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Comparative Study on Space Charge Distribution Measurements using PEA and PWP Methods on High Voltage Insulation

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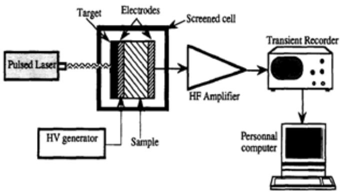
Graphical abstract



Abstract

Major drawbacks to high voltage insulator especially on electrical aging process have been an issue for decades. The internal electric field distribution due to the presence of local space charge will distort, which in turn may cause the insulating material to degrade and finally can lead to accelerated aging and electrical breakdown. Comprehension of space charge buildup in solid insulator is crucial to determine how aging occurs, thus enabling the prediction of insulator lifetime. Space charge measurement has been extensively researched in recent years and has become a common method of investigating solid insulator properties. Pressure Wave Propagation (PWP) and Pulsed Electro-Acoustic (PEA) are non-destructive dielectric testing methods used to determine the space charge distribution within the insulation. This paper presents the basic principles, typical measurement setup and comparison of results from several published papers on application of PWP and PEA methods to investigate space charge accumulation. The space charge distribution in the sample is measured as current and voltage signals obtained from PWP and PEA methods respectively. Judging from extracted results of other research, both methods show the capability to detect premature aging activities in the insulator, which is necessary for condition monitoring of high voltage insulators.

Keywords: Aging; breakdown; space charge; PWP; PEA

Abstrak

Kelemahan utama penebat voltan tinggi terutama padanya proses penuaan elektrik telah menjadi isu sejak beberapa dekad. Taburan medan elektrik di dalamnya akan terherot disebabkan oleh kehadiran cas ruang (space charge) setempat, yang seterusnya boleh menyebabkan degradasi bahan penebat yang akhirnya boleh membawa kepada penuaan dipercepatkan dan akhirnya pecah tebat elektrik. Kefahaman mengenai pembentukan cas ruang dalam penebat pepejal adalah penting untuk menentukan bagaimana penuaan berlaku, sekali gus membolehkan jangka hayat sesuatu penebat diramal. Pengukuran cas ruang telah dikaji secara meluas dalam beberapa tahun kebelakangan ini dan telah menjadi satu kaedah yang biasa dalam menyelidik sifat penebat pepejal. Perambatan Tekanan Gelombang (PWP) dan Denyut Elektro-akustik (PEA) adalah kaedah ujian dielektrik tidak musnah yang digunakan untuk menentukan taburan cas ruang dalam penebat. Kertas kerja ini membentangkan prinsip asas, persediaan pengukuran tipikal dan perbandingan keputusan daripada beberapa kertas yang diterbitkan ke atas aplikasi PWP dan PEA untuk menyiasat pengumpulan cas ruang. Pengagihan cas ruang dalam sampel diukur sebagai isyarat arus dan voltan yang masing-masing diperolehi daripada kaedah PWP dan PEA. Berdasarkan keputusan yang diekstrak daripada penyelidikan lain, kedua-dua kaedah menunjukkan keupayaan untuk mengesan aktiviti pra-matang penuaan dalam penebat, yang mana perlu untuk memantau keadaan penebat voltan tinggi.

Kata kunci: Penuaan; pecah tebat; cas ruang; PWP; PEA

1.0 INTRODUCTION

Many experiments conducted in the last several years have suggested that there is an influence of space charge buildup under electric stress on the performance of insulators. This includes distortion of electrical stress distribution due to space charge formation and accumulation, electrical treeing initiation, breakdown as well as insulation aging. Therefore, it is certain that presence of space charge greatly influences the electric field distribution within the material, resulting in enhancement of local electric fields which may lead to breakdown of insulation under nominal voltage. For this reason, it is possible to predict premature aging activities in an insulator from detection of space charge within its dielectric region.

Space charge measurement is a reliable non-destructive method and it has become a major concern of the electrical industry to investigate solid insulating material under high electric field. Space charge measurements provide researchers with means to detect magnitude, polarity and location of charge trapped in a dielectric. This shows that space charge measurement is a precious tool to evaluate the dielectric properties by comparing the tendency of material to accumulate charge. Many methods have been developed for probing space charge distribution in solid dielectrics. The most common method is by detecting the acoustic waves, as applied in Pressure Wave Propagation (PWP) and Pulsed Electro-Acoustic (PEA) methods [1], developed in Europe in late 70's and in Japan during the 80's [2] respectively.

In PWP [3, 4], an acoustic wave is usually generated externally either by a laser or piezoelectric transducer. This can be done by using the impact of short laser pulses [5] on a sample to be tested, whereas the piezoelectric transducer was acoustically coupled. Hence, methods such as Laser Induced Pressure Pulse (LIPP) and Piezoelectric Induced Pressure Pulse (PIPP) are developed. Both methods have the same principle of space charge measurement but different principles in the generation of acoustic waves. It is claimed in [6, 7] that there are problems when using laser to generate pressure waves (especially at high repetition rates) which are heating of the sample as well as damage to the sample. These drawbacks however can be avoided by using the piezoelectric transducer as in LIPP.

As opposed to PWP, an acoustic wave is internally generated in the PEA method [3, 4]. A voltage pulse applied to the sample will exert a force on the existing charges describe how the acoustic wave in PEA is generated. Various types of PEA systems [8] have been developed for DC electric field in determining the space charge distribution. They include three dimensional systems, transient systems, high and low-temperature systems as well as a portable and mountable system. The principles of PEA and PWP, including the measurement setup of the system and some results extracted from several published papers will be described in the following paragraphs.

■2.0 SPACE CHARGE THEORY

Generally, space charge is the charge density that exist in free space. All charged carriers including electrons, holes, charged particles or ions, which can exist within the dielectric material, trapped by or transported through the material under the application of external field also known as space charge [9]. In the context of dielectrics, space charge is an uncompensated real charge generated in the bulk of the sample. Space charge is important to consider in the insulation material because charge density, in any form, affects electric fields via Coulomb's Law.

A range of phenomena can caused space charge formation. This comprise a variation in conductivity, ionization of species within the dielectric, charge injection from the electrodes driven by a DC field not less than approximately 10 kV/mm [10, 11], and polarization in structures such as water trees. Of these phenomena, the first two contribute most to the space charge acumulation.

It is noteworthy to state that space charge will accumulate in the insulation material even though none of the space charge formation phenomena listed above occurs. This is influenced by the presence of space charge density, ζ due exclusively to the temperature gradient given by:

$$\zeta = \sigma E \bullet \nabla\left(\frac{\varepsilon}{\sigma}\right) \tag{1}$$

Where σ is the conductivity of the medium, ε is the absolute permittivity of the dielectric ($=\varepsilon_r \varepsilon_o$) , and E is the electric field. From Eq. (1), component σE is equal to steady state volume current density, J. When a homogeneous sample reach isothermal state, it will causes the ε and σ to vary spatially. Therefore, ζ ≠ 0 provided a flowing steady state current and (ε/σ) is not constant.

A wide variety of materials including ceramics, polymers and composites are homogeneous materials which contain both conductive and dielectric substances. However, interface mediums face a crucial problem since they are always inhomogeneous. This inhomogeneity causes loss when it is under voltage due to (ε/σ) gradient being not equal to zero [12]. Additionally, significant dependence of conductivity on the temperature and electric field also resulted in the accumulation of space charges.

In a resistively graded system, the magnitude of space charge due to a variation in conductivity is easily derived from Poisson's and current continuity equation as given in Carteisian coordinates by:

$$\zeta(x) = J\varepsilon \frac{d\rho(x)}{dx} \tag{2}$$

Where ζ is the space charge density, ε is the absolute dielectric constant, J is the current density, and ρ is the resistivity.

■3.0 PRINCIPLES OF PWP AND PEA

3.1 Pressure Wave Propagation (PWP)

A schematic diagram explaining the principles of PWP method is shown in Figure 1. An acoustic wave is generated when a pulsed electric field, $e_p(t)$ is applied to a piezoelectric transducer. In the case of LIPP, a laser would undertake the role of piezoelectric transducer. The charges in the material specimen are perturbed in turn as the generated acoustic waves propagate through the material specimen at the velocity of sound. This movement slightly modifies the internal electric field and causes a change of surface charge, σ_1 and σ_2 on both electrodes. This effect will be measured by the external circuit in term of current. The amplifier is used to amplify the measured signal since it is too small. The amplifier is fed to the oscilloscope and from there into a computer for signal processing and calibration purpose. The time (domain) signal of displacement current is directly related to the charge distribution within the sample. The charge distribution is acquired from the displacement current measured between the electrodes [13].

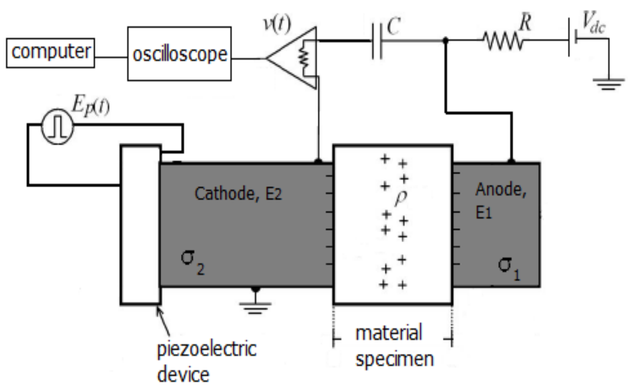


Figure 1 PWP space charge measurement

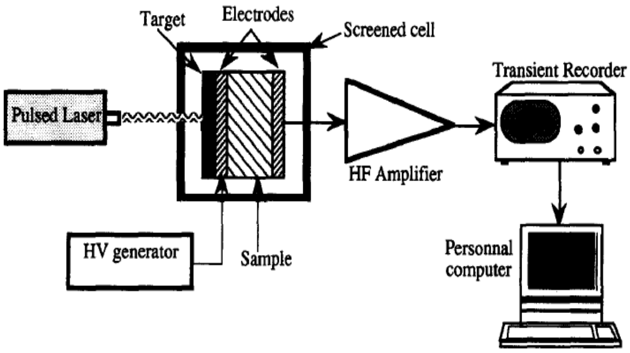


Figure 2 Experimental set-up of the PWP method [14]

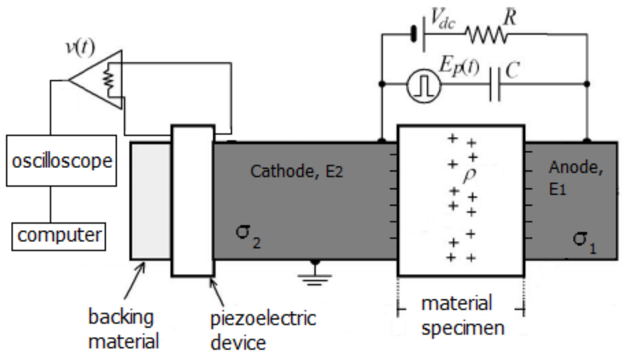


Figure 3 Principle of the PEA method

Figure 2 shows the example of measurement setup for the PWP method taken from [14]. The system usually consists of pulsed laser, high voltage generator, electrodes, high frequency amplifier as well as a dielectric sample. The changes in the internal electric field due to the propagation of pressure wave is measured as current at the external circuit. This current is recorded by transient recorder and can be monitored by a personal computer to provide the space charge distribution information. This typical measurement setup has been modified according to the industrial interest and demands by other researchers in [14].

3.2 Pulsed Electro-Acoustic (PEA) Method

The principles of PEA may be considered as the inversion of the PWP method. A schematic diagram of the principle of PEA method is explained using Figure 3. A very short, high voltage pulse that generated by a pulse source is applied to a material specimen that placed between two electrodes, E_1 and E_2. The space charge and charge at the electrodes experience the electrostatic force, also known as Coulumb force [4] due to the application of electric pulse, ep (t). This force causes the charge in the specimen to move slightly. The sudden movement of the charges launches an acoustic waves that is propagate in both direction, to E_1 and E_2. The wave propagating is initially moved to the electrode material in the direction of E_2. The electrode material acts as a delay block for the acoustic waves until its arrival at piezoelectric device in order to avoid the interference of electromagnetic noise caused by ignition of the electrical pulse. Meanwhile, the wave is first reflected at E_1 in the direction of E_1 and finally reflect back to the same acoustic path as E_2. These waves are detected by a piezoelectric sensor attached to the electrode. The piezoelectric device acts as a converter which converts the acoustic signal to an electric signal. This electric signal is fed into the amplifier and oscilloscope to acquire an easy measured signal, and finally to a computer. All captured signals will be stored in a computer for signal processing and calibration purpose. The amplitude of the signal that measured from the amplifier is related to charge density, and the delay indicates distance of the charges from the sensor which revealed the position of the charges [1, 4, 15].

Figure 4 shows an example of elementary setup of the PEA method adopted from [8]. Beside dielectric sample, the parts of the system usually consist of high voltage, electrode, amplifier, absorber, and piezoelectric device. This setup had been applied to several measurement setups [16-18] by modifying it in order to fulfill the requirement of the systems. For the high voltage part, a DC power source and pulse generator that mounted in parallel across two electrodes. A protecting resistor is connected in series to DC supply acts as current limiter in case of breakdown. In order to reduce the ripple voltage, a coupling capacitor is connected in series to the pulse generator. Typical values for the pulse voltage and pulse width are 0.1~2 kV and 5~200 ns, respectively [9].

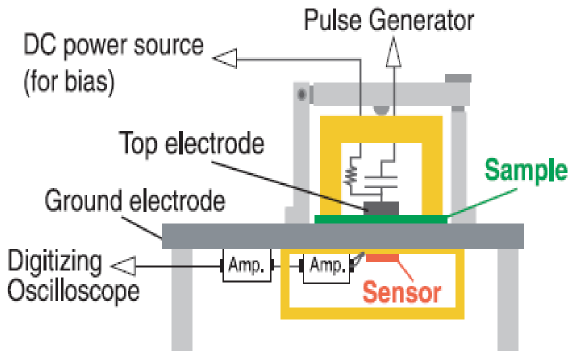


Figure 4 Basic set-up of the PEA method [8]

4.0 MEASUREMENT RESULTS AND DISCUSSION

Figure 5 shows an example of charge, electric field and potential distribution waveform represented by red line (q), blue line (E) and green line (P) respectively, extracted from [8]. These three profiles are obtained when a DC bias voltage is applied to a polystyrene sheet which does not contain internal charge. Since the sample contains no space charge, only the induced charges on the electrode were observed. The electric field distribution E(z) is obtained by integrating the charge profile, while the integration of E(z) provides the distribution of electric potential.

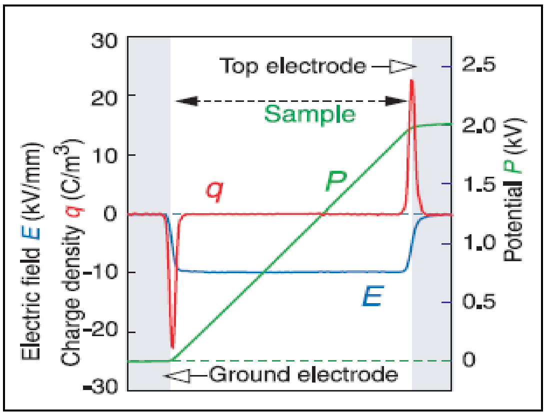


Figure 5 Example of profile obtained by PEA [8]

The resolution of the measurement system can be obtained from the widths of the peak and valley of the space charge density waveform. The peak and valley is actually representing the induced surface charges on the electrode. The system is said to have a high resolution when the widths between the peak and valley is narrower. It can be seen from the charge distribution profile in Figure 5 that there is no other peak or valley appearing in between them since the sample does not include any space charge.

An example of experimental results for Poly Methyl Methacrylate (PMMA) that contain space charge extracted from [19] is shown in Figure 6. The PMMA sample was irradiated by an electron beam at 200 keV and 1.0 nA/cm2 for 3 hour. The existence of valley between two peaks shows the occurrence of space charge distribution in the sample. This space charge ultimately changes the shape of electric and potential distribution waveform. The potential distribution in the sample resembles an inverse triangle as illustrated in Figure 6. The peak of inverse triangle located at the same position where the value of E(z) is zero. It is claimed in [19] that density of the space charge distribution in the specimen can be measured by measuring the amplitude of the valley.

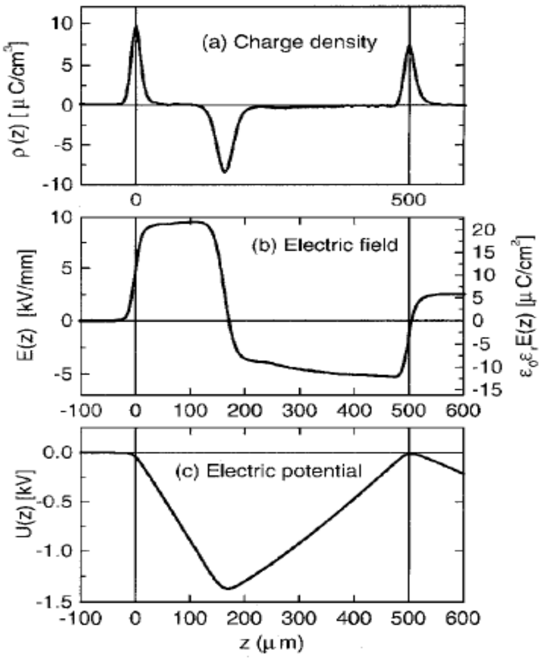


Figure 6 Experimental results of PMMA sample contain space charge [19]

The existence of space charge also can be characterized according to their polarity, homocharges and heterocharges. Homocharges refer to the charges with the same polarity to the adjacent electrode while heterocharges is reverse situation. Figure 7 shows an example of experimental results taken from [20] for Polycarbonate (PC) with titanium dioxide (TiO_2) filler that applied with 45.7 kV/mm for 3 hour to analyse the space charge behavior of the material for long-term exposure to a DC electric field. Homocharge is detected in the adjacent electrodes in both virgin and pre-stressed specimens. Small valley of heterocharge is discovered in pre-stressed PC-TiO_2 when measurement done 10 minutes after switching off 45.7 kV/mm charging field. However, there is large valley of heterocharge discovered when measurement done after 100 minutes after switching off.

Both PWP and PEA methods has received much interest by researchers throughout the world as can be seen by many papers published recently. PWP methods especially in LIPP provides advantages such the measurements are carried out relatively fast which requiring only about 1 μs for a 2mmthick polyethylene sample, the signal-to-noise ratio level is high and no problem of reflection at the sample boundary [18]. Nevertheless, heating of the sample as well as causing the sample suffered damage contribute to the weaknesses of PWP methods. Researchers in [21] have designed a three dimensional (3D) PWP system with a high frequency immersion ultrasonic transducer as the source of acoustic wave. This system has a capability of measuring the space charge characteristics in thin plaques of polymeric materials.

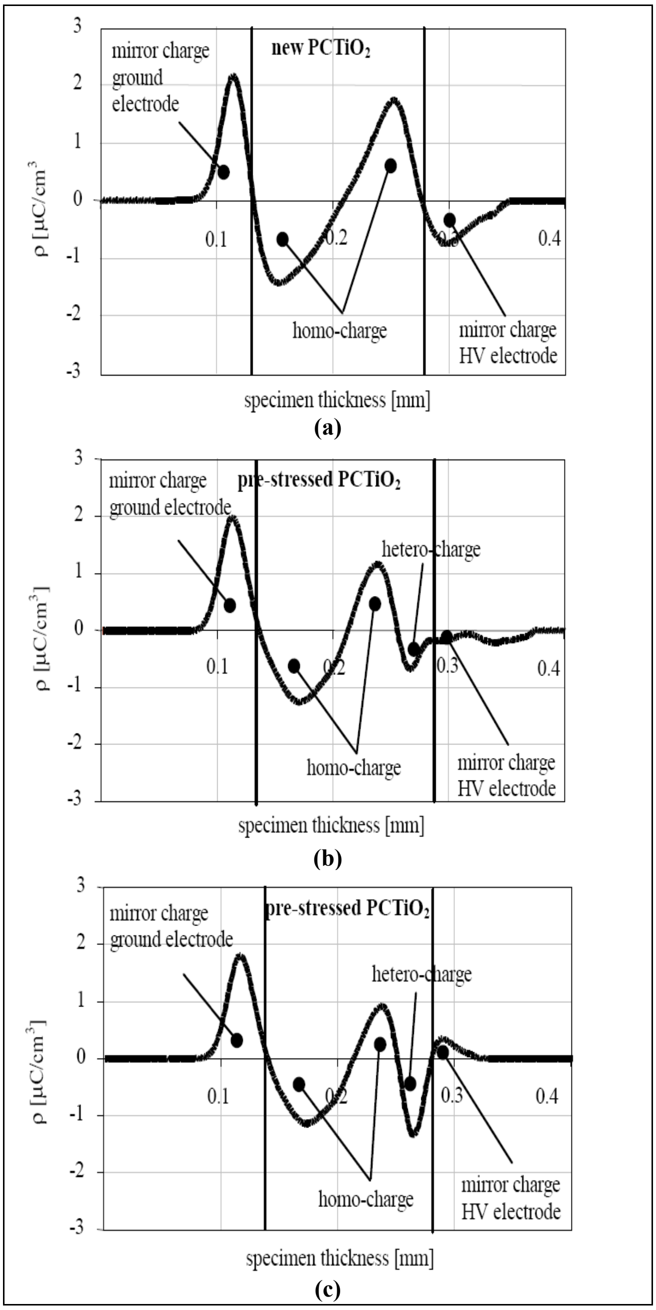


Figure 7 (a) Homocharge detected, (b) Homocharge and heterocharge detected measurement done 10 minutes after switching off 45.7 kV/mm charging field, (c) Homocharge and heterocharge detected measurement done 100 minutes after switching off 45.7 kV/mm charging field [20]

The interest on PEA arises because of the presence of space charge is easy to be measured. The density of the space charge distribution can be estimated directly from the amplitude of the peaks where space charge exists, without requiring complex mathematical treatment or deconvolution process. The development of portable PEA in [17] proves that PEA is easy and simple setup which makes it easy to apply into various environments and industrial needs. A portable space charge measurement system using PEA method had been developed in [17] employs a new voltage waveform generator. The output signal shows the space charge distribution directly, without the need for deconvolution. Since the space charge profiles change with time, researchers in [16] have developed the PEA system that can measure the space charge profiles for every 10μs for high speed measurement system. This development allows users to observe space charge dynamic under transient electrical stress such as AC field which contribute to the advantages of PEA.

Although the application of PEA for AC electric field is limited, by no means it can be neglected due to the wide usage of AC systems worldwide in transmission of electrical power. A temporary displacement of space charge can be seen more preferable under DC stressing condition application for PWP and PEA methods. In general, the flow of charge which maintains in the same direction allows a build-up of charge. This will significantly affect the electric field distribution inside the insulation. Whereas, the flow of charges inverts its direction rapidly in the AC situation prevent the growth of space charge at the insulation inhomogeneities. However, due to the development of increasingly sophisticated measuring technology, space charge distribution can be measured under AC stress.

In the author's opinion, the PEA method provide a safe system because the high voltage circuit and signal detection circuit are completely separated, preventing damage to the detection system in case of an electric breakdown occurs. In order to have less noisy output signal, the detection circuit is electrically shielded.

■5.0 CONCLUSION

With the increase of industrial application of space charge measurements, the two methods play an important role in measuring space charge to enable prediction of insulator lifetime. It is important to measure the existence of space charge since it modifies the electric field distribution within the insulation, resulting in enhancement of local electric fields, ultimately leading to breakdown. Both methods has a huge potential and should expand applicable research fields. Of the techniques discussed above, LIPP and PEA are the most frequently used nowadays. However, the application of both methods under AC stress is still under developed due to the difficulty to excite the space charge at exact times of the alternating electrical pressure. Further, the possibility of utilising the information from either methods for condition monitoring of insulators are being investigated.

Acknowledgement

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