VOL. 24, NO. 3, 2025, 310-327
elektrika.utm.my
ISSN 0128-4428

ELEKTRIKA
Journal of Electrical Engineering

Review on the Effect of Soil Properties and Ground Electrode on Soil Ionization Processes

Abdul Wali Abdul Ali[1*], **N. Agbor Etobi Arreneke**[2], **N. Mohamad Nor**[3] and **N. N. Ahmad**[3]

[1]Centre for Electric Energy and Automation (CEEA) Faculty of Engineering, Multimedia University, Cyberjaya, Malaysia.
[2]College of Technology (COT) Department of Electrical and Electronic Engineering, University of Buea, Buea, Cameroon.
[3]Centre for Electric Energy and Automation (CEEA) Faculty of Engineering, Multimedia University, Cyberjaya, Malaysia.

[*]Corresponding author: walikdr17@gmail.com

Abstract: Grounding systems are commonly used in residential and commercial power systems, industries, telecommunication systems, and utilities. Even though technologies and research have contributed to the development of grounding systems, there are still many cases of faults occurring in the system, causing a substantial economic loss. The grounding system needs to have low magnitude resistance to achieve its effectiveness. Under high impulse currents, the soil ionization process would take place, leading to the reduction of the soil resistivity. This would reduce ground resistance of the system, which reduces the rising of transient ground-potential on the ground surface; thus, providing a more effective grounding system. Soil ionization is affected by several factors, which can be taken into consideration during the grounding system design. Previously, in many papers, soil ionization has been investigated. However, a detailed study on factors affecting soil ionization was still needed. Therefore, in this paper, factors affecting soil ionization are investigated, which should be taken into consideration during grounding system design.

Keywords: Grounding System Design, Electrode Configuration, Ground Resistance, Impulse Polarity, Soil Breakdown, Soil Ionization, Soil Resistivity

Article History: received 8 April 2025; accepted 13 June 2025; published 22 December 2025
Digital Object Identifier 10.11113/elektrika.v24n3.727

1. INTRODUCTION

When the electric field developed between the soil grains overreaches its critical value, the area around the electrode becomes short-circuited, which occurs due to the electric discharges' appearance near the electrode. It is widely believed in the literature [1], [2], [3], [4], and [5], etc. that the mechanism of initiation of an arc and/or a streamer is the uncertainty, which occurs in the breakdown of soil under an impulse voltage. This nonlinear behaviour of the soil, which is initiated under the surge conditions, is due to two electrical mechanisms known as soil ionization and thermal effects.

As stated in [6], [4], [2], and [5], in the case of soil ionization, the arc initiation mechanism is fundamentally electrical. It starts when the electric field among the soil grains becomes high enough to start ionizing the air inside the voids. Several authors, including Liew and Darveniza [7], Kosztaluk et al. [8], Velazquez and Mukhedkar [9], Espel et al. [10] Cidras et al. [11], and Ala et al. [12] believed that during soil ionization mechanism the impedance of the buried electrodes reduces. They believed that each type of soil has a critical value for the electric field and when the electric field on the conductor surface exceeds this critical value, the dielectric breakdown takes place and this is when the soil ionization starts in the surrounding peripheries of the grounding system. Cidras et al. [11], believed that the soil ionization zone could be concentrated around the embeded conductors. When current is drained to the earth through a buried electrode, the electric field intensity can be given by equation 1.

$$J = \sigma E + \epsilon \frac{\partial E}{\partial t} \qquad (1) \qquad \text{(adapted from [11])}$$

where 'J' is the current density, 'σ' is the conductivity, 'E' is the electric field, 'ϵ' is the permittivity and 't' is time. The dielectric medium would breakdown, and an arcing conduction zone would establish when electric field 'E' reaches the critical value. Ala et al. [12] stated that the soil ionization region starts from the grounding electrodes' surface as, at that region, the current density is the highest. The region would extend to a distance where the current density decreases to a value that makes the electric field lower than the critical value.

In the case of thermal effect, the initiation mechanism is fundamentally thermal, i.e., when the voltage is applied, the flow of current towards the soil is mainly conducted by water. However, in the absence of water, the grounding system may become inadequately grounded, hence leading to various safety concerns and potential damage to equipment. Whereas during the flow of the high-temperature current through water, the water temperature rises too, which reduces the water's resistivity. As the heating rate is not uniform, all the currents flow toward some narrow, low resistivity channels. Thus, the breakdown is assumed to take place when the temperature of the water in a channel reaches the boiling point as that suggested by Snowden et al. [13], and Leadon R. E. et al. [14].

The discrimination between soil ionization and thermal mechanisms has been relatively indirect and inadequate. When there is a large combination of possible soil parameters such as water content, grain size, and electrical conductivity, etc., there is a high possibility of both mechanisms being correct for different parameter combinations. For example, on dry soil, the water on the grains perhaps does not flow continuously on specific paths over the soil, so, in this case, air breakdown or soil ionization would be the more plausible mechanism. In another case, where the soil is wet or water-saturated, there is no primary air in the voids, but the existence of small air pockets, water heating, or thermal mechanism is the more convincing process. However, N. M. Nor and Ramli [15] stated that the two mechanisms are discriminated according to the amount of absorbed energy. Sekioka S. et al. [16] has also mentioned that the foundation of all these models is derived from the basis of energy balance. To obtain such discrimination, for a given voltage, the energy ingested by wet soil and its water content is estimated and then correlated to the variation in the characteristics under the magnitudes of high impulse currents. There are several factors and features which affects the soil ionization significantly, thus, affecting grounding system performance under high impulse conditions as mentioned by [4], [17], and [12], which will be described in the next section.

2. FACTORS AFFECTING SOIL IONIZATION

Soil ionization is mainly affected by soil resistivity, ionization gradient, soil structure, impulse polarity, electrode configuration, and the soil breakdown as explained in [18], [9], [19], [20], [21], [13], [12], and [11], etc.

2.1 Soil Resistivity

Based on the widely mentioned theories and experiments [22], [19], [7] [23], [24], and [12], it is assumed that the resistivity of the ionization region reduces instantaneously. It was also found that the ionized soil resistivity keeps some definite value that is greater than the resistivity of the grounding conductors. Oettle E. E. [19] experimented to understand soil ionization's natural principle. When he applied the impulse voltage to the soil, and the field intensity reached between 7 kV/cm and 9 kV/cm around the inner spherical electrode, it was realized that the impedance of the soil sample was reduced accordingly. Thus, the critical electric field of the soil ionization was chosen as 8 kV/cm. The radius of the ionization region increased until the electric field intensity reduced to the critical field value, which can be mathematically represented as that written in equation 2.

$$r = \sqrt{\frac{\rho_0 I}{2\Pi E_0}} \qquad (2) \qquad \text{(adapted from [19])}$$

where $'r'$ is the radius of the soil ionization region, 'ρ_0' is the soil resistivity before soil ionization and 'I' is the peak current, which is related to the theoretical peak electric field, and 'E_0' is the critical electric field intensity. It can be seen clearly from the mathematical expression that the soil resistivity, peak impulse current, and critical electric field intensity are essential factors affecting the soil ionization region's radius.

Prousalidis et al. [25] conducted experiments on different soil types with different resistivities and different grounding configurations for the validation of their soil ionization model. In Table I, it could be seen that the radius of the soil ionization zone changed with respect to the soil resistivity, in which the soil ionization area is directly proportional to the resistivity of the soil.

Almeida and De Correia Barros [26] investigated soil ionization by developing a soil ionization model and simulating it. Their results showed that the electric field never exceeded its critical value. It was assumed that when the soil ionization occurs, the electric field becomes uniform in the area surrounding the electrode. They then divided the ionized region around the electrode into smaller shells, mathematically indicated by the symbol 'k' in the mathematical model shown in equation 4.

$$A_k = \frac{\rho_k I}{E_c} \qquad (3) \qquad \text{(adapted from [26])}$$

where 'A_k' is the surface area of the ionized shell, 'ρ_k' is the resistivity of the soil in the shell, 'I' is the injected current, and 'E_c' is the critical breakdown field of the soil. As the injected current increases, the electric field increases too. When the electric field exceeds the soil's critical breakdown value, the soil resistivity reduces, which causes the area of the ionized shell, A_k to reduce.

Table 1. Soil Resistivity and Radius of the Ionized Area for Different Types of Soil and Grounding Systems (adapted from [25]).

Soil Type	Initial Resistivity (Ωm)	The Radius of the Ionized Area (m)		
		Grounding Rod	Grounding Wire	Square Scheme
A (clay)	50	0.72	0.21	0.01
B (gravel)	500	2.29	1.35	0.21
C (sand)	5000	2.50	2	2.77

Liu Yaqing [23], Velazquez and Mukhedkar [9], Espel et al. [27], and Zhang Bo et al. [21] also proposed soil ionization models, in which the soil ionization would occur when the electric field intensity on the surface of the grounding electrode exceeds the critical ionization value. When the soil ionization initiates, the soil's radius significantly becomes directly proportional to the electric field intensity. When the electric field intensity finally starts reducing back and reaches the critical ionization value, the soil ionization radius becomes minimum. In these models, it was assumed that the soil ionization is uniform around the electrode, and it is affected by the soil resistivity, dissipating current, length of the electrode, and electric field intensity, as shown mathematically in equation 5.

$$r = \frac{\rho_0 I_d}{2\Pi l E_0} \qquad (4) \qquad \text{(adapted from [23])}$$

where 'r' is the radius of the soil resistivity, 'ρ_0' is the soil resistivity before the occurrence of soil ionization, 'I_d' is the dissipating current, 'l' is the length of the grounding electrode, and 'E_0' is the critical value for the electric field intensity to cause ionization.

Further, Sekioka S. et al. [20] proposed a current dependent grounding resistance model. The model was designed based on the energy balance of the soil ionization, in which the soil ionization zone grows with respect to the injected current. The resistivity of the soil ionization zone is much lower than the initial resistivity of the soil. The mathematical equation of his [20] model is written in equation 3.

$$S(r_c) = \frac{\rho_0 I_c}{E_c} \quad (5) \text{ (adapted from [20])}$$

where '$S(r_c)$' indicates the ionization zone surface area covering the distance from the electrode within the ionization zone, 'ρ_0' shows the soil resistivity before soil ionization, 'I_c' indicates the injected current, and 'E_c' indicates the soil ionization gradient. It can be seen from the mathematical equation that the surface area of the ionization zone does not only depends on the soil resistivity but also it depends on the injected current and the ionization gradient. As the surface area of the ionization zone is directly proportional to the soil resistivity, this indicates that the soil ionization mechanism is more effective in high resistivity soil. Sekioka S. et al. [20] also stated that the soil's resistivity does not quickly become zero, but it depends on several factors, i.e., time constant, temperature and water content, and when the current starts reducing, the resistivity starts increasing slowly. This is due to the energy stored in the segments, which continue to rise for a limited time.

On the other hand, M. Mokhtari et al. [28] modeled a grounding electrode. They considered the soil ionization factors and the current rising rate in the model, which was similar to the CIGRE model [29]. According to this model, the soil ionization initiates when the current injected into the ground exceeds its critical value, which depends on the soil's resistivity, the resistance of the grounding electrode, and the soil critical electric field intensity as represented mathematically in equation 6.

$$I_g = \frac{E_c \rho}{2\pi R^2} \quad (6) \text{ (adapted from [28] and [29])}$$

where 'I_g' is the critical value of the current at which soil ionization occurs, 'R' is the measured low-frequency resistance of the grounding electrode and 'Ec' is the critical electric field.

Espel et al. [10] investigated the relationship between ionization gradient and soil resistivity by conducting laboratory experiments. The value of the ionization gradient, E_c, was found less than 30 kV/cm regardless of increasing the value of soil resistivity, ρ. For 100 Ωm < ρ <1000 Ωm, E_c was found 8 kV/cm. This value was not affected by reducing the water content in the soil. For 1000 Ωm < ρ <25000 Ωm, E_c varied linearly. For 25000 Ωm < ρ <250,000 Ωm, E_c was found 17 kV/cm. These experimental results were different from Oettle's [30] and Korsuntcev's [31] theories, which state that the relationship between the soil resistivity and the ionization gradient is linear, as shown in equation 7 and equation 8.

$$E_c = 241\rho^{0.215} \quad (7) \text{ (adapted from [30])}$$
$$E_c = \rho j \quad (8) \text{ (adapted from [31])}$$

where 'E_c' is the soil's electric field strength, 'ρ' is the soil resistivity, and 'j' is the current density.

Víctor et al. [32] investigated on the same relationship and their results were similar to Espel et al. [10]. In the high resistivity soil, the size of the sand particles was having a linear relationship with the ionization gradient. However, this relationship was less apparent in low resistivity soil. The relationship between soil resistivity and ionization gradient was also investigated by Gonos and Stathopulos [33], who also investigated the relationship between soil resistivity and ionization gradient. They performed their experiments on two different samples of dry soil. The ionization gradient was found between 350 kV/cm to 1300 kV/cm for the soils having a resistivity of 150 Ωm to 1300 Ωm, as shown in Figure 1.

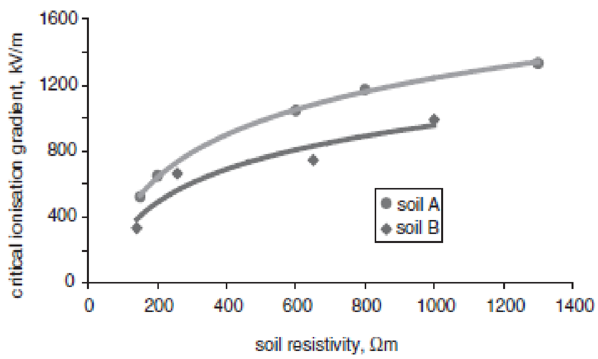

Figure 1. Effects of Soil Resistivity on the Ionization Gradient (adapted from [33])

Further, Cidras et al. [11] investigated soil ionization by performing laboratory experiments. It was found that the soil ionization becomes more significant with lower ionization gradient. From their laboratory experiments, the impulse resistance was reduced from 3.9 Ω to 3.47 Ω when the ionization gradient value was 1kV/cm. It decreased from 3.9 Ω to 3.67 Ω, when the ionization gradient value was 3 kV/cm and 3.9 Ω to 3.73 Ω when the ionization gradient value was 5 kV/cm.

Soil resistivity is further affected by other factors, i.e., grain size, physical and chemical properties of the soil (water and salt content, temperature porosity, soil density), and seasonal effects.

2.1.1 Grain Size

The soil consists of solid particles known as grains. Grains contain voids between them, filled with a phase of gas, generally, air or liquid. The interaction of these phases affects the behavior of the soil. Datsios and Mikropoulos [17] investigated the effect of grain size on the impulse breakdown of dry sands experimentally. In the experiment, five different samples of the sand having different grain sizes were chosen. They [17] found that the average breakdown gradient is lower for larger grain size. The breakdown gradient reduction was from 23 kV/cm to 14.5 kV/cm having a grain size of 0.4 mm to 4 mm, respectively. The corona inception resulted in the breakdown too. This was due to the uniform electric field in the air gaps. The corona inception in the voids filled with air indicates the ionization gradient is dependence on the sand pore size, which is the size of the air voids inside the grains. Hence, for corona to occur, the electric field of the conductors must exceed a critical threshold, called "disruptive potential gradient or breakdown strength of the gas (like air) surrounding the conductor which is directly related to soil ionization gradient.

The change in the grain size of the soil affects the moisture held inside the soil structure, and it affects the size of the air voids, which would then affect the soil resistivity. N. M. Nor et al. [34] investigated the electrical behavior of the two types of the soil grains (small grain size and medium grain size) by conducting high impulse current experiment. The diameters of the small grains were from 0.04 mm to 0.2 mm, and the diameters of the medium grains were from 0.06 mm to 0.6 mm. They observed that critical electric field gradient (Ec) is dependent of the ground electrode configuration, soil grain size and impulse resistance. These resistance values were lower for the medium grain size.

He et al. [35] later experimented with investigating soil grain size's effect on the critical electric field value. It was found that the soil particles of the smallest grain size had the highest critical electric field value. This is because the breakdown in the soil was due to the ionization of the air in the voids, in which the electric field was enforced with interruptions. For a soil sample with a larger grain size, it is easier to develop continuous discharges, which would lead to a lower critical electric field. It was also found that the average size of the air voids within the soil depends on the grain size. For example, a soil particle with a fine grain size would have small air voids, and a soil particle with a coarse grain size will have large air voids. They [35] also mixed two different soil samples to form a non-uniform grain size, which led to the irregular shapes of the air voids. This resulted in partial enforcement of the maximum electric field in the air voids, which led to a faster soil breakdown.

2.1.2 Physical and Chemical Properties of the Soil

IEEE standard 80 [18] illustrated the effects of the temperature, salt, and moisture contents on the soil's resistivity under fast impulse voltages and small conduction currents. It was found that the resistivity of the soil reduces with an increase in the salt content, water content, and temperature. In the soil, the electric current behaviour is mainly electrolytic; it depends on the ions' displacement in the pores. Therefore, the electric current is directly proportional to the amount of dissolved salt and water content, as stated by Samouëlian et al. [36]. It is also known that the resistivity of the soil is less affected when the salt content exceeds 10 %, the temperature reaches 0 °C, and the water content exceeds 22 %, as observed by N. M. Nor et al. [37]. For the current conductivity, salt needs to be in the ionized form. Thus, the presence of water in the soil leads to such paths of conductivity. Samouëlian et al. [36] mentioned that the soil's electrical conductivity depends on the quality of water in the pores and its quantity. However, when the viscosity of water reduces, increasing the temperature; resulted in an increment in the ion agitation, which leads to the reduction of the electrical resistivity. Campbell et al. [38] conducted laboratory experiments on 30 soil samples and observed an increment of 2.02 % in the soil's conductivity per °C from 15 °C to 35 °C was noted.

N. M. Nor et al. [39] conducted an impulse test on the sand having water contents of 1 %, 3 %, and 10 %. The resistance before and after the initialization of the ionization process was lesser for the sand with higher water content. This resistance was inversely proportional to the current magnitude, which indicates a nonlinear conduction procedure in wet sand. When the temperature of the soil increased, the resistivity of the soil was reduced. When the tests were repeated using different test mediums, a direct relationship between resistance and current was noted too. Lee et al. [2] also experimented with investigating the effects of water content on the soil breakdown characteristics. Four soil samples, having water contents of 2 %, 4 %, 6 %, and 8 %, were tested. At least ten shots of positive impulses were applied to each test sample. The effects of water content on the ionization's critical field value and the critical field value for the soil breakdown were investigated. It was found that both of the critical field values reduce with an increase in the water content.

Furthermore, laboratory experiments on the soil resistivity were performed by Garambois et al. [40], Michot et al. [41], and McCarter et al. [42]. It was found that the electrical resistivity was reduced with an increase in water content. A faster reduction in soil resistivity was noted when the water content was less than 15 %.

Snowden et al. [43] used soils prepared from sands with uniform grain size for their experimental study. Four soil samples were chosen, which were dried soil, and soils with a water content of 0.25 %, 1 %, and 4 % having a salt content of 0.3 (mg NaCl/g sand), 0.9 (mg NaCl/g sand), and 0.1 (mg NaCl/g sand), respectively. It was found that all of the soil samples were leading to different soil conductivities. For these different conductive soils, different breakdown characteristics were noted.

N. M. Nor et al. [37] performed experiments on the soil under DC and fast impulse conditions by adding both water and salt content to the sand samples. It was found that the salt content on the soil sample had a lesser effect on the reduction of soil resistivity value than the water content. The soil ionization was more apparent for the soil with lower water content. The soils, which contained higher water and salt contents, were less dependent on the current magnitude. Such soils lead to lower resistivity values, indicating less significance of soil ionization and smaller impulse resistance values. The impulse tests were conducted on the dry sand samples, too, in which the sand contained 0 % water content and 5 % salt. During these tests, small conduction currents and higher initial oscillations were observed due to the soil's capacitive effects and high resistivity.

Kolay et al. [44] studied the effects of salt on the electrical resistivity at different temperatures. It was found that the soil resistivity was reduced with an increase in salt content. This reduction was more evident for the soils at a lower temperature due to the soil's water content's saturation state. A sharp reduction was seen in the resistivity value when the salt concentration was less than 2 %. This was due to the release of sodium and chloride ions because the soil's resistivity mainly depends on the concentration of the ions.

Fukue et al. [45] conducted laboratory experiments on the soil to investigate the effects of sodium salt (NaCl) and potassium salt (KCl) on soil resistivity. The soil resistivity was reduced from 200 Ωm to 2 Ωm by mixing the sand with the water, which contained 30 g/KCl concentration. The soil's electrical resistivity was reduced from 200 Ωm to 50 Ωm by adding NaCl, i.e. 0.01 % of the total quantity of the soil to the water.

Figure 2 shows the effects of water content and the temperature on the breakdown characteristics of the soil. The experimental study on the soil was done by Jinliang et al. [46] on the soil having a water content of 0 % to 15 % at four different temperatures of the soil, which were 25 °C, 0 °C, -10 °C, and -20 °C. The water content was divided into three zones, zone 1 was from 0 % to 4 %, zone 2 was from 5 % to 7 %, and zone 3 was from 7 % to 15 %.

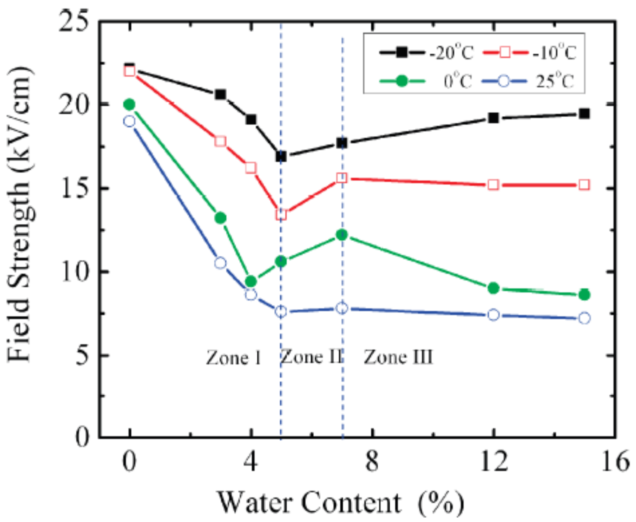

Figure 2. Effects of Water Content and Temperature on the Breakdown Characteristics of the Soil (adapted from [46])

It could be seen that in zone 1, the breakdown field value reduced by increasing the water content; this occurred at all temperatures except at 0 °C. After 4 % of water content, the ionization gradient value for soil at 0 °C temperature started increasing with an increase in water content. This was due to the saturation state of the water content in the soil, in which when the water content was increased, the E_c value of the frozen soil reduced, and the air remained as the dominant filler in the voids. The water existed as two portions, one portion existed as associated water, which was due to the electrostatic attraction of the soil particles, and the other portion was gravity water. In such a case, the water would be either in the ice form or liquid form, depending on the temperature. The water content increased the air gap, and thus, the air gap became irregular, which resulted in a reduction in the E_c value. However, the E_c value increased with an increase in water content in zone 2. This increment was 10 % at 0 °C and -10 °C, and lesser at 25 °C and -20 °C. Water is the material that fills the voids, and the water becomes ice at a lower temperature. Thus, the soil becomes less conductive. This caused a slight increase in E_c's value, and the breakdown mechanism was more like a solid. Thus, when the water content was further increased, the E_c became saturated. In zone 3, the E_c value at 25 °C and -10 °C increased by approximately 3 %, whereas these characteristics were significantly different at other temperatures. At 0 °C, the E_c value reduced by about 20 % up to the water content of 12 %, and then about 3 % with a further increase in water content. In contrast, at -20 °C, the E_c value increased around 10 % up to the water content of 12 %, and then it was reduced to around 3 % with a further increase in water content. Due to the increase in water content, the actual temperature was not low enough to freeze all the water. Thus, there was still an existence of the liquid water filling the air voids, which kept the E_c value lower. When the temperature dropped further, more water became frozen; thus, the value of E_c increased.

Archie [47] related the saturated soil resistivity with the porosity and pore fluid resistivity, as shown in equation 9. This model was further used and modified by Keller and Frischknecht [48], Waxman and Smiths [49], Shah and Singh [50], and Bryson [51]. Shah and Singh [50] validated Archie's formula and proposed a more generalized form of this model for the soil having fine grain size. Bryson [51] stated that the soil's electrical resistivity is related to several elements of porous media by developing an electrical mixing model of the soil.

$$\rho = a \times \rho_w \times n^{-m} \quad (8) \text{ (adapted from [47])}$$

$$\rho = a \times \rho_w \times n^{-m} \times S^{-p} \quad (9) \text{ (adapted from [48])}$$

where 'ρ' is the soil resistivity, 'a' and 'm' are the fitting and cementation parameters, 'n' is the porosity, 'ρ_w' is the resistivity of the pore fluid, 'S' is the degree of saturation, and 'p' is saturation exponent.

Yoon et al. [52] stated that soil resistivity changes with the change in porosity at a specific water content. A reduction in porosity enhances the connection between soil particles and pore fluids, which leads to a smoother flow of current and reduction in soil resistivity. Their experimental laboratory results indicated that the soil's resistivity reduces with a decrease in porosity based on the water content in the soil. These characteristics were different for the two different types of soil, as shown in Figure 3.

Abidin et al. [53] investigated soil resistivity's soil density effects. The soil density value was found higher for the compact soil than the loose condition. This was due to the higher quantity of the soil in the compact condition. Wilkinson [54] stated that the volume of voids containing air and water reduces with compaction of the soil.

However, these gaps still exist, which may not be further reduced. The volume of these voids is higher when the soil is loose, as shown in Figure 4. In both conditions, the voids may contain air and water. The soil resistivity basically depends on the existence of air or water inside the voids. However, the current propagates quickly in the compact soil as the voids gaps are smaller.

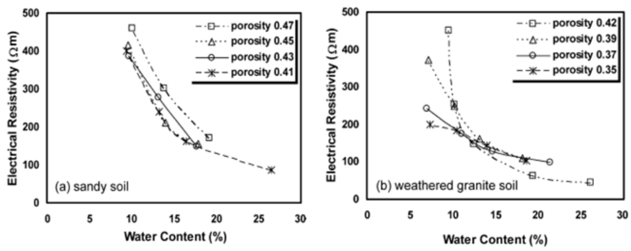

Figure 3. Electrical Resistivity versus Water Content of the Soil for Various Porosity Values (adapted from [52])

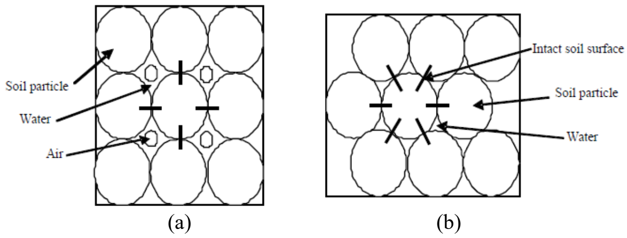

Figure 4. Soil Particles in Loose Condition (a), and Compact Condition (b) (adapted from [53])

Côté and Konrad [55] related the soil density with soil thermal conductivity and soil porosity, as shown in equations 11 and 12.

$$k_{sat\,(u)} = k_s^{1-n} \times k_w^n \qquad (10) \text{ (adapted from [55])}$$

$$n = 1 - \frac{\rho_d}{\rho_s} \qquad (11) \text{ (adapted from [55])}$$

where '$k_{sat\,(u)}$' is the unfrozen soil's thermal conductivity, 'k_s' is the thermal conductivity of soil particles, 'k_w' is the thermal conductivity of water, 'n' is the porosity of the soil, 'ρ_d' is soil's dry density, and 'ρ_s' is the density of soil particles. When the volume of voids changes, it changes the porosity of the soil. Thus, affecting the soil thermal conductivity. The grain size and the shape of the soil particles affect the soil's overall geometry and density. For example, the gravel with highly distributed particle size may have lower porosity than the fine sand with equal particle size.

2.1.3 Seasonal Effects

Many studies [56], [57], [58], [59], [60], etc. have been conducted on the seasonal influences over soil resistivity and grounding systems. The seasonal changes mainly affect the temperature and water content, affecting soil resistivity; thus, affecting soil ionization.

Gustafson et al. [60] conducted field experiments on the grounding resistance variations of a distribution system due to the seasonal changes. The impulse resistance was measured over periods of 15 months and 24 hours. The grounding rod electrodes used for the experiment were having a length of 8 feet and 16 feet. The experiments were performed on three different sites having low resistivity soil, medium resistivity soil, and high resistivity soil. The impulse resistance variation due to the seasonal changes was seen in all sites and grounding systems. This was due to the variation in soil upper layer resistivity value, mostly affected by seasonal variations.

Coelho et al. [61] investigated the seasonal influences on the soil resistivity and the grounding resistance at two different sites. The electrical resistivity of the soil with higher porosity indicated more significant variations due to the effects of rainfall. The electrical resistivity of the soil with lower porosity indicated smaller changes as a function of rainfall. The behaviour of soil resistivity was investigated as a function of rainfall for seven days and 30 days periods. It was found that the soil resistivity behaviour was significantly different during these two periods due to the cumulative rain. COMSOL Multiphysics simulation was performed to investigate the grounding impedance as a function of minimum and maximum rainfall. It was found that the grounding impedance value at the time of minimum rainfall was approximate twice the grounding impedance at the time of maximum precipitation.

Reffin et al. [59] performed eight field experiments starting from March 2018 until February 2019 during different months in Malaysia to investigate the seasonal influences on the grounding system's impulse characteristics. It was found that the soil resistivity of the first and second layers measured in 2018 is significantly different from the soil resistivity of both layers measured in 2019. A difference of 28 % was seen in the thickness of the upper soil layer. R_{DC} was measured for two configurations several times during the year. R_{DC} varied between 6.24 % to 31.9 %, and average impulse resistance changed between 21.1 Ω to 33.94 Ω during the year. The R_{DC} and impulse resistance was higher during the months of the year when the temperature was higher.

He et al. [62] investigated the influence of seasonal soil moisture on the grounding system's behaviour. The soil resistivity changed from 10 Ωm to 200 Ωm during the rainy season. The soil resistivity changed from 200 Ωm to 5000 Ωm during the cold season. The thickness of the soil top layer changed during the rainy and cold seasons, and these changes affected the grounding resistance significantly. In the rainy season, the increment in the soil top layer's thickness reduced the grounding resistance. This reduction was higher in the low resistivity soil. The thicker layer of low resistivity soil caused more current to be dispersed into the soil, which reduced the grounding resistance. When the low resistivity soil layer's height was higher than the burial depth of a grounding system, the grounding resistance reduced sharply. In the cold season, the increment in the soil top layer's thickness increased the grounding resistance. This increment in the ground resistance was very sharp when the soil top layer's height exceeded the burial depth of the grounding system. The grounding resistance increased more significantly in the higher resistivity soil. When the soil upper layer thickness is less than the grounding system's burial depth, the current injected into the grounding system flows into the bottom soil and a small part of it flows through the upper freezing layer of the soil. Thus, the grounding resistance remains almost unchanged. If the soil layer's thickness exceeds the burial depth of the grounding system, then the current has to flow through the above freezing soil layer, which has higher resistivity due to the freezing characteristics [62].

Similar to He et al. [62], Kushare and Unde [58] also investigated the impacts of seasonal variations on the grounding system's performance. They collected experimental data for three seasons, i.e., cold season, early spring season, and rainy season. The soil resistivity and the thickness of the upper soil layer in these three seasons were changed significantly. However, the soil resistivity of the bottom soil layer was found unchanged during the three seasons. These results were similar to the [62] results.

2. SOIL STRUCTURE

According to IEEE standard 80 [18], the soil is uniform when the soil resistivity in all soil layers is the same. However, if the soil resistivity is different in various soil layers, it is known as non-uniform soil. Soil layers with different soil resistivity values have been widely stated in the literature, including F. P. Dawalibi et al. [63], Chamizo et al. [64], Gonos and Stathopulos [65], Samouëlian et al. (Samouëlian et al., 2005), and Tabbagh et al. [66], etc. When the grounding electrode length is higher than the top layer of soil then it will be buried in multilayers of the soil. This will affect the grounding resistance due to the grounding electrode key parameters' variations [63].

Chamizo et al. [64] investigated the water and salt contents of the crust, top, and deep layers of the soil by conducting experiments in two different sites. A significant difference among the top and deep soil layers in the water content was noted, depending on the site. A range of 1.7 % to 40.15 % difference among the top and bottom layers was seen. The water content difference between the crust and top layers was found in a range of 2.9 % to 36 %. The water content was found highest in the deep layer in both sites. A significant difference in the salt content among the three soil layers was noted too. The soil top layer's calcium content was 87.7 % and 97.4 % of the calcium content of the bottom layer in the two sites, respectively. The crust layer's calcium content was found lowest in the first site and highest in the second site. These water and salt contents affect the resistivity of each layer of the soil.

IEEE standard 80 [18] stated that the polarity of the soil reflection coefficient 'K' affects a grounding grid's resistance. When the reflection coefficient is positive, which implied that the soil bottom layer is more resistive than the upper soil layer, the grounding resistance would be more than that of a uniform soil or a grid buried in the upper soil layer only. In the case of a negative reflection coefficient, in which the upper soil layer is more resistive than the lower layer of the soil, the grounding resistance would be less than that of uniform soil or when the grounding system is buried only in the upper layer of the soil. The soil upper layer height affects the grounding resistance too. When the soil upper layer height is higher than the grounding electrode's dimension, the performance of the grounding electrode would be similar to its performance in a uniform soil.

F. P. Dawalibi and Barbeito [67] measured the ground resistance by inserting the grounding rod electrode into the soil having five layers of different soil resistivity values. Initially, the grounding rod was inserted 5 feet inside the soil, and the measured grounding resistance was 1815 Ω. The measured value of ground resistance increased to 1852 Ω and 2000 Ω when the grounding rod electrode was inserted at 15 feet and 20 feet, respectively. This value was further reduced to 668 Ω and 14 Ω by inserting the rod at 30 feet and 100 feet depths. This was because the soil resistivity of each layer was different. The soil resistivity values of the middle layers were higher than the upper layer and bottom layers. The soil resistivity values of the bottom layers were lowest. The simulation results agreed with the experimental results.

F. P. Dawalibi et al. [63] also investigated the grounding rod electrode's current density when buried between different layers of soil. The variation in the current density was observed by changing the depth of the conductor. This was due to the soil resistivity, which was different for each soil layer. The soil resistivity was higher for the deeper layers accordingly, as shown in Figure 5. When the grid was buried at the lower depth, the current density was highest in extremity and lowest in the middle. When the grid depth increased, the current density decreased in extremity and increased in the middle. Further expanding the depth of the grid, the current density became almost uniform.

Mathematically, Salama, Sherbiny, and Chow [68] showed that the grounding resistance reduced with an increase in the height of the upper soil layer for a positive reflection coefficient. The grounding resistance increased with an increase in the upper soil layer's height for a negative reflection coefficient of the soil. These results were found similar to [18].

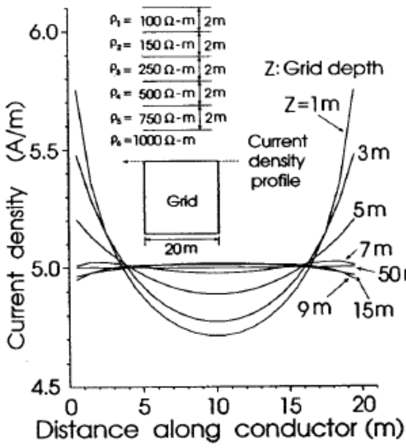

Figure 5. Grid Current Density at Various Grid Depth (adapted from Dawalibi et al. [63])

3. IMPULSE POLARITY

Petropoulos [69] showed the effects of impulse polarity on the grounding resistance. The difference between the grounding resistance due to the impulse polarity was significant, but the trends were not consistent. The grounding resistance was smaller under the positive impulse polarity. However, for some others there was no specific trend in the difference between the two polarities.

N. A. Idris et al. [70] conducted a laboratory experiment on dry sand. The impulse grounding resistance reduced with an increase in current, which was due to the soil ionization process. The resistance was found lower for the positive polarity, indicating that the soil ionization was more significant due to higher currents flow. The difference in the impulse resistance between the polarities was more significant for higher current, as shown in Figure 6.

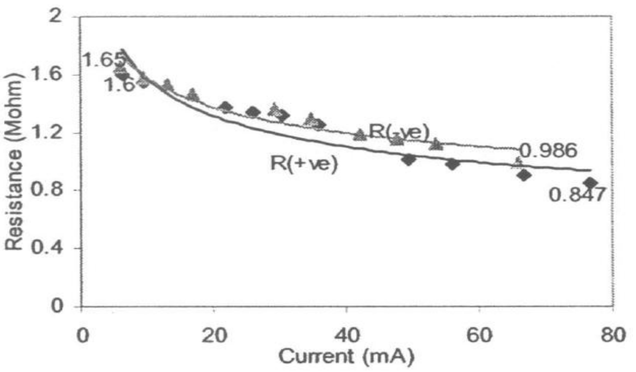

Figure 6. Resistance versus Current Characteristics for Positive and Negative Polarities (adapted from Idris et al. [70])

N. A. Idris et al. [71] also obtained the breakdown electric fields of 35.2 kV/cm and 36 kV/cm for positive and negative polarities, respectively, in dry sand. This could be due to the flow of streamers from the centre of the electrode towards the cathode under positive polarity voltages and vice versa under negative polarity. Assuming that the field distribution is uniform in the gaps, the electrons sweep into the anode when avalanche crosses the gap. This causes the production of a highly charged field near the anode and makes the ion density low elsewhere in the gap. Thus, it takes a lower electric field for the positive polarity to cause breakdown compared to the negative polarity. Furthermore, Meyer et al. [72] found that a leader streamer propagates from the rod's live terminal to the ground when a positive polarity was applied to the gaps of a rod-plane with barriers made of dielectric material. In contrast, a leader propagates from the ground to the rod-plane when applied with negative impulse polarity.

N. M. Nor and Ramli [73] investigated the impulse voltage polarity effects on the wet sand. It was found that there was a small difference of impulse resistance versus current characteristics under positive and negative voltage polarities. A slight difference was also noted in the breakdown voltages. This, however, was not caused by the impulse polarity. It was due to the thermal process occurred in the wet soil, which was not affected by impulse polarity. As shown in Figure 7, the soil ionization was more significant under positive voltage polarity.

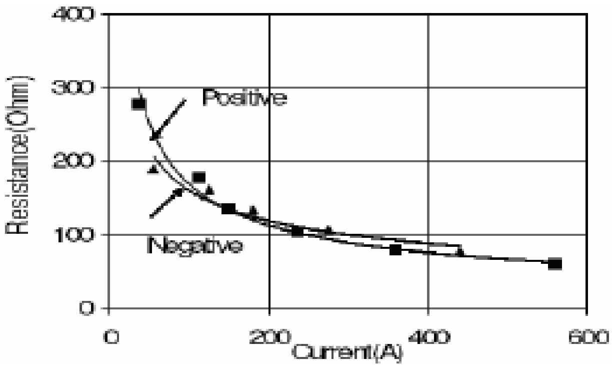

Figure 7. Resistance versus Current Plots for Positive and Negative polarities (adapted from N. M. Nor and Ramli [73])

Víctor et al. [32] investigated the critical breakdown field against resistivity characteristics under positive and negative voltage polarities. It could be seen from Figure 8 that on sand A and sand B, the critical field values were lower under positive voltage polarity. However, on sand C, the critical field values were lower under negative voltage polarity. Kuffel and Husbands [74] had earlier investigated the effects of impulse polarity on the breakdown voltage in sphere-gap of different spacing. The laboratory tests showed that sometimes the difference in the two polarities' breakdown voltage was not more than 1 %. Most of the time, this difference did not exceed 0.5 %.

More recent experiments were conducted by Zhao et al. [75], who found that there were higher breakdown voltages under negative polarity for a rod to rod gap, where there were larger differences between positive and negative breakdown voltages in larger gap spacing. However, in a slightly non-uniform field, and with a shorter electrode gap of 5 mm, breakdown voltage under positive impulse polarity was higher than breakdown voltage under negative impulse polarity. Reffin et al. [76] also conduced experiment on grounding systems' performance under both impulse polarities, using four soil samples. The impulse voltage and current patterns were similar under both polarities. However, the time to discharge to zero under negative impulses was higher for the first two soil samples and almost similar to positive polarity for the other two soil samples. The impulse resistance findings were found inconsistent. On the sample with the highest R_{DC}, the impulse resistance was smaller under the positive polarity. Meanwhile, for the soil sample in which the R_{DC} was lowest, the impulse resistance was smaller under the negative impulse polarity. For the soil samples with medium R_{DC}, the impulse resistance was independent of the impulse polarity. These results were similar to Víctor et al. [32], and Ali et al. [77] results. Also, Kuffel et al. [78] and Ali et al. [77] stated that the different polarity effects are more significant in higher resistivity soil, as the air voids in the soil particles are smaller compared to lower resistivity soil. Thus, the air breakdown is generally affected by impulse polarity.

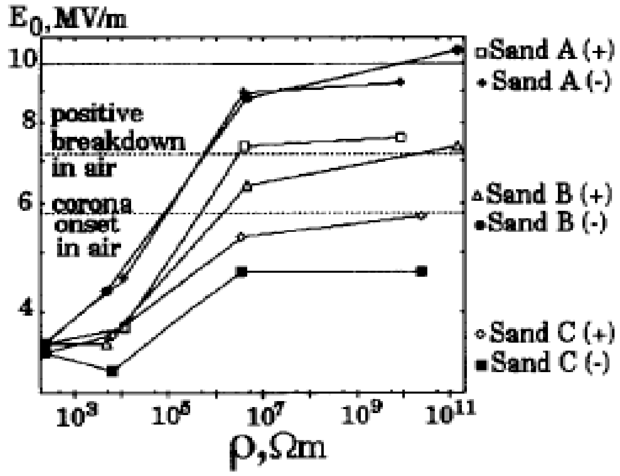

Figure 8. Critical Breakdown Field versus Soil Resistivity for Positive and Negative Polarities (adapted from Victor et al. [32])

Similarly, lower breakdown voltage under positive impulse polarity was seen for a CF31/N2 gas mixture in a highly non-uniform electric field, compared to negative impulse polarity. Darveniza [79] found lower breakdown voltage under negative impulse polarity than the positive impulse polarity for an air gap between the Cross-linked Polyethylene insulated conductors. Loboda and Scuka [80] found that impulse resistance values of various soils subjected to various front times of impulse voltages, from 2 to 10 us, were not affected by impulse polarity

Laverde et al. [81] conducted laboratory experiments to understand different backfill materials' electrical breakdown behaviour. They performed experiments on cement, air gap, and bentonite under positive and negative polarities. The breakdown voltage and breakdown time were significantly different under positive and negative polarities in the air gap and cement. However, the breakdown voltage and breakdown time were independent of polarities in bentonite. This was due to the high resistivity of cement and air gap, and low resistivity of bentonite. In the air gap and cement, the breakdown voltage and the breakdown time were lower under the positive polarity than the negative polarity.

4. ELECTRODES CONFIGURATIONS

It is widely known in the literature Lorentzou et al. [82], Yunus et al. [83], Tomaškovičová et al. [84], Tronchoni et al. [85], Ali et al. [86], and Slaoui and Erchiqui [87], that the soil ionization is affected by the grounding electrode configurations. He et al. [88] showed that reducing the grounding electrode length from 40 m to 10 m changes the shape of the ionized region from a cone into a cylinder. It is also known that the burial depth of the electrode changes the ionized region. For example, a smaller burial depth would lead to higher deformation. When the grounding electrode is hemispherical, the ionized zone would be a hemisphere [89], as shown in Figure 9. When the grounding electrode is a rod, the ionized zone would be as shown in Figure 10 [7]. The change in the shape of the ionized zone will affect the soil ionization.

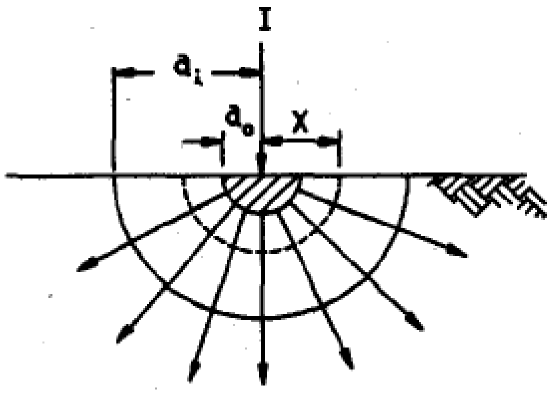

Figure 9. Ionized Zone for a Hemispherical Electrode (adapted from [89])

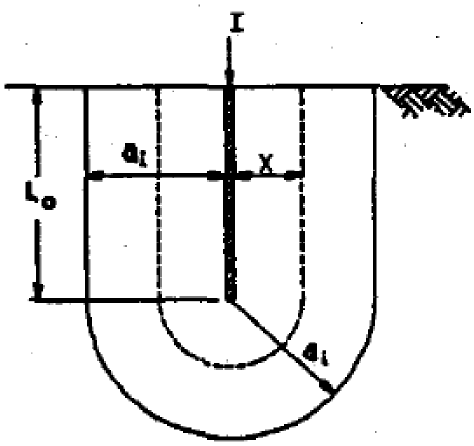

Figure 10. Ionized Zone for a Grounding rod Electrode (adapted from [7])

Petropoulos [69] modeled and tested spherical electrode, spherical electrodes equipped with seven spikes, and rod electrodes with seven spikes where the later two are as shown in Figure 11. Four models were used for the two types of electrodes with spikes, in which the length of the spikes was 2 cm, 4 cm, 6 cm, and 8 cm. All the tests were performed on the same day in order to avoid changes in the soil resistivity. The influence of the spikes on the impulse resistance was apparent. The impulse resistance of the rod electrodes with spikes was much lower than the sphere. The resistance reduced very fast due to the high field intensity at the bottom tips of the spikes. Both types of electrodes with spikes enhanced soil ionization. However, the impulse resistance was lower for the spherical electrode with spikes than the rod electrode with spikes. Increasing the length of the spikes has also reduced impulse resistance. However, soil ionization was more significant for the electrodes with a smaller length of the spikes.

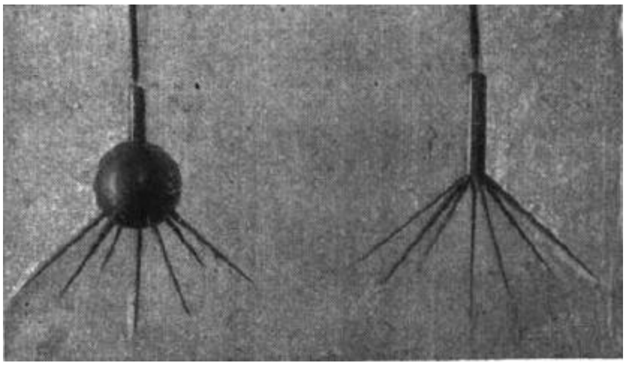

Figure 11. Spherical Electrode with Spikes and rod Electrode with Spikes (adapted from [69])

Gupta and Thapar [90] stated that the effect of soil ionization is more significant in the case of driven rods and point electrodes. In a long horizontal electrode, the current dissipated per unit length is small. Thus, soil ionization is less significant. Further, Geri et al. [91] investigated grounding electrodes' non-linear behaviour using experimental and simulation studies. A 1m vertical grounding rod electrode and a 5 m horizontal grounding wire were used during the experiment. A 55 % of resistance reduction was observed for the vertical rod electrode. However, the reduction was only 25 % for the horizontal grounding wire. The simulation results agreed with the experimental results.

Sekioka S. et al. [16] experimentally investigated the grounding electrode's transient behaviour under high impulse current. The rod electrodes used during the experiment were of different lengths and dimensions. It was found that the soil ionization was more significant for a smaller size of rod electrode. When current exceeded 10 kA, the impulse resistance values remained similar for all configurations. This could be due to a complete breakdown in the soil, in which the soil behaves like a pure conductor. The resistance and current characteristics were also dependent on the distance between the rod electrodes connected in parallel. These results were similar to [92], in which it was found that the soil ionization zone does not grow homogeneously. The soil ionization gradient depends on the dimension of the electrode configuration.

Elmghairbi et al. [93] investigated the effective length and the ability of horizontal earth electrodes to enhance the earthing system. The effective length of the horizontal earth electrode (installed under the ground at 30 cm from the ground surface) on the earthing system's impulse resistance was found to be less than 70 m. Reduction in the impulse resistance with an increase in the electrode's length was more significant at smaller lengths of the horizontal electrode, as shown in Figure 12. The rise time of the impulse waveform was directly proportional to the earth electrode’s length [94]. These results were similar to Yamamoto et al. [95] mathematical analysis. From Figure 12 it is also observed that the impulse resistance of the horizontal earth electrode at higher length was further reduced by installing a copper conductor having a cross-sectional area of 25 mm^2 on the ground surface in parallel with the horizontal electrode. This conductor was sectionalized in the same length as the buried horizontal electrode and connected to the horizontal electrode at the section points.

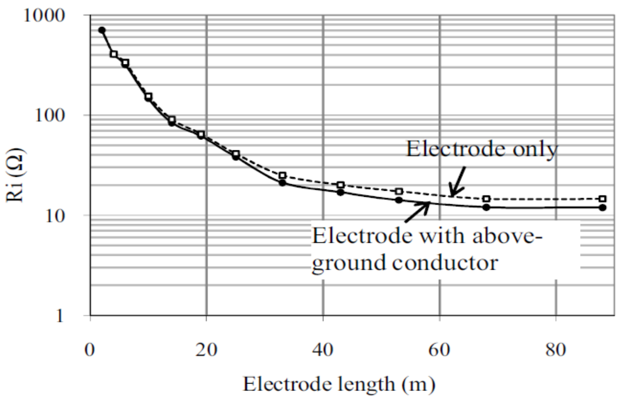

Figure 12. Effective Length of the Horizontal Electrode and its Effects on Impulse Resistance by Bonding it to an Earth Electrode Installed above Ground (adapted from Elmghairbi et al. [93])

Similarly, Ametani et al. [96] investigated the influences of depth and length of the horizontal electrode on the grounding resistance. It was found that the effect of the depth of the horizontal electrode on the grounding resistance depends on the length of the electrode. Three sizes of horizontal electrodes were used, having a length of 4 m, 6 m, and 8 m. The resistance reduced with an increase in depth; this reduction was more significant for the 4 m electrode. However, this reduction was not very significant for the other higher length of the electrodes, as shown in Figure 13. Similar results were obtained when the grounding resistance characteristics were investigated mathematically.

N. M. Nor et al. [34] conducted a field experiment and finite element method simulation to investigate the non-linearity of earthing systems. Three electrode configurations were used during the experiment, i.e., two, three and four vertical rod electrodes connected in parallel, respectively. It was found that the low frequency resistance (R_{DC}) was reduced with an increasing number of rod electrodes. The impulse resistance reduced with an increase in current, but this reduction was more significant for the lesser number of rod electrodes connected in parallel. This indicated that the higher the R_{DC}, the more significant would be the soil ionization. From the experiment of Vainer [97], it was revealed that the soil ionization only occurred in small grids in the high resistivity soil. The soil ionization was not significant in the bigger size grids.

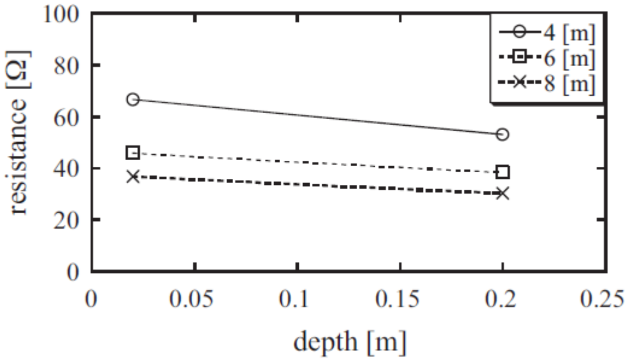

Figure 13. Impulse Resistance as a Function of the Depth of the Horizontal Electrode (adapted from Ametani et al. [96]))

Salari and Portela [98] investigated the effects of grounding electrode configurations on soil ionization using mathematical modeling and simulation. The investigations were performed on a single vertical rod electrode, two parallel vertical rod electrodes, and four parallel vertical rod electrodes. The reduction of the grounding impedance of the single vertical rod electrode was 69 %, and the reduction of grounding impedance for the two and four parallel vertical rod electrodes was 53 % and 39 %, respectively. This simulation results were in agreement to the earlier mentioned experiment results of N. M. Nor et al. [34], in which the soil ionization was more significant for the lesser number of rod electrodes. The electric field intensity was reduced when the number of rod electrodes increased as a higher number of electrodes increases the dimension of the grounding system. In the grounding system, the equivalent impedance of a grounding electrode is characterized by its transverse impedance. When the number of rod electrodes increased, the equivalent impedance was related to all grounding rod electrodes' mutual transverse impedance. These mutual parameters were less sensitive to the soil ionization. Thus, the relative importance of soil ionization was reduced. These results were similar to Liew and Daarveniza [7] experimental and Cidras et al. [11] computational results.

J. Li et al. [99] investigated the impulse response of different grounding electrode configurations using the finite element analysis, considering the soil ionization phenomenon. Seven electrode configurations were used; configuration 1: single horizontal wire electrode, configuration 2: three horizontal wire electrodes star connected, configuration 3: four horizontal wire electrodes star connected, configuration 4: eight horizontal wire electrodes square connected, configuration 5: a single vertical rod electrode, configuration 6: two vertical rod electrodes connected using a horizontal wire electrode, and configuration 7: four vertical rod electrodes star connected using horizontal wire electrodes. It was revealed that soil ionization is more significant in the vertical rod electrodes. Among the horizontal wire electrodes, soil ionization could not be seen in configuration 1 and configuration 4. However, soil ionization was more significant in configuration 2 compared to configuration 3. Among the vertical rod electrodes, soil ionization was more significant in the configurations, in which a lesser number of rod electrodes were used. This was due to the leakage current along the grounding grid branches, which increases with distance.

Analysis done by Yamamoto et al. [95] found that the impulse resistance reduction trend against the effective length characteristics of both horizontal and vertical electrodes. These characteristics were also found to be dependent on the soil resistivity, as shown in Figure 14.

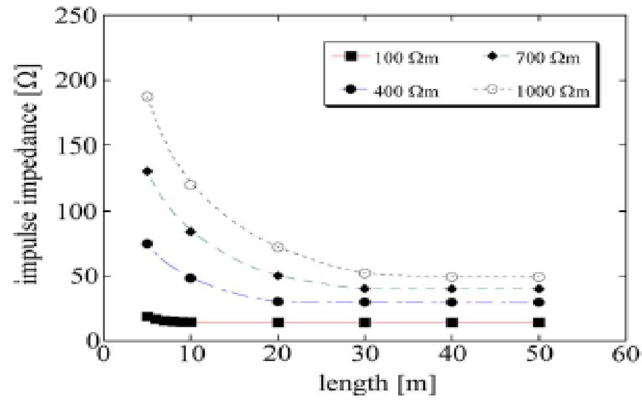

Figure 14. Effective Length of the Grounding Electrode (adapted from *Yamamoto et al.* [95])

5. SOIL BREAKDOWN

The electric field increases with an increase in the applied voltage's magnitude, as shown in equation 13. As stated earlier soil ionization initiates when the electric field reaches the critical value. Thus, soil ionization is also dependent on the magnitude of the applied voltage.

$$E = \frac{V}{r_i \ln\left[\frac{r_o}{r_i}\right]} \qquad (12) \text{ (adapted from N. Idris et al. [71])}$$

where 'E' is the electric field, 'V' is the applied voltage, 'r_i' is the inner radius of the electrode, and 'r_o' is the electrode's outer radius.

Soil breakdown occurs due to an increase in the magnitude of the applied voltage. This is noted from the voltage and current traces, in which a sudden drop in the voltage accompanies the sudden increase in the current. Before the occurrence of breakdown, the voltage increases to the peak and then decays slowly. At this moment, a leakage current flows through the soil, and it does not flow through the soil air gaps entirely until the breakdown delay time (t_D) ends, and the breakdown occurs [100], as shown in Figure 15. Flanagan et al. [100] also noticed that during the laboratory experiment, the breakdown delay time reduced from 200 µs to 11 µs when the applied voltage was increased from 135 kV to 203 kV. The computational results were in agreement with the experimental results.

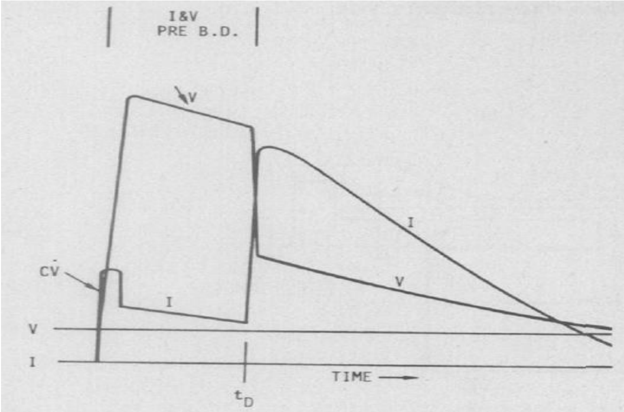

Figure 15. A Random Voltage and Current Traces Before and After Breakdown (adapted from [100])

It is widely believed in the literature [100], [101], [71], [88], [73], [88], and [102] that the magnitude of the applied voltage affects the delay time of the initiation of soil ionization. With an increase in applied voltage, the rise time of the voltage reduces. This leads to a more comfortable generation of free electrons in the soil particles' voids, which causes soil ionization; thus, reducing the time to breakdown. The soil breakdown delay time also depends on the soil's physical nature. The ions crash with one another due to the extreme discontinuity of the soil layers and the soil's water content, thus causing electrochemical polarization. This type of polarization causes the soil to have a large and scattered dielectric constant; therefore, leading to time delays [102].

N. A. Idris et al. [71] investigated the soil behaviour under high impulse current. The voltage magnitude at which the nonlinear effect becomes visible is known as the threshold voltage of the soil ionization. The experimental results revealed that the nonlinearity started to appear above the 15 kV applied voltage, which is the threshold voltage of that specific sand being used. It was found that the breakdown in the soil took place after some time delay. The time delay was inversely proportional to the voltage and current magnitudes. This was due to the propagation rate of ionization, which means that the ionization process is directly proportional to the voltage magnitude. The soil breakdown was not observed in the highly wet sand. This was due to the water containing gaps between the sand grains and the applied voltage, which was not enough to vaporize the water. Hence, a large amount of energy was needed for the ionization process to take place and to cause dry zones between the soil grains.

Different values of impulse voltages cause different time delays. He et al. [102] investigated the breakdown delay time and peak voltage characteristics. It was found that the breakdown delay time reduces as the peak voltage increases, as shown in Figure 16. These results were similar to N. M. Nor et al. [71] that breakdown in the soil only took place after some time delay which was inversely proportional to the voltage and current magnitudes.

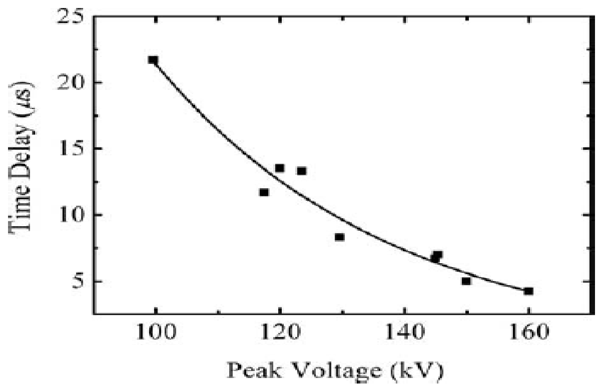

Figure 16. Impulse Breakdown Delay Time versus Peak Voltage Characteristics

B. H. Lee et al. [2] also conducted a laboratory experiment to investigate the characteristics of soil ionization. Two types of time delays were noticed in the voltage and current waveforms: the time delay in the initiation of the ionization, and the time delay to the second current peak, which indicates a breakdown in the soil. These time delays were reduced with an increase in the applied voltage. The reduction in the time delays regarding an increase in the applied voltage was much faster in the sand with low water content. Thus, the ionization and sand breakdown time delays were affected by the magnitude of applied voltage and the sand's water content. He et al. [103] also agreed with these results.

He et al. [102] investigated the breakdown delay time and its factors. The breakdown delay time was changed from over ten microseconds to several hundreds of nanoseconds by increasing the charging voltage. At low voltages, the delay time decreased sharply by increasing the charging voltage. However, this decrement became slower at high voltage. It was found that the impulse breakdown delay time increased following the water content of the soil. The soil breakdown delay also changed with the soil's temperature, where the breakdown delay was reduced with an increase in the temperature. The influence of water content and temperature reduced with an increase in applied voltage. The breakdown delay time was also dependent on soil density, where the breakdown time delay was increased with an increase in soil density. This was due to the air voids between the soil grains, in which the size of the air voids reduces with an increase in soil density. Thus, the free electrons cannot produce kinetic energy quickly to ionize the air. This increases the critical breakdown field value too. He et al. [102] also observed that the soil impulse breakdown delay time was slightly higher under negative polarity.

6. DISCUSSION OF FINDINGS

Many field experimental investigations on different earthing systems under fast impulse currents have been conducted in the past [6], [7], [17], [24], [69], [76], [100], and, etc. The results obtained from the field experiments were more realistic compared to the results obtained from the laboratory experiments and computational methods. The field experiments were performed by considering the soil resistivity value, earthing electrodes configurations, and the magnitude of the applied voltage. Soil ionization enhancement occurs in higher resistivity soil as there is no or very less water content in the gaps between the sand grains. Thus leading to the enormous dielectric difference between the soil and air gaps; therefore, causing electrical discharges. As of low resistivity soil, water is filled in the gaps between the soil grains, leading to the small dielectric difference between the soil and air gaps due to which no ionization process would take place, as stated in [8-13].

Two main parameters that affect the grounding system's design are grounding system electrode configurations and soil resistivity profile. The soil resistivity data varies over several orders of magnitudes to thousands of ohm-meters as mentioned in the standards [104] and [105]. This information deals with the grounding system performance at low voltage, usually different in practical grounding system applications under high impulse conditions.

Many studies were conducted by field measurement under high impulse conditions, in which the grounding systems consisted of a few electrodes as in [83] and [76], counterpoises as in [104] and [105], and full-scale grounding grids as in [106], [107], and [108]. These studies showed that when the practical grounding system is subjected to high impulse currents, the impulse resistance will reduce with an increase in current, and the impulse resistance will not depend on the current for some grounding system configurations.

These also include the soil resistivity values, which are significantly affected by moisture content, temperature, soil types, soil grain size, and a variation in the thickness of soil layers from one site to another. Despite much research work published on grounding systems' impulse characteristics for different soil resistivities, the measurements are still necessary due to many variations in soil. Elzowawi et al. [109] performed a series of tests, having a two-layer soil model with various thicknesses and water percentages content for both layers. This shows that it is essential to include soil resistivity values correlating with the impulse characteristics of grounding systems. Further, it has been proven that the soil resistivity and permittivity affect the response of grounding electrodes subjected to lightning currents and at various frequencies [110] and [111]. These studies [112] and [110] found that soil resistivity, hence impulse impedance, starts to increase at certain frequencies, depending on soil resistivity value. For low soil resistivity, an increase in impulse impedance starts at low-frequency values, while for high soil resistivity, higher frequency values cause an increase in impulse impedance. This shows that the impulse characteristics of grounding systems depend strongly on the electrical properties of soil.

It has been known that impulse polarity affects the performance of many dielectric materials, such as oil, gas, and solid insulators [78], [75] as well as other materials, namely conductive water [113], soil or grounding systems [74]. Among these, the typical observations on the differences due to impulse polarities are streamer propagation. Such streamers exhibit a distinctive treelike shape for a positive impulse, compared to resembling a bush under a negative impulse for all solid samples. The positive streamer flows from the centre of the electrode to the cathode, where the case is vice versa under negative polarity [114], [115], [116]. The grounding arrangements for the electrical systems require investigations under both impulse polarities. The lightning strikes data for each region under both impulse polarities is usually available. Improvements in the grounding systems can be made for the areas which most likely suffer from negative lightning strikes. Tropical countries such as Malaysia have more than 90% of their collected lightning strike data from 2004 to 2015 in the form of negative lightning strikes [117]. Therefore, it is essential to pursue the study, which can lead to a proper design of grounding systems, considering the effect of impulse polarities on grounding systems.

Limited studies have been conducted on the impact of impulse polarity of the earthing system under impulse characteristics [69], [70], [32], [74], [81], and [118]. Petropoulos [69], found that for similar electrode dimensions and soil resistivity, the critical electric field, E_c which is the onset of ionization, and the breakdown voltage were found higher under negative compared to the positive impulses. A few more studies were conducted on soil characterization under high impulse current for both impulse polarities, [70] and [74]. These studies were useful for understanding the grounding system characteristics under both impulse polarities in controlled conditions. However, to better understand soil ionization phenomena in uncontrolled conditions, it is essential to conduct the impulse tests under both impulse polarities in practical fields. Some studies found lower breakdown voltage and lower impulse resistance values of grounding systems under positive impulse polarity [70], [32]. However, some studies found lower breakdown voltage under negative impulse polarity [75], and [79]. In some studies, the results obtained under both impulse polarities were inconsistent [69] - [74]. Impulse polarity was found dependent on the R_{DC} values of the grounding systems too [76]. Loboda and Scuka [80] found that impulse resistance values were not affected by impulse polarity when subjected to various front times of impulse voltages (2μs to 10μs) at various soils. Generally, for high voltage applications, testing under positive rather than negative impulse polarity is more crucial, since breakdown normally occurs at lower voltage under positive impulse polarity. Thus, many tests on electrical equipment are performed under positive polarity. However, due to inconclusive observations noted in some studies, where there is a lower breakdown voltage under negative impulse polarity, especially in low R_{DC}. Therefore, it is essential to explore the soil characteristics under negative impulse polarity.

7. CONCLUSION

In this paper, factors affecting grounding system performance under high impulse conditions were reviewed. Soil ionization is a nonlinear characteristic of the grounding system. When the electric field in the soil grains exceeds the critical value, it ionizes the air inside the voids; thus, leading to a streamer or arc in the soil; at this time, soil ionization initiates. It reduces the impulse resistance of the grounding system. Soil ionization is directly affected by soil resistivity, soil structure, impulse polarity, electrode configurations, soil breakdown, and time response characteristics. These factors are affected by other sub-factors, which affect the soil ionization indirectly. In particular, soil resistivity is affected by the ionization gradient, the grain size of the soil, porosity, temperature level, water content, salinity level in the soil, and seasonal influences. Meanwhile, the soil breakdown and its time response characteristics are affected by soil structure and applied voltage.

8. RECOMMENDATIONS FOR FUTURE RESEARCH

Based on the results of investigations, some recommendations for possible future research include the following:

- New grounding system devices and configurations may be innovated and tested under high impulse condition at sites having different soil resistivity values.
- Grounding systems may be tested under both impulse polarities at sites having different soil resistivity values, in order to explore the knowledge on the effects of impulse polarity on grounding systems.
- The time response and impulse resistance characteristics affected by applied voltage level can be further investigated for different soil resistivity values.

REFERENCES

[1] R. D. Leadon R.E., T.M. Flanagan, C.E. Mallon, "Effect Of Ambient Gas On Arc Initiation Characteristics In Soil," *Ieee Trans.*, Vol. Nucl. Sci., No. 4572e4576, 1983.

[2] B. H. Lee, G. H. Park, H. G. Kim, And K. S. Lee, "Analysis Of Soil Ionization Behaviors Under Impulse Currents," *Journal Of Electrical Engineering And Technology*, Vol. 4, No. 1. Pp. 98–105, 2009.

[3] N. M. Nor, A. Haddad, And H. Griffiths, "Performance Of Earthing Systems Of Low Resistivity Soils," *Ieee Trans. Power Deliv.*, Vol. 21, No. 4, Pp. 2039–2047, Oct. 2006.

[4] P. Chowdhuri, "Impulse Impedance Tests On Laboratory Model Ground Electrodes," *Iee Proc. - Gener. Transm. Distrib.*, Vol. 150, No. 4, P. 427, 2003.

[5] F. E. Asimakopoulou, I. F. Gonos, And I. A. Stathopulos, "Methodologies For Determination Of Soil Ionization Gradient," *J. Electrostat.*, Vol. 70, No. 5, Pp. 457–461, 2012.

[6] H. M. Towne, "Impulse Characteristics Of Driven Grounds," *Gen. Electr. Rev.*, No. Pp. 605–609, 1929.

[7] A. C. Liew And M. Darveniza, "Dynamic Model Of Impulse Characteristics Of Concentrated Earths," *Proc. Inst. Electr. Eng.*, Vol. 121, No. 2, P. 123, 1974.

[8] Kosztaluk R., Loboda M. And Mukhedkar D., "Experimental Study Of Transient Ground Impedances," *Ieee Trans. Power Appar. Syst.*, Vol. Pas-100, No. 11, Pp. 4653–4660, 1981.

[9] R. Velazquez And D. Mukhedkar, "Analytical Modelling Of Grounding Electrodes Transient Behavior," *Ieee Trans. Power Appar. Syst.*, Vol. Pas-103, No. 6, Pp. 1314–1322, Jun. 1984.

[10] P. Espel, R. R. Diaz, A. Bonamy, And J. N. Silva, "Discharges In Resistive Soils," Vol. 19, No. 3, Pp. 1174–1182, 2004.

[11] J. Cidras, A. F. Otero, And C. Garrido, "Nodal Frequency Analysis Of Grounding Systems Considering The Soil Ionization Effect," *Ieee Trans. Power Deliv.*, Vol. 15, No. 1, Pp. 103–107, 2000.

[12] G. Ala, M. L. Di Silvestre, F. Viola, And E. Francomano, "Soil Ionization Due To High Pulse Transient Currents Leaked By Earth Electrodes," *Prog. Electromagn. Res. B*, Vol. 14, Pp. 1–21, 2009.

[13] D. P. Snowden And J. W. Erler, "Initiation Of Electrical Breakdown Of Soil By Water Vaporization," *Ieee Trans. Nucl. Sci.*, Vol. 30, No. 6, Pp. 4568–4571, 1983.

[14] Leadon R.E., Flanagan T.M., C. E. Mallon, And R. Denson, "Effect Of Ambient Gas On Arc Initiation Characteristics In Soil," *Ieee Trans. Nucl. Sci.*, Vol. Ns-30, No. No. 6, Pp. 4572–4576, 1983.

[15] N. Mohamad Nor And A. Ramli, "Electrical Properties Of Dry Soil Under High Impulse Currents," *J. Electrostat.*, Vol. 65, No. 8, Pp. 500–505, 2007.

[16] Sekioka S., T. Sonoda, And A. Ametani, "Experimental Study Of Current-Dependent Grounding Resistance Of Rod Electrode," *Ieee Trans. Power Deliv.*, Vol. 20, No. 2 Ii, Pp. 1569–1576, 2005.

[17] Z. G. Datsios And P. N. Mikropoulos, "Impulse Breakdown Characteristics Of Dry Sand: Effect Of Sand Grain Size," In *2016 33rd International Conference On Lightning Protection (Iclp)*, 2016, Pp. 1–4.

[18] IEEE Std 80-2013, *Ieee Guide For Safety In Ac Substation Gorunding*, Vol. 56. 2013.

[19] Oettle E. E., "The Characteristics Of Electrical Breakdown And Ianizalion Processes In Soil," *Trans. Sa Inst. Electr. Eng.*, Vol. P. 63-70, 1988.

[20] S. S., M. I. Lorentzou, M. P. Philippakou, And J. M. Prousalidis, "Current-Dependent Grounding Resistance Model Based On Energy Balance Of Soil Ionization," *Ieee Trans. Power Deliv.*, Vol. 21, No. 1, Pp. 194–201, Jan. 2006.

[21] Zhang Bo *Et Al.*, "Numerical Analysis Of Transient Performance Of Grounding Systems Considering Soil Ionization By Coupling Moment Method With Circuit Theory," *Ieee Trans. Magn.*, Vol. 41, No. 5, Pp. 1440–1443, May 2005.

[22] M. Loboda And Z. Pochanke, "Experimental Study Of Electric Properties Of Soil With Impulse Current Injections," *Light. Prot. (Iclp), 1985 Int. Conf.*, No. September 1985, 1985.

[23] Liu Yaqing, "Transient Response Of Grounding Systems Caused By Lightning : Modelling And Experiments," *Sci. Technol.*, P. 90, 2004.

[24] P. L. Bellaschi, R. E. Armington, And A. E. Snowden, "Impulse And 60-Cycle Characteristics Of Driven Grounds-Ii," *Trans. Am. Inst. Electr. Eng.*, Vol. 61, No. 6, Pp. 349–363, 1942.

[25] J. M. Prousalidis, M. P. Philippakou, N. D. Hatziargyriou, And B. C. Papadias, "The Effects Of Ionization In Wind Turbine Grounding Modeling," In *2000 10th Mediterranean Electrotechnical Conference. Information Technology And*

Electrotechnology For The Mediterranean Countries. Proceedings. Melecon 2000 (Cat. No.00ch37099), Vol. 3, Pp. 940–943.

[26] M. E. Almeida And M. T. De Correia Barros, "Accurate Modelling Of Rod Driven Tower Footing," *Ieee Trans. Power Deliv.*, Vol. 11, No. 3, Pp. 1606–1609, 1996.

[27] P. Espel, R. R. Diaz, A. Bonamy, And J. N. Silva, "Electrical Parameters Associated With Discharges In Resistive Soils," *Ieee Trans. Power Deliv.*, Vol. 19, No. 3, Pp. 1174–1182, Jul. 2004.

[28] M. Mokhtari, Z. Abdul-Malek, And Z. Salam, "An Improved Circuit-Based Model Of A Grounding Electrode By Considering The Current Rate Of Rise And Soil Ionization Factors," *Ieee Trans. Power Deliv.*, Vol. 30, No. 1, Pp. 211–219, Feb. 2015.

[29] Cigre, "Guide To Procedures For Estimating The Lightning Performance Of Transmission Lines," *Cigre Work. Gr. 33-01 Study Comm. 33 Overvoltages Insul. Coord.*, 1991.

[30] Oettle E. E., "A New General Estimation Curve For Predicting The Impulse Impedance Of Concentrated Earth Electrodes," *Ieee Trans. Power Deliv.*, Vol. 3, No. 4, Pp. 2020–2029, 1988.

[31] A. V. Korsuntcev, "Application Of The Theory Of Similitude To The Calculation Of Concentrated Earth Electrodes," *Elektrichestvo*, Vol. 5, Pp. 31–35, 1958.

[32] M. Víctor, M. Cabrera, S. Lundquist, And V. Cooray, "On The Physical Properties Of Discharges In Sand Under Lightning Impulses," *J. Electrostat.*, Vol. 30, Pp. 17–27, May 1993.

[33] I. F. Gonos And I. A. Stathopulos, "Soil Ionisation Under Lightning Impulse Voltages," *Iee Proc. - Sci. Meas. Technol.*, Vol. 151, No. 5, Pp. 343–346, Sep. 2004.

[34] N. M. Nor, M. Trlep, S. Abdullah, R. Rajab, And K. Ramar, "Determination Of Threshold Electric Field Of Practical Earthing Systems By Fem And Experimental Work," *Ieee Trans. Power Deliv.*, Vol. 28, No. 4, Pp. 2180–2184, Oct. 2013.

[35] R. Et Al. He, J.L., Gao, Y.Q., Zeng, "Soil Ionization Phenomenon Around Grounding Electrode Under Lightning Impulse.," In *Viii International Symposium On Lightning Protection*, 2005, Pp. 520–525.

[36] A. Samouëlian, I. Cousin, A. Tabbagh, A. Bruand, And G. Richard, "Electrical Resistivity Survey In Soil Science: A Review," *Soil Tillage Res.*, Vol. 83, No. 2, Pp. 173–193, Sep. 2005.

[37] M. M. Nor, "Review: Soil Electrical Characteristics Under High Impulse Currents," *Ieee Trans. Electromagn. Compat.*, Vol. 48, No. 4, Pp. 826–829, 2006.

[38] R. B. Campbell, C. A. Bower, And L. A. Richards, "Change Of Electrical Conductivity With Temperature And The Relation Of Osmotic Pressure To Electrical Conductivity And Ion Concentration For Soil Extracts1," *Soil Sci. Soc. Am. J.*, Vol. 13, No. C, P. 66, 1949.

[39] N. M. Nor, A. Haddad, And H. Griffiths, "Factors Affecting Soil Characteristics Under Fast Transients," *Int. Conf. Power Syst. Transients - Ipst*, Vol. 2, No. 2003, P. 6, 2003.

[40] S. Garambois, P. Sénéchal, And H. Perroud, "On The Use Of Combined Geophysical Methods To Assess Water Content And Water Conductivity Of Near-Surface Formations," *J. Hydrol.*, Vol. 259, No. 1–4, Pp. 32–48, Mar. 2002.

[41] D. Michot, Y. Benderitter, A. Dorigny, B. Nicoullaud, D. King, And A. Tabbagh, "Spatial And Temporal Monitoring Of Soil Water Content With An Irrigated Corn Crop Cover Using Surface Electrical Resistivity Tomography," *Water Resour. Res.*, Vol. 39, No. 5, May 2003.

[42] W. J. Mccarter, "The Electrical Resistivity Characteristics Of Compacted Clays," *Géotechnique*, Vol. 34, No. 2, Pp. 263–267, Jun. 1984.

[43] D. P. Snowden, E. S. Beale, And V. A. J. Van Lint, "The Effect Of Gaseous Ambient On The Initiation Of Breakdown In Soil," *Ieee Trans. Nucl. Sci.*, Vol. 33, No. 6, Pp. 1669–1674, 1986.

[44] P. K. Kolay, S. G. Burra, And S. Kumar, "Effect Of Salt And Napl On Electrical Resistivity Of Fine-Grained Soil-Sand Mixtures," *Int. J. Geotech. Eng.*, Vol. 12, No. 1, Pp. 13–19, Jan. 2018.

[45] M. Fukue, T. Minato, M. Matsumoto, H. Horibe, And N. Taya, "Use Of Resistivity Cone For Detecting Contaminated Soil Layers," *Eng. Geol.*, Vol. 60, No. 1–4, Pp. 361–369, 2001.

[46] Jinliang He, Baoping Zhang, Peng Kang, Rong Zeng, And Bo Zhang, "Lightning Impulse Breakdown Characteristics Of Frozen Soil," *Ieee Trans. Power Deliv.*, Vol. 23, No. 4, Pp. 2216–2223, Oct. 2008.

[47] G. E. Archie, "The Electrical Resistivity Log As An Aid In Determining Some Reservoir Characteristics," *Trans. Aime*, Vol. 146, No. 01, Pp. 54–62, Dec. 1942.

[48] G. Keller And F. Frischknecht, "Electrical Methods In Geophysical Prospecting," In *Pergamon Press*, 1966.

[49] M. H. Waxman And L. J. M. Smits, "Electrical Conductivities In Oil-Bearing Shaly Sands," *Soc. Pet. Eng. J.*, Vol. 8, No. 02, Pp. 107–122, Jun. 1968.

[50] P. Shah And D. Singh, "Generalized Archie's Law For Estimation Of Soil Electrical Conductivity," *J. Astm Int.*, Vol. 2, No. 5, P. 13087, 2005.

[51] L. S. Bryson, "Evaluation Of Geotechnical Parameters Using Electrical Resistivity Measurements," In *Earthquake Engineering And Soil Dynamics*, 2005, Pp. 1–12.

[52] G. Yoon, M. Oh, And J. Park, "Laboratory Study Of Landfill Leachate Effect On Resistivity In Unsaturated Soil Using Cone Penetrometer," *Environ. Geol.*, Vol. 43, No. 1–2, Pp. 18–28, Dec. 2002.

[53] M. H. Z. Abidin, F. Ahmad, D. C. Wijeyesekera, R. Saad, And M. F. T. Baharuddin, "Soil Resistivity Measurements To Predict Moisture Content And Density In Loose And Dense Soil," *Appl. Mech. Mater.*, Vol. 353–356, Pp. 911–917, Aug. 2013.

[54] I. Wilkinson, "Applied Geophysics," *Phys. Earth Planet. Inter.*, Vol. 69, No. 1–2, P. 142, Nov. 1991.

[55] J. Côté And J.-M. Konrad, "A Generalized Thermal Conductivity Model For Soils And Construction

Materials," *Can. Geotech. J.*, Vol. 42, No. 2, Pp. 443–458, Apr. 2005.
[56] L. Slater, A. Binley, R. Versteeg, G. Cassiani, R. Birken, And S. Sandberg, "A 3d Ert Study Of Solute Transport In A Large Experimental Tank," *J. Appl. Geophys.*, Vol. 49, No. 4, Pp. 211–229, Apr. 2002.
[57] P. . Jackson *Et Al.*, "Non-Invasive Moisture Monitoring Within An Earth Embankment — A Precursor To Failure," *Ndt E Int.*, Vol. 35, No. 2, Pp. 107–115, Mar. 2002.
[58] B. E. Kushare And M. G. Unde, "Impact Of Seasonal Variation Of Soil Resistivity On Safety Of Substation Grounding System," In *Fifth International Conference On Advances In Recent Technologies In Communication And Computing (Artcom 2013)*, 2013, Pp. 173–182.
[59] M. Reffin *Et Al.*, "Seasonal Influences On The Impulse Characteristics Of Grounding Systems For Tropical Countries," *Energies*, Vol. 12, No. 7, P. 1334, Apr. 2019.
[60] R. J. Gustafson, R. Pursley, And V. D. Albertson, "Seasonal Grounding Resistance Variations On Distribution Systems," *Ieee Trans. Power Deliv.*, Vol. 5, No. 2, Pp. 1013–1018, Apr. 1990.
[61] V. L. Coelho, A. Piantini, H. A. D. Almaguer, R. A. Coelho, W. Do C. Boaventura, And J. O. S. Paulino, "The Influence Of Seasonal Soil Moisture On The Behavior Of Soil Resistivity And Power Distribution Grounding Systems," *Electr. Power Syst. Res.*, Vol. 118, Pp. 76–82, Jan. 2015.
[62] J. He *Et Al.*, "Seasonal Influences On Safety Of Substation Grounding System," *Ieee Trans. Power Deliv.*, Vol. 18, No. 3, Pp. 788–795, 2003.
[63] F. P. Dawalibi, J. Ma, And R. D. Southey, "Behaviour Of Grounding Systems In Multilayer Soils: A Parametric Analysis," *Ieee Trans. Power Deliv.*, Vol. 9, No. 1, Pp. 334–342, 1994.
[64] S. Chamizo, Y. Cantón, I. Miralles, And F. Domingo, "Biological Soil Crust Development Affects Physicochemical Characteristics Of Soil Surface In Semiarid Ecosystems," *Soil Biol. Biochem.*, Vol. 49, Pp. 96–105, Jun. 2012.
[65] I. F. Gonos And I. A. Stathopulos, "Estimation Of Multilayer Soil Parameters Using Genetic Algorithms," *Ieee Trans. Power Deliv.*, Vol. 20, No. 1, Pp. 100–106, Jan. 2005.
[66] A. Tabbagh, M. Dabas, A. Hesse, And C. Panissod, "Soil Resistivity: A Non-Invasive Tool To Map Soil Structure Horizonation," *Geoderma*, Vol. 97, No. 3–4, Pp. 393–404, 2000.
[67] F. Dawalibi And N. Barbeito, "Measurements And Computations Of The Performance Of Grounding Systems Buried In Multilayer Soils," *Ieee Trans. Power Deliv.*, Vol. 6, No. 4, Pp. 1483–1490, 1991.
[68] M. M. A. Salama, M. M. E. Sherbiny, And Y. L. Chow, "A Formula For Resistance Of Substation Grounding Grid In Two-Layer Soil," *Ieee Trans. Power Deliv.*, Vol. 10, No. 3, Pp. 1255–1262, Jul. 1995.
[69] G. M. Petropoulos, "The High-Voltage Characteristics Of Earth Resistances," *J. Inst. Electr. Eng. - Part Ii Power Eng.*, Vol. 95, No. 43, Pp. 59–70, Feb. 1948.
[70] N. A. Idris, H. Ahmad, And M. N. Isa, "Impulse Impedance Tests On Laboratory Model Earth Electrode," In *Asia-Pacific Conference On Applied Electromagnetics*, 2005, Pp. 157–161.
[71] N. Idris, N. Nor, And H. Ahmad, "Effects Of Moisture Contents In Soil And Impulse Polarity Of Earth Electrode Under High Impulse Conditions," In *2006 Ieee 8th International Conference On Properties And Applications Of Dielectric Materials*, 2006, Pp. 822–827.
[72] H. K. Meyer, F. Mauseth, A. Pedersen, And J. Ekeberg, "Breakdown Mechanisms Of Rod-Plane Air Gaps With A Dielectric Barrier Subject To Lightning Impulse Stress," *Ieee Trans. Dielectr. Electr. Insul.*, Vol. 25, No. 3, Pp. 1121–1127, Jun. 2018.
[73] N. M. Nor And A. Ramli, "Soil Characteristics Of Wet Sand Under Different Impulse Polarity And Earth Electrode's Dimensions," *Ieee Trans. Dielectr. Electr. Insul.*, Vol. 15, No. 4, Pp. 910–914, Aug. 2008.
[74] E. Kuffel And A. S. Husbands, "The Influence Of Nearby Earthed Objects And Of The Polarity Of The Voltage On The Direct-Voltage Breakdown Of Horizontal Sphere-Gaps," *Proc. Iee Part A Power Eng.*, Vol. 108, No. 40, P. 302, 1961.
[75] S. Zhao, D. Xiao, P. Xue, R. Zhong, And Y. Deng, "Experimental Research On Polarity Effect Of Cf 3 I/N 2 Mixtures Under Lightning Impulse," *Ieee Trans. Dielectr. Electr. Insul.*, Vol. 25, No. 4, Pp. 1357–1363, Aug. 2018.
[76] M. Reffin, N. Nor, N. Ahmad, And S. Abdullah, "Performance Of Practical Grounding Systems Under High Impulse Conditions," *Energies*, Vol. 11, No. 11, P. 3187, Nov. 2018.
[77] A. W. Abdul Ali, N. N. Ahmad, And N. Mohamad Nor, "Effect Of Impulse Polarity On A New Grounding Device With Spike Rods (Gdsr)," *Energies*, Vol. 13, No. 18, P. 4672, Sep. 2020.
[78] J. Kuffel, E.; Zaengl, W.S.; Kuffel, *Hv Engineering Book*. Amsterdam, The Netherlands: Elsevier, 2000.
[79] M. Darveniza, "Electrical Breakdown Of Air Between Insulated Conductors," In *Proceedings Of The 6th International Conference On Properties And Applications Of Dielectric Materials (Cat. No.00ch36347)*, 2000, Vol. 2, Pp. 615–620.
[80] M. Loboda And V. Scuka, "On The Transient Characteristics Of Electrical Discharges And Ionization Processes In Soil," *Int. Conf. Light. Prot.*, No. November, Pp. 539–544, 1996.
[81] V. Laverde, M. Z. A. A. Kadir, And C. Gomes, "Performance Of Backfill Materials Under Impulse And Ac Testings," In *2012 International Conference On Lightning Protection (Iclp)*, 2012, Pp. 1–7.
[82] M. I. Lorentzou, A. G. Kladas, And N. D. Hatziargyriou, "Finite Element Modelling Of Grounding Systems Considering Electrode Geometry Effects," *Ieee Trans. Magn.*, Vol. 35, No. 3, Pp. 1757–1760, May 1999.
[83] M. S. M. Yunus, N. M. Nor, N. Agbor Etobi, And K. Ramar, "Performance Of Earthing Systems For Different Earth Electrode Configurations," *Ieee*

Trans. Ind. Appl., Vol. 51, No. 6, Pp. 5335–5342, 2015.

[84] S. Tomaškovičová, T. Ingeman-Nielsen, A. V. Christiansen, I. Brandt, T. Dahlin, And B. Elberling, "Effect Of Electrode Shape On Grounding Resistances — Part 2: Experimental Results And Cryospheric Monitoring," *Geophysics*, Vol. 81, No. 1, Pp. Wa169–Wa182, Jan. 2016.

[85] A. B. Tronchoni, D. S. Gazzana, G. A. D. Dias, R. C. Leborgne, A. S. Bretas, And M. Tello, "Impulsive Grounding Systems Embedded In Concrete: Theoretical And Practical Experiments," In *2016 51st International Universities Power Engineering Conference (Upec)*, 2016, Pp. 1–5.

[86] A. Abdul Ali, N. Ahmad, N. Mohamad Nor, M. Reffin, And S. Amanina Syed Abdullah, "Investigations On The Performance Of A New Grounding Device With Spike Rods Under High Magnitude Current Conditions," *Energies*, Vol. 12, No. 6, P. 1138, Mar. 2019.

[87] F. H. Slaoui And F. Erchiqui, "Evaluation Of Grounding Resistance And Inversion Method To Estimate Soil Electrical Grounding Parameters," *Int. J. Multiphys.*, Vol. 4, No. 3, Pp. 201–215, Oct. 2010.

[88] J. He, R. Zeng, And B. Zhang, *Methodology And Technology For Power System Grounding*. Singapore: John Wiley & Sons Singapore Pte. Ltd., 2012.

[89] A. M. Mousa, "The Soil Ionization Gradient Associated With Discharge Of High Currents Into Concentrated Electrodes," *Ieee Trans. Power Deliv.*, Vol. 9, No. 3, Pp. 1669–1677, Jul. 1994.

[90] B. R. Gupta And B. Thapar, "Impulse Impedance Of Grounding Grids," *Ieee Trans. Power Appar. Syst.*, Vol. Pas-99, No. 6, Pp. 2357–2362, Nov. 1980.

[91] A. Geri, G. M. Veca, E. Garbagnati, And G. Sartorio, "Non-Linear Behaviour Of Ground Electrodes Under Lightning Surge Currents: Computer Modelling And Comparison With Experimental Results," *Ieee Trans. Magn.*, Vol. 28, No. 2, Pp. 1442–1445, Mar. 1992.

[92] M. Hayashi, "Observation Of Streamer In The Soil By Surge Current," *J. Iee Jpn*, Vol. 87, No. 1, Pp. 133–141, 1967.

[93] A. Elmghairbi, M. Ahmeda, N. Harid, H. Griffiths, And A. Haddad, "A Technique To Increase The Effective Length Of Horizontal Earth Electrodes And Its Application To A Practical Earth Electrode System," In *2011 7th Asia-Pacific International Conference On Lightning*, 2011, Pp. 690–693.

[94] A. Elmghairbi, M. Ahmeda, N. Harid, H. Griffiths, And A. Haddad, "A New Method To Increase The Effective Length Of Horizontal Earth Electrodes," In *45th International Universities Power Engineering Conference Upec2010*, 2010.

[95] K. Yamamoto, S. Sumi, S. S., And J. He, "Derivations Of Effective Length Formula Of Vertical Grounding Rods And Horizontal Grounding Electrodes Based On Physical Phenomena Of Lightning Surge Propagations," *Ieee Trans. Ind. Appl.*, Vol. 51, No. 6, Pp. 4934–4942, Nov. 2015.

[96] A. Ametani, T. Chikaraa, H. Morii, And T. Kubo, "Impedance Characteristics Of Grounding Electrodes On Earth Surface," *Electr. Power Syst. Res.*, Vol. 85, Pp. 38–43, Apr. 2012.

[97] A. L. Vainer, ""Impulse Characteristics Of Grounding Systems," *Elektichestivo (Ussr)*, Pp. 23–27, 1966.

[98] J. C. Salari And C. Portela, "Grounding Systems Modeling Including Soil Ionization," *Ieee Trans. Power Deliv.*, Vol. 23, No. 4, Pp. 1939–1945, Oct. 2008.

[99] J. Li, T. Yuan, Q. Yang, W. Sima, C. Sun, And M. Zahn, "Numerical And Experimental Investigation Of Grounding Electrode Impulse-Current Dispersal Regularity Considering The Transient Ionization Phenomenon," *Ieee Trans. Power Deliv.*, Vol. 26, No. 4, Pp. 2647–2658, Oct. 2011.

[100] T. M. Flanagan, C. E. Mallon, R. Denson, And R. E. Leadon, "Electrical Breakdown Properties Of Soil," *Ieee Trans. Nucl. Sci.*, Vol. 28, No. 6, Pp. 4432–4439, 1981.

[101] A. W. Abdul Ali, N. N. Ahmad, N. Mohamad Nor, N. F. Idris, And F. Hanaffi, "Investigations On The Performance Of Grounding Device With Spike Rods (Gdsr) With The Effects Of Soil Resistivity And Configurations," *Energies*, Vol. 13, No. 14, P. 3538, Jul. 2020.

[102] J. He, B. Zhang, R. Zeng, And B. Zhang, "Experimental Studies Of Impulse Breakdown Delay Characteristics Of Soil," *Ieee Trans. Power Deliv.*, Vol. 26, No. 3, Pp. 1600–1607, 2011.

[103] J. He, X. Wang, R. Zeng, And X. Peng, "Influence Of Impulse Breakdown Delay Of Soil On Lightning Protection Characteristics Of Transmission Line," *Electr. Power Syst. Res.*, Vol. 85, Pp. 44–49, Apr. 2012.

[104] A. Haddad, H. Griffiths, M. Ahmeda, and N. Harid, "Experimental investigation of the impulse characteristics of practical ground electrode systems," in *2010 International Conference on High Voltage Engineering and Application*, 2010, pp. 469–472.

[105] S. Toshio, S. S., N. Naoto, and A. Akihiro, "Impulse Characteristics of Grounding Resistance of Counterpoise," *IEEJ Trans. Power Energy*, vol. 121, no. 5, pp. 671–676, 2001.

[106] S. Yang, W. Zhou, J. Huang, and J. Yu, "Investigation on Impulse Characteristic of Full-Scale Grounding Grid in Substation," *IEEE Trans. Electromagn. Compat.*, vol. 60, no. 6, pp. 1993–2001, Dec. 2018.

[107] D. Clark *et al.*, "Controlled Large-Scale Tests of Practical Grounding Electrodes—Part II: Comparison of Analytical and Numerical Predictions With Experimental Results," *IEEE Trans. Power Deliv.*, vol. 29, no. 3, pp. 1240–1248, Jun. 2014.

[108] Z. Stojkovic, M. S. Savic, J. M. Nahman, D. Salamon, and B. Bukorovic, "Sensitivity analysis of experimentally determined grounding grid impulse characteristics," *IEEE Trans. Power Deliv.*, vol. 13, no. 4, pp. 1136–1142, 1998.

[109] A. Elzowawi, A. Haddad, H. Griffiths, and D. Clark, "Investigation of soil ionization propagation

in two-layer soil samples," in *2015 50th International Universities Power Engineering Conference (UPEC)*, 2015, pp. 1–5.

[110] R. Alipio and S. Visacro, "Impulse efficiency of grounding electrodes: Effect of frequency-dependent soil parameters," *IEEE Trans. Power Deliv.*, vol. 29, no. 2, pp. 716–723, 2014.

[111] CIGRE, "Impact of Soil-parameter Frequency Dependence on the Response of Grounding Electrodes and on the Lightning Performance of Electrical Systems," in *Technical Brochure 781*, 2019.

[112] S. Visacro, R. Alipio, M. H. Murta Vale, and C. Pereira, "The Response of Grounding Electrodes to Lightning Currents: The Effect of Frequency-Dependent Soil Resistivity and Permittivity," *IEEE Trans. Electromagn. Compat.*, vol. 53, no. 2, pp. 401–406, May 2011.

[113] M. Hogg *et al.*, "Liquid water stressed with HV impulses: Effect of polarity on transient pre-breakdown processes," in *2011 IEEE International Conference on Dielectric Liquids*, 2011, pp. 1–4.

[114] R. Hanaoka, T. Kohrin, T. Miyagawa, and T. Nishi, "Creepage discharge characteristics over solid-liquid interfaces with grounded side electrode," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 9, no. 2, pp. 308–315, Apr. 2002.

[115] M. Víctor and M. Cabrera, "Photographic investigations of electric discharges in Sandy media," *J. Electrostat.*, vol. 30, pp. 47–56, May 1993.

[116] A. W. A. Ali, N. N. Ahmad and N. M. Nor, "Effects of impulse polarity on grounding systems," *2020 IEEE International Conference on High Voltage Engineering and Application (ICHVE)*, 2020, pp. 1-4.

[117] I. M. Rawi, M. Z. Abidin Ab Kadir, C. Gomes, and N. Azis, "A Case Study on 500 kV Line Performance Related to Lightning in Malaysia," *IEEE Trans. Power Deliv.*, vol. 33, no. 5, pp. 2180–2186, Oct. 2018.

[118] A. W. Abdul Ali and N. M. Nor, "On the Characterisations of the Impulse Breakdown in High Resistivity Soils by Field Testing," *Energies*, vol. 14, no. 9, p. 2401, Apr. 2021.