# Methodologies Adopted in Imaging of Electric Discharge in Soil under Impulse Voltages

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***Abstract*– The impedance of an earthing system becomes nonlinear when subjected to a high magnitude lightning current. This complicated behaviour was attributed to the soil ionisation phenomenon. It was found that studying the electric discharge and soil ionisation visually in the soil offers a better understanding of the nonlinear behaviour of the earthing systems and provides significant information on the development and the shapes of the discharge inside the soil. Extensive research has been carried out to study the discharge process in soil. However, only several techniques have been developed to visualise soil ionisation and electric discharge phenomena in soils. Therefore, in this paper, a critical review of these methodologies is presented to study the visualisation process. Results of high voltage tests and recorded discharge images are critically reviewed.**

***Index Terms*– discharge imaging, soil ionisation, sensitive films, glass bubble material.**

## I. INTRODUCTION

The soil ionization phenomenon is considered as one of the main causes for nonlinear behavior observed in the impedance of earthing systems under high magnitude currents such as those generated by lightning impulses. Despite the attention that the ionization phenomenon has drawn and the large number of experiments that have been carried out, the detailed nature of this phenomenon is not fully understood. The main focus of the soil ionization research has been on electrical field, current density and resistivity, by measuring the voltage and the current signals during the tests. However, studying the electric discharge visually in the soil was considered to be a very useful auxiliary tool to understand the dynamic development and the shapes of the discharge inside the soil.

Imaging process of the electric discharge in porous materials like soil is extremely difficult. Therefore, instead of capturing the light emitted from the discharge from outside the sample, techniques, such as photographic films, x-ray films and conducting paper, were used to record the electric discharge and the ionization phenomenon from inside the soil, by inserting such films near the electrodes within the sample. These methods have been applied to study the discharges in different soils with different grain sizes under different electrode configurations, to help obtain a better understanding of the factors that affect the discharge process in soil during the high impulse currents such as lightning currents.

In this paper, a detailed review of such imaging techniques is presented together with a description of previous tests carried out on different test samples, and a summary of some findings obtained from the captured images.

## II. IMAGING TECHNIQUES

Due to the relative high opacity of soil, the discharge cannot be seen from outside the soil. Hence researchers have utilized an alternative approach which is to place photo-sensitive films inside the soil near the active electrodes to capture an image of the discharge. Different types of films were used including;

### *A. X-Ray Film*

The X-ray film has been frequently used and was first used in 1967 by Hayashi [1] and then in [2] to capture the discharge using a hemispherical test rig. Subsequent tests with X-ray film were carried out by other researchers using a cylindrical coaxial test rig [3], a needle-plate, rod-plate, rod-semi-circular cylindrical plate [4], rod-hemispherical, rod-rod configurations [5, 6, 7], and horizontal electrode [8, 9]. In these studies, x-ray film was the main method to image the discharge; hence, several samples have been tested under diverse conditions, in terms of the sample and the applied voltage. As a result, many significant images and outcomes have been recorded and found. Moreover, x-ray film is still used as the major technique in this subject.

### *B. Photographic Film*

In [4], a black and white photographic film was used with needle-plate, rod-plate, rod-semi-circular cylindrical electrode configurations. Lightning current was applied onto soil samples with resistivity 117.5 Ω.m. X-ray films were also used in this study, so that a comparison could be made between the images obtained by both types of films. The authors found that the black and white film captured clearer images than those ones obtained by using x-ray film. Authors in [10] have also used photographic films to study the electric discharge in wetted soil with 10 % water content. Special test cell was designed and the film was placed under different electrode settings (horizontal and disk high voltage electrodes). Impulse voltage was applied and different images were recorded on the films. These images showed spark channels coming out from both ends of the horizontal electrode and coming out from the periphery of the disk electrode.

### C. Conducting Paper

A less common method, using conducting paper was reported in [11], where it was used in indoor and outdoor tests. For the indoor tests, current impulses were applied onto a soil sample which was placed in a box. This box was earthed through a conducting paper placed at the bottom to image the end of the current propagation. For the outdoor tests, a hole with dimension (12cm×12cm×10cm) was made in the ground and conducting paper was placed at the bottom of the hole to image the discharge. When the current discharge reached the conducting paper, it removed the top layer of the paper at the point where the current touched the paper, leaving traces on the surface of the conducting paper and holes in the case of breakdown due to high currents.

### D. Photography Camera

Due to the opacity of the soil, a photography camera is not usually employed to record the discharge inside the soil. However, a visible light camera was used with a particular test cell configuration in [3], where the test rig used a narrow glass tube of 13 mm diameter. In addition, the soil sample was very coarse sand, which provided relatively larger air voids. In the tests, positive and negative DC voltages were applied to the dry soil samples inside the glass tube and many discharges in the gaps between the sand grains were seen. These discharges extended over the sand particles surfaces to construct a streamer and the camera was able to detect and record the light from the discharges. The special test rig was designed in [10] to record the discharge with a digital camera, where the test rig had a glass window, so that the camera can observe the discharge. However, the HV electrode was pressed against the glass window. Hence, the spark channels occurred on the surface of the glass window not deep inside the soil, so the discharge was recorded from outside by the camera.

### E. Thermal Imaging

In a study conducted in [12], which set out to thermally image the change of the soil temperature during the test utilised an infrared camera. Lightning surges were applied to a dry soil sample in a cylindrical electrode arrangement. In addition, the thermal imager was used to record the temperature of the topsoil of the sample. After several discharges, it was observed that the temperature was slightly raised with the increment in the applied voltage, and the maximum temperature was observed around the active electrode.

The voltage was applied from 10 kV up to 75kV, and the temperature was increased with 1.9 °C during the test. This increase of temperature was attributed to the collision of the fast moving electrons with the other molecules and atoms of the air and the soil grains during the discharge.

### F. X-Ray Radiation

Another technique was introduced in [13]. X-ray radiation was utilised to capture the soil ionisation and discharge in the soil under surge currents. An x-ray imaging system (x-ray generator and digital radiography board) was used to apply the x-ray to the sample at the instant the impulse current was injected at the electrode. This electrode was placed in a tank full of sand.

The applied x-ray penetrated the soil sample and, then, was captured on a digital radiography board behind the tank. Grayscale images were obtained for several discharges with vertical and horizontal active electrode arrangements. After processing the images, it was found that the areas were exposed to a higher x-ray intensity were whiter, and those of less x-ray intensity were darker.

### G. High Speed Camera

A new methodology has been developed in [14], where a high speed camera was used to record the discharge. However, the material used in this study was not soil, but it was a glass bubble material, which has a transparent grains. The authors in this study have used a special sample arrangement placed in a transparent tube between rod to plane electrode configuration. Lightning and switching impulse voltages have been applied on the samples. High speed camera was operated at very high frame rate to capture the discharge (175000 fps for lighting tests and 100000 fps for switching tests).

Then, the recorded video frames were correlated with the applied voltage and measured current waveforms. This correlation process was very useful to understand the discharge process in conjunction with the applied impulse voltage. Dynamic changes of the discharge were captured by the high speed camera. Video frames with 5.5 µs and 9.8 µs time duration were recorded. The light intensity was found dependent on the current magnitude. The delay time before the current rise was attributed to the ionisation initiation and propagation from the HV electrode until it reaches the wet layer at the bottom of the sample. Different discharge scenarios have also been obtained.

## III. MATERIALS USED AS A TEST MEDIUM

Natural soils are the main material that has been used in most of the experiments reviewed. Different types of soils have been used as samples such as sand, clay, cultivated soil and red soil. To change the resistivity of the sample, different percentage of water were added to the samples, where the water content is calculated as a percentage from the dry sample mass. Thus, low moisture content such as 1% and 2% were adopted, and high moisture percentages like 5% and 10 % were also considered in the tests. Moreover, salted water was added to some samples to obtain an even lower soil resistivity. Different grain sizes were also used; for instance, very coarse, coarse and fine sand were used in [3].

An alternative approach to study soil ionization has used different substance, which is glass beads as in [5] ranging in size from 0.25mm diameter to 0.05mm diameter. The beads were wetted with salted water and lightning impulses were applied to the test cell. X-ray film was placed inside the material, near the rod-rod electrodes to record the discharge. Furthermore, in [14] glass bubble material (S38XHS) has been used. This material consists of hollow low-density glass microspheres (average diameter of 30 microns). It is an insoluble substance, which takes the form of a white powder, and is made from soda lime-borosilicate glass. However, due to its ability to transmit light, it was utilized in this study to investigate visually the electric discharge and soil ionization phenomenon.

Special sample arrangement was proposed, the sample was divided into two layers, the upper layer was dry glass bubbles (where the discharge is intended to occur). The lower layer was also divided to two sections; the right hand section was dry material, whereas the left hand section was wetted glass bubble with tap water.

## IV. RESULTS OF THE RECORDED DISCHARGES

Tree-like model streamer was captured by x-ray and photographic films using many different electrode configurations with dry and wet samples. For instance, in [2] the obtained tree-like images indicated that the development of the streamers was faster and more extensive in the case of a needle electrode The obtained images in [3, 6] showed positive and negative tree-like streamers depending on the applied impulse polarity, Single channel, multi-channel discharges and breakdown channels were observed on the conducting paper as in [11].

Negative streamers with positive retrograde streamers were captured on x-ray film under negative impulse voltage in [6]. Positive and negative streamers bridging between the two electrodes at the two endings of the glass tube were recorded by a photography camera[3]. A discontinuous soil ionization phenomenon was observed in [7], a strong ionization effect around the electrodes and a weaker zone between them was captured on an x-ray film. The authors have found that the dielectric non-uniformity of the soil, the size and shape of the soil grains were causing this phenomenon by changing the electric field distribution in the soil.

He et al [5], according to their x-ray images, considered that the ionization with large glass beads is stronger than that with the small beads, and that this could be due to the larger air voids with the large beads. Ionization in wet clay was also stronger than in the dry sand, and this could be attributed to the non-uniformity of the wet clay in terms of the grain size and water content. He et al [6] have used the theory of gas discharge to explain the obtained discharge images, where the discharge in dry sand is comparable to the electric discharge in air.

The authors in [8] have found that the shape of the discharge along the electrode starting from the injection point had a cone shape. The area of the discharge at the injection point was the largest, and it decreased as it moved away. This shape was formed because of the higher leakage current at the front terminal of the electrode, and they found that due to the great inductance of the electrode under the high frequencies of the impulse current, the leakage current would decrease as the current flowed further towards the far end. Therefore, they concluded that there is an effective length for the electrode under the impulse currents. In [11] it was concluded that the discharge current has the propensity to form a single propagating path with dry inhomogeneous soil, and the single channel breakdown mechanism in wet soil is different from that in dry soil, where the moisture content in the wet soil will conduct the current as soon as the voltage is applied while in the dry soil, air voids have to be ionized before any current conduction.

From [13], streamer discharge channels at the ends of both vertical and horizontal electrodes can be observed with various diameters and directions according to the excitation current and electric field distribution. Furthermore, the channel area was found to increase with the increase of the current magnitude.

Single channel discharge was recorded by the high speed camera in [14], where the current was flowing from the HV electrode to the ground according to the electric field lines. However, the correlation process was a new method to explain the electric discharge process, where the discharge can be observed step by step from the onset of the impulse wave until the end of the discharge. As a result, the dynamic development of the discharge was recorded and analyzed in conjunction with the voltage and current waveforms.

## V. DISCUSSION

The opacity of the soil made it very difficult to visualize the discharge, also there are several factors affecting the discharge process inside the soil, such as water content, and water settling, grain size, electrode configuration and the applied voltage. Besides, the soil consists of a mixture of components, for instance, diverse nonconductive soil grains, air, water, minerals, stones, organic substances etc. all these materials contribute in the complexity of the soil. Therefore, imaging the discharge development is considered very complicated process.

Techniques employing photographic films, x-ray films and conducting paper have been used to record and visualise the electric discharge and the ionisation phenomenon in the soil. It was found that, when the discharge occurs, the produced elements, such as light, x-rays, and heat, help to reflect and copy the discharge on these films. The photographic films can image the ionisation zone by capturing only the discharge light, whereas the x-ray films have the ability to record the propagating streamers, as the rays generated by the ionisation process, which could be x-ray, Ɣ-ray, ultraviolet, or a mixture of the three rays; can easily penetrate the cassette to copy the discharge onto the film inside the soil [15].

The distance between the electrode and the sensitive film must be taken in the account when using these techniques, because this distance determines the clarity and purity of the recorded images on the films [6]. So if the film was very close to the electrode, then the image could be distorted, and if the film was far from the electrode, then it may not capture the discharge. Thus to obtain a good image, the authors have used variable distances according to several factors, such as moisture content, grain size, electrode configuration and applied voltage. From the recorded discharge images, it was found that the discharge shape and propagation of streamers depended on grain size, moisture content and impulse polarity[3].

However, these methods suffer from some disadvantages, for instance, they are inefficient techniques in terms of the quality of the images, and they give a restricted view of the phenomenon. Also, they cannot capture the dynamic change of the discharge with time. Furthermore, if the discharge is too strong, the recorded images on the films will suffer from pierces and colour distortion, due to their thermal and light sensitivities. On the other hand, these techniques are simple, cheap, easy to use, and they have provided very useful images, which have helped with the understanding of the soil discharge phenomenon. From the reviewed studies, it was found that the use of x-ray films were most frequently reported despite in [4] the authors found that the black and white film has captured better and clearer images than x-ray film.

Using thermal camera to image the electric discharge in soil was not effective, because the thermal camera measures the temperature of the soil on the surface of the sample, not inside the sample around the electrode. In addition, several impulses need to be applied to obtain a clear temperature change on the soil (heating the sample). This may change the discharge process as the water content in the sample may evaporate. Furthermore, using the digital camera in [10] was a significant attempt in imaging the spark channels. However, pressing the electrode against the glass wall may considerably affect the discharge process, where the differences in the permittivities between the wetted soil and the glass could enhance the electric field on the glass surface and affect the whole process of the discharge.

Many electrode configurations were utilized, and most of these configurations produce a nonlinear electric field. Moreover, placing a film near the electrode could change the electric field behavior, and this might affect the whole discharge process. Moreover, different materials have been used as test medium to image the discharge, some of them are not type of soil, but due to their characteristics, they were used.

There are no standard settings and procedures for using these techniques, nor standard electrode configurations. As a consequence, all the reviewed studied have been carried out depending on the experience of the authors. Moreover, there is a growing body of literature that recognizes the importance of studying the electric discharge visually in the soil to find better explanations for the developments and the shapes of the discharge around the electrode. Therefore, new methodologies have been developed such as x-ray radiation and high speed camera with glass bubble material. These new methods have provided better images, and have captured the dynamic discharge changes.

## VI. CONCLUSIONS

An extensive review of the visual studies of the discharge in soil has shown that

1. Imaging electric discharge in soil is extremely difficult due to the opacity of the soil and due to many factors affecting the discharge process.
2. Imaging techniques have provided very important results to have a better understanding of the discharge phenomena in the soil.
3. Sensitive films techniques are considered basic and offer only a limited way to visualize the ionisation and the discharge phenomena in the soil.
4. Sensitive films cannot capture the dynamic change of the discharge development with time.
5. Despite the disadvantages of the sensitive films, x-ray film is still the most commonly used technique.
6. New methodologies such as high speed camera with glass bubble material offers wider view of the electric discharge by capturing the dynamic development of the discharge.
7. Different materials have been used to visualise the electric discharge.
8. Finding and developing new techniques that are able to record the dynamics of the discharge are required.

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