Feasibility of using a flat bottom electrode for PEA space charge measurement on mini-cables under high temperatures

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Abstract-* Pulsed Electro-Acoustic (PEA) apparatus has been developed to measure the space charge distribution inside XLPE based mini-cable insulation. The technique relies on the acoustic contact between the cylindrical cable surface and a flat aluminium plate to couple the acoustic waves to the sensor. This work addresses the feasibility of using this technique over a temperature range of 25 °C to 70 °C. The results demonstrate that increasing the temperature under constant clamping force causes the cable insulation to soften and distort increasing the contact area and signal from the PEA apparatus. However on subsequent cooling to 25 °C the mechanical distortion remains frozen-in with little change to the contact area. For reproducible space charge measurements it is necessary to first condition the cable sample by taking the cable and PEA through a temperature cycle before application of the applied voltage.

I. INTRODUCTION

Space charge measurement on cable insulation is of interest for cable manufactures in order to evaluate the reliability of HVDC polymeric cables. Under DC applied field, space charge accumulation is possible that alters the internal electric stress that can lead to the initiation of damage that eventually leads to electrical breakdown [1, 2]. HVDC cables are also subject to thermal stresses that lead to increased charge injection and extraction, transport and trapping of charge carriers and will influence the dynamics of space charge accumulation. Mini-cables, manufactured using the same methods and materials as commercial full size cables, have been used to study space charge accumulation as they are regarded as representative of full-size commercial cables. Due to the reduced size of mini-cables, the experimental cost and complexity are much less than that for equivalent experiments based on full-size cables. Moreover, accurate measurements of space charge dynamics are required for understanding and identifying the key physical processes that lead to space charge accumulation and in the development and verification of charge transport simulation models [3] that can predict space charge dynamics in commercial cables.

A variety of space charge measurement techniques have been developed during the last decades [4]. Among them, the Pulsed Electro-Acoustic (PEA) method [5] has been used extensively due to its apparatus simplicity and limited cost. The PEA method is inherently suitable for measuring flat thin film samples as the plane acoustic waves generated by space charge can propagate to a planar piezo sensor. More recent developments have been devoted to adapt the PEA technique for the measurement of space charge in cylindrical cable geometry samples. Two different methods have been proposed to couple the cylindrical acoustic waves produced in the cable insulation to the base electrode. One method [6] is to use a base electrode having a curved surface that matches the outer curved dimension of the cylindrical cable sample. In this case the acoustic waves will maintain a cylindrical profile when crossing into the base electrode. The alternative method [7, 8] is to use a flat base electrode and rely on the 'line of contact' between the cable surface and the base electrode to couple the acoustic wave. In this case, the 'line of contact' acts as a secondary source of cylindrical acoustic wavefronts that then propagate to the piezo sensor. The flat electrode PEA technique features flexibility in that the dimension (radius) of cable samples is not critical while for the curved electrode technique, the lower electrode must be manufactured with a curved channel that closely matches the cable sample under test. However the flat base electrode PEA technique is not without problems. The influence of clamping force on a flat electrode PEA space charge measurement system at room temperature has been evaluated previously [9]. It was found that the application of a clamping force acts to distort the profile of the cable insulation and the outer semicon layer to produce an 'area of contact' rather than an ideal line contact. This is illustrated in Fig. 1 where a finite element simulation was employed to determine the elastic deformation of the cable for a given clamping force. These simulations and subsequent experiments demonstrated that the amount of acoustic energy coupled through to the base plate and therefore the sensitivity of the PEA was related to the area of contact. Furthermore, the application of high clamping force also induce a non-ideal non-uniform mechanical stress within the measurement region which could influence the propagation of the acoustic waves as well as to modify the electrical properties of the insulation that influence space charge build-up. The present work discusses further the feasibility of using a flat electrode PEA system for space charge measurement in mini-cables under a range of isothermal temperature conditions between 25 °C and 70 °C.

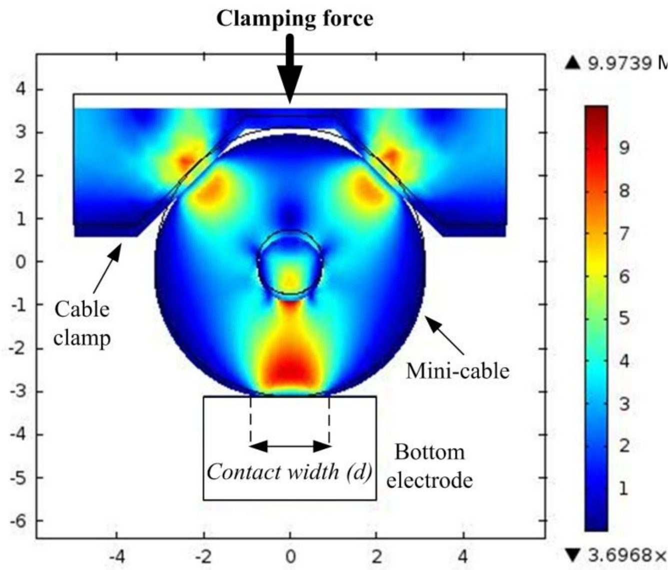


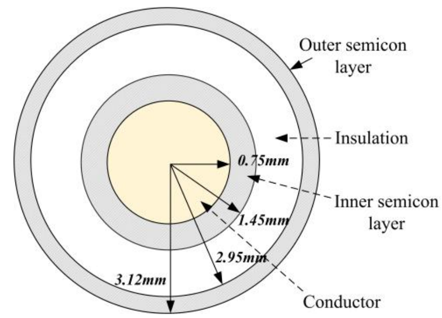
Fig.1 Surface plot of the von Mises stress [10] on the cross-section of mini-cable when applying 470N clamping force (semicon layer and insulation are included in the same domain due to their similar mechanical properties). [9]

II. Experimental

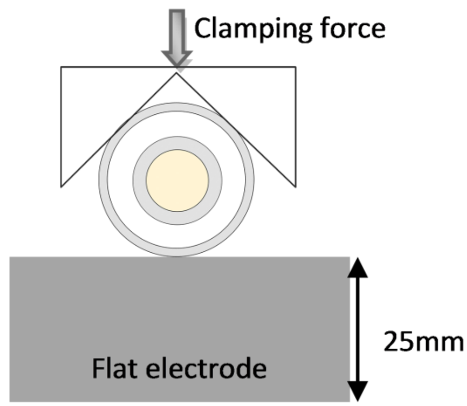
A. Experimental setup

In order to evaluate the feasibility of using a flat electrode PEA measurement system for measurement of space charge in mini-cables under high temperatures (up to 70 °C), a specifically designed measurement system used previously [9] for controlled clamping force was used. This system was fitted into a temperature controlled oven giving the ability of taking space charge measurements under a range of isothermal test conditions (25 ˚C to 70˚C). The piezo sensor employed in the PEA cell was a co-polymer of PVDF (PVDF-TrFE) film which features enhanced stability under high temperatures in excess of 70 °C [11].

The samples under tests were degassed XLPE mini-cables having a length of about 1.2m, which is short enough to be treated as lumped capacitor. The dimension of the insulation layer inner radius was 1.45mm and outer radius of 2.95mm extruded together with inner and outer semiconducting layers as shown in Fig. 2 (a). The DC bias voltage and voltage pulses were applied to the two ends of the cable conductor. The outer semiconducting layer was stripped back by 0.2m at each end of the mini-cable to prevent flashover between the central conductor and the earthed outer semicon layer. The flat base electrode was an aluminium block with mirror-finished surfaces on both sides having thickness of 25mm. The mini-cable was clamped against the flat surface of the bottom electrode through a three-point contact as illustrated in Fig. 2(b). The acoustic waves produced by space charge on application of the voltage pulse were then coupled form the mini-cable to the bottom electrode, and then onwards to the piezoelectric sensor, through the limited clamping force dependent contact area between the mini-cable and electrode.



(a)



(b)

Fig. 2. (a) Structure and dimensions of mini-cables. (b) Schematic diagram of the PEA cell with the flat electrode.

B. Space charge measurements

For convenience and to simplify interpretation of the PEA measurements, a low DC bias voltage of +8kV was applied to the inner conductor of the mini-cable under test. This voltage is sufficiently low to avoid space charge accumulation over the time scale of the experiments. The pulse voltage applied to the cable was 1kV for a duration of 25ns to induce acoustic waves. Therefore only the surface charges due to the applied bias voltage at two semicon/insulator interfaces would be detected by the PEA system. Space charge measurements were taken at intervals while subjecting the test system to a thermal cycle as shown in Fig. 3.

III. Results

The amplified raw signal from the piezo sensor was averaged over 1000 cycles to reduce the incoherent noise produced by the amplifier. Typical averaged signals recorded for a cable clamp force of 250N at temperatures of 25 ˚C (before the thermal cycle), 70˚C (during the thermal cycle) and 25 ˚C (after the thermal cycle) are shown in Fig. 4. Calibration and signal recovery algorithms (deconvolution of the instrument IRF, cylindrical geometry correction and correction for attenuation and dispersion of the acoustic waves) required to recover the space charge density from the raw data were not considered here as the main focus of this work was first to establish the experimental conditions required for reproducible data acquisition. In each case shown in Fig. 4, the time dependent voltage consists of two peaks, V_1 and V_2. The first peak is due to the acoustic waves generated by the negative charge at the outer semicon – insulator interface arriving at the piezo sensor. The second peak, V_2, is due to the acoustic wave produced by the positive charge at the inner semicon-insulator interface. The time delay between these two peaks is related to the temperature dependent acoustic wave velocity in the cable insulation material and the thickness of the insulation material. The time shifts, Δt, between the peaks of V_1 recorded at each temperature are due to expansion and change in acoustic velocity of the aluminium base plate as well as the outer semicon layer. Although the position of V_1 returns to the same time position following the temperature cycle, the position of V_2 becomes earlier in time after the thermal cycle compared to its position before the thermal cycle. The positive voltage overshoot after V_1 in all cases is due to the IRF of the system rather than due to the accumulation of space charge.

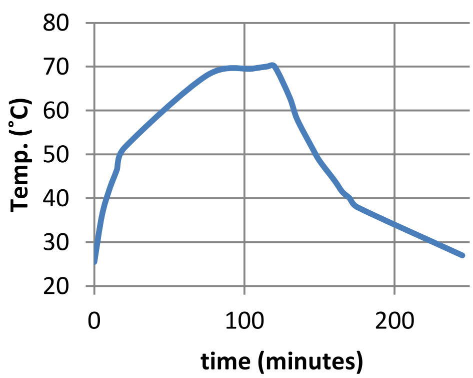


Fig. 3. Temperature of the PEA cell during heating and cooling processes of the thermal cycle.

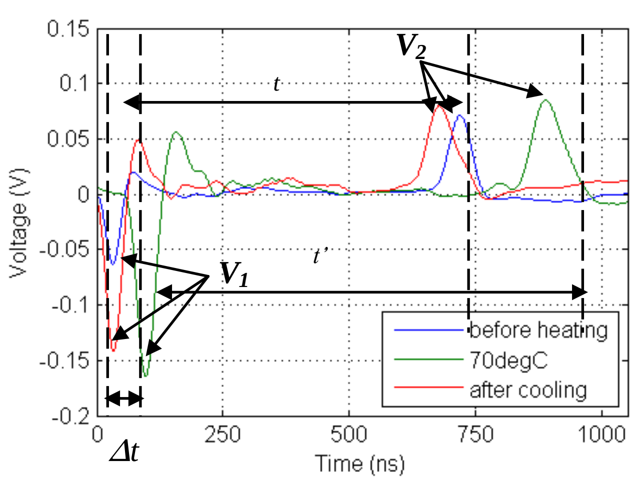


Fig. 4. Averaged raw output of the flat electrode PEA system with +8kVDC bias voltage and a clamping force of 250N applied on a 30mm cable clamp.

IV. Discussion

To compare the waveforms of Fig. 4 it is useful to normalise the time axis for the 70 °C data to take into account the different acoustic velocities of the aluminium base plate and the cable insulation at 25°C and 70 °C. According to [12], the acoustic wave velocity in XLPE decreases by 25% on increasing the temperature from 25 °C to 70 °C. Applying this correction and shifting the time axes of the three data sets to compensate for the change in acoustic velocity in the flat aluminium electrode, the averaged raw data, after converting the time axis to distance using the acoustic velocity at 25 °C can be re-drawn as shown in Fig. 5.

In Fig. 5, the initial PEA measurement taken at 25 °C before the thermal cycle differs significantly to that of the subsequent measurements taken at the elevated temperature of 70 °C and when the temperature is then returned back to 25 °C after the thermal cycle. First, the amplitude of the peak (V_1) measured at the beginning of the experiment is significantly less than the peak V_1 measured at 70°C and following return to 25 °C. The second peak, V_2, retains a similar amplitude for all three measurements but the initial measurement appears to have a reduced duration. The second difference between the original measurement at 25 °C and subsequent measurements is that the measured distance between the peaks has reduced on heating to 70 °C but that no further changed occurred when cooling back to 25 °C. This observation therefore demonstrates that as the temperature is increased to 70 °C, the softening of the cable insulation has caused the cable insulation to deform further under the same mechanical clamping force and therefore the additional deformation has resulted in an increase of the contact area between the cable insulation and the flat aluminium base plate. On cooling this deformation appears to be ‘frozen in’ with only slight decrease in the amplitude of the space charge profile.

In order to examine the shapes of the electrode peaks for the three sets of averaged raw data, the voltage data of Fig. 4 was normalised in terms of the peak voltage of peak V_1. Time shifts were introduced in order to superimpose the three peaks on top of each other as shown in Fig. 6. The normalisation process was then repeated for peak V_2 as shown in Fig. 7.

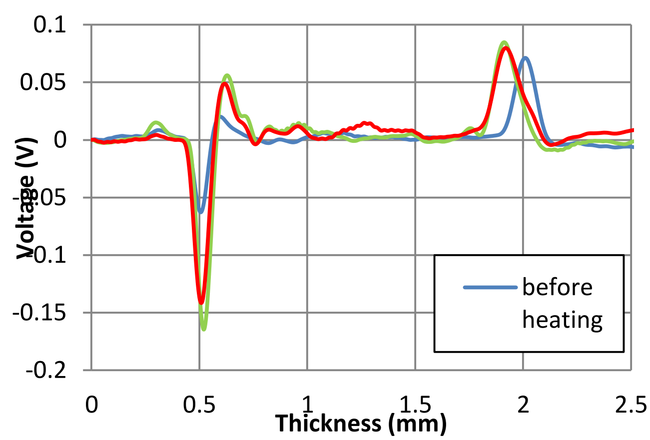


Fig. 5. Averaged raw data rescaled to correct for acoustic velocity difference at 25 °C and 70 °C and with time axis converted to distance.

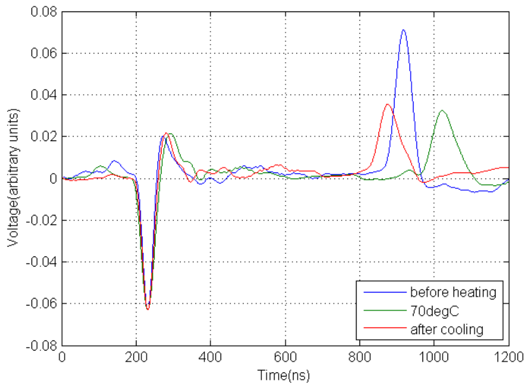


Fig. 6. Averaged raw output signal after normalisation of the amplitudes of the first peak, V_1. Time has been shifted to align peak V1for the three sets of data.

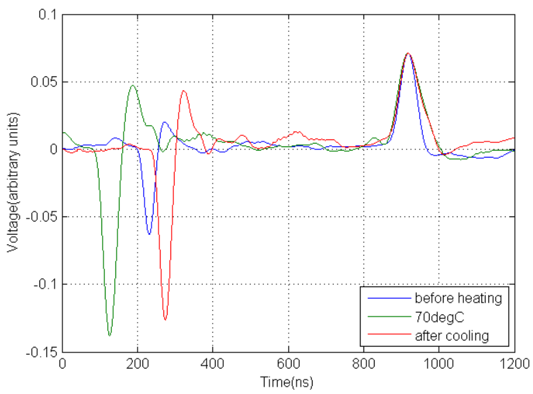


Fig. 7. Averaged raw output signal after normalisation of the amplitudes of the second peak, V_2. Time has been shifted to align peak V2for the three sets of data.

In Fig.6 the shape and duration of peak V_1 remains the same when the temperature is increased to 70 °C and following the thermal cycle. In addition, the positive overshoot is also the same for the three data sets and is due to the IRF of the system rather than the formation of heterocharge in the insulation close to the electrode. The distortion of the cable following the thermal cycle and the subsequent increase in area of contact therefore does not affect the shape of this pulse, only its amplitude as described earlier. However, as shown in Fig.7, the peak V_2 appears to broaden once the cable has been heated to 70 °C and this broadening is retained after the sample temperature is reduced to 25 °C. The initial heating of the sample appears to influence the shape of V_2 but from then on, the shape of V_2 is maintained when reducing the temperature back to 25 °C. The broadening of V_2 may be the result of the cable distortion reducing the cylindrical symmetry of the cable system.

V. Conclusions

The feasibility of using a flat base electrode PEA system for the measurement of space charge accumulation in mini-cables over the temperature range of 25 °C to 70 °C has been considered. The measurements demonstrate that when the mini-cable is taken through a thermal cycle from 25 °C to 70 °C and then back to 25 °C, under a constant clamping force, the cable insulation first suffers mechanical distortion when the cable is heated due to the softening of the cable insulation material that increases the area of contact between it and the PEA base plate. On subsequent cooling back to 25 °C, the cable retains the mechanical distortion and therefore the contact area. The results suggest that for reproducible data it would be necessary to condition the cable by applying a thermal cycle to the cable at the beginning of each experiment.

Acknowledgment

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