IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received February 14, 2021, accepted February 26, 2021, date of publication March 1, 2021, date of current version March 11, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3063018

The Impact of Substation Grounding Grid Design Parameters in Non-Homogenous Soil to the Grid Safety Threshold Parameters

NAVINESSHANI PERMAL[1], MISZAINA OSMAN[1], (Senior Member, IEEE),
AZRUL MOHD ARIFFIN[1], (Member, IEEE),
AND MOHD ZAINAL ABIDIN AB KADIR[2], (Senior Member, IEEE)
[1]Institute of Power Engineering, Universiti Tenaga Nasional, Jalan IKRAM-UNITEN, Selangor 43000, Malaysia
[2]Center for Electromagnetic and Lightning Protection Research (CELP), Advance Lightning, Power, and Energy Research (ALPER), Universiti Putra Malaysia, Selangor 43400, Malaysia

Corresponding author: Navinesshani Permal (nesshani@yahoo.com)

This work was supported in part by the Ministry of Higher Education (MOHE), Malaysia, through the Fundamental Research Grant Scheme (FRGS) 2020 under Grant FRGS/1/2020/TK0/UNITEN/02/13, and in part by Universiti Tenaga Nasional (UNITEN), Malaysia, through the UNITEN BOLD Postgraduate Scholarship Programme.

ABSTRACT It is important to ensure that a grounding system is designed with a low magnitude of earth resistance, so the protection system can divert the large fault current to earth effectively. The performances and protection level of a grounding system need to be acknowledged as the condition of soil structure changes with different soil characteristics. At present, there is a lack of systematic guide or standards for grounding grid designs that consider non-uniform soil and its impact on the grounding systems. By computing the grid safety threshold parameters consisting of the grid impedance, step, and touch voltages, a comparison has been made between uniform soil and two-layer soil models. Where the competence and level of safety of the grounding systems depend on the soil attributes, the significant impact of various soil conditions is seen. The evaluations on performance and safety assessment in two-layer soil conditions hold the novelty and originality as there is no such comparison and discussion have been made to date. These comparisons would help in forecasting the behavior and safety of the grounding system in various soil environments, which would provide engineers with additional expertise to design an effective and secure grounding system. This research would contribute to the existing body of knowledge by differentiating and predicting the performance of a grounding system when the characteristics of the soil differ significantly from uniform soil as most of the standards and guidelines only consider uniform soil while designing a grounding system, owing to its complexity at the site.

INDEX TERMS Grounding grid impedance, step voltage, touch voltage, multilayer soil, uniform soil, non-homogeneous soil.

I. INTRODUCTION

The effect of high Ground Potential Rise (GPR) caused by fault current can lead to faulty system operation, equipment damage, or potential risk to public and personnel safety [1]. The configuration of the grounding grid in the substation plays a key role in ensuring the safeness of the grounding system while the soil characteristics analysis including the number of soil layers, the thickness of the soil layer, and soil resistivity are the most essential factors to be considered before grounding design [2]–[7]. The designation of the grounding grid is performed cautiously due to various soil conditions at each substation, to achieve both protection and optimum investment.

Based on the geological structure of the earth, the soil resistivity varies widely [8]–[13]. By altering the spacing of the grounding electrodes, the soil resistivity profile developed at various depths can be used to determine the most suitable grounding configuration. The location chosen for the installation of the grounding system is dependent on the varying vertical and horizontal soil layers. Horizontal and vertical layers can differ in a region selected for the installation

The associate editor coordinating the review of this manuscript and approving it for publication was Akshay Kumar Saha.

of the grounding system. For instance, a grounding system placed in a horizontal two-layer soil structure would behave contradictorily from a structure of vertical two-layer soil. Such variants include soil resistivity in each soil layer and thickness of the first soil layer or each layer in multilayer soil structure. The location of the grounding system is another critical aspect that needs to be addressed. If the grounding system is positioned in the horizontal soil layer as a whole, the thickness and resistivity of the first layer may impact the nature of the grounding system. Conversely, if a grounding system is installed in a vertical soil layer, the ratio of grounding area placed in medium either low soil or high soil resistivity will determine the efficiency of the grounding system. Hence, only direct measurements would be able to produce an accurate estimation of the soil resistivity and soil layering structures [14]–[16].

A common prevailing view is that the most dangerous conditions have resulted from conditions where the soil resistivity is high. The grounding of electrical systems focuses mainly on safety which includes the avoidance of threats of electrical shock to human life. Thus, a design of the grounding system needs to be planned, evaluated, and managed to achieve this vital objective [17]–[20]. Current grounding grid designs which are well described in standards and guidelines are based on homogenous soil conditions [15], [21]–[23].

Most of the safety assessments and design procedures of the substation grounding system are incorporating homogeneous soil conditions as the input to the calculation of safety threshold values. A detailed review of the grounding system behaviors in homogeneous soil conditions has been published in [24]. Although there is extensive research on grounding behavior in uniform [4], [5], [25] and two-layer soil; top layer depth of two-layer soil [14]; the number of grounding meshes [26]; length of ground rods in two-layer soil [27]; algorithms [3], [6], [28] and reflection factors [29], [30] there is still no complete analysis currently available which comprises the impact of grounding grid dimensions, the number of ground rods and the impact of grid depth as the grid design varies in two-layer soil on grounding grid behaviors and safety. Most of the investigations were based on many assumptions and different physical approaches, which resulted in many equations developed over the last few decades. Practicality, this concern has caused several issues to the power utility when designing the substation grounding systems owing to the complexities of parameters, variation in grid design and soil conditions to be considered. The present work provides an alternative approach to illustrate the problem geometry, with the aid of Current Distribution, Electromagnetic Interference, Grounding, and Soil Structure Analysis (CDEGS) software, which allows the selected grid design to reflect on the output or criteria to be achieved i.e. the safety and the performance aspects. Besides, there is no side by side comparisons and discussions have been done to date between two-layer and uniform soil structures. These side by side comparisons demonstrates the difference of grounding behaviors and safety level when a grounding grid is placed in two-layer soil compared to uniform and if the procedures for grounding system designing in current standards and guidelines would be safely applicable when a grounding grid system is to be placed in a two-layer soil structure.

For example, a large grounding system that is unsafe in high resistivity uniform soil might be safe when it is buried in the high resistivity top layer of a two-layer soil structure. This might be due to the presence of a longer rod in the low resistivity bottom layer. Then again, there are also constraints to use longer rods in a two-layer soil structure. This paper, therefore, explores the effect of various parameters of the grounding design, such as the grid size, mesh size, the number and length of vertical electrodes attached to the main grounding grid, and the grid depth buried in different soil environments. Such studies are critical for assessing the grounding behavior and protection level in uniform and two-layer soil structure.

Besides, this paper also analyzes and compares the effect on the grounding performance of top soil layer height and surface layer resistivity. It is crucial to evaluate the nature of the soil so that an appropriate grounding system can be planned and designed.

II. INPUT PARAMETERS & METHODOLOGY

A. SUBSTATION GROUNDING DESIGN PARAMETERS

The power frequency response of 50 Hz is calculated for grounding grids of different design and compared between uniform soil and two-layer soil model with high (1000 Ωm) and low (100 Ωm) resistivities. The thickness of the top layer of the soil is 5m. The grids were centrally energized with a fault current of 30 kA. To initiate the grounding design parameters analysis, the grounding grid sizes are first varied from 30 m x 30 m to 130 m x 130 m with mesh size maintained at 10 m x 10 m for all grounding grids.

Then, the mesh sizes are varied from 5 m x 5 m to 21.7 m x 21.7 m while the grid size is maintained at 130 m x 130 m which is referred from the size of a typical Main Intake Substation 132/33/11 kV in [31], [32]. The grid is buried in the depth of 0.5m into the soil. At this stage, there are no additional vertical grounding rods attached to the main grid as demonstrated in Fig. 1 below. Fig. 1 below shows a 130 m x 130 m grounding grid with a 10 m x 10 m mesh size.

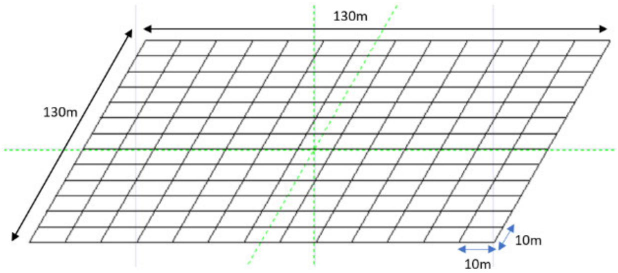


FIGURE 1. **130m x 130m grounding grid with 10m x 10m mesh size.**

Once the analysis on grounding grid sizes and mesh sizes is completed, several vertical rods are now attached to the main grounding grid. The grounding grid size is 130 m x 130 m with a 10 m x 10 m mesh size. The number of vertical rods is varied from 4 rods to 16 rods arranged along the grid's perimeter. Fig. 2 below shows the positions of 16 vertical rods attached to the main grounding grid. Each rod measures 2 m in length. The final stage of analysis was on the variations of the length of rods. The length of 4 rods was varied from 2 m to 6 m as shown in Fig. 3 while other system parameters are similar to the previous simulation on the variation of the number of rods. The summary of the grounding design analysis with grids buried 0.5m into the soil is shown in Table 1 below. Each design is classified into different case numbers.

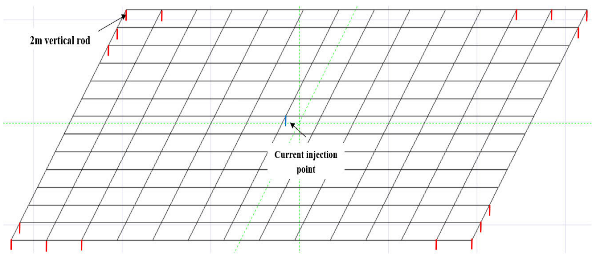


FIGURE 2. Positions of 16 vertical rods attached to the main grid.

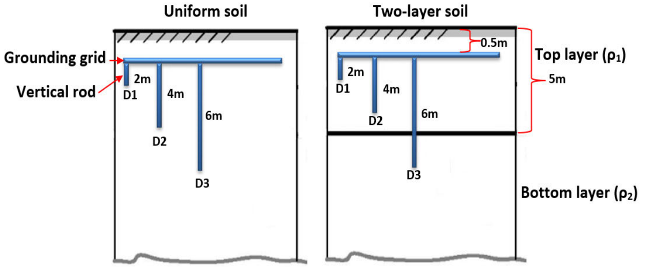


FIGURE 3. Visual representation of the lengths of vertical rods in uniform and two-layer soil.

B. SOIL STRUCTURE

The soil influences the grid safety threshold parameters (grid impedance, step, and touch voltages) through soil resistivity where it determines the flow of fault current from a ground electrode to the surrounding soil. If an inadequate grounding system design is installed in a high resistive soil, the fault current dissipation through the system will cause higher grid impedance, touch and step voltages. When the soil resistivity is less than 300 Ωm, the consequences of frequency can be omitted. However, for soil resistivity above 300 Ωm, the frequency effect becomes significant. It is recommended to consider the consequence of frequency when the soil resistivity falls in the range of 300 Ωm to 700 Ωm [33], [34], which is considered as medium resistivity. Nevertheless, the impact of frequency is compulsory above 700 Ωm. Therefore, the soil resistivity in this paper is assumed as 100 Ωm for low resistivity and 1000 Ωm for high resistivity.

TABLE 1. Analysis of grounding design parameters with a grid depth at 0.5m into the soil.

Design Parameters	Case number
Grounding grid size	
30m x 30m	A1
50m x 50m	A2
130m x 130m	A3
Grounding mesh size	
5m x 5m	B1
10m x 10m	B2
16.3m x 16.3m	B3
21.7m x 21.7m	B4
Number of electrodes	
4 rods	C1
8 rods	C2
13 rods	C3
16 rods	C4
Length of electrodes	
2m	D1
4m	D2
6m	D3

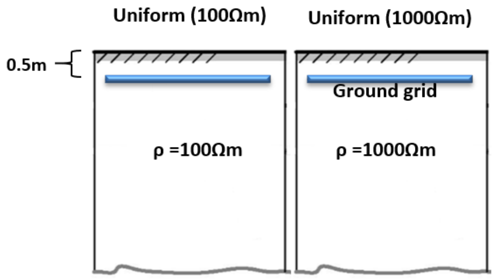


FIGURE 4. Uniform soil.

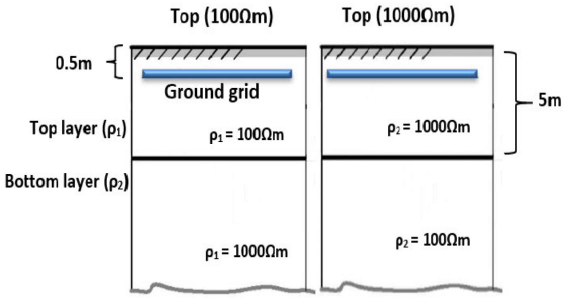


FIGURE 5. Two-layer soil structure.

Uniform soil in this paper consists of low resistivity (100 Ωm) and high resistivity (1000 Ωm). For the two-layer soil model, the top layer thickness of the soil is 5m with 1000 Ωm resistivity for Top (1000 Ωm) and 100 Ωm for Top (100 Ωm) while the lower layer thickness is at infinity depth with 100 Ωm resistivities for Top (1000 Ωm) and 1000 Ωm for Top (100 Ωm) as in Fig. 4 and 5 below.

C. SAFETY THRESHOLD FOR STEP AND TOUCH VOLTAGE

The safety threshold for step and touch voltage is calculated as in (1) and (2) based on IEEE 80-2013 [1] for the body-weight of 50 kg. E_{step} is the step voltage in V, E_{touch} is the touch voltage in V, C_s is the derating factor of the surface

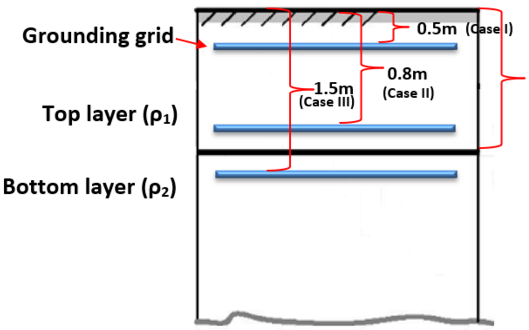


FIGURE 6. Illustration of grounding grid's depth buried into the soil.

layer, ρ_s is the resistivity material of the surface layer in Ωm, and t_s is the period of shock current period in seconds.

$$E_{step50} = (1000 + 6C_s\rho_s).\frac{0.116}{\sqrt{t_s}} \tag{1}$$

$$E_{touch50} = (1000 + 1.5C_s\rho_s).\frac{0.116}{\sqrt{t_s}} \tag{2}$$

The safety threshold is 945 V and 353 V for step and touch voltage respectively in uniform soil with low resistivity (100 Ωm). For uniform soil with high resistivity (1000 Ωm), the threshold value is 1130 V and 400 V for step and touch voltage respectively. The threshold value for grid impedance is considered as 5 Ω according to IEEE 80-2013 [1] and Malaysian Utility standard [31]. For touch voltage, the graphs show the maximum touch voltages which are at the corners of profile boundaries shown in Fig. 7(b). The safety evaluation is done by considering a radius about 3 m from the fault location (inside the red circle).

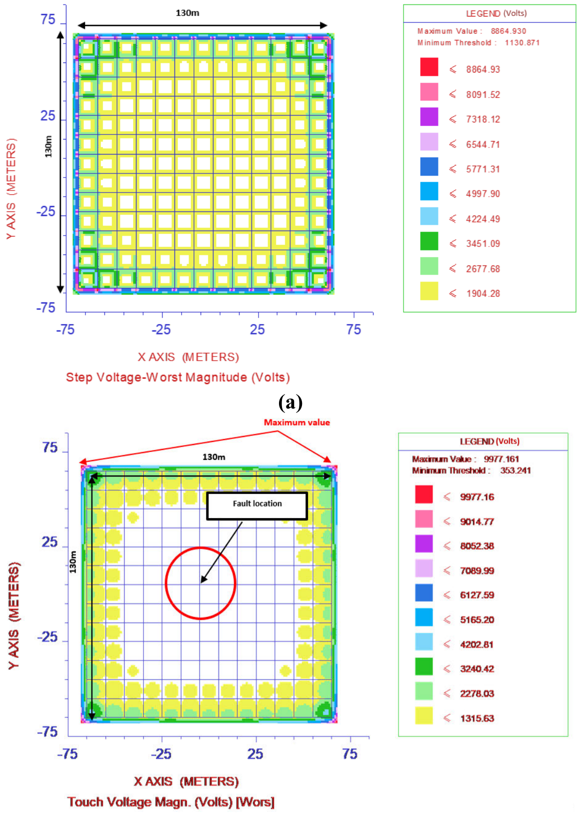
Section III below analyzes the behavior and safety of different parameters of the grounding design in different soil conditions. This assessment is done by evaluating the grid safety threshold parameters (grid impedance, step, and touch voltages). In this paper, a grounding grid is considered safe when all three safety threshold parameters mentioned above have complied.

III. RESULTS & DISCUSSIONS

A. INFLUENCE OF DESIGN PARAMETERS ON GROUNDING BEHAVIOR AND SAFETY

1) GRID SIZE

The results show the values of impedance, touch, and step voltage for different grid sizes in various soil conditions. Fig. 7(a) and Fig. 7(b) show the examples of step and touch voltage plotting using CDEGS simulation software. At the corners of the grid, the step and touch voltages are seen as the highest. It is noticeable in Fig. 8, Fig. 9, and Fig. 10 that the grid impedance, step, and touch voltages respectively have similar patterns where the magnitudes decrease as the grid size increases. Generally, the grid sizes are highly dependent on the area chosen to install the grounding system. A reduction of 77 % can be seen for grid impedance in 130 m x 130 m grid size compared to a 23 % of reduction in 130 m x 130 m grid sizes in a two-layer soil structure with a top layer of high resistive.



(a)

(b)

FIGURE 7. Safety voltages for 130 m x 130 m grounding grid. (a) Step voltage (b) Touch voltage.

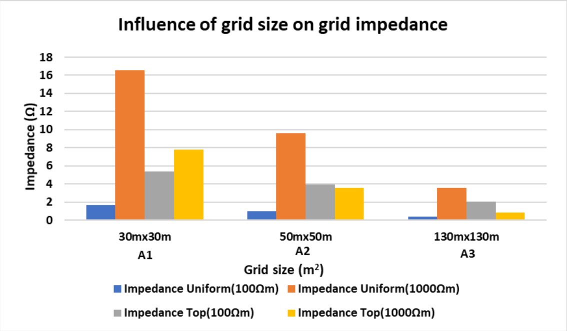


FIGURE 8. Graph of grid impedance in various soil conditions for increasing grid sizes.

Conversely, the percentage of step voltage reduction is the highest; 57% for 50 m x 50 m in two-layer soil with a high resistive top layer compared to uniform soil, where the percentage of step voltage reduction is almost similar (51 % for 50 m x 50 m) in both high and low soil resistivity. The. The similarity between low resistivity and high resistivity uniform soil could be due to the absence of external factors such as soil layers and varying soil resistivity between layers.

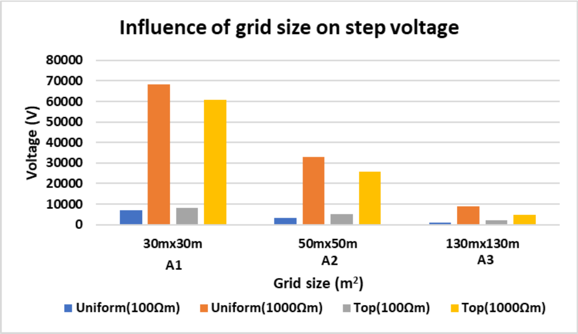


FIGURE 9. Graph of step voltage in various soil conditions for increasing grid sizes.

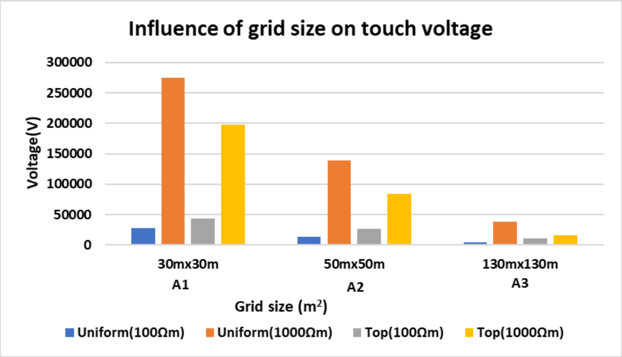


FIGURE 10. Graph of touch voltage in various soil conditions for increasing grid sizes.

The findings demonstrate that when the top layer is more resistive than the bottom layer, the grid impedance in two-layer soil is lower than that of the same grounding system in uniform soil with high resistivity. This is due to the uniform dispersion of current density all over the grounding conductors. In contrast, when the bottom layer is more resistive than the top layer, the grid impedance is higher in two-layer soil than that in uniform soil with low resistivity due to higher current density at the perimeter of the grounding system.

The grid size does not have a significant impact in terms of behavior when it is placed either in uniform soil and a two-layer soil structure with different resistivities. But the size of a grounding system does influence the grounding system's security. A grounding system has to be large so that the impedance will be below tolerable value. But still, a large grid does not guarantee a safe condition when it is placed in high resistivity uniform soil or a two-layer soil structure. Table 3 shows the overall safety evaluation of the grounding system which complies with all three tolerable values. It can be seen that all three sizes are unsafe in uniform soil and two-layer soil structure regardless of soil resistivity. Additional amendments are therefore required, such as reducing the size of the mesh or attaching vertical rods to the primary grounding grid to create a safe grounding grid.

TABLE 2. Variations of grounding grid depth for each grounding design Parameters.

Depth of grid buried	Grounding grid size	Case number
0.5m	30m x 30m & 130m x 130m	A1-I & A3-I
0.8m		A1-II & A3-II
1.5m		A1-III & A3-III
	Grounding mesh size	
0.5m	10m x 10m & 21.7m x 21.7m	B2-I & B4-I
0.8m		B2-II & B4-II
1.5m		B2-III & B4-III
	Number of electrodes	
0.5m	4 rods & 16 rods	C1-I & C4-I
0.8m		C1-II & C4-II
1.5m		C1-III & C4-III
	Length of electrodes	
0.5m	2m & 4m	D1-I & D2-I
0.8m		D1-II & D2-II
1.5m		D1-III & D2-III

TABLE 3. Safety evaluation of a grounding system for different grid sizes.

Grid size	Uniform soil		Two-layer soil	
	Uniform (100Ωm)	Uniform (1000Ωm)	Top (100Ωm)	Top (1000Ωm)
30m x 30m	Not safe	Not safe	Not safe	Not safe
50m x 50m	Not safe	Not safe	Not safe	Not safe
130m x 130m	Not safe	Not safe	Not safe	Not safe

2) MESH SIZE

This section analyzes the influence of different mesh sizes on a 130 m x 130 m grounding grid. A similar pattern to different grid sizes can be observed in this section for different mesh sizes in Fig. 11, Fig. 12, and Fig. 13. As the mesh size gets bigger, the impedance, touch, and step voltage increase. As shown in Fig. 7(a) as well as Fig. 7(b), the maximum values for step and touch voltages can also be seen near the corners of the grid.

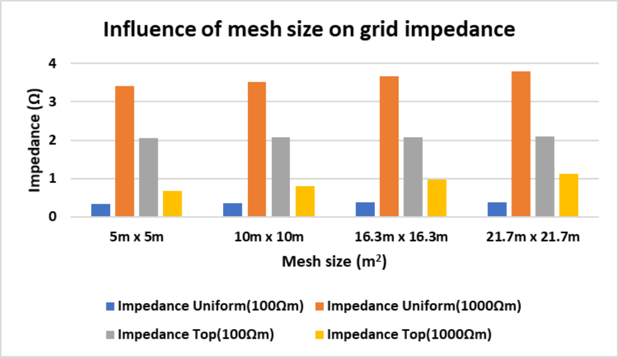


FIGURE 11. Graph of grid impedance as mesh sizes increase in different soil conditions.

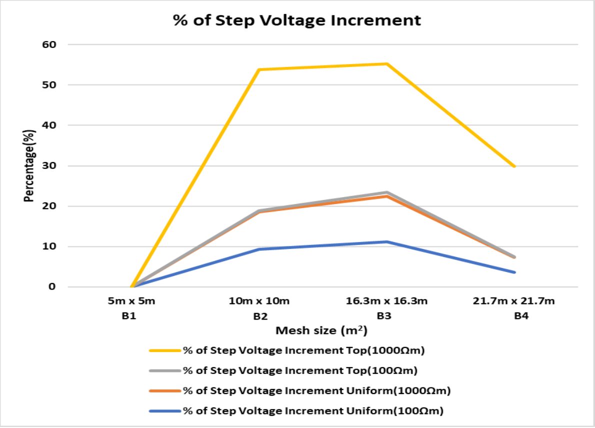


FIGURE 12. Graph of percentage increment for step voltages as mesh sizes increase in different soil conditions.

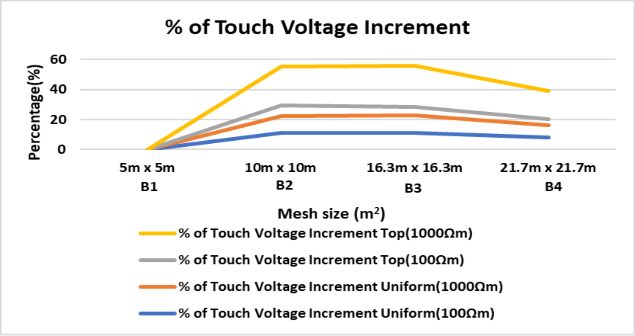


FIGURE 13. Graph of percentage increment for touch voltages as mesh sizes increase in different soil conditions.

The percentage of step voltage increment of impedance, step, and touch voltages in uniform soil with a high resistivity is similar to the uniform soil with low resistivity. For example, a 9 % step voltage increment can be seen for 10 m x 10 m mesh size. An increment of 1 7% can be seen for grid impedance in 10 m x 10 m grid size compared to 15 % of the increase in 21.7 m x 21.7 m mesh sizes in a two-layer soil structure with a top layer of high resistive. The percentage grid impedance increment from 10m x 10m till 16.3 m x 16.3 m mesh sizes are small and start to drop after 16.3 m x 16.3 m mesh size for all soil conditions. This shows that the mesh size has reached its effective size. As explained in [35], [36] an effective size is achieved when an increase in grounding design parameters does not give a significant improvement of the corresponding grounding impedance.

Similar to grounding grid size, the mesh size of a grounding system also does not have a major impact in terms of behavior when it is placed either in uniform soil and two-layer soil structure with different resistivities. But the mesh size of a grounding system does influence the safety of a grounding system.

All the mesh sizes have an impedance below the tolerable value regardless of soil conditions; uniform soil or two-layer soil with different resistivities but the step and touch voltages differ for each soil condition. An overall safety evaluation can be seen from Table 4 where only a 130 m x 130 m grounding grid with 5 m x 5 m mesh size is safe in uniform soil with low soil resistivity. Therefore, further modifications need to be done so that the grid is safe for all soil conditions.

TABLE 4. Safety evaluation of a grounding system for different mesh sizes.

Mesh size	Uniform soil		Two-layer soil	
	Uniform (100Ωm)	Uniform (1000Ωm)	Top (100Ωm)	Top (1000Ωm)
5m x 5m	Safe	Not safe	Not safe	Not safe
10m x 10m	Not safe	Not safe	Not safe	Not safe
16.3m x 16.3m	Not safe	Not safe	Not safe	Not safe
21.7m x 21.7m	Not safe	Not safe	Not safe	Not safe

3) NUMBER OF RODS

This section analyzes the influence of a different number of vertical rods on a 130 m x 130 m grounding grid with 10 m x 10 m mesh size where it was unsafe as in Table 4. In this analysis, 2 m length of vertical rods is placed on the grounding's periphery. Fig. 14 and Fig. 15 show the graph of the step and touch voltage reduction percentage of a different number of rods in different soil conditions. The magnitudes decrease for all soil conditions when the rods are added. In step voltage, there is a substantial reduction when the rods are increased from 4 to 13 rods (10.5 %) and not much difference is seen when the rods are increased from 13 to 16 rods (0.95 %) in low resistivity top layer soil. Compared to two-layer soil, the percentage of reduction when adding vertical rods in uniform soil is much smaller. This could be due to the influence of soil layers and the resistivity of the neighboring soil layer on the current dispersion through vertical rods which is absent in uniform soil.

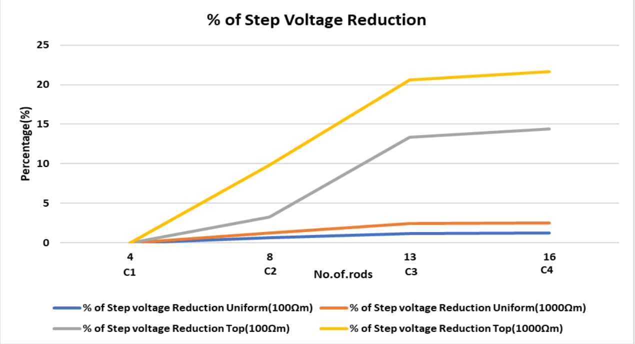


FIGURE 14. Graph of percentage reduction for step voltage as the vertical rods' number rises in different soil conditions.

Even though the safety parameters' magnitudes reduce as the number of rods increases, a sufficient number of rods is needed to make a grounding system safe. From Table 5, it is observed that a grounding system with an additional more than 13 vertical rods is safe in low and high resistivity uniform soil and low resistive top soil layer in a two-layer soil

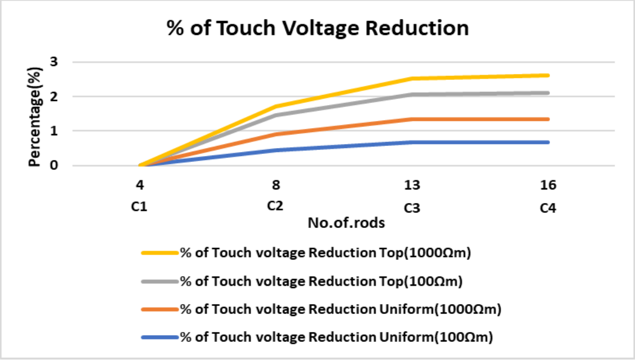


FIGURE 15. Graph of percentage reduction for touch voltage as the vertical rods number rises in different soil conditions.

TABLE 5. Safety evaluation of a grounding system for a different number of vertical rods.

Number of rods	Uniform soil		Two-layer soil	
	Uniform (100Ωm)	Uniform (1000Ωm)	Top (100Ωm)	Top (1000Ωm)
4	Not safe	Not safe	Not safe	Not safe
8	Not safe	Not safe	Not safe	Not safe
13	Safe	Not safe	Safe	Not safe
16	Safe	Safe	Safe	Not safe

structure. Whenever there is a limitation on grounding size, adding a sufficient number of vertical rods to the grounding grid would help in dissipating fault current away from the earth's surface, where peaks of step and touch potentials are lessened. Besides, the number of rods that are required is also dependent on the length of rods used which will be discussed in the next section iv. To make the grounding system safe in a two-layer soil structure with a top layer of high resistive, the length of rods used should be longer.

4) LENGTH OF RODS

Fig. 16, Fig. 17, and Fig. 18 show that an increase in impedance, step, and touch voltage can be noticed at the 6m length for two-layer soil with a low resistivity top layer. This is due to the influence of the high resistive bottom soil layer as the vertical rods passed beyond the two-layer soil boundary at 5m. When the length of the rod is long enough to penetrate the high resistive bottom soil layer, its resistivity influences the behavior of the grounding system where it will increase the grid impedance, touch, and step voltage. The high resistivity bottom layer causes more current flow towards the lower resistivity in the top layer thus increasing the grounding impedance touch and step voltage. From Table 6, it can see that longer rods are only useful when it is used in two-layer soil with less resistivity bottom layer as more current will disperse through a longer rod which makes the grounding system to be safe.

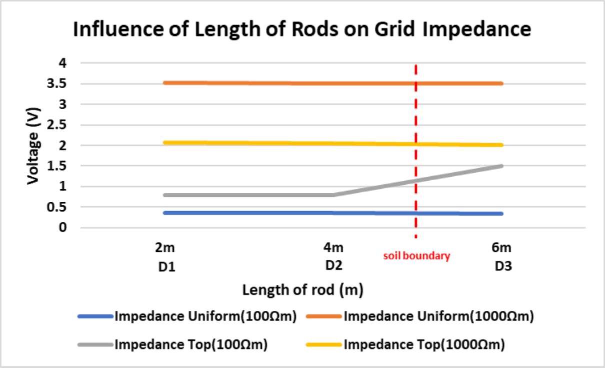


FIGURE 16. Graph of impedance for increasing length of vertical rods in different soil conditions.

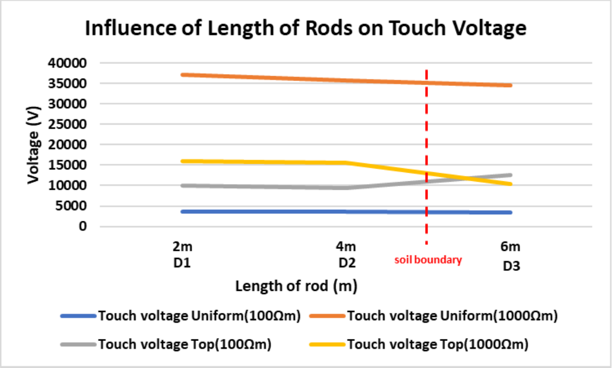


FIGURE 17. Graph of touch voltage for increasing length of vertical rods in different soil conditions.

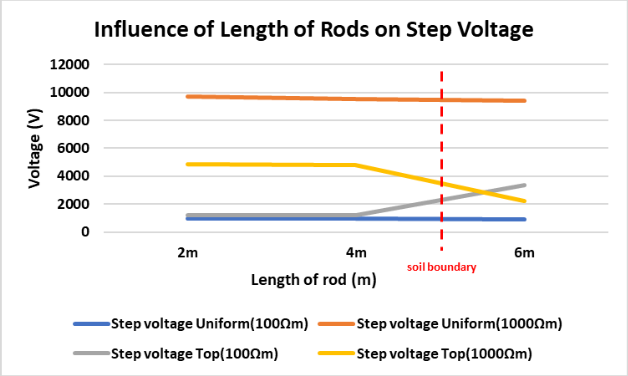


FIGURE 18. Graph of step voltage for increasing length of vertical rods in different soil conditions.

TABLE 6. Safety evaluation of a grounding system for different lengths of vertical rods.

Length of rod	Uniform soil		Two-layer soil	
	Uniform (100Ωm)	Uniform (1000Ωm)	Top (100Ωm)	Top (1000Ωm)
2m	Safe	Not safe	Not safe	Not safe
4m	Safe	Not safe	Not safe	Not safe
6m	Safe	Not safe	Not safe	Safe

B. INFLUENCE OF GRID BURIAL DEPTH ON GROUNDING BEHAVIOR

In determining the protection of a grounding system, particularly in the two-layer soil model, the depth of the grid buried

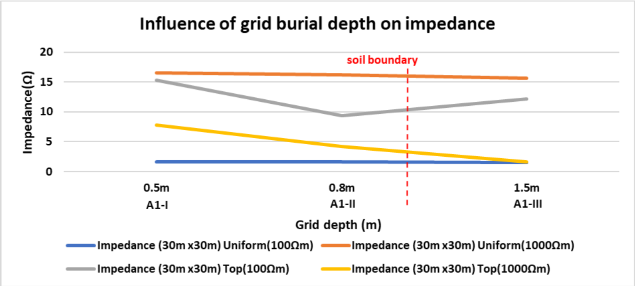


FIGURE 19. Graph of impedance for increasing grid burial depth in different soil conditions for 30 m x 30 m grid size (10 m x 10 m mesh size).

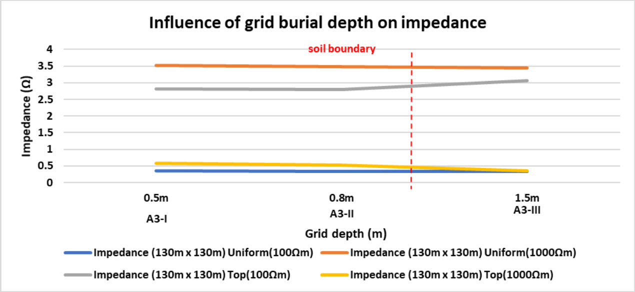


FIGURE 20. Graph of grid impedance for increasing grid burial depth in different soil conditions for 130 m x 130 m grid size (10 m x 10 m mesh size).

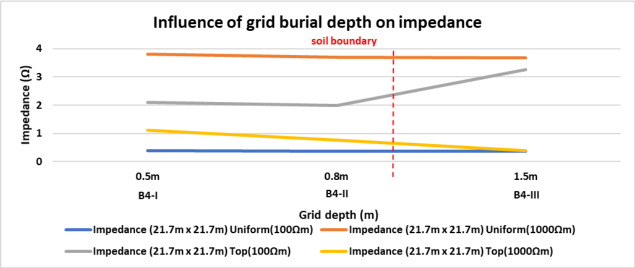


FIGURE 21. Graph of impedance for increasing grid burial depth in different soil conditions for 21.7 m x 21.7 m mesh size (130 m x 130 m grid size).

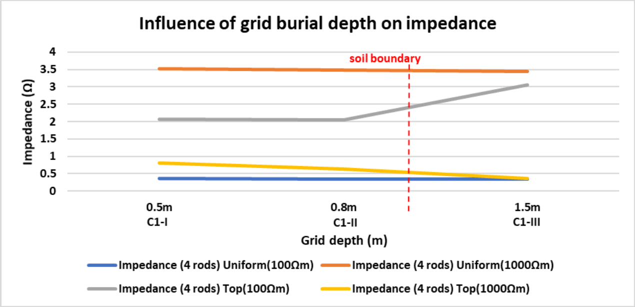


FIGURE 22. Graph of grid impedance for increasing grid burial depth in different soil conditions for 4 vertical rods.

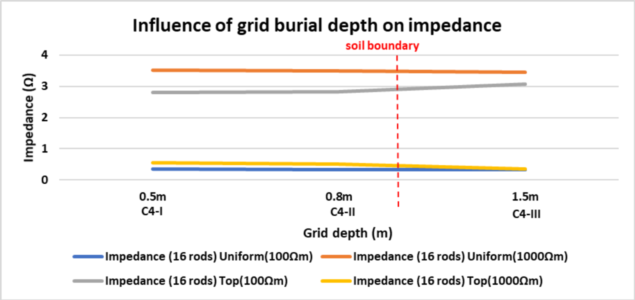


FIGURE 23. Graph of grid impedance for increasing grid burial depth in different soil conditions for 16 vertical rods.

in the soil also plays an important role apart from varying the design parameters of a grounding grid, such as expanding the grid size, reducing mesh size, adding more vertical rods with a longer length. The grid burial depth is normally in the interval of 0.5 m to 1.5 m or 2.0 m to 2.5 m in some cases according to [1].

The reduction for impedance for smaller grid size (30 m x 30 m with a mesh size of 10 m x 10 m) is noticeable which is about 19 % compared to bigger grid size (130 m x130 m with a mesh size of 10 m x 10 m) which is only 8 % as in Fig. 19 and Fig. 20. For uniform soil, as the grid depth increases, the impedance reduces and a substantial drop in impedance can be seen for uniform soil with high resistivity. The first layer height of two-layer soil for this analysis is 1 m. A similar pattern of behavior can be found when the topsoil layer varies which will be explained in the next section C. For two-layer soil, the impedance increases as the depth increase after the soil boundary in the low resistive topsoil layer because the high resistivity bottom layer causes more current flow towards the lower resistivity in the top layer thus increasing the grounding impedance.

Alternatively, increasing the grid's depth in high resistive top layer soil decreases the impedance value until the boundary of two-layer soil. The impedance value after the soil boundary is similar to that in uniform soil with low resistivity. A similar pattern as in different grid sizes can also be observed for different mesh sizes as shown in Fig. 21.

Fig. 22 and Fig. 23 displays a similar behavior for both the number of rods. There is no large reduction that can be seen for increasing the grid depth in high and low resistivity uniform soil. For two-layer soil with a low resistivity top layer, the impedance reduces significantly when the depth increases to 0.8m and started to increase when it reaches the soil boundary at 1 m for 4 rods. For 16 rods in Fig. 23, a similar pattern with a lower magnitude of impedance can be observed. The reduction rate is smaller after 1.5 m grid depth for both numbers of rods.

Compared to varying rod numbers, grid sizes and mesh sizes, the rod length in different grid burial depth is crucial in determining the grounding behavior and protection in two-layer soil structure. Similar to Fig. 22, the reduction is not obvious for both lengths of rods in high and low uniform soil. The analysis compared 30 m x 30 m and 130 m x 130 m grounding grids to analyze the influence of the combination of grid size and length of the rod as the depth of burial increases.

As can be seen in Fig. 24, the impedance reduces at 0.8 m depth and start increasing as it nears the boundary at 1m for a smaller grid (30 m x 30 m) with short rods (2 m). For 4 m rods, the impedance almost constant before the soil boundary, and start increasing after passing through the boundary as in Fig. 25. As mentioned earlier, the impedance increases as the depth increase after the soil boundary for the top layer with lower resistivity because the high resistivity bottom layer causes more current flow towards the lower resistivity in the top layer thus increasing the grounding impedance.

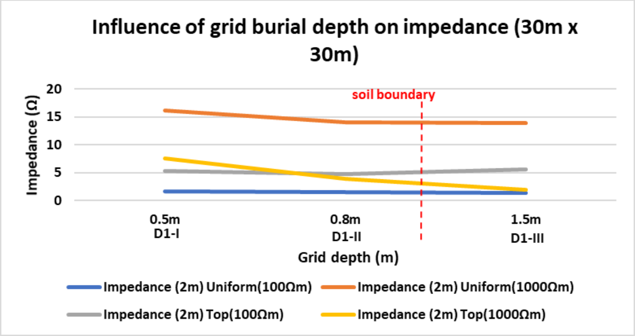


FIGURE 24. Graph of impedance for increasing grid burial depth in different soil conditions for 2 m rod length (4 rods) in a 30 m x 30 m grounding grid.

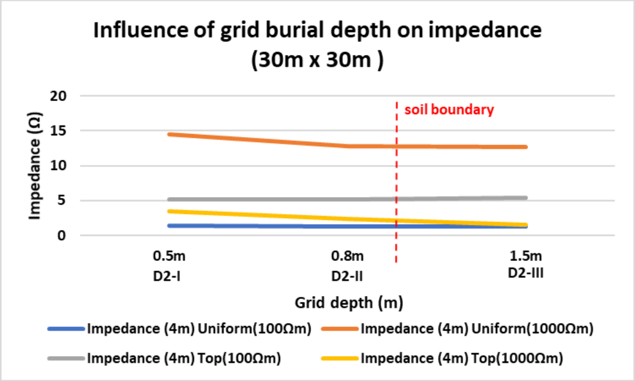


FIGURE 25. Graph of impedance for increasing grid burial depth in different soil conditions for 10m rod length (4 rods) in a 30 m x 30 m grounding grid.

For a larger grid (130 m x 13 0m) placed in a low resistive top soil layer as in Fig. 26 and Fig. 27, more reduction can be seen for shorter rods (2m) compared to longer rods (4 m) before the soil boundary because of the position of shorter rods in low resistivity top layer. Although the 4m rods are in the high resistive bottom layer, the large grid size with increasing grid depth helped to reduce the grid impedance. After a certain depth, for example, 1.5 m, there is no many changes in the impedance value.

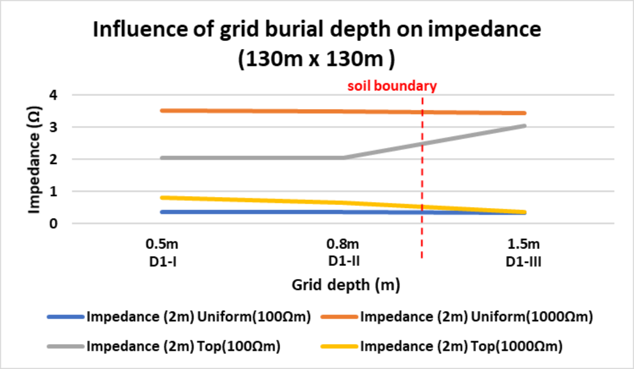


FIGURE 26. Graph of impedance for increasing grid burial depth in different soil conditions for 2 m rod length (4 rods) in a 130 m x 130 m grounding grid.

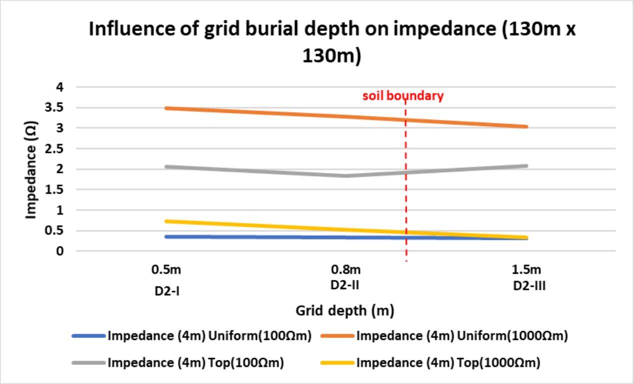


FIGURE 27. Graph of impedance for increasing grid burial depth in different soil conditions for 4 m rod length (4 rods) in a 130 m x 130 m grounding grid.

As no noticeable decrease in impedance resistance is accomplished by increasing the depth, this depth may be taken as an indicator of the optimum depth of the grid burial. This analysis shows that the length of the rod is dominant in determining the grid's impedance when a grid is small while grid size is dominant in determining the grid's impedance when the length of the rod reached a high resistive soil layer.

C. INFLUENCE OF SOIL TOP LAYER HEIGHT ON GROUNDING IMPEDANCE

The information on soil properties is important before designing a grounding system. The behavior of the grid is not only affected by the soil resistivity in each layer but also by the top layer height. This analysis is important as a piece of knowledge to predict the impedance pattern which would help in deciding on the length of additional vertical rods based on the topsoil layer height.

In a two-layer soil model, the findings described in the previous section are based on the top layer soil height of 1m. The bottom soil influences the grounding impedance value when the height of the top layer is sufficiently small in a horizontal two-layer soil model. The grounding impedance varies within a range determined by a lower limit corresponding to the low resistivity uniform soil model and an upper limit corresponding to the uniform soil with high soil

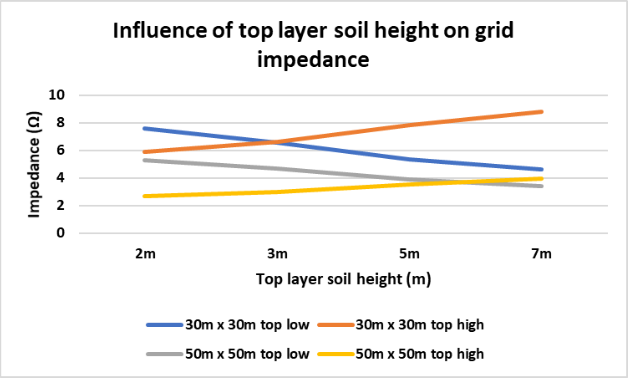


FIGURE 28. Dependence of grid impedance on the top layer height for different grid sizes.

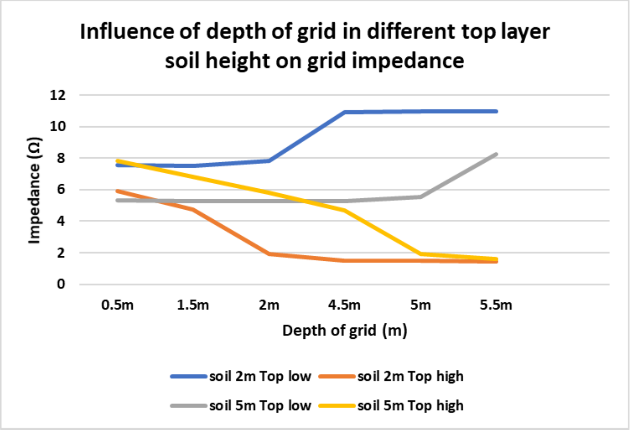


FIGURE 29. Influence of depth of grid in different top layer soil height on-grid impedance.

resistivity when the height of the top layer is changing. The grid impedance of a grounding system placed in a 3 m top layer height with low resistivity is lower than the grounding system placed in a top layer height with high resistivity and vice versa for a top layer height of 7 m. These two variation curves might cross at some point (same impedance value) regardless of grounding size, as demonstrated in Fig. 28 and Fig. 29. A smaller (30 m x 30 m) grid has a smaller cross point at 3m topsoil layer height compared to a bigger grid (50 m x 50 m) with a larger cross point at approximately 6 m topsoil layer height.

Fig. 30 shows that there is a significant reduction or increase that can be seen when the depth of the grid buried is similar to the height of the soil top layer. For example, if the soil top layer height is 1.0 m with low resistivity, it would be best not to exceed the grid burial depth more than 1.5 m because the impedance value will increase from 9.6 Ω to 12.22 Ω. In a two-layer soil structure, the soil boundary plays an important role in determining the behavior of a grounding system which also corresponds to the depth of the grid buried. It is suggested that a grounding system should be buried in a low resistivity medium (within a soil boundary for low resistivity top layer and after the soil boundary for high resistivity top layer) to reduce the impedance.

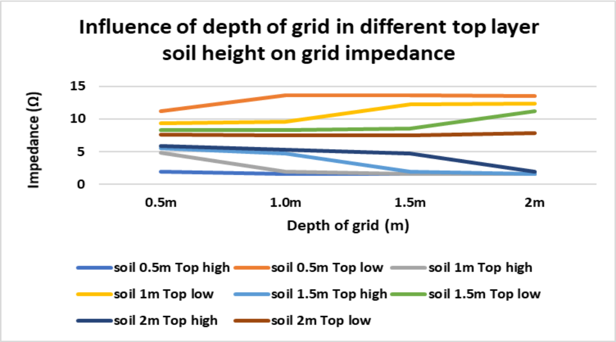


FIGURE 30. Influence of depth of grid in smaller top layer soil height on-grid impedance.

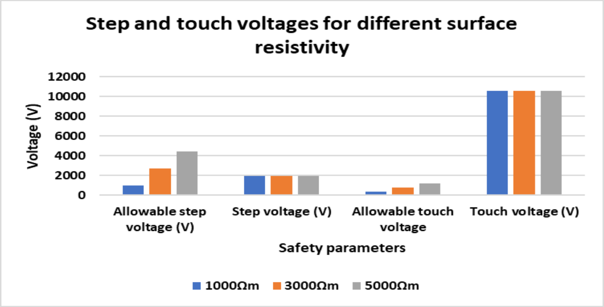


FIGURE 31. Graph of allowable step and touch voltages and step and touch voltages for different surface layer resistivity in low resistivity top layer soil structure.

D. INFLUENCE OF SURFACE LAYER RESISTIVITY ON GROUNDING BEHAVIOR

Surface layer material resistivity is one of the critical core parameters for the secure, economical, and reliable design of the substation grounding grid. Generally, a thin coating of surface material such as crushed limestone, granite, asphalt with a very high resistivity is used for covering the substation. Oftentimes, surface layer thickness (h_s) of 0.10 m to 0.15 m is used [1]. The analysis is done for 3 different surface layer resistivity (1000 Ωm, 3000 Ωm, 5000 Ωm) with 0.15 m of layer thickness. Fig. 31 illustrates the influence of material resistivity of the surface layer on acceptable touch and step voltages and grounding behavior in the top soil layer with low resistivity.

It indicates that the allowable limits of safety voltages increase as surface resistivity increases, whereas the grounding behavior for all surface resistivities is the same. There is no impact on grounding behavior as the surface resistivity differs. Similar behavior can also be observed for uniform soil with high and low resistivity and two-layer soil structure with high resistivity top layer. Increasing the surface resistivity helps further in reducing the need of using additional numbers and length of vertical rods to enhance grounding safety. According to the analysis, the magnitudes of allowable step and touch voltage in low resistivity uniform soil are similar to low resistive topsoil layer in two-layer soil structure and an identical pattern is also observed at high resistive uniform soil and high resistive topsoil layer in two-layer soil structure.

IV. RESULTS VALIDATION

As the results presented in this paper are purely based on the CDEGS simulation software, it is important to validate the results to ensure their reliability and accuracy. In CDEGS, there are various modules available to analyze different grounding, electromagnetic, and transient problems. The results produced by each computation module in CDEGS is tested to ensure its accuracy and validity complied for various cases documented internally, and numerous fundamental cases that are available on electronic media. These cases in each module are retested before releasing a new version. The results are authenticated by comparing them through well-documented publications and reports with previously obtained results. These validation reports and publications can be accessed through [26].

V. CONCLUSION

A typical safety threshold parameter evaluation includes the impedance of the substation grounding grid, touch, or step voltage under faulty conditions. However, owing to the complexity of site topology, often the chosen or available area for substation design is a non-uniform soil type. It is well-known and commonly understood that most of the investigations were based on many assumptions and different physical approaches, which resulted in many equations developed over the last few decades based on uniform soil. Thanks to the advancement of the technology, the design, and research on grounding systems have gone through years of knowledge discoveries, with the availability of computer-aided software specifically for grounding system studies such as CDEGS, which allows the engineers to understand several aspects of designs that influence safety and performance of the systems. The efficiency and safety of grounding systems are understood to be closely linked to soil characteristics. In this paper, the soil resistivity was defined and compared between uniform and two-layer earth structures. These comparisons are important so that the behavior and safety of a grounding system can be predicted earlier where it will provide engineers with primary knowledge and valuable instructions to design a substation grounding system that is safe for both public and working personnel. In terms of behaviors, there is no significant impact on the grounding system when the grid sizes, mesh sizes, and several vertical rods change in different soil resistivities. Increasing grid sizes and the number of rods and reducing mesh sizes would help the grid to be safe by reducing the impedance, step, and touch voltages under threshold values. But, grounding grid depth and the length of vertical rods, play an important role in minimizing grid impedance to some extent. The length of the rod determines the position of the rod in the soil layer in which the corresponding soil resistivity influences the grounding behavior as the depth varies. Besides, it can be concluded that when a grid is small in size, the length of the rod is important in determining the grid's impedance while for a larger grid size is dominant in determining the grid's impedance when the length of the rod reached high resistive soil layer.

Although impedance, step and touch voltage magnitude in high resistivity uniform soil is higher compared to low resistivity soil, the percentage of reduction of these grid safety threshold parameters is similar between high resistivity and low resistivity uniform soil because there are no other external factors such as the soil layers and different soil resistivities to reduce or increase the parameters' magnitudes. This shows that there is a linear relationship between grid design parameters and grid safety threshold parameters in uniform soil but in two-layer soil, the safety parameters are only linear up to a certain extend. For example, the impedance of a grounding grid reduces linearly in uniform soil as the depth of the buried grid increases, but the impedance decreases linearly in two-layer soil before it exceeds the boundary of the soil. After the soil boundary, the impedance magnitude depends on the soil resistivity under which the grid is buried. This condition is also applicable for grounding design parameters such as the number of rods, length of rods, etc.

This proves that there will be a major error if the presence of non-homogeneous soil condition is not being considered in the substation grounding design analysis. Another important parameter to consider in a two-layer soil structure is the topsoil height. A grounding grid positioned in a two-layer soil with a high resistivity top layer would have a lower impedance value when the depth of the top layer is significantly smaller. This would be an advantage by not requiring any additional vertical rods attached to the grounding grid if it has complied with the safety threshold parameters. On the other hand, a large height of the top layer with high resistivity will have a high impedance value. Therefore, it would require longer vertical rods attached to the grounding grid so that the longer rods would penetrate the low resistivity bottom soil layer and disperse more current into the soil to make the grounding system safe.

In terms of safety evaluation from Table 3, 4, 5, and 6, no similar grounding system is safe in all soil conditions. For example, even though the grounding behaviors improve as grid size increases, a larger grid that is safe in low resistivity uniform soil, is not safe in a two-layer soil structure with a top layer of high resistive. According to the results, it can be concluded that a 130 m x 130 m grounding grid is not safe for the mesh size is either 5 m x 5 m or 10 m x 10 m without any additional vertical rods. Therefore, additional vertical rods are needed to enhance the safety of the grounding grid. At least 13 vertical rods with 2 m length are needed for the grounding rods to be safe in all soil conditions except for a two-layer soil structure with a top layer of high resistive. If only 4 rods are chosen, the length of rods needs to be at least 6 m length for the grounding grid to be safe in uniform soil with low resistivity and a two-layer soil structure with a top layer of high resistive. Thus, a detailed analysis of the soil condition needs to be carried out for critical substations, where at least 2 layers of soil structure need to be identified. Assuming the soil where a grounding system will be installed to be uniform would cause a major error and risk the grounding's safety level.

REFERENCES

[1] *IEEE Guide for Safety in AC Substation Grounding*, IEEE Standard 80-2013, 2013.

[2] K. A. Vyas and J. G. Jamnani, "Optimal design of grounding system for HV/EHV substations in two layered soil," *Int. J. Emerg. Technol. Adv. Eng.*, vol. 2, no. 5, pp. 383–392, 2012.

[3] M. Moradi, "Analysis of transient performance of grounding system considering frequency-dependent soil parameters and ionization," *IEEE Trans. Electromagn. Compat.*, vol. 62, no. 3, pp. 785–797, Jun. 2020.

[4] S. G. Pavel, V. Maier, C. Ciorca, H. G. Beleiu, and I. Birou, "Optimal design of the vertical Earthing with electrodes arranged in line," *Appl. Sci.*, vol. 10, no. 3, pp. 5–8, 2020, doi: 10.3390/app10031177.

[5] S. Nikolovski, G. Knežević, and Z. Baus, "Assessment of step and touch voltages for different multilayer soil models of complex grounding grid," *Int. J. Electr. Comput. Eng.*, vol. 6, no. 4, pp. 1441–1455, 2016, doi: 10.11591/ijece.v6i4.10637.

[6] B. Gursu and M. C. Ince, "Limiting GPR in a two-layer soil model via genetic algorithms," *J. Franklin Inst.*, vol. 346, no. 8, pp. 768–783, 2019, doi: 10.1016/j.jfranklin.2009.07.003.

[7] L. K. Sing, N. Yahaya, S. R. Othman, S. N. Fariza, and N. M. Noor, "The relationship between soil resistivity and corrosion growth in tropical region," *J. Corrosion Sci. Eng.*, vol. 16, pp. 1–11, Jan. 2015.

[8] C. C. Tung and S. C. Lim, "Performance of electrical grounding system in soil at low moisture content condition at various compression levels," *J. Eng. Sci. Technol.*, vol. 12, no. 1, pp. 27–47, 2017.

[9] M. Nassereddine, J. Rizk, M. Nagrial, and A. Hellany, "Estimation of apparent soil resistivity for two-layer soil structure," *Int. J. Energy Environ.*, vol. 1, no. 3, pp. 427–446, 2010.

[10] V. Vycital, D. Topolanek, P. Toman, and M. Ptacek, "Sensitivity analysis of Earthing system impedance for single and multilayered soil," *CIRED, Open Access Proc. J.*, vol. 2017, no. 1, pp. 428–431, Oct. 2017, doi: 10.1049/oap-cired.2017.1108.

[11] J. Yang and J. Zou, "Parameter estimation of a horizontally multilayered soil with a fast evaluation of the apparent resistivity and its derivatives," *IEEE Access*, vol. 8, pp. 52652–52662, 2020, doi: 10.1109/ACCESS.2020.2980875.

[12] R. R. A. Coelho, A. E. C. Pereira, and L. M. Neto, "A high-performance multilayer Earth parameter estimation rooted in chebyshev polynomials," *IEEE Trans. Power Del.*, vol. 33, no. 3, pp. 1054–1061, Jun. 2018, doi: 10.1109/TPWRD.2017.2664738.

[13] J. Ma and F. P. Dawalibi, "Computerized analysis of grounding plates in multilayer soils," *IEEE Trans. Power Del.*, vol. 24, no. 2, pp. 650–655, Apr. 2009, doi: 10.1109/TPWRD.2008.2005887.

[14] J. Nahman and I. Paunovic, "Resistance to Earth of Earthing grids buried in multi-layer soil," *Electr. Eng.*, vol. 88, no. 4, pp. 281–287, Apr. 2006, doi: 10.1007/s00202-004-0282-y.

[15] M. Mokhtari, Z. Abdul-Malek, and C. L. Wooi, "Integration of frequency dependent soil electrical properties in grounding electrode circuit model," *Int. J. Electr. Comput. Eng.*, vol. 6, no. 2, pp. 792–799, 2016, doi: 10.11591/ijece.v6i2.9527.

[16] T. Takahashi and T. Kawase, "Analysis of apparent resistivity in a multilayer Earth structure," *IEEE Trans. Power Del.*, vol. 5, no. 2, pp. 604–612, Apr. 1990.

[17] M. Kižlo and A. Kanbergs, "The causes of the parameters changes of soil resistivity," *Sci. J. Riga Tech. Univ. Power Electr. Eng.*, vol. 25, no. 25, pp. 43–46, Jan. 2009, doi: 10.2478/v10144-009-0009-z.

[18] B. Thapar and V. Gerez, "Equivalent resistivity of non-uniform soil for grounding grid design," *IEEE Trans. Power Del.*, vol. 10, no. 2, pp. 759–767, Apr. 1995, doi: 10.1109/61.400855.

[19] J. Zou, Y. Q. Liu, J. S. Yuan, J. L. He, L. Cao, J. Lee, and S. Chang, "Analysis of the toroidal HVDC grounding systems in horizontal multilayer soils," *IEEE Trans. Magn.*, vol. 42, no. 4, pp. 1435–1438, Apr. 2006, doi: 10.1109/TMAG.2006.871456.

[20] O. Ramos-Leanos, F. A. Uribe, L. Valcarcel, A. Hajiaboli, S. Franiatte, and F. P. Dawalibi, "Nonlinear electrode arrangements for multilayer soil resistivity measurements," *IEEE Trans. Electromagn. Compat.*, vol. 62, no. 5, pp. 2148–2155, Oct. 2020, doi: 10.1109/TEMC.2020.2970149.

[21] R. Shariatinasab and J. Gholinezhad, "The effect of grounding system modeling on lightning-related studies of transmission lines," *J. Appl. Res. Technol.*, vol. 15, no. 6, pp. 545–554, Dec. 2017, doi: 10.1016/j.jart.2017.06.003.

[22] M. Abdel-Salam, A. Ahmed, M. Nayel, and A. Zidan, "Surface potential and resistance of grounding grid systems in homogeneous soil," *Electr. Power Compon. Syst.*, vol. 35, no. 10, pp. 1093–1109, Jul. 2007, doi: 10.1080/15325000701297109.

[23] J. A. Güemes-Alonso, F. E. Hernando-Fernández, F. Rodríguez-Bona, and J. M. Ruiz-Moll, "A practical approach for determining the ground resistance of grounding grids," *IEEE Trans. Power Del.*, vol. 21, no. 3, pp. 1261–1266, Jul. 2006, doi: 10.1109/TPWRD.2006.874121.

[24] N. Permal, M. Osman, M. Z. A. A. Kadir, and A. M. Ariffin, "Review of substation grounding system behavior under high frequency and transient faults in uniform soil," *IEEE Access*, vol. 8, pp. 142468–142482, 2020, doi: 10.1109/access.2020.3013657.

[25] M. Mokhtari, Z. Abdul-Malek, and G. B. Gharehpetian, "A critical review on soil ionisation modelling for grounding electrodes," *Arch. Electr. Eng.*, vol. 65, no. 3, pp. 449–461, Sep. 2016, doi: 10.1515/aee-2016-0033.

[26] M. G. Unde and B. E. Kushare, "Grounding grid performance of substation in two layer soil—A parametric analysis," *Int. J. Eng. Sci. Emerg. Technol.*, vol. 1, no. 2, pp. 69–76, 2012, doi: 10.7323/ijeset/v1_i2_8.

[27] B. Anggoro, R. H. Dharmawanwas, H. N. K. Ningrum, J. Burhan, and M. R. B. Tamjis, "Grounding impedance characteristics for two-layer soil of vertical rod configuration with variation of length and diameter," *Int. J. Electr. Eng. Informat.*, vol. 10, no. 4, pp. 799–815, 2018, doi: 10.15676/ijeei.2018.10.4.12.

[28] T. Lu, L. Qi, and X. Cui, "Effect of multilayer soil on the switching transient in substations," *IEEE Trans. Magn.*, vol. 42, no. 4, pp. 843–846, Apr. 2006, doi: 10.1109/TMAG.2006.871665.

[29] O. E. Gouda, T. El-Saied, W. A. A. Salem, and A. M. A. Khater, "Evaluations of the apparent soil resistivity and the reflection factor effects on the grounding grid performance in three-layer soils," *IET Sci. Meas. Technol.*, vol. 13, no. 4, pp. 469–477, 2019, doi: 10.1049/iet-smt.2018.5336.

[30] X. Tong, X. Dong, and B. Tan, "High current field test of impulse transient characteristics of substation grounding grid," *J. Eng.*, vol. 2019, no. 16, pp. 2018–2021, Mar. 2019, doi: 10.1049/joe.2018.8826.

[31] *Substation Design Manual*, TNB Distrib. Division, Dept. Asset Manage., Tenaga Nasional Berhad, Malaysia, 2012.

[32] *Electricity Supply Application Handbook Version 3.1*, Tenaga Nasional Berhad, Malaysia, 2019, vol. 3.

[33] C.-H. Lee, C.-N. Chang, and J.-A. Jiang, "Evaluation of ground potential rises in a commercial building during a direct lightning stroke using CDEGS," *IEEE Trans. Ind. Appl.*, vol. 51, no. 6, pp. 4882–4888, Nov. 2015, doi: 10.1109/TIA.2015.2399618.

[34] *Impact of Soil-Parameters Frequency Dependence on the Response of Grounding Electrodes and on the Lightning Performance of Electrical Systems*, CIGRE, Paris, France, Oct. 2019.

[35] J. He, Y. Gao, R. Zeng, J. Zou, X. Liang, B. Zhang, J. Lee, and S. Chang, "Effective length of counterpoise wire under lightning current," *IEEE Trans. Power Del.*, vol. 20, no. 2, pp. 1585–1591, Apr. 2005, doi: 10.1109/TPWRD.2004.838457.

[36] A. El Mghairbi, M. Ahmeda, N. Harid, H. Griffiths, and A. Haddad, "Technique to increase the effective length of practical Earth electrodes: Simulation and field test results," *Electr. Power Syst. Res.*, vol. 94, pp. 99–105, Jan. 2013, doi: 10.1016/j.epsr.2012.04.015.

NAVINESSHANI PERMAL received the bachelor's degree in electrical and electronics engineering, and the master's degree in electrical engineering from Universiti Tenaga Nasional, Malaysia, in 2014 and 2018, respectively, where she is currently pursuing the Ph.D. degree in electrical engineering. She is currently a Research Assistant with Universiti Tenaga Nasional. Her research interests include grounding of power systems and transient analysis.

MISZAINA OSMAN (Senior Member, IEEE) received the bachelor's degree in electrical engineering from the University of Southampton, U.K., in 1999, and the Ph.D. degree in electrical engineering, in 2004. She is currently an Associate Professor with the Institute of Power Engineering, Universiti Tenaga Nasional (UNITEN). She is also a Professional Engineer (P.Eng.), a Chartered Engineer (C.Eng.), and a member of the Institute of Engineering and Technology (IET), U.K., The Institution of Engineers Malaysia (IEM), the National Mirror Committee of IEC TC81 (Lightning Protection) and a country's representative of IEC TC 81 Meeting, and the CIGRE Working Group C4.50 (Evaluation of Transient Performance of Grounding System in Substation). Her research interests include power system grounding, lightning protection, and high voltages.

AZRUL MOHD ARIFFIN (Member, IEEE) received the bachelor's degree (Hons.) in electrical engineering and the Ph.D. degree from the University of Southampton, U.K., in 2004 and 2008, respectively. He is currently an Associate Professor and the Director of the Programme Management Office, Universiti Tenaga Nasional (UNITEN), Malaysia. He is also a Professional Engineer (P.Eng.) registered with the Board of Engineers Malaysia (BEM).

MOHD ZAINAL ABIDIN AB KADIR (Senior Member, IEEE) received the bachelor's degree in electrical and electronic engineering from Universiti Putra Malaysia and the Ph.D. degree in high voltage engineering from the University of Manchester, U.K. He is currently a Professor with the Faculty of Engineering, Universiti Putra Malaysia. He is also the Founding Director with the Center for Electromagnetic and Lightning Protection Research (CELP), Universiti Putra Malaysia. His research interests include high voltage engineering, lightning protection, electromagnetic compatibility, and power system transients. He is a Professional Engineer (P.Eng.), a Chartered Engineer (C.Eng.), and a Professional Technologist (P.Tech.). He is an IEEE Power and Energy Society (PES) Distinguished Lecturer in the area of lightning and high voltage engineering.

• • •