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# INVESTIGATION OF IMPULSE DISCHARGES IN TWO-LAYER WET AND DRY SOIL SAMPLE

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**Abstract**: Soil ionization phenomena in dry soils are considered the main cause of the observed nonlinear behaviour under impulse voltages, the very high resistivity of the dry soil falling dramatically at the instant of breakdown. In this study, a two-layer columnar test sample composed of a glass bubble material was used to investigate the associated ionisation and breakdown processes. Three voltage dividers were utilised to measure the applied lightning voltage and intermediate voltages at two probes located at fixed heights in the sample. A current transformer was used to measure the current flowing through the sample. When the voltage is high enough and after a certain delay time, current flow from the active electrode was detected by the current transformer, but the measured applied voltage did not show any indication of breakdown. The current stream in the dry material could be due to the ionisation of the air voids among the dry grains, which could support the ionisation phenomenon in dry soil, and the wet part voltage rose at the instant of current rise, while the voltage across the dry section shows occurrence of a breakdown. An equivalent circuit model of the sample with EMTP software was also proposed to simulate the behaviour of the discharge.

## 1 INTRODUCTION

The design of earthing systems and the efficiency of lightning protection schemes of ground structures depends on the impulse characteristics of the soil and its nonlinear transient behaviour under lightning impulse conditions. In areas of high soil resistivity, unsatisfactory earthing may result, particularly under dry soil conditions. With dry soils under high magnitude impulse voltages/currents electrical discharges are initiated within the soil, leading eventually to ionisation of the soil around the injection electrode. The discharge initiation is attributed to enhanced electrical field in the air pockets trapped between the soil grains. The level of this enhancement may be influenced by thermal and/or electrical processes or their combination thereof. The thermal process is characterised by resistive heating of the sample, and this process has less effect when it occurs in dry soils, as the water content is much reduced to cause current conduction. The electric field effect is stronger when the difference between the dielectric properties of the soil medium and the trapped air bubbles between the soil particles is significant, giving rise to larger electric fields in the air pockets which have a weaker dielectric strength. Above a certain electric field threshold, ionisation of the air takes place and propagates in the soil away from the injection electrode. This ionisation process explains the drop of the measured resistivity in earth electrodes subjected to high impulse currents and the formation of discharge channels and ionised zones [1-4].

The extent of the ionisation region expansion and the velocity of its propagation depend on the applied voltage/field. The discharge channel creates a low resistivity path in which the high discharge current will flow through the soil [5]. Before ionisation start and due to the high resistivity of the dry sand, negligible current is expected to flow.

In [6], a hemispherical test cell container was adopted. Sand with selected water contents was tested and simulated. An RC equivalent circuit was derived. However, this set up does not allow visualisation of the ionisation discharge because the materials used. A visual study of the impulse discharge in porous glass bubble materials was performed by the authors in [7], where the discharge was recorded by a high speed camera. The camera was used to record the light emitted by the discharge through the porous dielectric glass bubble material, consisting of hollow soda lime-borosilicate glass microspheres with average diameter 30 microns. The advantage of this light transparent material is that it allows observing the emitted light due to discharges occurring deep inside the sample.

In this paper, work is undertaken to obtain a visual evidence of soil ionisation. To visualise soil ionisation, a new test set up configuration was developed. The initiation of the discharge in a dry material, the ionisation expansion, and the eventual breakdown of the process were studied. With this new arrangement, the extent and propagation velocity of the ionisation region were also investigated. To achieve this, intermediate voltage probes were used in the dry layer of the material to measure the dynamic change of voltage during the discharge propagation process within the ionisation zone.

# 2 TEST PROCEDURE

## 2.1 TEST ARRANGEMENT

Figure 1 shows the test circuit consisting of a rod-plane electrode configuration. The glass-microspheres material was placed in a vertical plastic tube. A Haefely impulse voltage generator with four stages, which can generate up to 400 kV, was used for the lightning impulse tests. Two voltage dividers with ratios 27931:1 and 2000:1 were used to measure the applied voltage and the voltage across different regions of the sample. A wideband current transformer with sensitivity 1 V/A was used to measure the current flowing in the sample. Voltages and current signals were captured on a fast LeCroy digital oscilloscope.

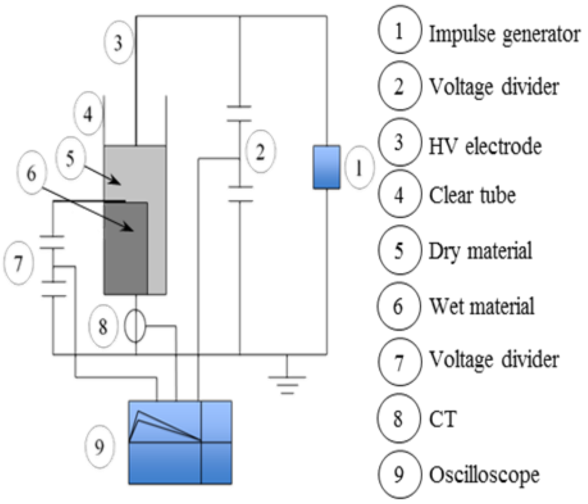

**Figure 1** Test circuit

## 2.2 SAMPLE PREPARATION

The Perspex test cylinder was filled two-layer glass bubble material areas; (a) the upper layer is a dry glass bubble material, which is in contact with the high voltage electrode, will be the region where the ionisation will take place, and (b) the lower region, which is in contact with the earth electrode, was further divided into two subsections: ii) The right hand subsection contained glass bubble material wetted with tap water, and (ii) the other subsection was filled with dry material. This test arrangement was developed to allow conduction in the wet region while ionisation was encouraged in the dry region closer to the high voltage electrode.

Using only dry material, does not show measurable conduction current until the full breakdown of the sample with very high current, i.e. ionisation and full breakdown may take place at the same time.

# 3 THRESHOLD OF DISCHARGE INITIATION

In this test, only one voltage divider was used to measure the applied voltage. The lightning impulse voltage was applied in steps until a voltage level at which a current flow from the HV electrode to the ground was detected by the current transformer. This current is thought to be due to the ionization phenomenon in the air pockets trapped between the microspheres. Figure 2 shows an example of the voltage and current waveforms of the discharge. As can be observed on the voltage and current waveforms of Figure 2, there is a time delay before the current start s to increase, which could indicate to the time for the ionization to set up and its current to flow through high resistivity material. A further increase of the applied voltage is accompanied with the reduction of this delay time.

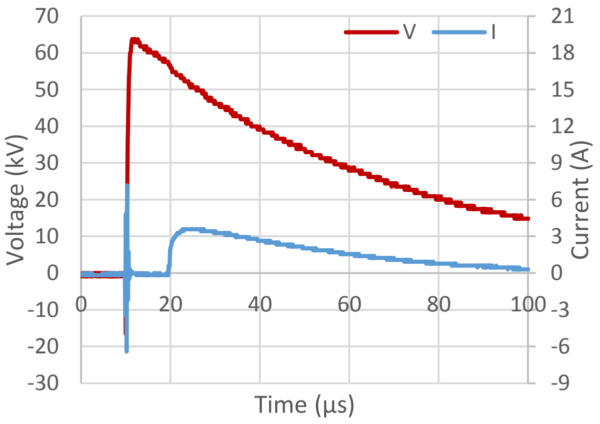

**Figure 2** Voltage and current traces of a discharge

# 4 WET LAYER VOLTAGE MEASUREMENT

To understand the current flow in the dry layer, prior to breakdown of the sample material, a voltage probe was inserted in the tube at the interface between the upper dry section and the lower wetted section to quantify the voltage drop across the wet material section as shown in Figure 1. By measuring this voltage it is also possible to calculate the voltage across the upper dry region. For this test, lightning impulse voltages were applied to the sample in increasing steps until current conduction was detected.

The applied voltage ($V_t$), voltage of the wet zone ($V_w$) and the current (I) were recorded as shown in Figure 3. $V_w$. was found to rise at the instant of first current rise, which confirms that there is delayed ionization propagation from the active electrode to the boundary of the wet zone.

Furthermore, calculation of the voltage across the dry zone ($V_d = V_t - V_w$) indicates a breakdown of the dry material after the discharge reaches the wet–dry boundary. Based on these findings, it is, therefore, likely that ionization initiates in the close proximity of the high-voltage electrode, where the electric field magnitude is highest, and then expands and propagates through the dry material. This expansion creates a low resistivity path for the current to flow and cause a localized breakdown across the dry zone. As soon as the dry zone fully breaks down, most of the applied voltage will be applied to the now relatively high resistance wet layer. Such process is characterized by the absence of any indication of breakdown in the applied voltage ($V_t$). At higher applied voltage magnitudes, both layers undergo a full breakdown, as can be observed in Figure 4.

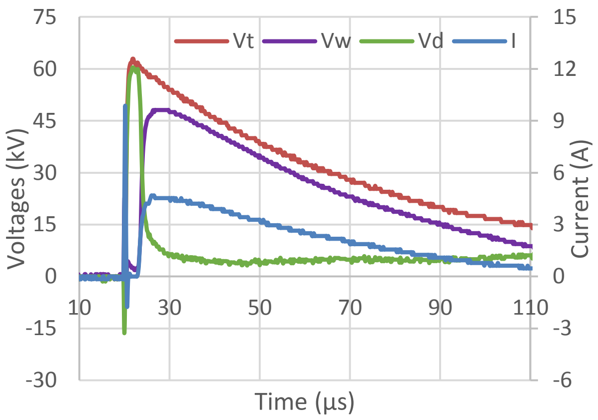

**Figure 3** Two voltages and current traces measured with no breakdown

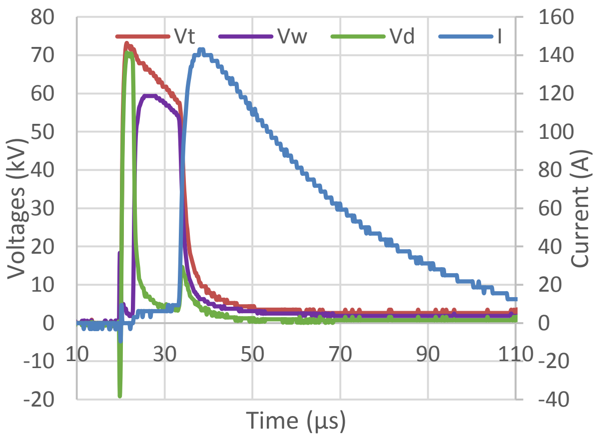

**Figure 4** Two voltages and current traces measured with a full breakdown

## 5 IONISATION PROPAGATION IN DRY LAYER

This test is developed to investigate the ionisation initiation, its expansion and propagation through the dry glass bubbles, which will eventually lead to the breakdown of the dry material layer. For this purpose, a third probe with ratio 1000:1 was installed in the test cylinder as depicted in Figure 5. This additional probe was placed half-way between the high voltage electrode and the wet-dry regions interface. Hence, this set up will allow visualisation of the ionisation development as it propagates down from the high voltage electrode towards the wet layer. Such set up will then be used to estimate the propagation velocity of the ionization in this region.

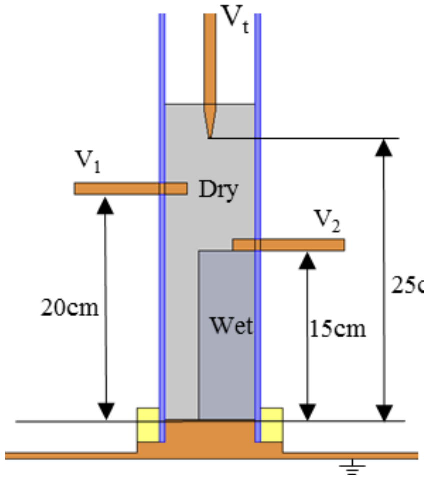

**Figure 5** Sample and voltage probe arrangement

At an applied voltage of 60kV, no current is detected, and ($V_1$, $V_2$) did not measure any voltage except a capacitive voltage at the beginning of the discharge. As the voltage is increased up to 62kV, a voltage rise can be seen on $V_1$ which indicates that the discharge has propagated only up to this probe in the middle of the dry layer as illustrated in Figure 6.

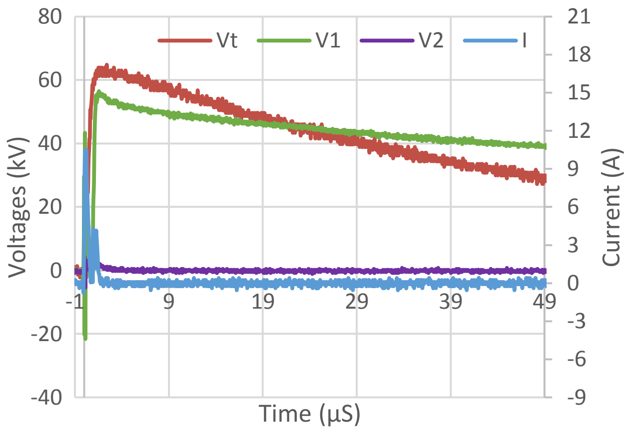

**Figure 6** Three voltages and current traces measured with limited streamer propagation in dry layer

After approximately 23µs, the measured $V_1$, exceeded the applied voltage $V_t$, which could be due to the accumulation of charges provided by the ionisation that led to build up a higher voltage than the decaying applied voltage. Moreover, when the applied voltage magnitude is further increased, the ionisation phenomenon propagated up to the wet layer, where the two probes ($V_1$ and $V_2$) measured different voltages according to their location in the sample as shown in Figure 7. This indicates that the local electric field at the tip of the ionisation discharge is high enough to drive the propagation of the ionisation zone from the active electrode area as far as the wet layer boundary. In addition, there are different delay times between the measured voltages ($t_1$, $t_2$), which indicates that the discharge has varying velocities at each stage of the propagation.

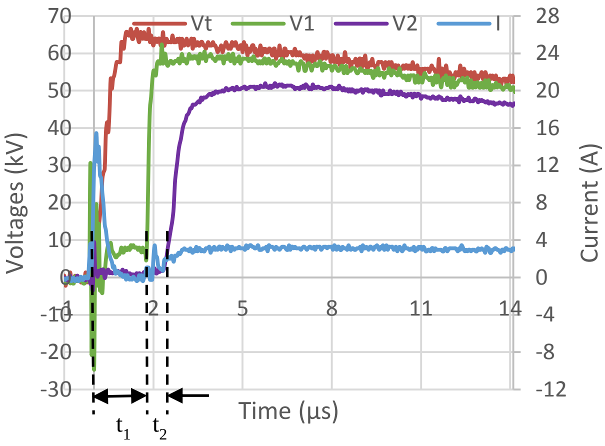

**Figure 7** Three voltages and current traces measured with full streamer propagation in dry layer

Observing the traces shown in Figure 7, it is important to note that the $t_1$ after which the voltage at half-way in the upper dry layer starts to increase does not only represent the propagation time of the discharge up to $V_1$ probe location, but it also includes the time taken for the soil ionization initiation. As indicated earlier, this discharge initiation is thought to be mainly driven by the electrical rather than the thermal process, which supports the results presented in [8, 9,10,11]. Moreover, the total delay time ($t_1$+$t_2$) of the current tends to reduce as the applied voltage magnitude increases, possibly corresponding to the ionisation having faster initiation and propagation velocity. Using the measured data for $t_2$, an estimated ionisation propagation velocity of 6.25 cm/µs.

## 5 PROPOSED EQUIVALENT CIRCUIT

From careful analysis of the discharge voltage and current impulse traces for the case without full breakdown event and without the two voltage probes in the middle of the test sample (see Figure 2), an initial current peak indicating the capacitive behaviour of the sample can be observed. Due to the high resistivity of the material, no resistive current flow is detected until ionisation when the breakdown of the dry zone takes place.

From a separate test, it was found that the wet layer has a nonlinear resistance. However, the strongest nonlinearity in the sample is found in the dry material, where the ionisation phenomenon and then the breakdown of this layer force the dry material to have much lower resistance, even lower than the wet layer. The value of the dry layer impulse resistance changes from discharge to discharge, but tends to decrease as the applied voltage increases. Therefore, the proposed equivalent circuit (Figure 8) of the discharge in this test set up configuration is represented with (a) a capacitor to simulate the capacitive effect, (b) this capacitor is connected in parallel with a non-linear resistor to simulate the resistance of both the dry and wet parts during the current conduction, (c) a switch to simulate the initiation of the current and (d) an inductor to simulate the equivalent inductance of the circuit which controls the current rise time. The circuit was built with the EMTP software.

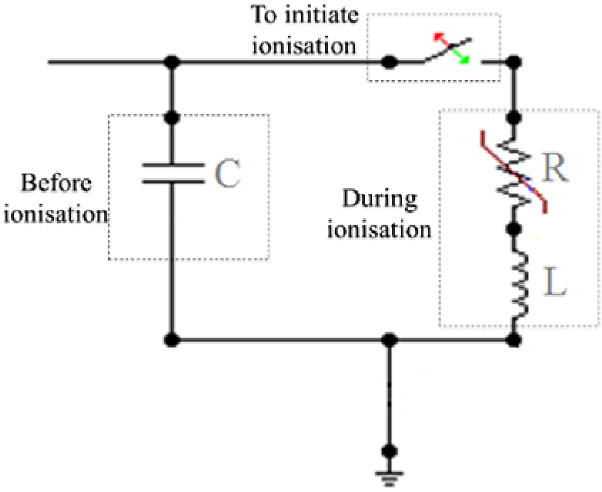

**Figure 8** Equivalent circuit of the discharge

In this work, the equivalent circuit parameters were derived from the following expressions:

(a) Capacitance, C,

$$C=13pF \tag{1}$$

(b) Resistance, R,

$$R=19482.i^{-0.233}\ \Omega \tag{2}$$

(c) Inductance, L,

$$L= 9mH \tag{3}$$

As can be seen in Figure 9, good agreement is obtained between measured and simulated results.

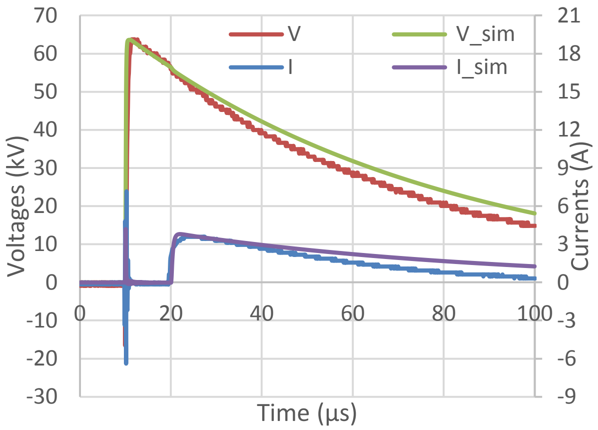

**Figure 9** Actual and simulated voltages and currents of the discharge

## 6 CONCLUSION

The proposed two-layer configuration of dry and wet glass bubble material contained in a cylindrical test container made of Perspex was found useful for the visualisation of soil ionisation phenomenon and the quantification of some of its parameters.

The delay time for initiation of soil ionisation around the HV electrode and its propagation velocity towards the earth electrode were estimated from the fast measurements under lightning impulse application. This investigation suggests that initiation of the ionisation process may be attributed to field enhancement in the air voids inside between the glass bubble microspheres within the bulk material. If the applied electric field is high enough, it can sustain the expansion of the ionisation extending towards the wet material interface and, eventually, a full breakdown towards the earth electrode.

Furthermore, in this work, an estimate of the velocity of ionisation propagation was derived from the measurement of voltage at various points along the length of the test cell. This velocity is found to be dependent on the applied field.

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