A system for PEA space charge measurement on HVDC mini-cables under different isothermal temperatures

Influence of cable clamping force on PEA measurements

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***Abstract*—A Pulsed Electro-Acoustic (PEA) apparatus has been developed to measure the space charge distribution inside cable insulation. The technique relies on acoustic contact between the cylindrical cable surface and a flat aluminium plate to couple the acoustic waves to the sensor. This work addresses the practical issue of the clamping force required to maintain good contact and how this may alter the measured space charge distribution. Space charge measurements on mini-cables (model cables) were carried out over a wide range of clamping force and additionally a finite-element simulation model has been developed to model mechanical deformation of mini-cables and provide data that cannot be easily obtained from experiments. A clamping force range for reproducible measurements at room temperature has been determined by comparing results from a group test on a mini-cable.**

Keywords—PEA; cable deformation; clamping force

I. Introduction

The PEA method has been used extensively to measure space charge distributions in flat (usually thin film) samples and the technique has matured during the last decade [1]. Applying the PEA method to cylindrical samples (cables) was first attempted using a curved base electrode and piezoelectric senor (PVDF film) [2] to match the curvature of the cable surface and maintain the cylindrical propagation of acoustic waves. However, practical difficulties arise when using a curved electrode. Firstly, a good homogeneous acoustic coupling is hard to obtain if the cable has a non-perfect curvature. Secondly, the curved electrode can only be used for cables of one size. To overcome these difficulties, cable PEA systems with a flat earth electrode have been developed [3-5]. In this case, acoustic waves are coupled to the flat aluminum electrode along the 'line' of contact. However, it is noticeable that cables of cylindrical geometry would deform when being pressed against the flat electrode thereby changing the area of contact through which the acoustic waves pass from cable to electrode. Induced mechanical strain could also influence the propagation of the acoustic waves and directly alter space charge accumulation. Thus there is a degree of uncertainty when clamping the cable to the PEA electrode; raising a practical question of how much force (or pressure) should be used. Moreover this becomes important when doing high temperature measurements where cable samples become softer and exhibit enhanced deformation due to the different thermal expansion coefficients of the insulating material and the clamping system. In this paper the acoustic wave propagation through a cylindrical cable/plane electrode PEA system will be considered experimentally as a function of clamping force to address the problem of how clamping pressure affects cable deformation and the PEA output signal.

II. PEA Space charge measurement system for mini-cables with flat electrode

A. Acoustic Path

The acoustic path for a flat electrode PEA system for cables [6] is illustrated in Fig. 1. Under an applied voltage pulse, acoustic waves are generated by displaced space charges within the cable insulation. These will travel through the cable insulation, outer semicon layer, aluminum bottom electrode and finally act on the piezoelectric sensor. As the extruded semicon layers are made from carbon loaded insulation [7], they will have similar acoustic properties to the insulation material. In this case, there is no significant acoustic reflection at the outer semicon layer/insulation interface. Air surrounding the mini-cable sample acts as a soft boundary for the acoustic wave, so nearly all acoustic energy would be reflected back into the cable at the cable/air surface. Only the 'window' of contact between the outer semicon layer and the plane electrode will allow acoustic waves to propagate from the cable into the plane electrode and onwards towards the piezoelectric sensor. As the mini-cables deform under the clamping force, the contact area and accordingly the total acoustic energy transmitted into the bottom electrode will change with clamping force at the same temperature or at different temperatures due to a change of clamping force from thermal expansion and softening of the cable insulation material.

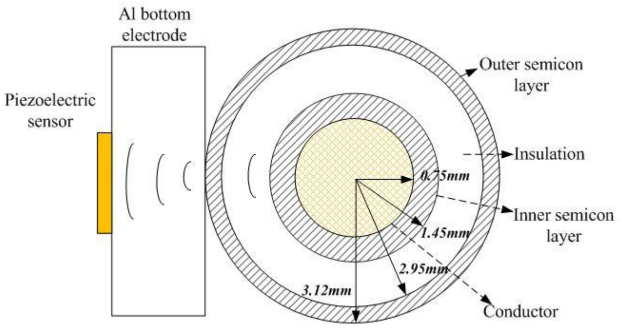

Fig. 1. Acoustic path and dimension of the mini-cable.

B. *Piezoelectric sensor voltage*

The output voltage, V_p, of a piezoelectric film is given as:

$$V_p = \frac{Q}{C} = \frac{kPA}{(\varepsilon_0 \varepsilon_r / t) A_P} \quad (1)$$

Where, Q is induced charge on the piezoelectric film, C is the equivalent capacitance of the piezoelectric film which depends on its dielectric permittivity ε_r, thickness t and area A_p. A pressure, P, acts on cable contact area, A, and a constant k takes into account the cylindrical propagation of the acoustic waves in the aluminium base plate and the piezo-electric constant of the sensor. For a PEA system designed for thin film (planar) samples, the area of the film sample between electrodes is usually similar to the area of sensor film. In this case, due to the plane acoustic waves produced it is usually taken that the sample area A and the area of the sensor film A_p have approximately the same value. However for cable PEA system with a flat electrode, the contact between the cylindrical cable and the flat bottom electrode is a line contact whose area of contact is small hence producing acoustic waves with cylindrical wavefronts. The acoustic energy contained in these will spread out into the aluminium plate before reaching the piezo sensor. It is also difficult in practice to use a piezoelectric film having an area smaller than the contact area between sample and bottom electrode. In addition, reducing the area of sensor film results in a reduction of its capacitance, which would worsen the impedance match between the piezo-sensor and amplifier as discussed in [8]. Consequently, for cable PEA system with flat bottom electrode, the actual acoustic energy reaching the sensor will be dependent on the area of contact, A, as well as the fixed quantities of base electrode thickness and area of the piezo film, A_p.

III. EXPERIMENTS AND SIMULATION

A. *Experimental*

In order to verify the effect of clamping pressure on the acoustic path described above and to evaluate how clamping force affects the internal strain in the cable insulation that may also affect acoustic wave propagation, a series of experiments to measure space charge in mini-cables has been undertaken at room temperature. The measurements were obtained using a PEA space charge measurement system specifically designed for variable cable clamp force. The structure and dimension of the mini-cable has been given in Fig.1. During the tests a relatively low DC bias voltage of 10kV was applied to the cable conductor to generate a maximum internal field of 10 MVm^{-1} sufficiently low to avoid space charge accumulation in the insulation and such that only surface charges at the two semiconductor layer/insulation interfaces are produced. The mini-cable was clamped to the bottom plane electrode using a spring loaded cable clamp that is integrated on to the PEA cell. The clamp has a length of 30mm in line with the axial direction of mini-cable. Measurable and reproducible clamping force was then achieved by controlling the compression of a spring.

B. *Simulation*

The contact area between the cable and electrode is of primary interest. To calculate the deformation of the cable subject to the specific clamp force in our system, a simulation model was developed using COMSOL Multiphysics. This enables the evaluation of the contact area of cable. In addition, the maximum mechanical stress within the cable insulation was also calculated. This stress could lead to induction of a non-homogeneous radial mechanical stress in the cable insulation across which the space charge measurement is conducted. In addition, there is a fundamental limit for the clamping force to prevent the onset of mechanical damage to the insulation of the cable (e.g. when plastic deformation starts).

A typical simulation result is shown in Fig.2. A mini-cable sample with the same dimensions as shown in Fig.1 is clamped to the bottom electrode using 3-point contact. The length of the cable clamp is 30mm along the cable axial direction. When a force of 470N was applied, onto the cable clamp, the contact width, d, is approximately 1.35mm. The high clamping force also results in high compressional stress in the vicinity of the inner and outer semicon layers. The maximum von Mises stress in the cable was calculated to be around 10 MPa.

Since the length of contact area is fixed by the size of cable clamp, the contact area, A, varies in proportion to the contact width d. The results from repeat simulations for various clamping force are shown in Fig.3.

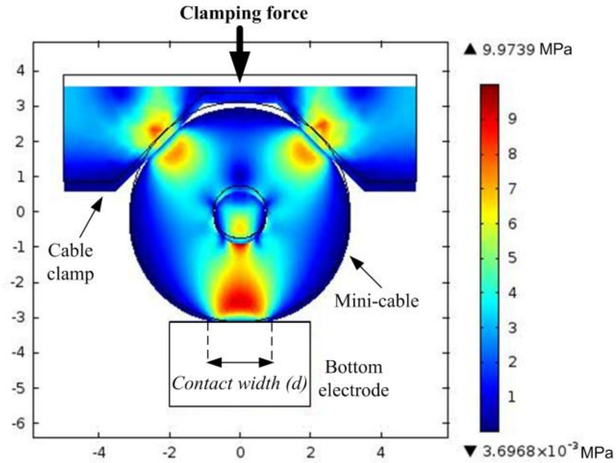

Fig. 2. Surface plot of the von Mises stress [9] on the cross-section of mini-cable when applying 470N clamping force. (semicon layer and insulation are included in the same domain due to their similar mechanical properties).

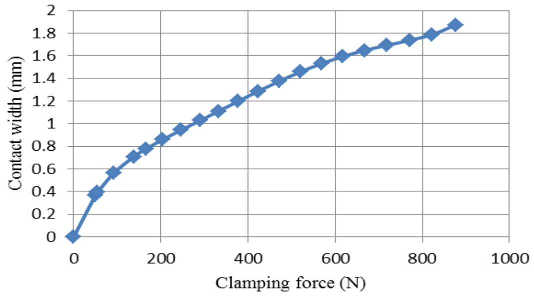

Fig. 3. Contact width, d, between the cable and bottom electrode as a function of clamping force.

A plot of the maximum von Mises stress induced within the insulation domain under a range of clamping force is shown in Fig.4. Assuming the yield stress of the insulation material is around 10 MPa, the clamping force is required to be below 500N to avoid plastic deformation of the cable (or even lower to avoid delamination at the semicon/insulation interface).

IV. SPACE CHARGE RESULTS AND DISCUSSION

A. *Raw data*

Raw data obtained from the time averaged amplified output signal of the piezo sensor of the PEA cell is shown in Fig. 5 for a range of cable clamping force. The area of the voltage signal (integral of piezo-voltage over time) under the peak corresponds to the semicon/insulator interface charges and these areas are proportional to the net charge density once corrections have been made for dispersion and attenuation of the acoustic signal as it propagates through the insulating material.

The smallest possible spatial resolution of the space charge at P_1 and P_2 is determined by the width of the voltage pulse acting on the cable conductor. In this case, pulses with a width of 20ns and magnitude of 800V were utilized. However, as the acoustic wave suffers dispersion and attenuation as it propagates through the cable insulation and semicon layers, the acoustic signal from the outer semicon/insulation interface, P_1, is less attenuated and dispersed compared with pulse P_2 and it maintains about the same width as the pulsed voltage [10]. The acoustic wave generated at the inner semicon/insulation interface travels through the whole of the XLPE insulation (1.5mm) and outer semicon layer resulting in significant pulse

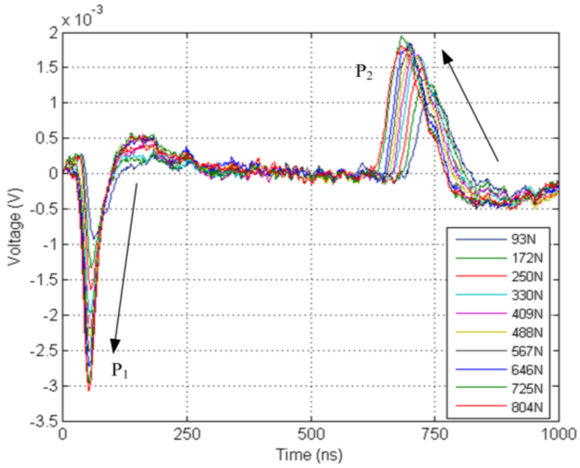

Fig. 5. Raw output data of the mini-cable PEA system. A range of clamping force were applied on a mini-cable with HVDC=10kV, pulse 800V, 20ns.

broadening. The half-height pulse width of P_2 is about twice that of P_1. Normally for space charge measurements, the raw data has to be processed to recover the space charge distribution. It is essential when acquiring the raw data that the frequency response of the system must be flat over the range of frequencies present in the acoustic wave. In the case of P_1 in the raw data shown in Fig. 5, it will contain higher frequency components than P_2. The shape of P_1 shows that a frequency dependent acoustic transmission coefficient does not exist at the cable/bottom electrode interface as no variation of the duration and shape of P_1 is found under different clamp force.

B. *Response with clamping force*

According to the raw data shown in Fig. 5, the voltage signal becomes greater with higher clamping force. Moreover P_2 shifts to left and broadens slightly with increasing clamping force. This is due to the compressive deformation of the mini-cable reducing the thickness of the insulation. The variation of peak area of P_1 and P_2 are plotted in Fig. 6. The area under P_2 was found to be higher than under P_1 owing to the cylindrical geometry of the cable in which the electric flux density and interface charge density is highest at the inner semicon/insulator interface. The peak areas are observed to increase with clamping force. In Fig. 7, the ratio of peak area to contact width is plotted as a function of clamping force.

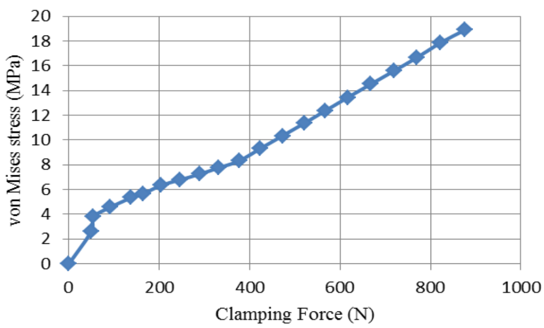

Fig. 4. Maximum von Mises Stress in the cable insulation domain under different clamping force applied on the cable.

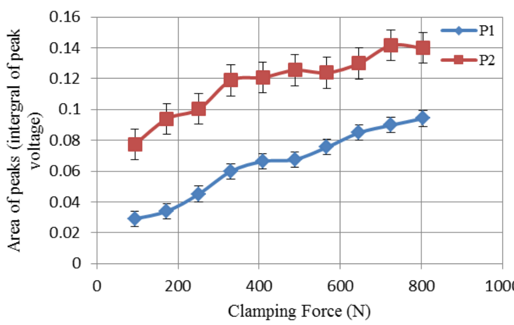

Fig. 6. Area of the signal peaks under different clamping force.

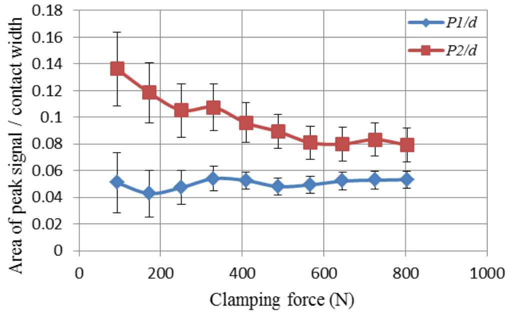

Fig. 7. The ratio of the area of signal peaks to the contact width at different clamping force

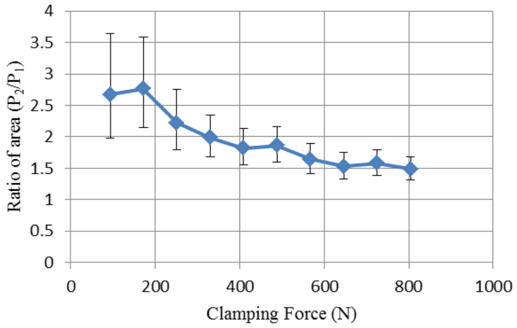

Fig. 8. Ratio of peak areas as a function of clamping force

The ratio of peak area to contact width, P_1/d in Fig. 7, is independent of the contact force (to within experimental uncertainties) confirming that the acoustic energy transferred from the cable to the plane electrode is proportional to contact area. However at low clamping force, the contact obtained experimentally is not well controlled as indicated by the error bars and may have a quite different contact area compared to the values obtained through simulation.

The ratio of P_2/d shown in Fig. 7 and the ratio of the two areas of the two peaks, P_1 and P_2, shown in Fig. 8, decrease as a function of increasing clamping force. For clamping forces above 500N, and hence exceeding the compressive yield stress of the insulation, the ratio remains constant within the measurement error. However the downward trend observed in the data below 500N in Figs. 7 and 8 are due to stress induced changes in the acoustic wave propagation characteristics of the insulating material (absorption and dispersion). This is also reflected in the raw data of Fig. 5 where a slight increase in the pulse width of *P2* is observed with increasing contact force indicating an increase in the dispersion of the acoustic wave as it travels through the cable insulation.

The observations above have obvious consequences for signal calibration and in the processing required to extract the space charge profile. Correction of attenuation and dispersion is usually achieved by comparison of the pulse shapes of P_1 and P_2 in the frequency domain [11] to obtain the attenuation and dispersion propagation parameters for the cable insulation material. In addition variation in the contact area due to changes of temperature will also require the raw signals to be recalibrated and reprocessed for experiments conducted at different temperatures.

V. Conclusion

The effect of clamping force on the measurement of space charge in mini-cables using the PEA technique has been evaluated. Cable deformation under increased mechanical clamping of the cable onto the base plate of the PEA results in an increase of the contact area and coupling of acoustic energy to the piezo sensor contributing to an enhanced PEA signal. No significant deformation dependence was found for the acoustic transmission coefficient at the cable/bottom electrode interface for this PEA system. However there was some indication that induced mechanical stress in the cable insulation may inflence the propagation coefficients of the acoustic wave in the insulating material. The work described here demonstrates the necessity to confirm or otherwise discount the impact of cable clamping force on measured space charge, otherwise the technique is likely to impose systematic errors on measured data.

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