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EXPERIMENTAL STUDIES ON SURFACE DISCHARGE DYNAMICS AND DECAY UNDER DIFFERENT VOLTAGE WAVEFORMS AND ELECTRODE SHAPES

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Abstract: This paper studies the development and decay of surface discharge under various voltage waveforms and electrode shapes in air at atmospheric pressure. The electro-optical Pockels method is utilised to measure and quantify the distribution of surface charge. Charge is deposited on the surface of the Bismuth Silicon Oxide (BSO) sensing crystal from a high voltage needle or mushroom electrode. Sinusoidal, square pulse and ramp voltage waveforms of different polarities are generated in order to investigate the differences in the total surface charge, inception voltage and distribution pattern of positive and negative discharges. The total charge deposited can be found by integrating the post-processed charge density over the entire surface. This technique also enables the study of charge decay with time.

1. INTRODUCTION

The accumulation of charge on insulator surfaces changes pre-breakdown conditions, causes field distortion and may initiate flashover during the polarity reversal process [1, 2]. For this reason, it is usually recommended to avoid subjecting equipment such as gas-insulated switchgear (GIS) to dc electric field conditions.

In recent years, much effort has been devoted to develop measurement methods in order to monitor the expansion of surface charge, to understand the dielectric properties of the solid/gas interface and ultimately to improve insulation system performance. However, such methods using the electrostatic probe, dust figures and Lichtenberg figures suffer from a number of drawbacks, e.g. being static, non-quantitative, destructive and/or computationally expensive [3-5].

The introduction of the electro-optical Pockels experiment in the early 1990s has helped overcome the above problems to a great extent [6]. The Pockels method offers an on-line, non-destructive and quantitative measurement of the surface charge distribution. As the spatial and temporal resolutions of the measurement system only depend on the thickness of the sensing crystal and the framing rate of the camera respectively, the discharge dynamics and decay process can be examined.

Using this method, different aspects of surface discharge have been studied. In particular, the impact of the applied voltage waveform has been examined by using sinusoidal, square pulse and ramp waveshapes. The dependence of the charge distribution on the electrode shape has also been investigated by using needle and mushroom electrodes. In addition, the decay of the deposited charge has been quantitatively observed using the post-processed results.

2. EXPERIMENTAL SETUP

The diagram in Figure 1 shows the general setup of the Pockels experiment. A 17 mW HeNe laser source is utilised to generate a coherent polarised light of 632.8 nm wavelength. The light is expanded to a diameter of 30 mm using a Galilean beam expander before arriving at the polarising beam splitter (PBS). The PBS serves as both a polariser and analyser. Having passed through the PBS, the input light is polarised horizontally. It is then modulated by the optical phase modulator (OPM), which is subject to a square pulse train fed from an amplifier. The OPM is made of a 1 mm thick BSO crystal with the principal axes positioned 45° with respect to the horizontal.

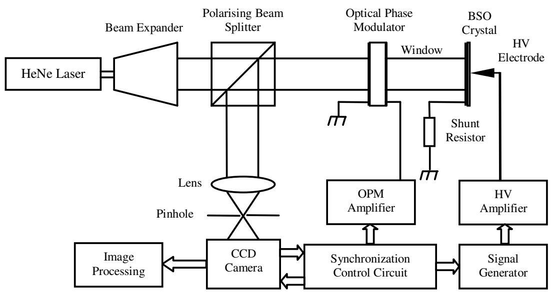

Figure 1: General setup of the Pockels experiment.

The sensing Pockels crystal is wedge polished to approximate dimensions of 20x20x0.16 mm^3 with one side grounded via a transparent electrode (Indium Tin Oxide) and a shunt resistor to measure the discharge current. A needle electrode of 5 µm radius of curvature or a mushroom electrode is placed 100 µm distant from the other side of the crystal in order to avoid any undesired mechanical birefringence. The applied voltage waveform is programmed by a function generator and amplified using a high voltage amplifier.

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The light reflected from the back face of the crystal passes through the PBS again and only the vertical component of the light is transmitted to the CCD camera. The lens and pinhole are placed in between the PBS and camera in order to block unnecessary reflections. The OPM operation, discharge triggering process and camera capturing are all synchronised by the synchronisation control circuit programmed in a peripheral interface controller (PIC). Images obtained from the camera are transferred to a personal computer for further image processing after each experiment.

3. MEASUREMENT PRINCIPLE

In the absence of an electric field, the Pockels crystal is isotropic and free of natural birefringence. When charge is present on the surface an electric field is induced across the crystal. The principal axes are rotated and altered accordingly to become fast and slow axes. Two field components of the incident light propagating through the crystal in this case would travel with two different velocities forming a phase shift. This phase retardation can be expressed as a linear function of the surface charge density as follows

$$\Phi_{(x,y)} = \frac{\pi}{\lambda \varepsilon_o \varepsilon_r} n_0^3 r_{41} \sigma_{(x,y)} d \qquad (1)$$

where λ is the wavelength of the incident polarised light, ε_o the permittivity of free space, ε_r the relative permittivity of BSO (56), r_{41} the electro-optic coefficient (5x10^{-12} mV^{-1}), n_o the BSO refractive index for light at normal incidence (2.54 at 632.8 nm wavelength), $\sigma_{(x,y)}$ the surface charge density at point (x,y) (Cm^{-2}) and d the crystal thickness (160 μm). On the other hand, the relationship between the light intensity and the phase retardation of the reflected light can be written as

$$I_{(x,y)} = T_{(x,y)} I_{0(x,y)} \sin^2\left(\Phi_{(x,y)}\right) + I_{offset(x,y)} \qquad (2)$$

where $T_{(x,y)}$, $I_{0(x,y)}$ and $I_{offset(x,y)}$ indicate the total transmittance of the system at point (x,y), maximum light intensity distribution and the constant offset intensity respectively.

The offset quantity and natural birefringence of the optical system can be eliminated by the use of the OPM. Details on the use of the OPM and relevant image processing procedures can be found elsewhere [7] and are not repeated here. The total charge deposited on the surface can be found by integrating the post-processed charge density over the crystal surface.

4. RESULTS

4.1. Influence of Electrode Shapes

In order to investigate the influence of electrode geometry, experiments were performed with two different types of electrode, a sharp, needle electrode and a blunter, mushroom-shaped electrode. Shown in Figure 2 are results obtained from discharging 2 cycles of ±5 kV peak 50 Hz AC voltage from a needle electrode. While the applied voltage, discharge current and total calculated charge are plotted in Figure 2a, the charge distributions at various times are given in Figures 2b to 2e. The current waveform is used here to qualitatively indicate the instants of discharge activity.

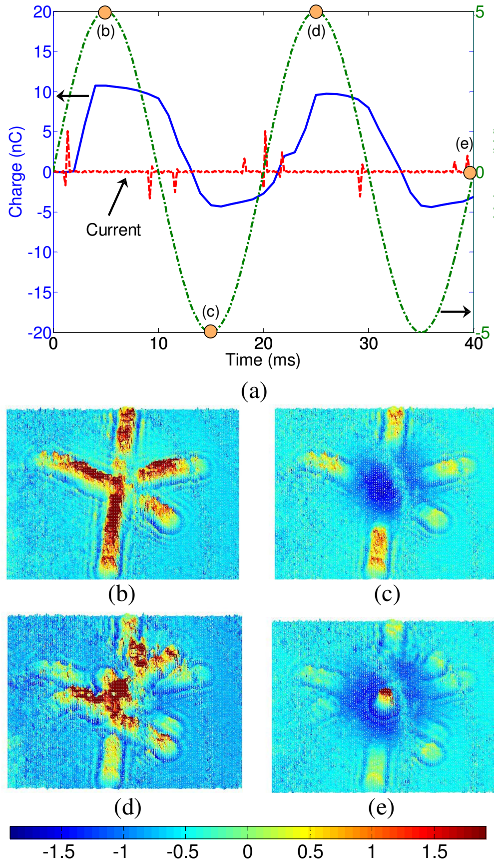

Figure 2: Surface discharge from a needle electrode, ±5 kV peak 50 Hz AC voltage (units nC/mm^2). (a) voltage, current and total charge waveforms, (b) charge distribution at 5 ms, (c) at 15 ms, (d) at 25 ms and (e) at 40 ms (7 mm x 7 mm).

As can be seen, the total charge waveform follows the applied voltage. It, however, lags the voltage curve by a few milliseconds due to the discharge inception voltage. It is also interesting to note that the maximum positive peaks are always higher than the negative counterparts and that at the end of the second cycle the residual charge is negative. The high magnitude in the positive charge is probably due to the further development of positive streamers as compared to the negative charge (Figure 2b and 2d). In the negative half-cycles, the density of the circular negative charge is higher than the combination of the residual positive tips and the positive back discharge (Figure 2e) leading to an overall negative charge.

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Figure 3 details the mushroom electrode and surface discharge results from applying an identical voltage waveform as above. The purpose of using a mushroom electrode is to study the behaviour of surface discharge under different electric field strengths. The field in front of the mushroom head is reasonably uniform whereas the field round the edge is highly non-uniform. As a result, a circular positive cluster of charge is deposited at the mushroom head and positive streamers start developing from there (Figure 3c). Similar to that observed in the previous case, the total charge waveform follows the voltage curve and the magnitude of the positive peaks are higher than the negative ones (and higher than those in the needle case). However, it is worth noting that unlike the previous observation the total surface charge in this case returns to zero after both cycles. This may be accounted for by the fact that the negative discharge phase in this case does not develop a circular distribution of negative charge as before. The negative charge tends to follow the track of the positive streamers left from the previous positive phases (Figures 3d and 3f).

4.2. Influence of Voltage Waveforms and the Decay Process

In order to understand the differences between positive and negative surface discharges, square pulses of opposite polarity were applied to the needle electrode. The pulse duration was kept constant at 10 ms and the magnitude was ±4 kV. In the positive pulse case, filamentary streamers are formed as soon as the voltage waveform reaches 4 kV (Figure 4b); the total surface charge obtained is just under 15 nC. These streamers stay stationary during the 10 ms duration of the pulse. At the end of the pulse (20 ms) there is a drop in the total charge; this is due to the formation of a negative back discharge (Figure 4c). When the applied voltage drops down to zero, the charge distribution is monitored in time. One can see that the total charge decays to zero after around 300 ms in an exponential manner. Evidence is shown in Figures 4d and 4e where the charge density reduces significantly after 150 and 300 ms.

Results obtained from discharging a negative pulse are shown in Figure 5. It confirms the fact that negative discharge deposits less charge than the positive counterpart due to the formation of the circular charge cluster. Similar to the previous AC voltage case, back discharge is observed as soon as the voltage drops to zero (Figure 2c). In terms of charge decay, however, it is interesting to note that it takes longer for negative charge to decay (350ms) and the decay process is more linear compared to that observed in the positive case. The decay process for both positive and negative discharges in this experiment occurs over a short time scale compared to the decay processes described in the literature for polyethylene materials [8]. This may suggest that charge injection barely occurs due to the crystallised structure of the BSO crystal and that discharge activity in air dominates.

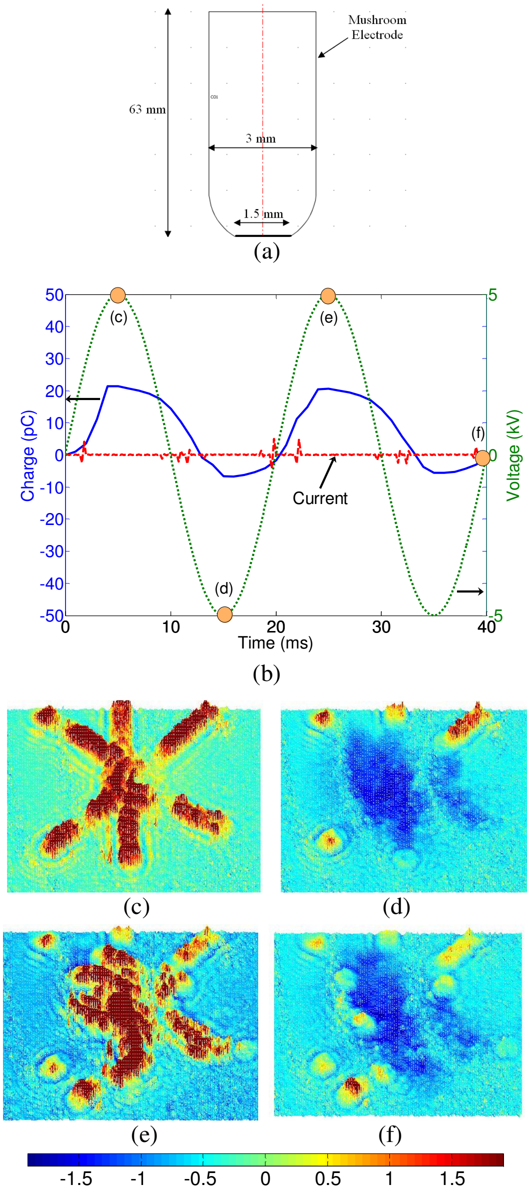

Figure 3: Surface discharge from a mushroom electrode, ±5 kV peak 50 Hz AC voltage (units nC/mm^2). (a) voltage, current and total charge waveforms, (b) charge distribution at 5 ms, (c) at 15 ms, (d) at 25 ms and (e) at 40 ms (7 mm x 7 mm).

Ramp voltages of opposite polarity were also utilised in order to study the inception voltage and the development of the discharges as the applied energy linearly increases. Shown in Figure 6 are results obtained from applying a positive ramp voltage (linearly increase from 0 to 6 kV from 0 to 40 ms). It is clear that the total charge increases in a step-wise manner. This can be explained by the charge distributions shown in Figures 6b to 6e which were measured at 11, 18, 29 and 36 ms. When the voltage reaches around 1.7 kV (11 ms) a small area of positive charge is deposited giving rise to the first step in the total charge curve. Around 3 kV, four branches of streamers are formed leading to the second step. Just

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above 4 kV, four new branches develop in the space that is not occupied by the previous streamers. Lastly before reaching 6 kV, two more streamers grow occupying the rest of the space.

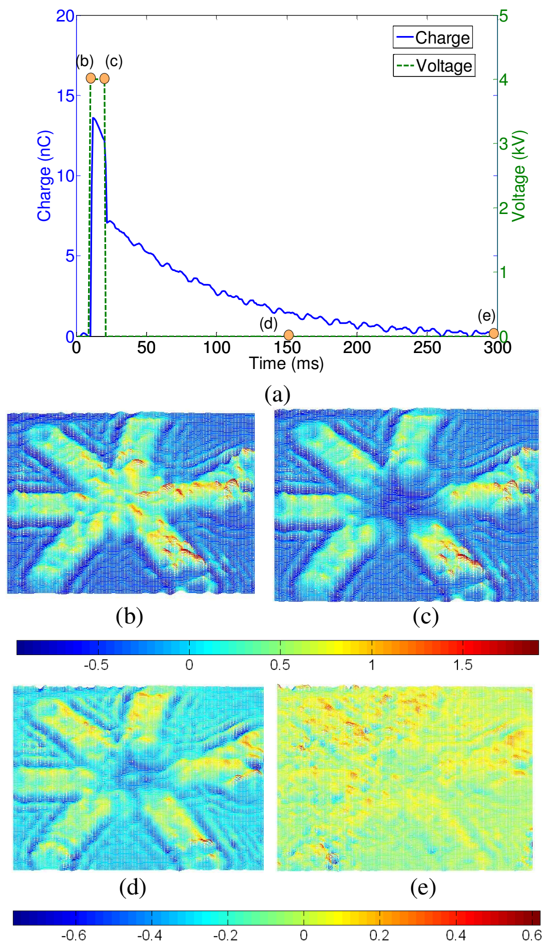

Figure 4: Surface discharge from a needle electrode, +4 kV 10 ms pulse voltage (units nC/mm^2). (a) voltage and total charge waveforms, (b) charge distribution at 10 ms, (c) at 20 ms, (d) at 150 ms and (e) at 300 ms (5 mm x 5 mm).

In contrast to the positive ramp, the development of the negative ramp discharge is less complex. Shown in Figure 7 are the voltage and total charge waveforms obtained. One can see that negative discharge starts around 2 kV. The total charge rises linearly with the increasing voltage. This is due to the fact that negative surface discharge develops radially in a circular shape. The charge distributions are similar to Figure 5 hence are not shown here again.

5. CONCLUSION

Using the Pockels effect, this paper has investigated different aspects of surface discharge. In particular, the effect of using different electrodes on the discharge behaviour was studied. The results show the clear distinctions between the development of negative discharge from a mushroom electrode and from a needle electrode in an AC voltage. The trend of negative charge following the tracks of previously deposited positive streamers may explain the zero residual charge after two cycles as opposed to the needle case. Using square pulses, it was confirmed that positive discharge deposits more charge than negative discharge and that positive charge decays exponentially while negative charge decays linearly. Ramp voltages were utilised to determine that positive discharge has a lower inception voltage and that the total charge grows in a step-wise manner as compared to the more linear growth observed in the negative case.

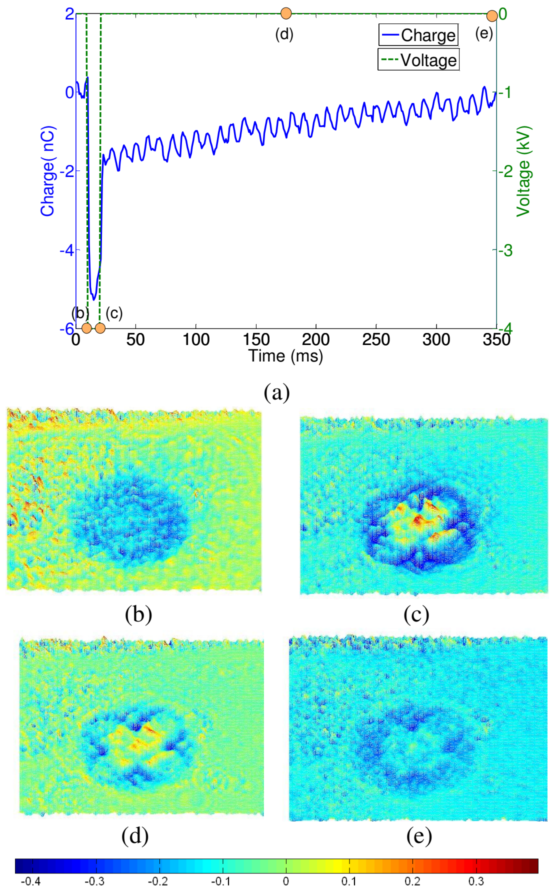

Figure 5: Surface discharge from a needle electrode, -4 kV 10 ms pulse voltage (units nC/mm^2). (a) voltage and total charge waveforms, (b) charge distribution at 10 ms, (c) at 20 ms, (d) at 175 ms and (e) at 350 ms (5 mm x 5 mm).

6. ACKNOWLEDGMENTS

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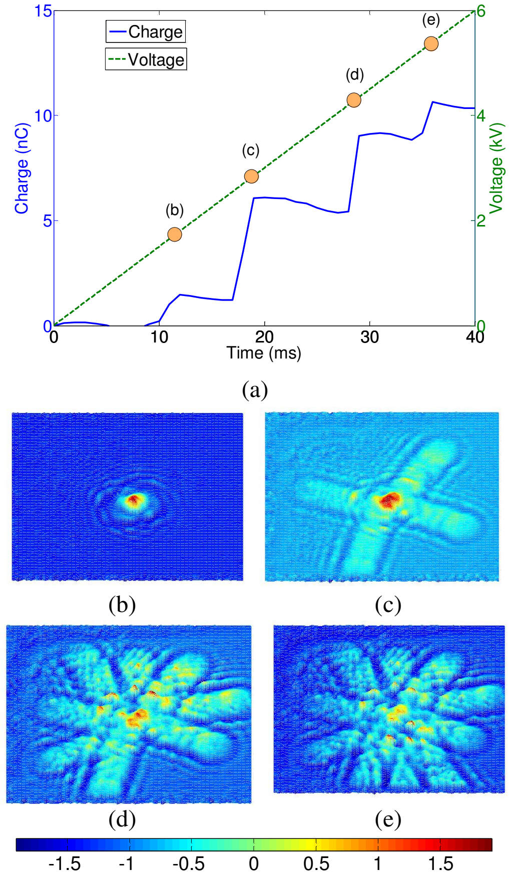

Figure 6: Surface discharge from a needle electrode, positive ramp voltage (units nC/mm^2). (a) voltage and total charge waveforms, (b) charge distribution at 11 ms, (c) at 18 ms, (d) at 29 ms and (e) at 36 ms (5 mm x 5 mm).

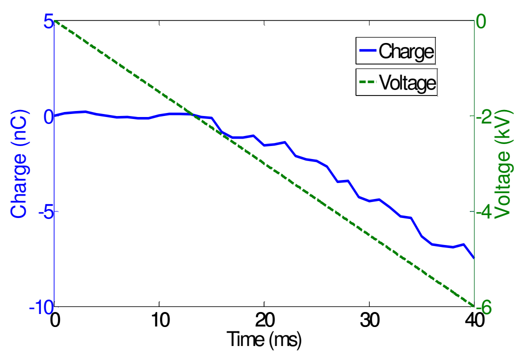

Figure 7: Surface discharge from a needle electrode, negative ramp voltage. Voltage and total charge waveforms.

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