Visualization of the Ionization Phenomenon in Porous Materials under Lightning Impulse

A. Elzowawi, A. Haddad, H. Griffiths

***Abstract*—the electric discharge and soil ionization phenomena have a great effect on the performance of earthing systems, especially under lightning currents. These phenomena create a nonlinear behaviour in the soil around the earthing electrode, where the resistivity of the soil drops to a lower value allowing the current to increase to a higher magnitude. Very limited studies have been conducted to image the soil ionization discharge developments from the earthing electrode in the soil. However, the imaging process of the electric discharge in opaque porous materials such as soil is extremely difficult. Therefore, in this study, a photographic investigation of the electric discharge in a new dielectric glass bubble material was conducted. Also the expansion of the ionization zone in this material was investigated with a specially-adapted sample configuration.**

A rod - plane electrode configuration was utilized in the test rig. The sample was placed in a Perspex vertical tube, so that the discharge light can be visible and recorded by a fast camera. Voltage probes were installed in the tube to measure the voltage at different places in the sample. Standard lightning and switching impulse voltages were used in these experiments. Synchronized frames of the recorded video with voltage and current waveforms allow visualization of the dynamic change of the discharge at various times during the impulse. It was observed that the expansion of the ionization zone does not have a constant speed and the resistance of the ionization zone is not the same throughout the zone.

***Keywords*— Expansion of soil ionization, imaging of soil ionization, soil ionization.**

I. INTRODUCTION

THE nonlinear behaviour caused by soil ionization in earthing systems under high lightning currents affects the rise of earth potential in electrical power network. However, the detailed mechanism of this phenomenon is not fully understood. Therefore, a number of experimental investigations have been conducted to study and understand this phenomenon. One of the important features that researchers have focused on is the visualization of the ionized region in the soil medium around the earthing electrode during the discharge. However, due to the opacity of the soil, imaging this phenomenon inside the soil is not straightforward, as a visual camera cannot detect light which may emanate from the discharge. Therefore, alternative techniques to image the ionization discharge inside the soil were developed, for example, X-ray films are considered as one of the most common used techniques [1-6], and black and white photographic films were also used [4]. These two types of films are very sensitive to light and x-rays. According to [6], x-rays can be produced during soil ionization discharge. A less common technique to image the discharge in the soil was reported in [7], in which a conducting paper was used. It was shown that, when the discharge streamer reaches the conducting paper, it erodes the top layer of the paper at the points where the current touches the paper. This, in turn, leaves tracking traces on the surface of the conducting paper and holes in the case of breakdown puncture due to high currents. These techniques were used near the electrodes within the test soil sample so that the discharge can be captured and recorded on these films. Given the complexity and resolution of these methods, they are considered limited when quantifying the ionization region and its expansion.

In this paper, a new porous dielectric material, consisting mainly of glass bubble material (S38XHS), was used as the test medium. The glass bubble material consists of hollow low density glass microspheres with an average diameter of 30 microns. It is a white powder and an insoluble substance, which is made from soda lime-borosilicate glass. Hence, the light could be transmitted through it. A Photron FASTCAM SA5 high speed camera was utilized to record the dynamic development of the discharge and then correlating the recorded video with the measured voltage and current waveforms.

II. TEST ARRANGEMENTS

A. *Test Setup:*

A new test cell, with rod-to-plane electrode configuration, was developed to conduct the ionization visualization experiments. To allow the discharge light to be visible to the high speed camera, the sample was placed in a Perspex clear tube with 8cm diameter and 50cm height, as shown in Fig. 1. Impulse voltage generators were used to generate standard lightning and switching impulse voltages. A capacitive voltage divider with a ratio 27931:1 was connected to the active electrode to measure the voltage, and a current transformer with a sensitivity 0.1 V/A was used to measure the current flowing through the test sample. The signals of

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both transducers were captured on a LeCroy Wavejet 314 digital oscilloscope.

The test circuit is shown in Fig. 2. The high speed camera was placed outside the Faraday cage, and was linked to a controlling computer to acquire the recorded videos. The camera was operated at a very high frame rate to record the dynamic changes of the discharge with a range of few microseconds.

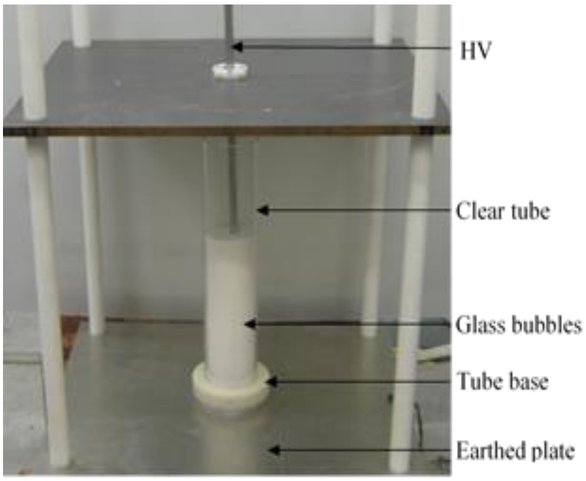

Fig. 1. Test cell

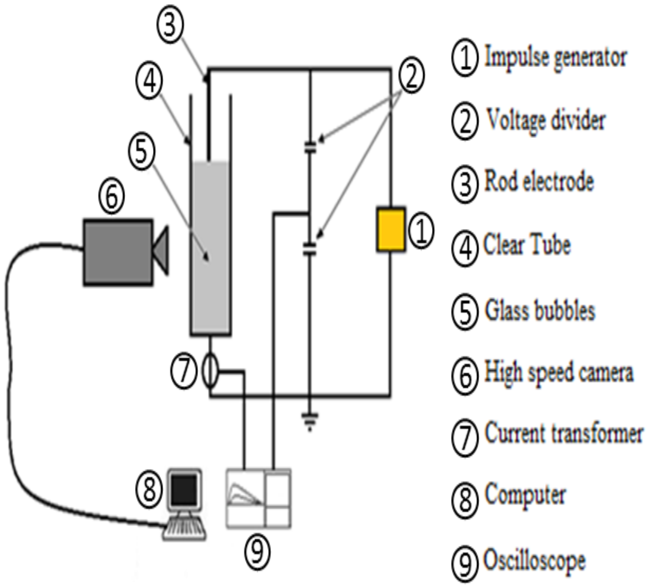

Fig. 2. Test cell

B. *Sample Preparation*

When a high impulse voltage is applied to dry glass bubbles as shown in Fig 2, the material exhibited a very high resistance, and no conduction current was detected until the full breakdown occurred. Often, the breakdown current flowed at the interface between the glass bubble material and the inner surface of the test tube, indicated by the marked path.

To avoid the above current path scenario and to ensure that the whole discharge occurs inside the material, the sample was sectioned into two layers inside the tube; an upper layer of dry glass bubble material is placed next to the high voltage electrode from where the ionisation initiates, and a lower layer region situated next to the earth electrode which was further divided into two subsections. The right hand subsection contained glass bubble material wetted with tap water, this section was arranged to face the camera, and the other subsection was filled with the material but dry. This particular arrangement is adopted to ensure that conduction occurs within the wet side facing the camera This new arrangement has shown significant improvements to the test, where the current now flows towards the less resistive section from the upper dry material layer. Also, in this case, conduction current without breakdown was detected and recorded.

The wetted material was thoroughly mixed to obtain a good moisture distribution amongst the glass microspheres, then this mixture is poured into the lower right hand subsection of the tube until it reaches a designated height within the test cell. Following this, pressure was applied manually on the material to ensure that the mixture is suitably compacted and distributed uniformly in the tube and to prevent formation of any large air gaps inside this layer. The dry material was then poured over the wet material to fill the rest of the tube up to a height which embeds the high voltage electrode inside the material.

III. LIGHTNING IMPULSE TESTS

The high speed camera capture rate was set to operate at 175000 frames per second, and the camera is positioned to have a suitable window to visualize the whole dry material part. With the adopted frame rate, frames with 5.5 μs duration each will be recorded. Because of the camera triggering limitations, thousands of frames will be recorded but only the frames containing the discharge will be extracted during the analysis stage.

Standard lightning impulse voltages were applied to the test material sample. The impulse generator firing was used to trigger the high speed camera and record the dynamic discharge development process in the dry glass bubbles.

A. *Discharge without a Breakdown*

The impulse voltage was increased in small steps until a voltage magnitude at which the electric field is high enough to cause current flow from the high voltage electrode to the ground. This current was measured using the current transformer and the event was recorded by the camera. In this case, the voltage did not show any sign of breakdown. It is believed that the current flow in the dry material could be due to the drop of the material resistivity caused by the ionization process in the air cavities among the dry microspheres, analogous to soil ionization in common soils.

Moreover, noting the considerable time delay measured with the current waveform in relation to that of the applied voltage, it can be said the initial current rise indicates the time it takes for the ionization phenomenon to expand from around the HV electrode and extend towards the ground electrode. At higher applied voltages, it was found that the delay time is reduced, which indicates that the ionization propagates faster.

From the processed recorded video, it was observed that the intensity of the emitted light from the discharge correlates with the current magnitude. So, as the current increases, the light intensity increases. In this work, the recorded video was synchronized with the measured voltage and current waveforms, by pairing the video frames from the high speed camera with specific instants on the voltage and current impulse traces.

Fig. 3 shows an example of synchronized voltage and current waveforms with particular frames. Each time division in the figure is equivalent to a time of 5.5 µs, corresponding to each video frame of 5.5 µs. Therefore, on the figure, each frame is associated with the corresponding time division of the electrical signals. The light intensity in each frame captures the discharge in this time range. The height of the frame represents that of the entire dry material part, and the frame width represents the tube diameter. Note that the location of the HV electrode tip is at the top of each frame.

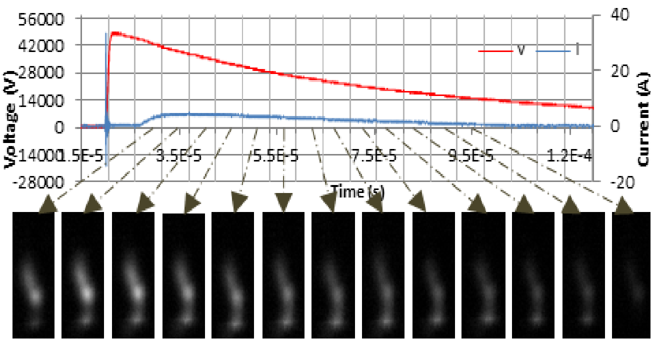

Fig. 3. Synchronized video frames with voltage and current waveforms without a breakdown event.

B. *Discharge with a Breakdown:*

As can be seen on Fig. 4, once a sufficiently high magnitude voltage is applied to the test sample, conduction current is measured; with the current increase starting after a shorter time delay. After a further period of time, the current increases significantly at the instant of full breakdown, and this is accompanied with a significant drop in voltage decaying to zero voltage magnitude. The occurrence of breakdown is explained by the breakdown of both layers (dry and wet) of the test sample. This will be further investigated in Section V. At the onset of the ionisation current, a very faint light can be seen through the material. This then developed further to form a very bright arc-like light, representing the breakdown event.

IV. SWITCHING IMPULSE TEST

Using a similar sample configuration as adopted for the lightning test, a switching impulse voltage was used. In this test, 100,000 frames per second was set as the operating frame rate for the high speed camera. In this case, each frame corresponds to a 9.8 µs time interval. Switching voltages were applied up to a level at which a current was detected by the current transformer, and light is visible on camera recorded frames.

Compared with the lightning test results, the detected current in this test continued for a much longer time period because of the longer duration of the applied impulse voltage. Consequently, much longer recorded video duration with larger number of frames was generated. To reduce the number of frames, only frames at the instant of interest were selected as shown in the Fig. 5. Similar discharge behaviour to the lightning test was observed at the beginning of the current rise, where the brightness of the discharge light was corresponding to the current magnitude until about 215 µs (frame number 22). Of particular interest and less easy to explain, as the current was falling, a rise in the illumination of the discharge light can be seen in the frames (42-142), as shown on Fig. 5. More experiments need be carried out and parameters like electron density should be quantified to investigate this phenomenon. According to the study reported in[8], this increase in the light brightness may be due to the increase in electron density.

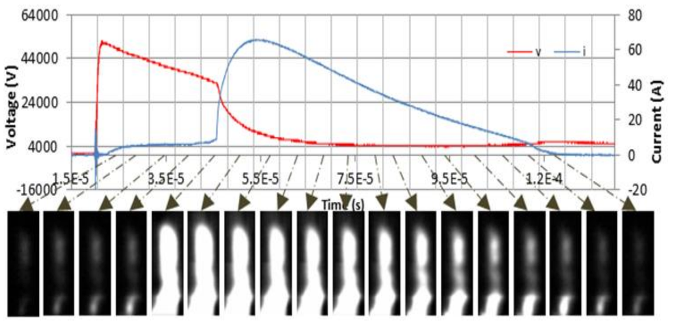

Fig. 4. Synchronized video frames with voltage and current waveforms with a breakdown event.

V. WETTED SECTION VOLTAGE MEASUREMENT TEST

To investigate the effect of soil ionization in the dry material, especially before complete breakdown occurs, a voltage probe was installed in the tube at the interface between the upper dry section and the lower wetted section. This will allow measurement of the voltage across the wet material section which, in turn, will help with the calculation of the voltage across the dry section and will investigate the delay time seen before the current rise.

Lightning impulse voltages were applied to the sample, until a current conduction was detected. Fig. 6 shows an example of measured traces of the voltages and current. As can be seen on the figure, the voltage across the wet part, V_w, starts to increase at the instant of current increase, which confirms the ionization propagation time to expand from the active electrode until the wet part. Also, when the voltage across the dry material (V_d) was calculated and plotted with the rest of the parameters, it shows that the dry material section breaks down once the ionization reaches the wet part and the current starts, as shown in Fig. 6.

Therefore, it can be said that the ionization initiates around the surface of the HV electrode where the electric field magnitude is highest, and then expands through the material.

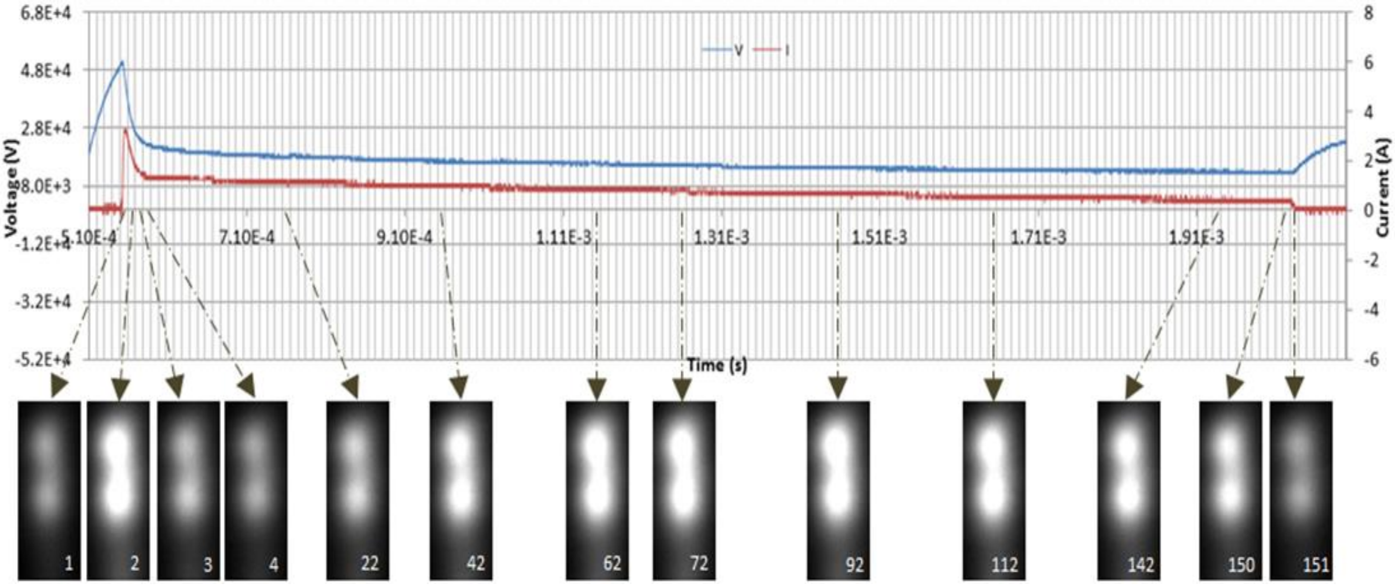

Fig. 5. Synchronized video frames with voltage and current waveforms in the case of switching voltage.

This expansion creates a low resistivity path for the current to flow and cause a breakdown of the dry section. As soon as the dry section breaks down, most of the applied voltage will be applied to the wet section, this explains why the applied voltage does not exhibit any features of breakdown. At much higher applied voltages, a full breakdown across the test sample (wet and dry sections) occurs. Fig. 7 shows the measured voltages and current for such scenario. It can be observed that the dry layer breaks down first and then followed by the breakdown of the wet layer. The above observations can be verified with the captured frames shown in Figs. 3 and 4.

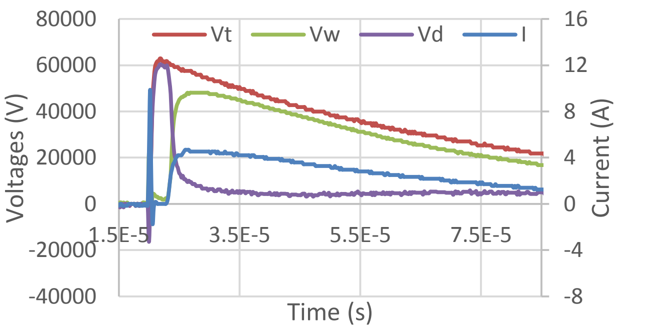

Fig. 6. Waveforms of the measured parameters with no breakdown

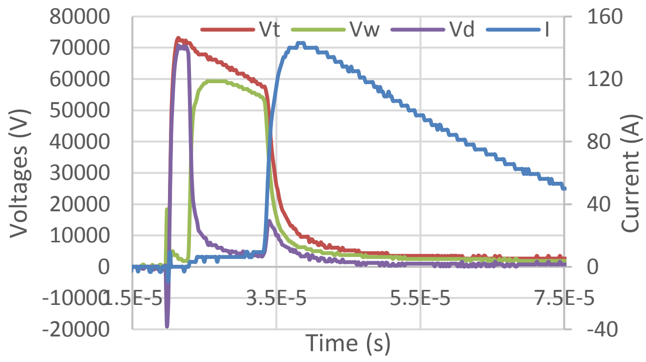

Fig. 7. Waveforms of the measured parameters with a breakdown

VI. CONCLUSION

The ionization and breakdown phenomena were visualized and studied in a material made of glass bubble. Synchronized frames of the recorded high speed video with voltage and current waveforms allowed visualization and monitoring of the discharge phenomena at various times during the impulse, which provided a unique observation of the dynamic changes in the discharge development. Similar results were obtained with lightning and switching voltages.

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