Effect of Grid Depth on the Performance of Ground Grid under Influence of Line to Ground Fault

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Abstract—**There are many factors that affect the grounding process, so adapting these factors helps in achieving the best results for the grounding system. It is important to study some natural properties around the ground grid to create an appropriate environment for the grounding process. This paper aims to study the effect of the grid depth on the performance of the grounding grid with the effect of applying a specific line fault based on the experimental work and using simulation program based on Finite Element Method (FEM). The effect of the change in the laying depth of the grid was monitored on the total ground resistance, the Earth Surface Potential (ESP), the current density, and the electric field of the ground grid. Also, the following soil properties have been taken into consideration; the water content, the thermal and electrical conductivity, heat capacity, density, and the relative permittivity coefficient of the soil. From the obtained results, it is noticed that by increasing the depth of the grounding grid, a decrease in the total ground resistance was observed and there is a change in the performance of the ground grid.**

The findings of this investigation offer priceless insights: as grid depth rises, there is a noticeable decrease in overall ground resistance, indicating improved grounding system performance. Variations in ESP, electric field distribution, and current density further highlight the complex nature of the effects of grid depth. The study is significant in that it emphasizes the crucial part that soil characteristics play an important role in determining how grounding systems behave and the need to take these factors into account when designing a grounding system. This study makes a substantial contribution to grounding system optimization, potentially enhancing electrical safety and dependability in a variety of applications. It provides a starting point for further investigation and improvement in the search for better and more effective grounding solutions.

Keywords—Finite element method; ground grid; line fault; lightning; soil resistivity; grounding.

I. INTRODUCTION

The paramount importance of safeguarding electrical systems under all conditions necessitates the constant and effective operation of grounding systems. These systems are indispensable in addressing issues associated with electromagnetic compatibility within electrical power systems. Whether during routine operations or in the face of unexpected disruptions, a robust grounding system ensures that electrical faults follow the path of least resistance with utmost expediency, all while adhering to equipment and operational limitations.

Importantly, this protective measure aims to safeguard the lives of workers, eliminating the potential for hazards that could result in fatalities [1]. One common grounding system, the ground grid buried at a specific depth, finds widespread use, particularly in electrical substations and major industrial facilities. It serves as a reliable means to accommodate fault currents and mitigate electrical shocks effectively. To maximize the efficiency of a grounding system, one critical aspect that demands attention is grounding impedance, as underscored by Azmi et al. [2]. Furthermore, Gouda et al. [3] conducted an extensive investigation into the number and arrangement of soil layers, layer thickness, and the reflection factor between these layers. These factors significantly influence the total ground resistance of grounding systems. In a complementary vein, Meng et al. [4] introduced an innovative approach for reducing ground resistances by excavating deeper and filling these excavations with materials characterized by lower resistance. The effectiveness of a grounding system is contingent on several factors, including the type and quality of grounding electrodes, soil conditions, and the precision of installation techniques. Regular testing and maintenance routines are indispensable for ensuring that the grounding system consistently operates efficiently and remains effective in protecting against electrical hazards. Furthermore, efforts have been made to optimize the soil surrounding the grounding grid to align it with the specific requirements of the grounding system [5]. Crucially, one of the foremost factors influencing grounding system performance pertains to the properties of the soil encompassing the grounding grid system. This soil functions as an electrical conductor, facilitating the smooth flow of current from the grounding electrodes into the earth. The resistivity of this soil, indicative of its capacity to conduct electricity, exerts a profound impact on the efficiency of the grounding system [6] – [10]. Soils characterized by high resistivity, such as arid or rocky soil, can elevate grounding system resistance, potentially leading to higher voltages and creating safety hazards. Conversely, soils with low resistivity, like saturated or sandy soil, offer an improved pathway for current dissipation, culminating in a more effective grounding system [2], [4], [10], [11]– [13]. Hence, it is imperative to consider both soil type and its resistivity when designing and installing grounding systems. Soil resistivity testing may be imperative to pinpoint the optimal location and size for grounding electrodes, guaranteeing the establishment of a secure and efficient grounding system [1], [5], [14]– [16].

This paper delves into the critical factor of the depth at which the ground grid is embedded within the soil. The research encompasses two distinct soil types: sandy soil in the first instance and clay soil in the second instance. Employing the finite element method, this study investigates the impact of grid depth on crucial parameters, including total ground resistance, ESP, and current density, all within the context of specific line fault occurrences. These investigations contribute to a deeper understanding of grounding system dynamics and offer insights into optimizing their performance.

II. MATERIALS AND METHODS

A. *Materials Characteristics*

One of the most important properties of soil affecting the performance of the ground grid is the total ground resistance of the soil surrounding the grid conductors. Total ground resistance refers to the overall electrical resistance of the grounding system, which includes the resistance of the grounding electrode, grounding conductor, and the resistance of the earth itself [21] – [23]. A low total ground resistance is desirable for effective grounding, as it provides a low impedance path for fault current to flow to the ground [24] – [26]. For clear observation of the influence of the soil, the copper was used for electrodes in the grounding box. Copper is a common choice of material for grounding conductors due to its excellent electrical conductivity, corrosion resistance, and durability. Copper grounding conductors can effectively conduct electrical energy to the grounding electrode, which provides a low resistance path for fault current to flow to the ground. Two types of soil were used to study the effect of the grid depth considered the soil properties such as the water content as well as thermal and electrical conductivity, heat capacity, density, and the relative permittivity coefficient of the soil. In the first time, sandy soil was used in the test, while in the second time, clay soil was used. For clear observation of the influence of the properties of the soil, copper was used for the conductors of the ground grid. Copper is a common choice of material for grounding conductors due to its excellent electrical conductivity, corrosion resistance, and durability. Copper grounding conductors can effectively conduct electrical energy, which provides a low resistance path for fault current to flow to the ground.

B. *Water Content*

The water content in the soil surrounding the grounding system can affect its overall performance. Moisture content in the soil plays a crucial role in reducing the resistance of the grounding system. Water has a lower resistivity than soil, so when the soil around the grounding conductor is wet, the grounding resistance decreases, resulting in better electrical performance [17] – [20]. However, too much water can lead to excessive corrosion of the grounding electrode and conductor, which can reduce the system's effectiveness over time. Therefore, it is important to design the grounding system to account for the expected soil moisture content and to regularly inspect and maintain the system to ensure proper performance. So, the water content was measured for each sample separately in addition to, the electrical resistance of sandy soil with water, leachates, and seawater were measured. It has been observed that, the resistance of sandy soils decreases rapidly with increasing water content as mentioned by another author’s Pandey [27]. The relationship between water content and electrical resistance for sandy and silty soils was explored [28]. A quantitative of this relationship can be used in the geotechnical appraisal of soil slopes. The water content was measured through the following relationship Eq. 1 [29]-[30].

$$\text{Water content, } W.C = \frac{M_W}{M_D} \times 100\% \qquad (1)$$

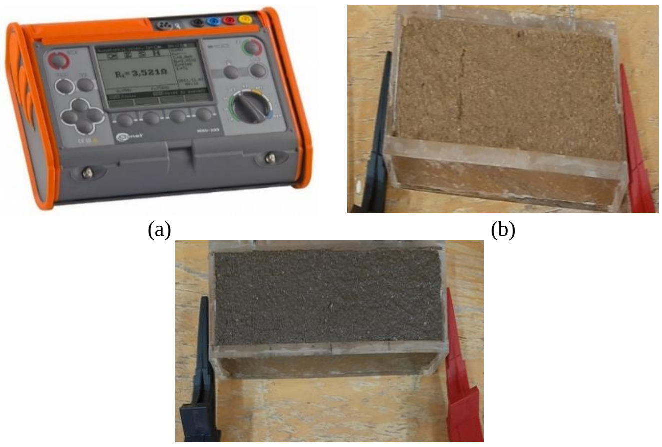
Where, M_W mass of water and M_D mass of the dry sample.

C. *Soil Electrical Resistance Measurement*

Soil electrical resistance measurement is a fundamental process for determining the electrical resistance of the soil surrounding a grounding system or earth electrode. This measurement is typically carried out using specialized instruments like the Sonel (MRU-200) device. The Sonel (MRU-200) serves as a ground resistance tester or soil resistivity meter, specifically designed to assess the electrical resistance of soil in proximity to grounding systems. The operation of the Sonel (MRU-200) device relies on the four-point method, which involves a precise sequence of steps. It begins by injecting a controlled electrical current into the soil through two current probes. Simultaneously, the voltage difference between two potential probes, positioned at a known distance from the current probes, is measured. By utilizing this four-point method, the device accurately quantifies the soil resistance. Additionally, it has the capability to calculate soil resistivity based on the measured resistance values. Furthermore, the device can assess the grounding resistance of either the grounding electrode or the entire grounding system. Its portability, battery-operated functionality, and data storage capabilities make the (MRU-200) model from Sonel a versatile tool, extensively employed in various industries and applications such as telecommunications, power distribution, and industrial and commercial installations. To measure the total ground resistance of each soil sample, a sample box is employed. This box is constructed from plexiglass, featuring a 4 mm thickness and internal dimensions of 4×3×20 mm. Both sandy and clay soil samples, as previously mentioned, are subjected to total ground resistance measurements using this sample box. The specific resistance of the soil is determined by placing the sample within the well-defined soil box. This setup allows for precise measurement of the soil resistance, as illustrated in Fig. 1. Subsequently, the specific resistance is derived through a well-established relationship in Eq. 2. This method provides essential data for understanding the electrical characteristics of the soil, which is crucial for designing and optimizing grounding systems and ensuring their effective performance.

$$\rho = (R \times A)/L \tag{2}$$

Where, ρ Specific resistance of the soil, R Resistance of the soil, L Length of the sample box, A Cross section area of the sample box.



(a) (b) (c)

Fig. 1. Soil electrical resistance measurement: (a) Sonel (MRU-200) soil resistance measurement instrument. (b) soil box model with sandy sample (c) soil box model with clay sample

The equivalent theoretical total earth resistance can be obtained by the use of Laurent expression [31], which has the following formula Eq. 3:

$$R = \frac{\rho}{D} + \frac{\rho}{L} \tag{3}$$

With ρ being the earth resistivity, while L is the total length of grid conductors. D is the diameter of a round plate covering the same area A as the grid Eq. 4.

$$D = (4/\pi)^{1/2} A^{1/2} \tag{4}$$

IEEE Guide [32] recommends the expression obtained by extending the Laurent's formula for the effect of the depth (d) of grid burial Eq. 5.

$$R = \frac{\rho}{L} + \frac{\rho}{\sqrt{20A}}\left(1 + \frac{1}{1 + d\sqrt{20/A}}\right) \tag{5}$$

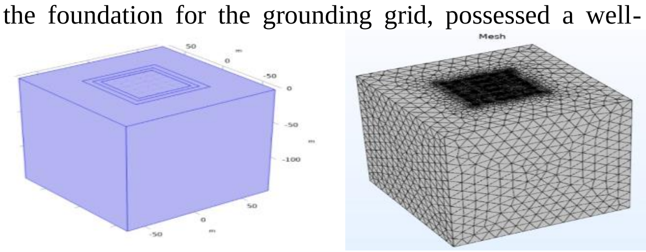
Finally, all the values of the properties of the materials used in the test were entered into the simulation model, such as the soil resistivity, as well as the values of the properties of the soil and the copper of the grid connectors using FEM method.

III. SIMULATION MODEL

A. *Model Design Specifications*

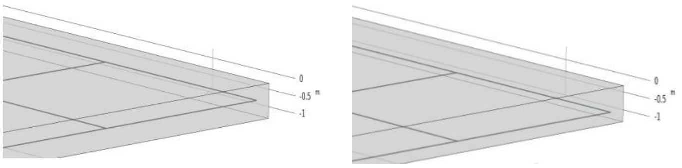
The effects of the soil surrounding a 50 m × 50 m ground grid with 25 mesh were studied at different depths (d = 0.5 m and d = 0.75 m), the simulation model was presented in Fig. 2.

In the conducted experiments, each conductor within the grounding system was configured with a uniform radius (r = 10 mm) and a consistent length (L = 50 m). The base layer, serving as the foundation for the grounding grid, possessed a well-defined area measuring 144 m × 144 m and an overall height of 144 m. Two distinct scenarios were examined: in the first case, the base soil was composed of sand, while in the second case; clay soil was employed as the base soil. Notably, the depth of the ground grid, denoted as "d," was intentionally varied, ranging from 0.5 m to 0.75 m from the base soil, as illustrated in Fig. 3. For each of these scenarios, the research objectives encompassed the comprehensive assessment of various key parameters, including total ground resistance, ESP, current density, and the electric field. These assessments were conducted under the influence of a specific line fault, simulating real-world fault conditions. The distinctive characteristics of the soil, encompassing properties such as resistivity, were duly incorporated into the simulation model. Additionally, it is worth noting that copper, renowned for its exceptional electrical conductivity, corrosion resistance, and durability, was chosen as the material for the electrical conductors within the grounding grid. The simulation model employed in this study leveraged FEM to accurately capture the behavior and interactions within the grounding system. The grid conductors were thoughtfully designed based on nodes of equal potential, allowing for a meticulous examination of the system's performance under varying conditions. This research approach offers a robust foundation for understanding the impact of grid depth, soil type, and other factors on grounding system behavior, providing valuable insights into the optimization of grounding solutions.



(a) *(b)*

Fig. 2. (a) Simulator model consists of ground grid and the soil (b) Mesh elements of FEM

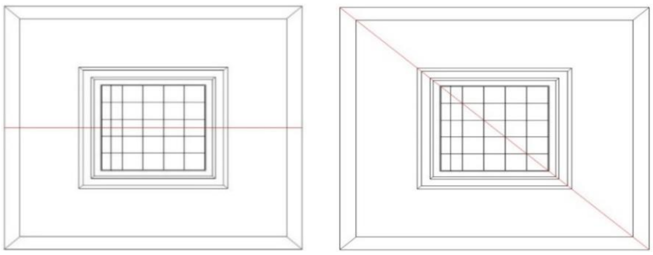


(a) (b)

Fig. 3. Ground grid buried at depth d; (a) d =0.5m, (b) d =0.75m

B. The Cut Lines Profiles of Model Simulator and Characteristics of Line to Ground Fault

Fig. 4 shows the profiles of the cutting lines that were used in the simulation model to obtain the curves expressive of the factors studied in this work. The factors are studied along the profile line, whether the profile line is central or diagonal.



(a) *(b)*

Fig. 4. The 2D planar view of the cut line profiles of the simulator model for all curves of the results: (a) Central profile, (b) Diagonal profile

To investigate the behavior of ground grid with different parameters for better performance this line current was applied for each case study with the same value (I_f = 28 KA) and time period. Fig. 5 shows the feeding position of the current on the grid, as it is the same feeding position for all cases studied during this work.

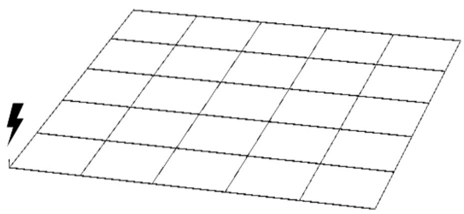


Fig. 5. The feeding position of the line to ground current on the grid

C. Study Cases

The simulator model was fed with the values of soil resistivity given in table 1. The simulator model was designed based on the water content as well as the thermal, electrical conductivity, heat capacity, density and the relative permittivity coefficient for sand and clay soils. To examine the performance of the grounding grid at different depths of the grid, the following characteristics were investigated; resistance, ESP, current density ,and the electric field. The study was carried out according to the grid depth data illustrated in Table 1.

Table 1: Study cases using simulation model

Study Case	Grid Depth d (m)	ρ (Ω.m)
(a) Change of grid depth in pure Clay soil		
d = 0.5	0.5	44.57
d = 0.75	0.75	
(b) Change of grid depth in pure Sand soil		
d = 0.5	0.5	431.88
d = 0.75	0.75	

IV. RESULTS AND DISCUSSIONS

A. Water Content

The influence of water content on soil electrical resistance is a pivotal observation in understanding and optimizing grounding system performance. Water content in the soil emerges as a significant factor that has the potential to greatly enhance the effectiveness of grounding systems. A key takeaway is that higher water content in the soil tends to reduce its electrical resistance, a phenomenon that aligns with established findings [34]-[35]. Soils capable of retaining water content over an extended period exhibit more favorable characteristics for grounding systems. This is since they consistently maintain a lower resistance value, offering better conductivity for electrical currents. Essentially, the soil's ability to retain moisture ensures that it maintains a reduced resistance profile most of the time, which is conducive to effective grounding [36]. Fig. 6 provides a visual representation of the measured resistance values for both sandy and clay soils at various levels of water content. A notable trend is evident from the results: there exists an inverse relationship between soil resistance and water content. In other words, as the water content in the soil increases, the soil's electrical resistance decreases. This inverse proportionality holds true for all types of soil studied in this research. However, the extent of this change in resistance varies from one type of soil to another. For instance, the results indicate that sandy soil is more significantly impacted by changes in its water content compared to clay soil. This implies that sandy soil, when adequately moistened, offers a more pronounced reduction in electrical resistance, making it a potentially favorable choice for grounding applications when soil moisture can be controlled or maintained [38]-[39]. The observed relationship between soil resistance and water content underscores the importance of soil moisture management in optimizing grounding systems. It suggests that selecting the right soil type and ensuring adequate moisture content can lead to more efficient and reliable grounding solutions, with the specific choice of soil dependent on factors such as local conditions and the desired grounding system performance.

Table 2 presents the extent of the resistance change for the soil sample with change in the soil proportions at specific water content for each sample. This change in the resistance shows that each soil retains most of its properties despite changing the water content.

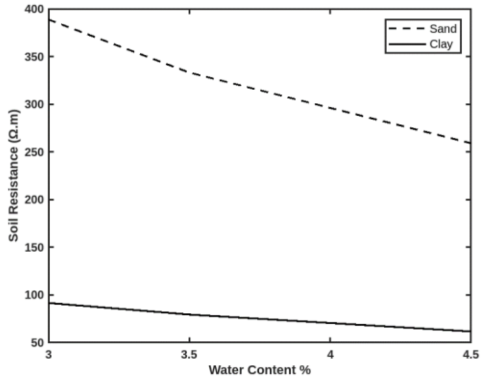


Fig. 6. Relation between the water content and the resistance of sandy and clay soils

Table 2. Specific resistance of soil samples at the certain water content

Soil Type	W. C (%)	ρ (Ω.m)
Sand	2.7	431.88
Clay	6.25	44.57

To ensure accuracy and reliability, the study relied on obtaining an average of ten measured values for ten separate samples. These measured values were obtained using the Sonel (MRU-200) device for each case under investigation. The use of this averaging approach serves to represent a more comprehensive and robust measurement of the resistance associated with each specific scenario being studied. A noteworthy finding of the study is the distinctive electrical characteristics exhibited by sand and clay soils. Sand is characterized by a notably high specific resistance, while in stark contrast; clay soil is recognized for its relatively low specific resistance. These differences in specific resistance between the two types of soil are significant, as they directly impact the electrical behavior and effectiveness of grounding systems. To incorporate these real-world characteristics into FEM simulator, the resistance values obtained for both sand and clay were employed. This integration of actual resistance values into the simulation programs contributes to enhancing the simulator's accuracy and relevance. The simulator was designed to replicate the grounding grid with copper conductors, mirroring the practical application of grounding systems. By incorporating the specific resistance values of sand and clay, the simulator operates with a greater degree of fidelity, closely approximating real-world conditions. This alignment with actual values provides valuable insights into the performance of grounding systems in different soil types and helps in designing and optimizing grounding solutions tailored to specific soil characteristics and environmental conditions.

B. *Total Ground Resistance with Changing of Grid Depth*

The depth of the ground grid represents a significant factor with a noteworthy impact on the overall performance of the grounding system. Therefore, it was imperative to examine this factor under the influence of various soil types. The investigation revealed that altering the depth of the grounding grid led to corresponding changes in the total ground resistance. However, the magnitude of this change varied depending on the type of soil involved. Specifically, when the depth of the grounding grid was increased in sandy soil, the resulting difference in resistance was considerably more pronounced compared to the case of clay soil. This observation highlights the sensitivity of clay soil to changes in grid depth, resulting in a more significant impact on resistance values which obtained with the computations of simulation software, as evidenced in Table 3.

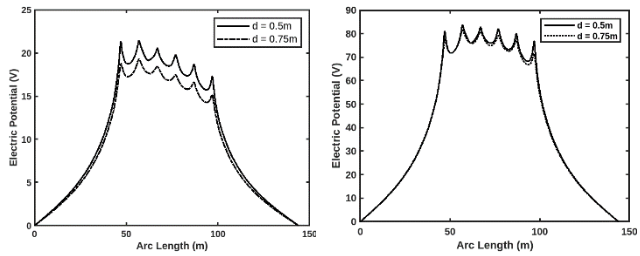
Table 3: Values of the total ground resistance in case of sand and clay base soil at grid depth d

d(m)	ρ_{clay} (Ω.m)	ρ_{sand} (Ω.m)	Rg (mΩ)	
			clay	sand
0.5	44.57	431.88	3.5	1.22
0.75			3.3	1.21

C. *Ground Grid behavior with Changing of Grid Depth*

1) *Effect of Grid Depth on ESP*

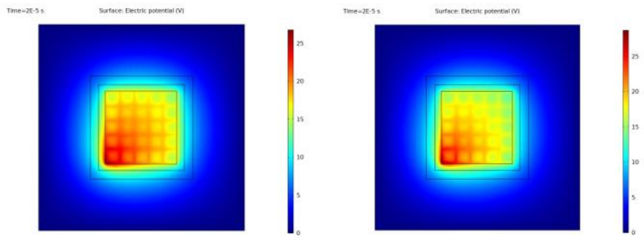
The investigation into the effect of grid depth on ESP revealed a notable and consistent trend in both sandy and clay soils. There is an inverse proportion between ESP and the depth of the ground grid. It means that if the grid is placed at a greater depth from the earth surface, the value of the earth surface potential will decrease. The variation in ESP between a grid depth of 0.5 m and 0.75 m for both sandy and clay soils is visually represented in Fig. 7. This trend is characterized by an inverse relationship between ESP and the laying depth of the ground grid. In practical terms, this means that when the grounding grid is positioned at a greater depth beneath the Earth's surface, the corresponding value of Earth Surface Potential decreases.



(a) (b)

Fig. 7. ESP in the case of soil with single type of structure; (a) the central profile of pure clay at depth 0.5 & 0.75m, (b) the central profile of pure sand at depth 0.5 & 0.75m

To grasp the underlying reasons for this phenomenon, it's essential to consider the fundamental principles of grounding systems. When the grounding grid is located at a greater depth, it facilitates more efficient dissipation of electrical energy into the surrounding soil. This deep placement creates a highly conductive pathway for fault currents to flow into the earth. As a result, a larger proportion of the electrical energy is effectively channeled into the ground, away from the Earth's surface. This reduction in voltage potential at the Earth's surface, represented by ESP, enhances safety, and mitigates the risk of hazardous electrical conditions. It ensures that in the event of a fault or electrical surge, as the voltage levels on the Earth's surface remain lower, reducing the likelihood of electrical shocks or other safety hazards. Furthermore, this finding underscores the practical importance of choosing an appropriate depth for grounding grids when designing grounding systems. By strategically placing the grid at a greater depth, engineers can optimize the system's effectiveness in minimizing voltage potential on the Earth's surface, thereby enhancing both safety and overall system performance. This observation underscores the importance of careful depth selection when designing grounding systems, as it directly influences the level of safety and effectiveness in preventing hazardous voltage conditions on the Earth's surface. **Error! Reference source not found.** Fig. 8 shows the difference in the behavior of ESP in the case of soil with single type of structure and the change in the performance of the grounding grid in the case of placing the grid at a depth of 0.5 m from the performance of the grid in the case of placing it at a depth of 0.75 m in clay soil and sandy soil. it was noted that there is a difference from depth 0.5 to 0.75 m.

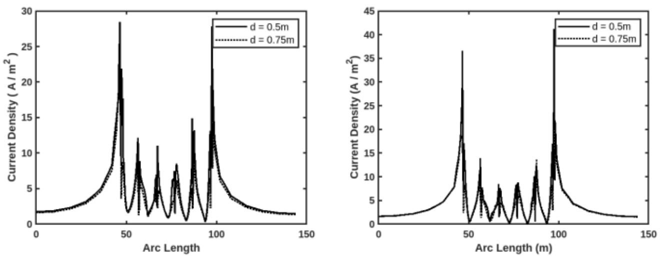


(a) (b)

Fig. 8. Behavior of ESP in the case of soil with single type of structure; (a) pure clay at depth 0.5 m, (b) pure clay at depth 0.75 m

2) *Effect of Grid Depth on Current Density and Electric Field*

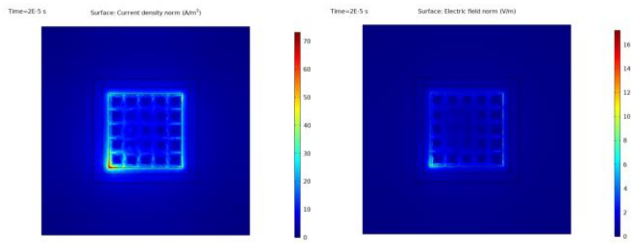
When analyzing the current density and electric field behavior within the grounding grid, a noticeable variation in values was observed in certain nodes on the ground grid, as depicted in Fig. 9 and Fig. 10. The key finding here is that when the grid is positioned at a depth of 0.5 m, both the current density and electric field values are notably higher compared to when the grid is placed at a depth of 0.75 m. This observation underscores the significant role played by the depth of the grounding grid in influencing the grid's performance.



(a) (b)

Fig. 9. ground current density in the case of soil with single type of structure; (a) Central profile of pure clay at depth 0.5 & 0.75m, (b) Central profile of pure sand at depth 0.5 & 0.75m

A shallower placement of the grid at 0.5 m depth results in higher values for both current density and electric field. Conversely, when the grid is positioned at a greater depth of 0.75 m, these values decrease. Furthermore, it's important to recognize that this change in performance between a depth of 0.5 m and 0.75 m is not consistent across different soil types. The magnitude of this change varies depending on the specific soil characteristics. For example, the impact on current density and electric field differs between sandy and clay soils. This finding underscores the influence of soil properties on the behavior of these parameters within the grounding grid. To provide more specific example, Figure 10 illustrates the difference in behavior between the two depths of the grid within clay soil with a single type of structure. It's evident from the figure that the current density and electric field exhibit distinct behaviors when comparing depths of 0.5 meters to 0.75 meters. In essence, this study demonstrates that the depth of the grounding grid is a critical design consideration, as it not only affects total ground resistance and ESP but also has a substantial impact on the behavior of current density and electric field within the grid. Engineers and designers should carefully consider these factors when optimizing grounding system performance, as the specific soil type and depth of the grid play pivotal roles in achieving the desired electrical characteristics and safety levels.



(a) (b)

Fig. 10. Behavior of the electric field in the ground grid in the case of soil with single type of structure; (a) Clay at depth 0.5 m, (b) Clay at depth 0.75 m

V. CONCLUSION

The inverse proportionality observed between soil resistance and its water content, wherein soil resistance decreases with increasing water content, is a fundamental finding applicable to all soil types investigated in this study. However, the extent of this change varies between different soil types. This observation underscores the importance of understanding and managing soil moisture levels when designing grounding systems, as it significantly influences their performance. Furthermore, the depth of the grounding grid emerges as a critical parameter that profoundly impacts various aspects of grounding system performance, including total ground resistance, ESP, current density, and electric field behavior within the ground grid. To note, when the grid depth was 0.5 meters in clay soil, the total resistance of the ground was 3.5 milliohms, while at a grid depth of 0.75 meters, it was 3.3 milliohms.

The study reveals that increasing the depth of the grounding grid results in a notable decrease in total ground resistance. This reduction is accompanied by changes in ESP values and the current density flowing through the grid. There is an inverse proportion between ESP and the depth of the ground grid. It means that if the grid is placed at a greater depth from the earth surface, the value of the earth surface potential will decrease. The variation in ESP between a grid depth of 0.5 m and 0.75 m for both sandy and clay soils is very clear. This means that when the grounding grid is positioned at a greater depth beneath the Earth's surface, the corresponding value of ESP decreases.

Considering these findings, it is recommended to position the grounding grid as deep as possible to achieve optimal grounding system performance. Importantly, these changes in the depth of the grounding grid's impact on performance extend beyond technical considerations. They also have practical implications for human safety, particularly in the vicinity of the grounding grid. The observed alterations in grounding system behavior highlight the interconnectedness of grounding system design with both technical and safety aspects. In the end, this study underscores the multifaceted influence of the grounding grid's depth on its performance, emphasizing the need for a comprehensive approach to grounding system design. By optimizing the grid's depth, engineers can enhance not only the efficiency of the grounding process but also the safety of individuals in proximity to the grid. This holistic understanding of grounding systems is crucial for ensuring reliable electrical infrastructure and safeguarding human well-being.

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