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# Review of Space-charge Measurement using Pulsed Electro-Acoustic Method: Advantages and Limitations

Habibu Hussaini*, Ashraf Ahmad Adam,*Ajagun Abimbola Susan*
*(Department of Electrical and Electronics Engineering, Federal University of Technology, Minna, Nigeria

**ABSTRACT**
The pulsed electro acoustic (PEA) technique is the most widely used method to measure space charge distributions in insulating materials. The PEA technique has undergone some advancement since the over twenty years it was first implemented such as in its spatial resolution and sensitivity. In this article a review of the technique was carried out and its advantages, limitations, progress and prospects were discussed.
**Keywords**- Review, space charge, pulsed electro acoustic technique, insulating materials

## I. INTRODUCTION

The presence of space charges in insulation materials become cause for concern when they accumulate and then distort the electric field distribution within the material. This is because such distortion generates high electric field that could lead to breakdown, electrical aging [1] and electrostatic discharge of the insulation materials [2], [3]. When the space charge accumulates and garners a reasonable density, its local field strength could exceed the breakdown strength of the insulation material; hence leading to the material failure [4]. The term space charge was first used to describe the electronic charge that buildup in the space between the cathode and anode of a vacuum diode, due to electron emission from the cathode [4]. Space charge is rarely found in equipment's used under ac stress; however, they exist in equipment being used under dc stress [5]. Insulation materials are used to protect high voltage equipment's from overheating and power loss, but these insulation materials often experiences stress due to the high voltage the equipment they are insulating carries. When they are under stress the insulation materials easily get damaged due to stress induced aging.

The pulsed electro-acoustic (PEA) method gives quantitative information about the space charge present in an insulation material [5] to help engineers to design equipment's that use insulation materials such as HVDC cables better insulation materials, and control of electrostatic discharge phenomena [6]. There are two major techniques used to measure space charge in insulation materials and they are the destructive and non-destructive techniques.

The destructive techniques involved the use of powders (gives only qualitative information about the insulation material); a filed mill or a capacitive probe (gives quantitative information about the insulation material) at the first attempt made to quantify space charge in insulation materials. These techniques involved the cutting of the insulation material into slabs in order to measure space charge within it, hence destroying the material [5]. The other destructive techniques include thermally stimulated current (TSC), thermally stimulated surface potential (TSSP), and thermoluminescence (TL) methods [7], [8], [9].

The non-destructive techniques [10], [11], [12] were later developed over two decades ago to prevent destruction of insulation materials during space charge measurement and they include the thermal shock method (TSM), the pressure wave propagation (PWP) method, the laser induced pressure pulse (LIPP) method, and the pulsed electro-acoustic (PEA) method [5]. The non-destructive techniques used the same physical effect to measure space charge, but subject insulation materials sample for measurement to different temporary disturbance; however the information retrieved after measurement is identical [3], [13]. The non-destructive techniques also require calibration before the quantitative space charge density can be obtained [14].

The two common methods used to measure space charge distribution are the Pressure Wave Propagation (PWP) method and Pulsed Electro-acoustic (PEA) method. The PEA method can be applied to AC or DC fields. However, its DC application for measuring space charge would be the focus of this paper review and its advantages, limitations, progress and prospects discussed.

The paper is organized as follows: Section I of the paper gave a general introduction on space charge and its measurement techniques, the principle of operation, calibration and system response of the pulsed electro-acoustic technique was discussed in section II, Section III talked about the advantages and limitations of the PEA method, the progress and prospects of the PEA technique was looked at in section IV, Section V discussed the conclusion of the review.

## II. PULSED ELECTRO-ACOUSTIC (PEA) METHOD

The pulsed electro-acoustic method was first created in 1987 [15], [16, [17] by the research group of prof. T. Takada working in cooperation with prof. C. M. Cooke [5]. This is the most widely used technique in the field of space charge measurement [18] compared to other methods. It is cheap, simple in structure and easy to implement.

### 2.1 Principle of Operation

The principle of the PEA technique is based on the Lorentz force law and acoustic wave propagation in one dimension [19].

The pulsed electro-acoustic technique involves the application of high voltage, high frequency pulsed voltage probe across the sample which space charge profile is to be determined in order to stimulate motion of its internal charges thereby generating acoustic waves within the material [20] as shown in Fig. 1. The acoustic waves generated then propagate in the sample and are detected as electric signal by a piezoelectric sensor connected to the ground electrode. The amplitude of the signal is proportional to the charge quantity [16]. The space charge distribution is monitored as a function of time and measured quantitatively. The density and polarity of the space charge is obtained from the physical characteristic of the generated acoustic wave.

However, the detected output signal in the PEA method do not give the space charge profile of a sample under measurement directly, due to the limited frequency band of the ceramic piezoelectric transducer (PZT) used [21]. A deconvolution technique developed in 1988 [22] is used to obtain the space charge profile of the sample.

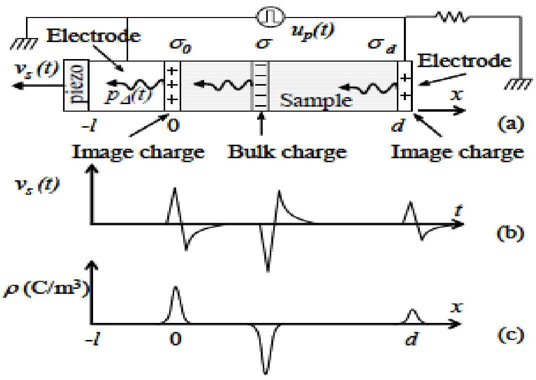


Fig. 1: Principle of the PEA method. (a) Charged regions give rise to acoustic waves under the effect of a pulsed field (b) Piezoelectric sensor gives a voltage vs(t). (c) Signal treatment gives the spatial distribution of image and internal charges [6], [23].

The applied DC voltage is usually in the range of 5-40 kV, depending on the sample thickness. The pulse voltage and width are in the range of 0.1-2 kV and 5-200 ns, respectively [5]. The acoustic pressure wave p(t) generated in the sample and the output signal of the system both expressed as a function of time is as shown in equation (1) and (2) respectively [21].

$$p(t) = K[\sigma(0)e_p(t) + u_{sa}\int_0^\infty \rho(\tau)e_p(t-\tau)d\tau + \sigma(d)ep(t-dusa)] \quad (1)$$

Where K is the transmission coefficient of the acoustic wave in the ground electrode sample interface, sampling time is t, d is the sample thickness, and the acoustic velocity in the sample is $u_{sa}$.

$$v_s(t) = K[\sigma_1 + \sigma_2 + u_{sa}\Delta T\rho(x = u_{sa}t]e_p \quad (2)$$

Where $\sigma_1$ and $\sigma_2$ are the surface charges at the electrodes, ΔTis the width of the pulse, the bulk charge is ρ, and $e_p$ is the amplitude of the pulse voltage.

### 2.2 Calibration and System Response

Calibration is very significant and carried out in order to get an accurate quantitative analysis of space charge in solid dielectrics [24]. A novel calibration method in the presence of space charge in dielectric materials using the PEA techniques was developed in [24]. The calibration enables the plot of the charge profile in units of charge density, μ C/cm$^3$ [21].

The system response of the PEA technique comprises of the transducer and amplifier response coupled with the attenuation and dispersion of the acoustic wave as it moves through the system. The distortion occurs in a situation whereby the transducer and amplifier do not pass the complete frequency content of the original acoustic signal [5]. Also, distortion occurs when the frequency response of the amplifier is not flat, amplifier's high cut-off frequency is too low, or when both amplifier and transducer act as a high-pass filter [5]. This affects the accuracy of the quantitative analysis of the space charge distribution. However, this effect of system response is removed through appropriate calibration method. The method adopted depends on the sample [14].

The charge density calibration method for the PEA technique is as given in equation (3) in frequency domain [25], [26].

$$[\frac{\sigma(0)}{u_{sa}\Delta\tau} + R(f) + \frac{\sigma(a)}{u_{sa}\Delta\tau}\exp(-j2\pi f\frac{a}{u_{sa}})] = \varepsilon_0\varepsilon_r\frac{V_{dc}}{a}\frac{1}{u_{sa}\Delta\tau}\times\frac{V(f)}{V_0(f)} \quad (3)$$

Initially a DC voltage is applied to the sample to induce surface charges, however in order to avoid bulk charge formation, the voltage is set around 1-2 kV (low and short) for few seconds. The output signal of the PEA method is a voltage as shown in equation

(3), the component $(\varepsilon_0 \varepsilon_r \frac{V_{dc}}{a})(\frac{1}{u_{sa}\Delta\tau})$ is obtained from calculation, the deconvolution procedure performed in order to obtain the space charge distribution of a sample is represented by the component $\frac{V(f)}{V_0(f)}$ in which $V_0(f)$ is the Fourier transform of the output signal proportional to the surface charge density σ(0). The Fourier transform of the space charge distribution is V (f). The impulse of the system function is $V_0(f)$. Component $\frac{V(f)}{V_0(f)}$ is the space charge response recovery signal after the effect of the system function is removed [25]. Subsequently, the space charge signal is obtained. Further discussion on PEA's calibration can be found in [14], [24].

## III. ADVANTAGES AND LIMITATIONS

The two most widely used non-destructive techniques for space charge measurement are the PEA and PWP methods [26]. The PWP is further divided into two based on the generation principles of the narrow acoustic wave. These are the Piezoelectric Induced Pressure Wave (PIPW) method [12], and the Laser Induced Pressure Propagation (LIPP) method [27]. Both PIPW and LIPP have the same principle for space charge measurement[28]. In order to look at the advantages and limitations of the PEA technique, this report first compared the two techniques mentioned.

### 3.1 Comparison between the PEA and PWP Methods

The comparison of the characteristics of both techniques is as presented in TABLE 1.

TABLE 1
COMPARISON OF THE PEA AND PWP METHODS adapted from [26]

| Characteristics | PEA | PWP | |
|---|---|---|---|
| | | PIPWP | LIPP |
| Excitation method | Electric pulse | Pressure wave by piezoelectric device | Pressure wave by pulsed laser irradiation |
| Sample thickness | 100 µm-20mm | 100 µm-1.0 mm | 50 µm-20mm |
| Relative resolution | 2-5% | 2-5% | 2-5% |
| Minimum Space resolution | ~ 5 µm | ~ 5 µm | ~ 2 µm |
| Noise and electric shielding | High voltage and signal circuits totally separated Can be used in the event of corona discharge occurrence. | High voltage and electric circuits separated by coupling capacitor. Cannot be used when corona discharge occurs. | |
| Fast varying space charge distribution measurement | Possible | Possible | No report about it. |
| Measurement signal | Pressure signal | Displacement current | Displacement current |

### 3.2 Advantages

The PEA method has the following advantages over other techniques used in space charge measurement;

1) Simple and Robust Equipment: This allows the PEA method to be deployed in various environments and industrial applications [24].
2) Safe Method: For the PEA both high voltage and acoustic detecting circuits are electrically separated through the ground electrode, as a result protecting the amplifier and oscilloscope from damage in the event of an electric breakdown [29]. Hence, regarded as the safest technique for space charge measurement in cable samples through high voltage application.
3) Simple Principle of Operation: The PEA techniques do not need complex mathematical treatment just like the LIPP and PWP [14]. It has a simple modeling and is easy to implement for both plaque and cable samples [24].
4) Less Noisy Output Signal: This is due to the fact that the PEA's detection circuit can be shielded electrically [29].
5) It has a lower cost compared to other technique due to its simplicity.

### 3.3 Limitations

1) Only Two Dimensional Measurements: The conventional PEA technique can only measure space charge in amplitude and spatial location along the thickness of a sample. The planar non uniformities in the surface direction are not accounted for.
2) Measurement of Cables with Different Radius: The PEA technique has problem in the measurement of cables with different radius as modification is required of aluminium block

electrode, acoustic sensor, and PMMA absorber before it allows the change in cable radius [29]. This is quite a tasking and time consuming thing to do.

3) Spatial Resolution: The highest positional resolution that can be obtained using the conventional PEA technique is approximately 3 µm with deconvolution and 10 µm without deconvolution [20]. This is because the system spatial resolution is determined entirely by the pulse width and sensor thickness [29]. As a result, it cannot be used in applications with thin samples as low as 10 µm and approximately 1 µm spatial resolution, such as electron beam charge deposition in spacecraft charging and for high energy and plasma physics apparatus.

## IV. PROGRESS AND PROSPECTS OF THE PEA METHOD

The PEA method has undergone some improvements as discussed in the following;

### 4.1 Three-Dimensional Observation

New 3D PEA space charge measurement systems were developed [30] using acoustic lens and a new scanning system with small detecting electrode [31] to improve the measurement capability of the conventional PEA technique. The later allows space charge accumulated in small areas such as defects in insulating materials like voids, or trees, when high voltage is applied on the insulation material to be measured. The former allows accurate measurement of 3-D space charge profiles when the profiles do not change rapidly with time. This makes it easy to monitor long time ageing phenomena [32].

### 4.2 High Resolution

A refined PEA measurement system was developed [33] for use in thin dielectric materials. The conventional PEA method was only able to measure space charge of thick dielectrics materials of about (1-5mm). The refined system was able to improve the resolution of the PEA technique to 3 µm using the Fast Fourier Transform deconvolution to compensate for the piezoelectric sensor. Resolution in the lateral and thickness direction has been improved to approximately 100 µm and 2 µm respectively making it possible to investigate internal charge behaviors in composite materials such as insulation layers of printed circuit boards [32].

### 4.3 Portable PEA System

The conventional PEA system data requires computer deconvolution in order to display the space charge distribution of an insulation material. Maeno developed [23] a new PEA system whose output signal can display the space charge distribution directly on a portable oscilloscope without the need for deconvolution. This makes it possible to measure space charge distribution on site and can be used in various industrial applications. However, the spatial resolution of the space charge measurement of the new system is 10 µm as that of the conventional system [13].

Other advancements includes high repetition rate (time resolution) system capable of measuring space charge profile every 10 µs up to maximum of 1 ms [34], and an increase sensitivity of approximately 0.03-0.15 C/mm3[2].

The future of the PEA technique would be in its application in the nano dielectrics research field for space charge measurement, especially their interfaces with the electrodes [13], [35].

## V. CONCLUSION

The PEA measurement technique for space charge measurement has greatly improved since the over twenty years it was first introduced, as a result of advancement in technology. Most of the limitations identified with the conventional PEA system have been improved upon coupled with its advantages; hence it would continue to be the most widely used technique for some time to come.

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