Review of Acoustic Methods for Space Charge Measurement

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Abstract—In the last decade, due to the increased use of direct current, the space charge accumulation phenomenon has reached more interest. In this regard, several non-destructive measurement systems were used. In particular, for solid dielectrics, the acoustic methods have had greater success. This review presents a brief historical evolution of the Pulse Electro-Acoustic (PEA) method, describing the working operation, the thicknesses analyzed and the spatial resolution for the different configurations of the PEA cell. The Pressure Wave Propagation (PWP) method in both configurations Piezo-PWP and Laser Induced Pressure Pulse (LIPP) is also described.

Keywords—Space charge; acoustic method; Pulse Electro-Acoustic; Pressure Wave Propagation method; Piezo-PWP; LIPP; Laser Induced Pressure Pulse method.

I. INTRODUCTION

Dielectric materials used in most electrical systems are affected by an electrical degradation due to several factors [1]. Space charge phenomenon mainly characterizes the direct current applications. As example, in cables used for High Voltage Direct Current transmission (HVDC), made of crosslinked polyethylene XLPE, it has been noticed that the space charge plays an important role in degradation, due to the distortion of the electric field with respect to the Laplacian field (ideal case), with the consequence of strong local stresses [1]-[3].

By considering the relevance of the space charge due to its negative effects previously mentioned, many researchers have been interested to overcome the challenges related to this phenomenon. In fact, many scholars have been interested in the physics of this phenomenon both in the past years [4]-[8] and in recent years [9]-[11].

During the years, these research groups have also developed different nondestructive measurement systems for the characterization of dielectric materials from the viewpoint of space charge accumulation. These systems are divided into three main families: acoustic and thermal [12]-[14] methods for measurements on solid dielectrics and optical method [13] for measurements also in liquid dielectrics. This review focuses the attention on the methods related to the acoustic family, which are the most used over the past ten years. In particular, a short historical evolution of the Pulse Electro-Acoustic (PEA) method is developed. This method has had great success, thanks to the simplicity and robustness of the measuring cell. The last review article concentrated on this method was edited by K. Fukunaga [15], while the recent review concerning other methods such as the PWP (Pressure Wave Propagation) was developed by S. Holè [16]. The comparison between these two methods is reported in several works [17]-[22].

More in particular, this paper will describe the principle of operation of the main methods, their different configurations, their applications, the thicknesses analyzed and the spatial resolution, with data updated to 2015, all summarized in table I.

II. ACoustic METHODS

The principle of the acoustic methods is based on the propagation within the sample of a pressure wave. This wave can be generated directly from a space charge inside the sample (PEA method), or externally (PWP method). The space charges, for both methods, will be subject to an external perturbation and will move slightly, causing a change of voltage or current detectable in the external circuit, according to the type of method used [14].

A. The PEA method

The PEA method was developed by Takada in 1987 [23]. The working operation is based on the one-dimension Coulomb force law and the principle diagram for a flat sample is shown in figure 1. It consists essentially of a high voltage direct current generator (HVDC), which is used in order to create a high electric field within the sample, a pulse generator e(t) used to generate the acoustic wave (the charges are vibrating because of the pressure pulse), a piezoelectric transducer based on a 9 μm thick polyvinylidene fluoride (PVDF), which allows the conversion from an acoustic signal to a voltage signal. Finally, the amplifier allows the signal amplification and the output voltage signal is, then, sent to a PC for data processing [14], [24]. Over the last years the principle of the cell has remained unchanged, except for the size and the material of the components adopted and the thickness of the sample to be tested.
### Table I – Overview of the resolution and thicknesses used in the different measuring techniques

<table>
<thead>
<tr>
<th>METHOD</th>
<th>Configurations</th>
<th>Thickness (µm)</th>
<th>Resolution (µm)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>PEA</td>
<td>Flat specimen</td>
<td>25 - 27000</td>
<td>1.6</td>
<td>This is the best value of resolution reached, obtained by the smaller thickness, using a pulse voltage of 100 V and width 0.6 ns</td>
</tr>
<tr>
<td></td>
<td>Three-Dimensional</td>
<td>250 - 750</td>
<td>16</td>
<td>The resolution value in the table refers to the vertical direction. In the side direction it is equal to 100 µm</td>
</tr>
<tr>
<td></td>
<td>Two-Dimensional</td>
<td>100 - 300</td>
<td>15</td>
<td>The value of resolution in the vertical direction is obtained for thicknesses from 100 µm. In the side direction it is 1.5 mm and depends on the distance between the sensors</td>
</tr>
<tr>
<td></td>
<td>Open Upper Electrode</td>
<td>189 - 500</td>
<td>1 – 10</td>
<td>The resolution is equal to a few micrometers. The system is used to measure surface charges and internal charge, even during irradiation</td>
</tr>
<tr>
<td></td>
<td>Portable PEA</td>
<td>500</td>
<td>10</td>
<td>The performance of this method are very similar to those of the classic PEA</td>
</tr>
<tr>
<td></td>
<td>Cables</td>
<td>3500 - 20000</td>
<td>100 - 1000</td>
<td>Although the resolution is in the order of millimeters, the thickness of the insulation tested are significant</td>
</tr>
<tr>
<td>PWP</td>
<td>Piezo - PWP</td>
<td>50 - 1000</td>
<td>5</td>
<td>The resolution value obtained for the smaller thickness in the application of dielectrics irradiated. In other cases the resolution is equal to 2 - 5 %</td>
</tr>
<tr>
<td></td>
<td>LIPP</td>
<td>&lt; 1000</td>
<td>– 1</td>
<td>This resolution value refers to the general case. Using a femtosecond laser pulse, the resolution comes to 50 nm</td>
</tr>
</tbody>
</table>

The components of the PEA cell are described in [25], while the profiles of space charge in different materials investigated with thickness of the range between 27 mm and 25 µm are described in [26] and [27], respectively. In order to improve the measurement resolution of the described method, Y. Tanaka et al. [28] modified further the size and the type of some PEA cell components, such as the pulse generator characteristics. Therefore, the spatial resolution is included in the range 1.6 µm and 3 µm for samples of thickness 25 - 100 µm [28].

The PEA cell with adequate modifications can be used to make simultaneous measurements of space charge and conduction current [29]-[30]. For measurements under temperature gradient the first experiment was carried out by Takada et al. in 1996 [31], in which the LiNbO3 crystal was used as a transducer in order to obtain a stable output signal for the high temperatures reached in the cell [31]. In [32]-[33] the PVDF transducer is used because of a lower thermal gradient, whereas in [34] the new recovery algorithm for these types of measurements is reported.

#### B. Three-Dimensional PEA method

Three dimensional measurements of space charge have been proposed by Imaizumi et al. [35]. The 3D PEA working operation is very similar to the classic PEA described in the previous section. The main feature in the first historical application [35] is that the sample is moved along the x – y coordinates and the output measurements are detected along x, y and z. Years later, in order to measure the 3D distribution in a faster way, a numerical control of a movable detector composed by the transducer and an acoustic lens is developed and the sample under test is maintained fixed [36]. This method is also called “Acoustic Lens method” and the resolution is 12 µm along the thickness direction and 0.5 mm in the side direction [36]. In the work of T. Maeno et al. [37] the thickness range of the samples is between 250 and 750 µm and the resolutions in the vertical direction and in the side direction are equal to 16 µm and 100 µm, respectively. More details and type of applications are reported in [38]-[41].

#### C. Two-Dimensional PEA method

For real-time measurements needed for the evaluation of the transient behavior of the space charge, Fukuma has developed a two dimensional measuring system [42]. The principle of operation is similar to the classic PEA, except for the higher number of sensors arranged in a line below.
the lower electrode [42]. The system detects the charges along the thickness and the side direction with a lateral resolution that depends on the distance between the sensors. If the distance is 3 mm, the lateral resolution assumes the same value (3 mm) [42]. The cost of the A/D converter is a relevant challenge in this method, because it depends on the number of input channels. This problem has been solved by using a semi-conductor matrix switch and one channel A/D converter [43]. In [42]-[44] materials of different thickness between 100 and 300 μm were tested, obtaining a resolution of 15 μm in the thickness direction and 1.5 mm in the side direction for sensors placed at 1.5 mm [44].

D. Open Upper electrode

Dielectric materials used in spacecrafts are subject to special environmental conditions. In these cases, the surface charge should also be considered. For this purpose, in 2004 [45] a new configuration of the PEA cell called “Open Upper electrode” was developed, in which the top electrode remains detached from the sample. The scheme of the cell is presented in [45]. The differences from the classic configuration consist in the size of the components and in the separation of the contact between the upper electrode and the sample. In order to adapt the voltage pulse to the sample (and find a good compromise between applied voltage and sensitivity of the charge detection), the work in [46] proposes a gap of 1 mm between the electrode and the sample. In [47] the calibration of the system is described, while in [48]-[49] the new set-up called “Open Ring Electrode (ORE)” is reported. In comparison with the classic configuration, this method ensures the measurements during electronic bombardment. In addition, the tested sample thickness is in the range between 189 μm [48] and 500 μm [45] with a resolution of a few micrometers [46].

E. Portable PEA

The “Portable PEA” has been developed in order to carry out on-site measurements of space charge through a easily portable system [50]. The difference compared to previously described methods consists in a different waveform provided by a pulse generator. Thus, the distribution of space charge can be directly observed on the oscilloscope, avoiding the encumbrance of the computer [50]-[51]. The voltage pulse will be smaller in width and the resolution, equal to 10 μm for thickness samples of 500 μm, will be very close to that of the traditional PEA [51]. Slightly modifying the PEA cell of this configuration, it is possible to detect measurements inside the irradiation chamber. This set-up is called “Mountable PEA” and it is well explained in [15],[38] and [52].

F. PEA for cable

The first historical application of the PEA method for coaxial geometries was performed by Fukunama [53]. This method is destructive for space charge measurements on cable samples, because the copper tape must be removed to insert the electrodes of the PEA cell around the external semiconductor [54]-[55]. In [56]-[57] tests were carried out on XLPE insulated cables and in [58] the new protocol for measurements on full-size cable during the PQ test and the TYPE test is proposed. To prevent the change of the electrode dimensions for the analysis of cables with different sections, it is possible to use the floating ground electrode [59]. This type of cell has allowed the measurements of insulation thicknesses between 3.5 and 5 mm [59]-[62].

The tests under temperature gradient are carried out by using a current transformer placed in proximity to the cable to heat the internal conductor of cable [63]. The thicknesses tested is in the range between 3.5 and 20 mm [56], [62], [64] and the resolution for the larger cross-section cable is in the order of tenths of a millimeter [56]. Measures under temperature gradient were also performed for mini-cables. The related scheme is shown in [65] and the thickness is about 1.5 mm [66]-[68].

G. The PWP method

The PWP method was developed by Laurenceau in 1976 [72]. The scheme is shown in [14] and the same components of PEA cell are involved (figure 1). However, the pulse generator urges the piezoelectric transducer, which is not used as the acoustic wave detector, but as pressure wave generator. This wave, by passing through the lower electrode, crosses the sample and perturbs the space charge, causing a variation of the surface charge on the electrodes and, consequently, variation in time of the current. This variation will bring information on the distribution of space charge [13]-[14].

In dependence of the type of wave pressure source, the PWP method can be named differently. As example, the “Piezoelectric Induced Pressure Wave Propagation method”, PIPWP, or Piezo-PWP, uses the transducer as in the previous case [73]-[75]. Additional techniques are listed in [76]-[77]. The most used is called Laser Induced Pressure Pulse (LIPP) method. This method uses a laser to generate a pressure wave. The high-intensity laser pulse strikes a target, which is in contact with one of the electrodes placed at the ends of the sample. The material (usually liquid) placed in the target/electrode interface thermally expands when the laser energy crosses it. Therefore, the induced expansion generates the pressure pulse, which will propagate along the sample. The variation of the charge induced at the electrodes generates a displacement current, from which it is possible to carry out informations on space charge [12]-[14],[78]. Compared to the PIPWP method, the principle of charge detection remains the same. However, a higher spatial resolution due to the steeper rise fronts of the pressure pulse is obtained [12], [78]. By using a laser pulse with energy equal to 180mJ and a thin layer of indian ink interposed between the target and the electrode, the resolution improves [78]. In the past years the LIPP method
was used for 100 μm – 1 mm thick samples, with 1 μm of spatial resolution [12]-[14]. Recently, by a femtosecond laser pulse and an electro-optic sampling, it was possible to test ultra-thin insulating materials used in integrated circuits with 50 nm of spatial resolution [77]. The PWP method in the PIPWP configuration is used by Takada et al. for measurements on dielectric irradiated with resolution of 5μm for sample of thickness 50 μm [74], [79].

III. CONCLUSIONS

During the recent years different nondestructive methods for space charge measurement have been developed and this work has summarized them, describing their principle of operation, their configurations, their applications and the related spatial resolution. In particular, the acoustic methods were the most used to test solid dielectrics. The PEA is used for one, two and three dimensional measurements of thin insulating materials, as well as for thick insulated cables. Furthermore, the Portable PEA system is used for on-site measurements.

Finally, the PWP and LIPP methods are used for flat samples and for measurements on irradiated dielectrics.

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