreviations

LIPP laser induced pressure pulse

PIPP piezoelectric induced pressure pulse

3 Principle of the method

The principle of the PWP method is shown schematically in Figure 1.

The space charge in the dielectric and the interface charge are forced to move by the action of a pressure pulse wave. The charge displacement then induces an electrical signal in the measuring circuit which is an image of the charge distribution in the short-circuit current measurement condition. The expression for the short-circuit signal is

$$i(t) = C_0 \int_0^d \mathrm{B}\, E(x) \frac{\partial p(x,t)}{\partial t} dx \qquad (1)$$

where

$E(x)$ is the electric field distribution in the sample;

d is the thickness of sample;

$p(x, t)$ is the pressure pulse wave in the sample, which depends on the electrode materials, dielectric sample material, the condition of coupling on the interface, etc.;

C_0 is the sample capacitance without the action of pressure pulse wave.

C_0 depends on the thickness of sample, and its surface area which is equal to the area of action of pressure pulse wave. The constant $\mathrm{B} = x\ (1 - a/\varepsilon)$ only depends on the characteristics of the dielectric materials. For heterogeneous dielectric materials, B is a function of space. For homogeneous dielectric materials, B is not a function of space and can be put in front of the integral. In this proposition, only homogeneous dielectric materials are considered, B is a constant.

In Equation (1), the electric field distribution can be obtained if it is deconvolved.

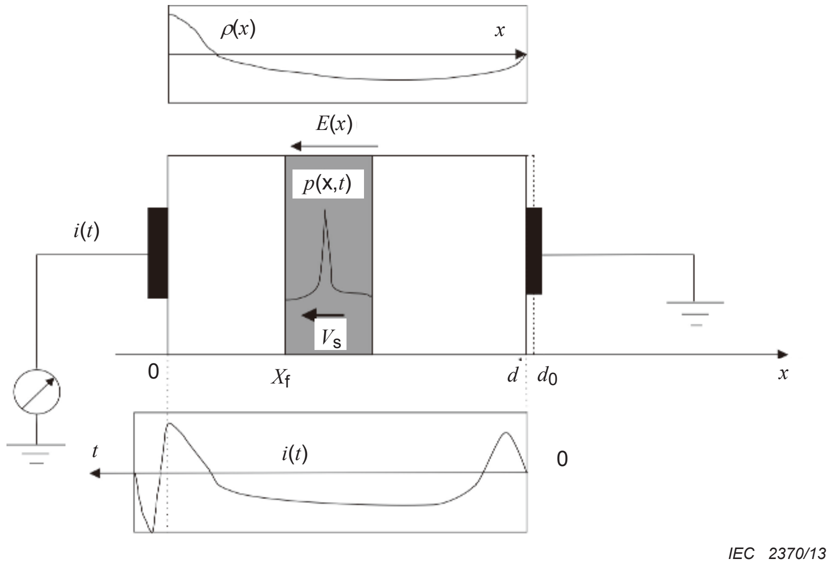

Figure 1a – Applied pressure pulse and measured short-circuit current signal

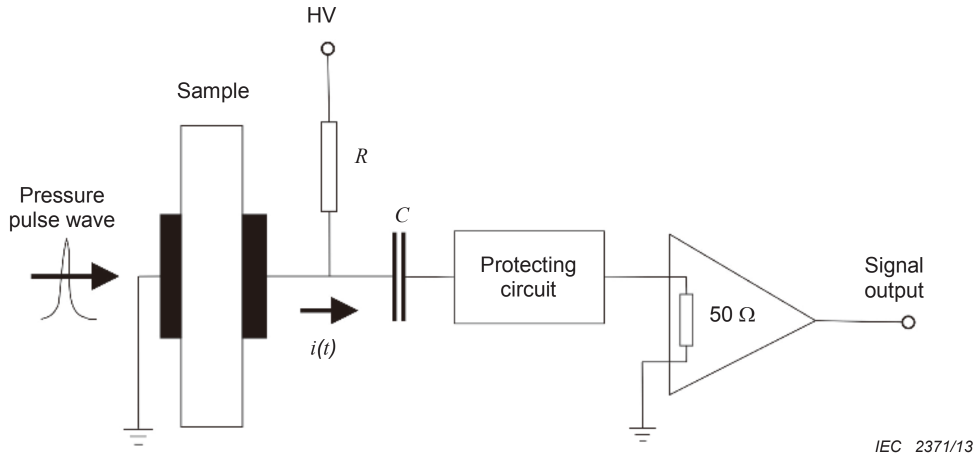

Figure 1b – Measuring schematics

Figure 1 – Principle of the PWP method

The applied pressure pulses can be generated by different techniques, but the same kind of analysis can be done for any of these techniques. The main practical PWP method can be divided into two ways: a pressure pulse is induced by a powerful pulse laser, a technique called LIPP method, and a pressure pulse generated by a piezoelectric device, a technique called PIPP. The sensibility and resolution of PWP method depends mainly on the amplitude and width of pressure pulse. The advantage of the LIPP method is to produce high sensitive measurements. The advantage of the PIPP is to obtain a better spatial resolution.

In the case of a narrow pulse, e.g., the width of the pressure pulse is much less than the thickness of sample

$$\int_0^t \mathrm{i}(t')\,\mathrm{d}t' = C_0 \mathrm{B}\overline{E(x=v_\mathrm{s}t)} \int_0^d p(x,t)\,\mathrm{dx} \qquad (2)$$

where

$\tau \ll [min(d_0, d_\mathrm{x})]/v_\mathrm{s}$	is the pressure pulse duration;
v_s	is the sound speed in the sample;
$\overline{E(x=v_\mathrm{s}t)}$	is the mean electric field during the pressure pulse width.

Because sound loss and sound dispersion in polymer dielectrics exist, the amplitude of $p(x,\ t)$ will decrease, and the width of $p(x,t)$ will increase during the propagation of a pressure pulse wave in the sample. But for the polymer dielectrics, the main action is the sound dispersion, therefore, even if $p(x,t)$ is not a constant in the dielectrics, its integral $\int_0^d p(x,t)\,\mathrm{dx}$ remains constant during its propagation in the sample.

From the above equation and from the signal obtained with a sample free of charges and submitted to an intermediate voltage V_0, $B\int_0^d p(x,t)\,dx$ can be obtained since in the case the electric field $\overline{E(x = v_s t)} = E_0$ is a constant and the sample capacitance C_0 in direct proportional to the thickness of the sample. This can be used as a calibration for the other measurement.

4 Sample conditions

A dielectric insulating material is suggested, for example polyethylene, with a thickness of 1 mm or 2 mm, planar plaque sample with a diameters sufficiently large to avoid edge discharges, typically larger than 20 cm usually for 60 kV.

5 Electrode materials

The selection of electrode materials depends on the method of the generation of the pressure pulse wave. Usually, semi-conductive electrodes with EVA+carbon black or PE+carbon black are used. For laser PWP (also called LIPP), the suitable thickness of semi-conductive electrode is about 0,5 mm, and it has to be less than 1 mm.

6 Pressure pulse wave generation

The suggested pressure pulse wave should have a 20 – 50 ns duration, and 1 – 10 MPa amplitude. It can be produced by a piezoelectric driven device, or by a pulsed powerful laser. If the powerful laser is used, the suggested energy is about 300 – 500 mJ per pulse with 3 – 7 ns duration.

7 Set-up of the measurement

The practical set-up of the measurement is shown in Figure 2. In the practical set-up, the length l_{ab} of the connection between the sample and the output connector should be less than 0,5 m. The length l_{bc} of the connection cable with the characteristic impendence of 50 Ω between the output and the protecting circuit should be less than 0,5 m. The length l_{de} of the connection cable with the characteristic impendence of 50 Ω between the protecting circuit and the amplifier should be less than 0,5 m. And, the total length of $l_{bc}+l_{de}$ should be less than 0,5 m too. The amplifier with 40 dB and 200 MHz bandwidth is suitable. The input impedance of the amplifier should be strictly 50 Ω to avoid the unwanted reflecting signal.

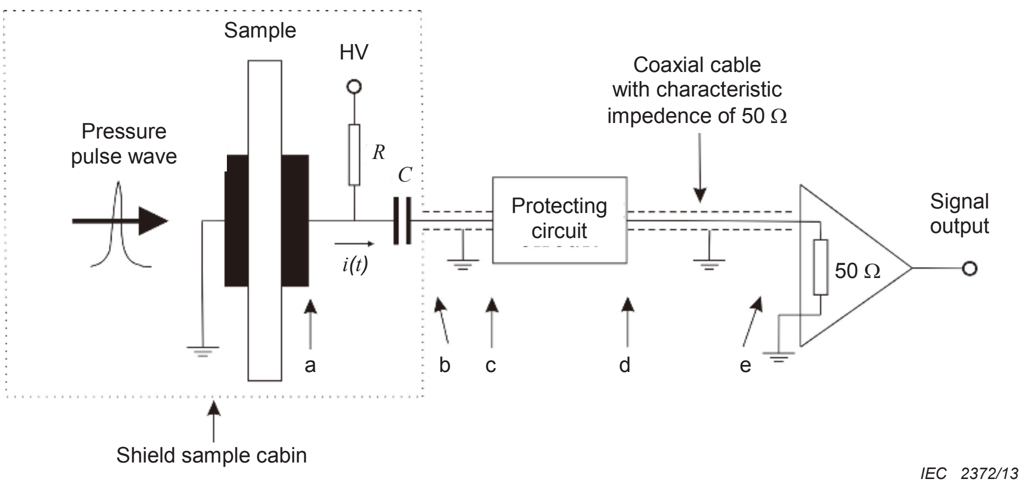

Figure 2 – Set-up of measurement of the PWP method

The practical protecting circuit is shown in Figure 3. Diodes in the protecting circuit should have a fast recover time to overcome the quick overvoltage. The resistor in the protecting circuit is better with 5 Ω, but without residual induction.

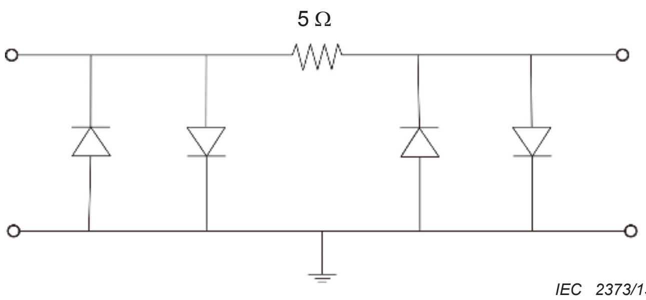

Figure 3 – Sample of protecting circuit

8 Calibrating the electric field

For the planar plaque sample with a thickness of 1 – 2 mm, the applied field for calibration is about 5 – 10 kV/mm during the short period of time (typically less than 10 s) in order to avoid space charge injection and accumulation. If space charges already exist in the sample prior to the calibration measurement, it is possible to construct the calibration measurement from a measurement under voltage as explained before and to subtract from it the signal measured under short-circuit just before or just after the measurement under voltage.

9 Measurement procedure

To implement the same dielectric insulating materials, the same electrode materials, and the same interface condition between the electrode and insulator, one sample with the thickness d_0 is used as the calibrating sample, and another sample with the thickness d_x is used as the testing sample.

For the calibrating sample with the thickness of d_0, voltage V_0 is applied during a short period of time. The internal electric field in the sample is $E_0 = -V_0/d_0$ in absence of space charge. With the action of the pressure pulse wave, the measured short-circuit current signal will be

$$\mathrm{i_c}(t) = C_0\mathrm{B}\int_0^{\mathrm{d_0}} E_0 \frac{\partial p(x,t)}{\partial t}\mathrm{d}x \tag{3}$$

Applying an integration over time on this current signal, one obtain

$$\int_0^{\mathrm{t}} \mathrm{i_c}(t')\,\mathrm{d}t' = C_0\mathrm{B}E_0\int_0^{\mathrm{d_0}} p(x,t)\mathrm{d}x \tag{4}$$

where $\overline{E_0} = E_0$ since the electric field is a uniform.

For the testing sample with the thickness of d_x, the measured short-circuit signal is

$$\mathrm{i_m}(t) = C_0\mathrm{B}\int_0^{\mathrm{d_x}} E(x)\frac{\partial p(x,t)}{\partial \mathrm{t}}\mathrm{d}x \tag{5}$$

Now, the internal electric field depends on the applied voltage and space charge. It is therefore no longer a uniform field but varies as a function of the space position. After integration over time, one has

$$\int_0^{\mathrm{t}} \mathrm{i_m}(t')\,\mathrm{d}t' = C_\mathrm{x}\mathrm{B}\overline{E(x=v_\mathrm{s}t)}\int_0^{\mathrm{d_x}} p(x,t)\mathrm{d}x \tag{6}$$

10 Data processing for the experimental measurement

The integral of the pressure pulse wave is the same for the testing sample and for the calibrating sample, i.e.

$$\int_0^{\mathrm{d_0}} p(x,t)\,\mathrm{d}x = \int_0^{\mathrm{d_x}} p(x,t)\,\mathrm{d}x \tag{7}$$

If the active area pressure pulse wave is S_0, there is

$$C_0 = \frac{\epsilon_0 \epsilon_r S_0}{d_0}, \qquad C_x = \frac{\epsilon_0 \epsilon_r S_0}{d_x}, \qquad E_0 = -\frac{V_0}{d_0} \tag{8}$$

So, one has

$$\frac{\int_0^t i_m(t')dt'}{\int_0^t i_c(t')dt'} = \frac{\frac{\varepsilon_0 \varepsilon_r S_0}{d_x} B \overline{E(x=v_s t)} \int_0^{d_x} p(x,t)dx}{-\frac{\varepsilon_0 \varepsilon_r S_0}{d_0} B \frac{V_0}{d_0} \int_0^{d_0} p(x,t)dx} = \frac{-d_0 \overline{E(x=v_s t)} d_0}{d_x V_0} \tag{9}$$

It can be obtained

$$\overline{E(x=v_s t)} = \frac{-\int_0^t i_m(t')dt'}{\int_0^t i_c(t')dt'} \times \frac{d_x V_0}{d_0^2} \tag{10}$$

If the thickness and tested area are equal for the testing sample and for the calibrating sample, $d_0 = d_x$

$$\overline{E(x=v_s t)} = -\frac{V_0}{d_0} \times \frac{\int_0^t i_m(t')dt'}{\int_0^t i_c(t')(11)dt'} = E_0 \times \frac{\int_0^t i_m(t')dt}{\int_0^t i_c(t')dt'} \tag{11}$$

Therefore, the internal electric field can be obtained from the above equation. The method is suitable both for the sample under voltage and for sample in short-circuit containing space charge.

It can be noticed that the denominator of that expression should be a constant since the electric field is uniform in the case of the calibration measurement. In order to improve signal to noise-ratio, the denominator can be safely replaced by the amplitude of the integral once calculated, or by the integral of the first peak as

$$\overline{E(x=v_s t)} = -\frac{V_0}{d_0} \times \frac{\int_0^t i_m(t')dt'}{\int_0^{5\tau} i_c(t')dt'} = E_0 \times \frac{\int_0^t i_m(t')dt'}{\int_0^{5\tau} i_c(t')dt'} \tag{12}$$

In this equation, τ is the duration of the pressure pulse in the sample, the denominator of the equation is no longer a function of time, but the definite integral of the first peak of measured current. The upper limit of the integral is set to 5 τ, so that it is for ensuring to include the first peak of current. The upper limit can be adjusted according to the condition.

11 Measurement examples

11.1 Samples

The plaque LDPE sample with 1,16 mm thickness and 20 cm diameter, the EVA+CB electrodes with 0,6 mm thickness and 5 cm diameter are attached on the LDPE sample by hot-press. In this example, the calibrating sample and testing sample is the same sample.

11.2 Pressure pulse generation

The laser pulse with 500 mJ energy and 6 ns duration produced by a Nd:YAG pulsed laser, radiates on the EVA+CB electrode directly. It introduces the pressure pulse wave in the sample by the plasma ablation on the electrode surface. Since the acoustic impedance is very similar for the LDPE sample and for the EVE+CB electrode, the reflection on the interface between LDPE and EVE+CB can be ignored.

11.3 Calibrating of sample and signal

Under the temperature of 40 °C, the relative low voltage (–5,8 kV) is applied on the sample. The signal is measured in short duration. The internal electric field is 5 kV/mm, and sound velocity can be obtained by the measured signal, vs = 2 017 m/s.

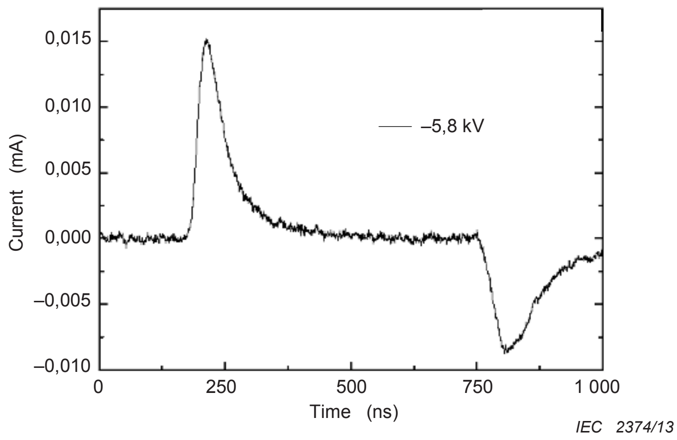

Figure 4 – Current signal under –5,8 kV

11.4 Testing sample and experimental results

Under the same temperature, a relative high voltage (–46,4 kV) is applied on the same sample for 1,5 h. The evolution of the signal is measured. The applied internal electric field is 40 kV/mm (see Figures 5 to 7).

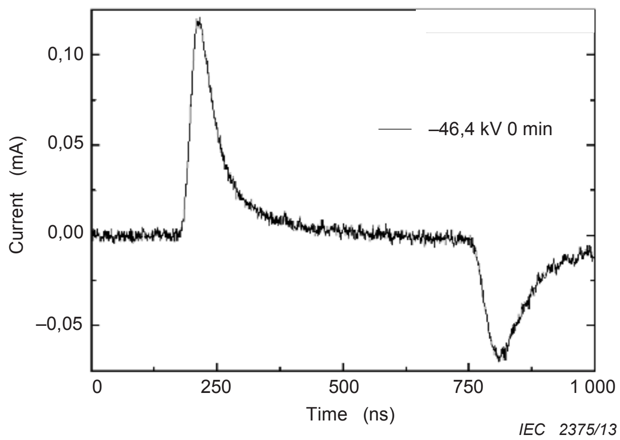

Figure 5 – First measured current signal (<1 min)

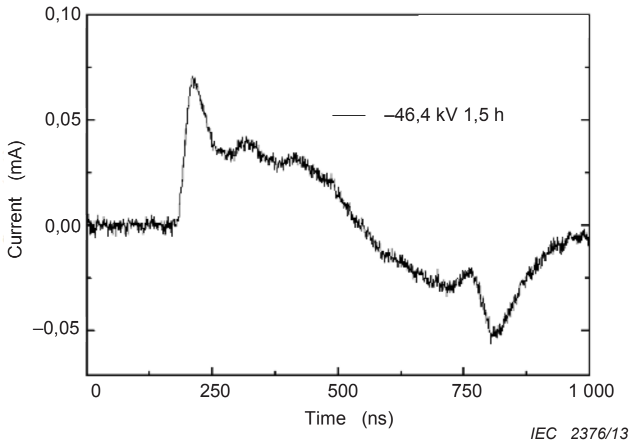

Figure 6 – Signal under –46,4 kV, 1,5 h

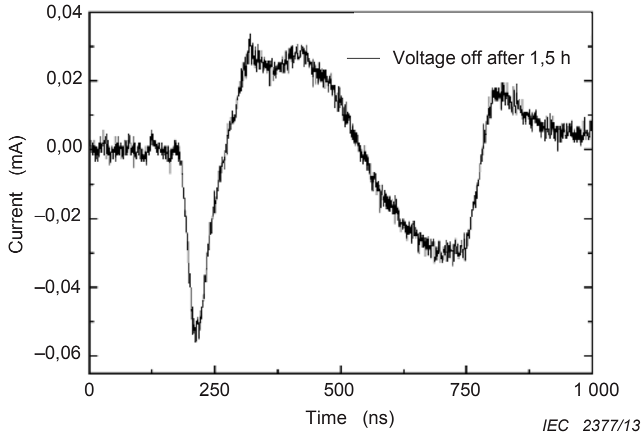

Figure 7 – Measured signal without applied voltage, after 1,5 h under high voltage

11.5 The internal electric field distribution

Figures 8 to 11 show the electric filed distribution for the various voltages.

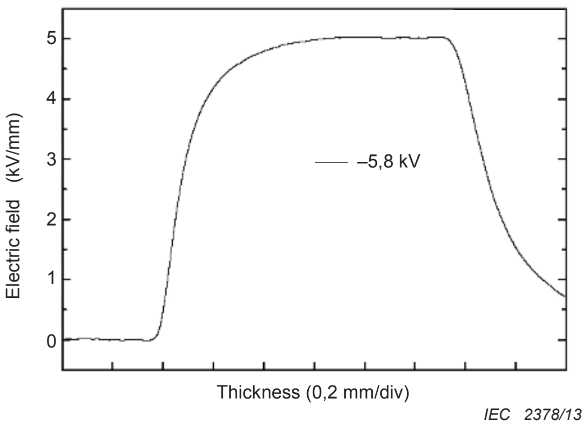

Figure 8 – Internal electric field distribution under –5,8 kV

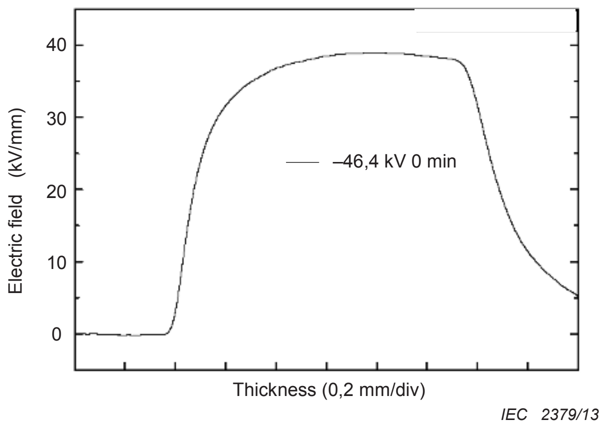

Figure 9 – Internal electric field distribution under –46,4 kV, at the initial state

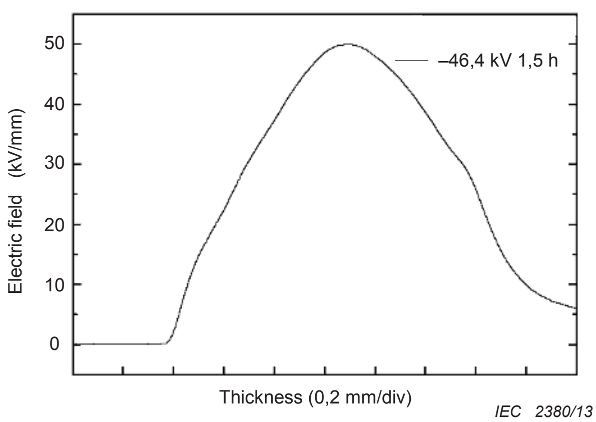

Figure 10 – Internal electric field distribution under –46,4 kV, after 1,5 h under high voltage

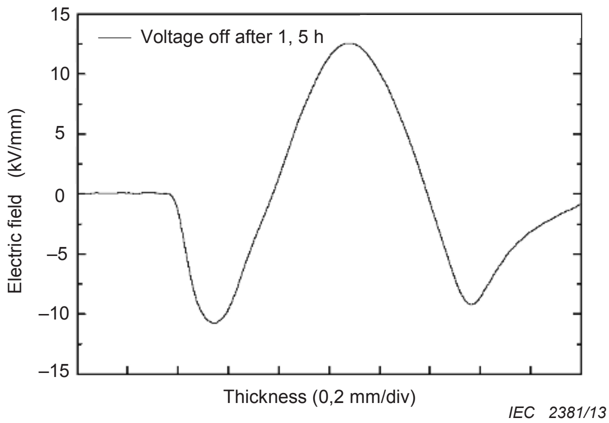

Figure 11 – Internal electric field distribution without applied voltage after 1,5 h under high voltage

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