Discharge current distribution in stratified soil under impulse discharge

Fawwaz Eniola Fajingbesi1,2*, Nur Shahida Midi1, Elsheikh M. A. Elsheikh1, Siti Hajar Yusoff1

1Department of Electrical and Computer Engineering, International Islamic University Malaysia
2Department of Physics Electronics and Earth Science, Fountain University Osogbo Nigeria

E-mail: fawwazfajingbesi@yahoo.com

Abstract. The mobility of charge particles traversing a material defines its electrical properties. Soil (earth) have long been the universal grounding before and after the inception of active ground systems for electrical appliance purpose due to it semi-conductive properties. The soil can thus be modelled as a single material exhibiting semi-complex inductive-reactive impedance. Under impulse discharge such as lightning strikes to soil this property of soil could result in electric potential level fluctuation ranging from ground potential rise/fall to electromagnetic pulse coupling that could ultimately fail connected electrical appliance. In this work we have experimentally model the soil and lightning discharge using point to plane electrode setup to observe the current distribution characteristics at different soil conductivity [mS/m] range. The result presented from this research indicate above 5% shift in conductivity before and after discharge which is significant for consideration when dealing with grounding designs. The current distribution in soil have also be successfully observed and analysed from experimental result using mean current magnitude in relation to electrode distance and location, current density variation with depth all showing strong correlation with theoretical assumptions of a semi-complex impedance material.

1. Introduction

Electrical discharge from lightning phenomena has long been investigated mostly for the sole purpose of designing better and more efficient lightning protection systems. The general effects from lightning strike to earth are so severe to humans, their livelihood and equipment. In several literature, this effect have been grouped into direct and indirect lightning strike effects [1]. The effects from this strike on a target is expected to vary where the direct is more intense as all the enormous energy is dissipated through the object. The indirect strike could cause harm in the form of electromagnetic pulse coupling or leading to a ground potential rise (GPR) that end up failing systems in its vicinity [2].

A lightning discharge whose pathway is directly between a cloud and the soil surface without going through a high rise object or any man made facility is referred to as an indirect lightning strike just as lightning hitting an object before the ground surface is called a direct strike [2, 3]. There are enormous literature on direct strike and its effect compared to an indirect lightning strike. The detrimental effect that could result from an indirect strike is believed to be significant and require more attention due to the widespread development of new and sensitive technological devices [4].

The soil due to its large impedance have long been the universal ground for all electrical operation including lightning discharge from clouds. This soil impedance however vary in accordance to several factors under the umbrella of soil electrical conductivity. It is believed that the severity from indirect
lightning stroke would vary due to this soil characteristics making it difficult to design a universal efficient protection system to combat indirect lightning strike damages. One way to make clear of indirect discharge lightning phenomena and soil characteristics influence is by investigating the discharge propagation in soil when lightning strike on the surface.

This research aims to investigate the discharge phenomena of lightning strike to soil surface. In this work, impulse discharge was applied on a soil surface as an imitation to lightning strike on soil surface. The discharge propagation was then observed and discussed using the discharge current distribution during the process on a laboratory scale.

2. Experimental Setup and Procedures
An experimental setup consisting of a point to plane electrode system as shown in figure 1 was developed to produce an imitation of the lightning discharge phenomena on soil surface. 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 5mm airgap. There are nine grounding electrodes divided into five horizontal electrodes (E1 – E5) and four vertical electrodes (E6 – E9) inside a plastic tub. Electrode 1 is a 1 mm thick, 40 mm diameter circle-shaped copper electrode. Electrodes 2 until 5 are ring-shaped copper electrodes with 1 mm thickness. The outer radius is 40 mm longer than the inner radius. All the electrodes were attached to an acrylic sheet and were set at the bottom of a 480 mm diameter plastic tub. Electrodes 6 until 9 are 0.1 mm thick and 40 mm width copper tape attached to the inner side wall of the plastic tub. There were 15 mm spaces between each horizontal and vertical electrode. Electrode 1 until 8 were set as under soil electrodes while electrode 9 was set as the surface electrode. The soil surface level was set 220 mm from the bottom electrodes. The discharge electrode was connected to 280 kV impulse voltage generator (TERCO) to generate spark discharge at the air gap leading on the soil surface.

The experiment was conducted by applying 22 – 28 kV of standard lightning impulse voltage (1.2/50μs) to the discharge electrode depending on the conductivity of soil sample under test with a distance of 5 mm between the soil surface and the point electrode. The discharge current due to the soil surface discharge were observed at each of the 9 grounding electrodes using a current probe (Pearson 6585) connected to a digital oscilloscope (LeCroy Waverunner 625Zi). In this experiment, the soil conductivity were altered by increasing the soil moisture content to obtain conductivity ($\sigma = 10.63$ and 20.42 [mS/m]) corresponding to a moisture (14.07 and 23.16 [%]) respectively. The soil electrical conductivity were also measured using earth resistance meter (Megger DET4TCR2) prior to and after the discharge process. This offered a more insight to understanding the effect of indirect lightning discharge and soil electrical conductivity.

![Figure 1. Experimental setup for observing lightning discharge phenomena](image-url)
3. Result and Discussion

3.1. Voltage and current waveform

Figure 2 and 3 shows the voltage and current waveforms at the minimum (\( \sigma = 10.63 \) [mS/m]) and maximum (\( \sigma = 20.42 \) [mS/m]) conductivity respectively in the range chosen. From the waveforms, it can be seen clearly that the discharge process between soils of different conductivity are distinct from each other. For \( \sigma = 10.64 \) [mS/m], the input current and the discharge current waveforms are seen to follow similar pattern that is proportional to the input voltage waveform where the increase or decrease in current is seen to follow the increase or decrease in the input voltage. At higher conductivity soil, \( \sigma = 20.42 \) [mS/m] shown in figure 3, a sudden drop in input voltage and current waveform is observed followed by a second peak as time elapsed. The input current and the discharge current waveforms are not exact replica of the input voltage waveform. This suggest that a breakdown occurs in soil as conductivity increase. Also the evident of a second peak shows the characteristics of breakdown in soil [5]. Considering the peak discharge current and voltage in figure 2 (a) and figure 3 (a) measured at the discharge electrode, the discharge current increase with the conductivity. This is because the required voltage for the discharge to occur at the air gap decreased with increase in soil conductivity.

![Figure 2](image1)

**Figure 2.** (a) Input voltage and current waveform at \( \sigma = 10.64 \) [mS/m]. (b) Electrode discharge current waveforms at \( \sigma = 10.63 \) [mS/m]

![Figure 3](image2)

**Figure 3.** (a) Input voltage and current waveform at \( \sigma = 20.42 \) [mS/m]. (b) Electrode discharge current waveforms at \( \sigma = 20.42 \) [mS/m]

3.2. Discharge current distribution

The distribution of discharge current in soil at two different conductivity is expressed in terms of discharge current magnitude and density. Figure 4(a) show the discharge current peak magnitude [A] measured at the nine underground electrodes. The current magnitude distribution on each electrode

![Figure 4](image3)
follows similar pattern across each electrode with increase in conductivity however with greater magnitude at each electrodes. This signifies that current distribution depends on the soil electrical conductivity. Figure 4(b) shows the current density \([\text{A/m}^2]\) at each grounding electrode. The current density offers better insight of the current distribution since the electrodes (E1 – E9) area vary from one another. From this data in figure 4(b), current density can be seen to decrease as the electrodes moved further away from the discharge point horizontally for all conductivity. In the vertical electrodes E6 – E9 the current density is seen to rise as the electrode moved closer to the soil surface however started declining after electrode E8. It can be concluded that discharge current is generally distributed into the soil which is to the bottom of the discharge local point (E1) regardless of the soils conductivity. Similarly if the current density in figure 4(b) on each electrode as (E1 – E9) can be expressed as a function of their relative position from the discharge point providing a better insight on the current distribution inside the soil.

![Figure 4](image.png)

**Figure 4.** (a) Discharge current magnitude and (b) Discharge current density at grounding electrodes

The discharge current density as a function of electrode distance from the local point of discharge on the surface \(d\) is shown in figure 5(a). From this graph, it shows the discharge current on the electrode decreased with increase in the distance from the localized discharge point. This almost uniform decrease signifies a uniform drop in the electric potential traversing the soil. Figure 5(b) shows the current density as a function of depth, \(z\) for electrode E6 – E9 that share infinitesimal same distance, \(d\). Although an initial increase in current density is observed with increase in soil depth around the surface region the subsequent data shows that as the depth of electrode increase, the discharge current density of the electrodes decreases. This is also likely associated to the decline in electric potential reaching this region. However the initial increase could be associated to the current

![Figure 5](image.png)

**Figure 5.** Discharge current density as a function of distance (a) and depth (b)
accumulation on the surface region prior to soil ionization breakdown or partial discharge [6, 7]. In general, this results shows that soil depth and distance is also a factor that affect the discharge distribution in soil.

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) spark discharge on the soil surface is shown in figure 6. This graph shows a significant difference in the conductivity of the soil before and after imitated lightning discharge. This also validates the occurrence of permanent soil ionization breakdown during the discharge process. Hence, the design of an efficient protection system should take into account the soil ionization phenomena.

4. Conclusion
In this work, lightning discharge on soil surface 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 was investigated. From there, discharge characteristics were observed. From the experiment it can be concluded that complete discharge occurred depending on conductivity of the soil. Furthermore, on the discharge current distribution, regardless of the soil conductivity, discharge current penetrates into the soil which is to the right below the discharge local point. Also, as conductivity increase, the percentage of discharge current distributed to the soil surface and inside increased. The electric potential propagation in soil with low conductivity is lower hence result in incomplete discharge compared to the propagation in higher conductivity. Finally, soil ionization is seen to occur frequently in higher conductivity.

Acknowledgment
This research has been supported by Malaysian Ministry of Higher Education Research Grant, RAGS15-063-0126.

References
[1] G Punekar and C Kandasamy 2011 Serbian J. Electr. Eng. 8 245–262
[2] A Kalair, N Abas, and N Khan 2013 J. Light. Res. 5 11–28
[3] N Malcolm and R Aggarwal 2014 2014 IEEE PES General Meeting | Conference & Exposition 1–5,
[4] R Brooks 2010 The World Offshore Renewable Energy Report 2004-2008 2 Department of
Trade and Industry’s Renewables 2010

[5] N S Midi and R I Ohyama 2011 Annu. Rep. - Conf. Electr. Insul. Dielectr. Phenomena, CEIDP 223–226

[6] A Elzowawi, A Haddad, H Griffiths, and D Clark 2015 2015 50th International Universities Power Engineering Conference (UPEC) 2015–Novem 1–5

[7] J He and B Zhang 2015 IEEE Trans. Ind. Appl. 51 4924–4933