High Voltage Discharge Profile on Soil Breakdown Using Impulse Discharge

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Abstract. Grounding terminals are mandatory in electrical appliance design as they provide safety route during overvoltage faults. The soil (earth) been the universal ground is assumed to be at zero electric potential. However, due to properties like moisture, pH and available nutrients; the electric potential may fluctuate between positive and negative values that could be harmful for internally connected circuits on the grounding terminal. Fluctuations in soil properties may also lead to current crowding effect similar to those seen at the emitters of semiconductor transistors. In this work, soil samples are subjected to high impulse voltage discharge and the breakdown characteristics was profiled. The results from profiling discharge characteristics of soil in this work will contribute to the optimization of grounding protection system design in terms of electrode placement. This would also contribute to avoiding grounding electrode current crowding, ground potential rise fault and electromagnetic coupling faults.

1. Introduction

Experiments on electrical conductivity of soil have long been investigated for numerous reasons ranging from its use in agricultural purpose to use in electrical grounding systems. The soil electrical conductivity vary with time and place due to factors like pH, moisture and available nutrients present\([1, 2]\). The naturally existing variation in such soil property makes it difficult in designing efficient grounding system for electrical terminal. Furthermore, this soil properties could also vary due to electrical activities in its vicinity such as lightning strikes, over voltage power dissipation and other electrical activity leading to soil ionization and breakdown\([3, 4]\).

In several literature, this adverse effect of soil conductivity variation at grounding sites have majorly been attributed to ground potential rise (GPR) that can directly fail connected systems or increasing the risk and occurrence of step and touch voltage harmful to humans and other living organism\([5 – 7]\). Protection designs against the detrimental effects from the enormous electrical discharge of lightning phenomena strongly rely on a total dissipation through the soil whose impedance isn’t constant\([8]\). With designs of more sensitive technological devices that are susceptible to effect resulting from earth impedance fluctuations in widespread profiling the breakdown would provide better information for optimization of grounding protection systems. One way to make clear of soil characteristics influence on current distribution and breakdown properties is by investigating the discharge propagation in soil when exposed to high voltage discharge.

This research aims to profile the discharge breakdown phenomena of soil when subjected to high voltage discharge. In this work, high voltage impulse discharge was injected on a soil surface.
discharge propagation resulting in ionization and breakdown was then observed and discussed using the discharge current distribution during the process on a laboratory scale.

2. Experimental Setup and Procedures

The experimental setup design shown in figure 1 consist of a point to plane electrode system. The stratified point to plane electrode system is designed to offer a dielectric two-phase gas-solid experimental environment. The point electrode is an 8 mm diameter pointed stainless steel electrode which serve as the discharge electrode. The discharge electrode tip is separated from the soil surface by a 5 mm airgap. There are nine grounding electrodes subdivided into five horizontal (E1 – E5) and four vertical (E6 – E9) electrodes placed inside a plastic tub. Electrode 1 is a 1 mm thick, 40 mm diameter copper electrode. Electrodes 2 until 5 are ring-shaped copper electrodes with 1 mm thickness each. Their outer radius is 40 mm longer than their inner radius. Electrodes (E1 – E5) were attached to an acrylic sheet placed at the bottom of a 480 mm diameter plastic tub. Electrodes (E6 – E9) are 0.1 mm thick and 40 mm width copper tape attached to the inner wall of the plastic tub with a 15 mm separation between each horizontal and vertical electrode. Electrode (E9) is placed leveled with the soil surface and electrodes (E8 – E1) were set as under soil electrodes respectively. The soil surface level was set 220 mm from the bottom electrodes. The discharge electrode is connected to a 280 kV impulse voltage generator (TERCO) to generate high voltage spark discharge on the soil surface.

The experiment was conducted by continuously injecting 25 – 28 kV of standard impulse voltage (1.2/50µs) to the discharge electrode at a distance of 5 mm from the soil surface. The discharge current due to the soil ionization and breakdown in the soil were observed at each of the 9 grounding electrodes using a current probe (Pearson 6585) connected to a digital oscilloscope (LeCroy Waverunner 625Zi) and the discharge breakdown condition on the surface was recorded using a digital camera (RICOH CX3) at 5fps shooting speed. In this experiment, the variation in soil pH was achieved by varying the soil moisture content and available nutrients resulting in an increase at the soil electrical conductivity as shown in table 1. The available nutrients was varied adding various weight of fertilizer (NPK and Ca(OH)$_2$) also shown in table 1. The soil electrical conductivity were also measured using earth resistance meter (Megger DET4TCR2) prior to and after the discharge process.

![Figure 1. Experimental setup for observing lightning discharge phenomena](image-url)
Table 1. Soil electrical conductivity variation through physical properties alteration

| Constituents | Soil(kg) | Water(mL) | NPK 11-11-11 (g) | NPK 4-16-16 (g) | Ca(OH)\(_2\) (g) | Moisture[%] | Conductivity [mS/m] |
|--------------|----------|-----------|------------------|-----------------|-----------------|-------------|-------------------|
|              | 30       | 3300      | 100              | 0               | 0               | 23.98       | 29.31             |
|              | 30       | 3600      | 100              | 100             | 0               | 24.78       | 43.53             |
|              | 30       | 3900      | 100              | 100             | 100             | 25.57       | 57.89             |

3. Result and Discussion

3.1. Voltage and current waveform

Figure 2, 3 and 4 shows the voltage and current waveforms at \( \sigma = 29.31, 43.53 \) and \( 57.89 \) [mS/m] respectively. Figure (a) shows the typical injected voltage and current waveform while figure (b) shows the discharge current waveform relative to the breakdown currents at the soil layer around the grounding electrodes resulting from the injected discharge. From the waveforms, it can be seen clearly that the discharge process between soils of different conductivity are distinct as the breakdown phenomena are clearly evident with increase in conductivity from each other. The presence of soil ionization breakdown is confirmed with the sudden drop in input voltage and current waveform which becomes more stepper with increase in conductivity shown in figure 2, 3 and 4 respectively. The evolvement of the discharge current in this figures is somewhat synchronized with that of the injected input current where the increase time pattern and decrease time pattern are almost matching each other. The observed secondary peaks further down the line as time elapses also suggest a multiple secondary ionization breakdown or partial discharge which could be due to micro-voids in soil as the electric potential traverse the soil [9]. Also the input current and the discharge current waveforms are not in sync with the input voltage waveform which further suggest that further breakdown occurs in the soil as conductivity increases [10]. Looking at the variation in the peak discharge current at grounding electrodes and the injected voltage relationship as a function of soil conductivity, it shows that the discharge current increase linearly with the conductivity as the required voltage for the dielectric breakdown and discharge to occur decreased with increase in soil conductivity[11, 12].

![Figure 2](image-url) (a) Input voltage and current waveform at \( \sigma = 29.31 \) [mS/m]. (b) Electrode discharge current waveforms at \( \sigma = 29.31 \) [mS/m]
3.2. High voltage breakdown discharge
Following the analysis of figure 2 – 4, the waveforms strongly support the occurrence of soil ionization and breakdown phenomena. The discharge emission profile captured at 4 different times using the RICOH CX3 digital camera during the multiple injection discharge on soil surface with 3 conductivity $\sigma = 29.31$, 43.53 and 57.89 [mS/m] is shown in figure 5 – 7. The discharge conditions labeled (a) – (d) are captured at different intervals during the multiple injection process on each of the three conductivity.

Figure 3. (a) Input voltage and current waveform at $\sigma = 43.53$ [mS/m]. (b) Electrode discharge current waveforms at $\sigma = 43.53$ [mS/m]

Figure 4. (a) Input voltage and current waveform at $\sigma = 57.89$ [mS/m]. (b) Electrode discharge current waveforms at $\sigma = 57.89$ [mS/m]

Figure 5. Spark Discharge on Soil Surface with Increase in Conductivity, (a) $\sigma = 29.31$ [mS/m]
Figure 6. Spark Discharge on Soil Surface with Increase in Conductivity, (a) $\sigma = 43.53$ [mS/m]

Figure 7. Spark Discharge on Soil Surface with Increase in Conductivity, (a) $\sigma = 57.89$ [mS/m]

From figure 5, it can be seen that there were no visible spark discharge propagation directly on the soil surface. The discharge to the soil surface were thin and localized at a point not far from the discharge electrode tip with minimal difference over the time period as shown in figure 5(b) – (c). In figure 5(d), the discharge channel increased signifying further breakdown would occur with more discharge injection. The discharge channel to soil surface in figure 6 is a lot wider than that seen in the lower $\sigma = 29.31$ [mS/m]. Also the width and the impact zone on the soil surface shows an increase with time as shown by figure 6 (a) – (d). From figure 7, one would see that not only does the discharge channel grow wider but also become branched occupying larger localization area on the soil surface as seen in figure 7 (a) – (d). This is because the increase in soil conductivity resulted in larger area for current propagation easily. Also this increase in electric conductivity resulted in lowering the air-soil phase dielectric breakdown voltage. From all these observations, it can be concluded that the discharge emission on the surface and soil ionization breakdown is strongly associated with the voltage and current waveforms.

3.3. Soil electrical conductivity
The shallow soil conductivity measured before (pre-ECs) and after (post-ECs) along with the deep soil conductivity measured before (pre-ECd) and after (post-ECd) the high impulse spark discharge on the soil surface is shown in figure 8. This graph shows a significant difference in the conductivity of the soil before and after imitated lightning discharge. This difference in the conductivity measured shows the reason for increase in the discharge channel as observed by the images of discharge condition shown in figure 5 – 7. This also validates the occurrence of permanent soil ionization breakdown during the discharge process.
Figure 8. Soil σ variation due to impulse discharge

4. Conclusion
In this work, high voltage discharge breakdown of soil was investigated using impulse discharge applied to the surface of soil placed in a point to plane electrode system. The soil sample at different conductivity obtained from soil with different moisture content, available nutrient and pH was investigated. From there, breakdown discharge characteristics were observed. From the experiment it can be concluded that complete discharge leading to multiple soil ionization and breakdown occurred depending on conductivity of the soil. Furthermore, the breakdown that occur result in varying the electrical conductivity of the soil. The soil ionization is seen to occur readily in higher conductivity and the permanently alters the electrical conductivity of the soil after multiple injection.

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