RESEARCH PAPER
Contrib. Sci. & Tech Eng, 2025, 2(1)
Homepage: https://cste.journals.umz.ac.ir/
DOI: 10.22080/cste.2025.28758.1015

Effects of Non-Homogeneous Soils on Variation of Step and Touch Voltage Patterns in H.V. Substations Utilizing Finite Element Method

Asaad Shemshadi [1]*, Pourya Khorampour [1]

[1] *Department of Electrical Engineering, Arak University of Technology, Arak, Iran.*

Article Info
Received 04 March 2025
Accepted 18 March 2025
Available online 18 March 2025

Keywords:
Step Voltage;
Touch Voltage;
Ground Grid;
Homogeneous and Heterogeneous Soil;
Finite Element Method;
Electrical Protection,
Electrical Field;
Electrical Potential.

Abstract:
Grounding systems play a crucial role in ensuring the safety and reliability of high-voltage substations. However, variations in soil composition, particularly the presence of heterogeneous layers such as rock, can significantly impact grounding effectiveness. This study investigates the effects of non-homogeneous soil on step and touch voltage patterns using the Finite Element Method (FEM) in COMSOL Multiphysics. The simulation compares grounding performance in homogeneous and heterogeneous soils, analyzing electric potential and field distribution. A sensitivity analysis is conducted to assess the impact of varying soil resistivity on grounding safety. Additionally, different grounding techniques are compared to identify optimal solutions for mitigating potential hazards. The results indicate that heterogeneous soils increase step voltage and potential gradients, posing higher risks for personnel and equipment. The findings provide essential insights for improving grounding system designs in complex soil environments and expand new technical horizons to accurately investigate new enhanced grounding grid structures.

***Corresponding Author:** shemshadi@arakut.ac.ir

Supplementary information: Supplementary information for this article is available at https://cste.journals.umz.ac.ir/

Please cite this paper as: Shemshadi, A., & Khorampour, P. (2025). Effects of Non-Homogeneous Soils on Variation of Step and Touch Voltage Patterns in H.V. Substations Utilizing Finite Element Method. Contributions of Science and Technology for Engineering, 2(1), 12-18. doi:10.22080/cste.2025.28758.1015

1. Introduction

In all electrical installations, especially in industrial complexes, earth connection is one of the most essential measures to protect persons and equipment and improve system performance. According to the IEEE std 80-2000 standard, two main design objectives should be achieved in any grading system under normal and fault conditions. These goals are [1-3]:

1. Providing a way to dissipate electric currents in the ground without exceeding the operational limits and equipment.

2. Ensuring that no one is exposed to hazardous electric shock near the landfill.

When running a high-pressure post, a network of parallel conductors is buried at the bottom and appropriate depths (about 0.3 to 1.5 m) to electrically ground the potential. Also, rods of length proportional to the strength of the soil are positioned vertically in the ground and connected to the ground network to reduce the equivalent resistance of the ground network [4-6]. The ground system in a substation should be designed and implemented to limit the increase of the potential of the ground network to an acceptable level, thereby ensuring the safety of personnel, the health of the equipment, and the service of the substation in normal and fault conditions, be provided. The general reason for connecting the equipment to the ground and creating a ground network is to provide adequate safety for those in contact with the equipment. It also provides adequate protection for electrical equipment against deterioration or failure of other purposes of the earth's grid. Therefore, it is part of the design and engineering operations of high-voltage substations, ground system design, and the connection of high-pressure equipment and steel structures. As such, all equipment installed on the ground is at the same voltage as the ground voltage [7-15].

The purpose of this article is to investigate the surface potential of the surface distribution network to investigate the step voltages, especially at the posts where the buried rock layer is located below the grid. In this project, the impact of heterogeneous (rocky) soil on the low ground on the electric field and the electric potential distribution

*ISSN **3060-6578***

patterns will be analyzed by COMSOL software, whose principles are based on the finite element method. First, the electric field and the electric potential patterns on the homogeneous soil will be examined. Then, the study discusses and compares the electrical field and the electrical potential patterns for the non-homogeneous soil.

2. Design and Finite Element Simulation

The finite element method is a numerical method for solving problems in the fields of engineering and mathematical physics. This method converts the desired problem into an algebraic equation system and obtains estimated values of unknown parameters for several distinct points in the problem definition range. The solution of the finite element method is to divide the big problem into smaller and simpler parts. The simple equations that represent these finite elements are put together in a larger equation system and form the general form of the problem. The study or analysis of a phenomenon using FEM is known as finite element analysis .

In the COMSOL Multiphysics software, the design of the ground grid is shown in Figure 1.

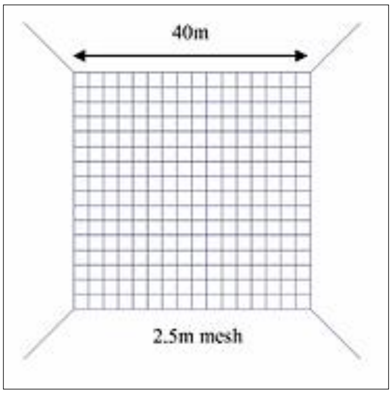

Figure 1. Ground Grid Map

For proper consideration, place the grid into a cube five times the size of the grid, as shown in Figure 2. This is done to consider potential changes in this study environment as zero. The earth's grid lies 0.8 meters above the ground.

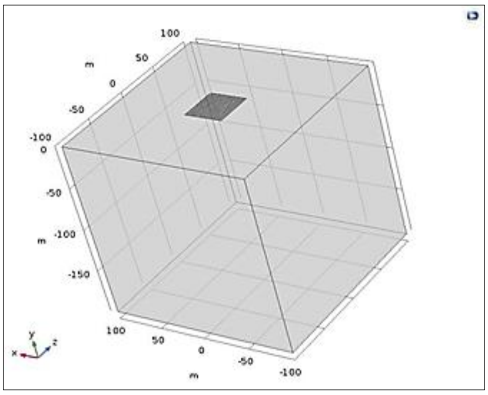

Figure 2. The study area for the land grid

Then, the network is analysed in two different ways:

1- Underground soil layer should be uniform.

2- Underneath the ground network is a layer of soil and rock.

For soil and rock, consider another cube and place it 6 meters below the first cube. The first layer, which is soil, lies within the first 6 meters, and the rest of the space is considered rocky.

Now, let's discuss the characteristics of the system under study. The ground grid is made of copper. Tables 1 to 3 give the characteristics of the copper, soil, and rock layers, respectively.

Table 1. Specifications of copper

Property	Variable	Value	Unit	Property Group
Relative Permittivity	EpsilonR-iso	1	1	Basic
Electrical Conductivity	Sigma-iso	5.988e7	[S/m]	Basic
Heat Capacity	Cp	385	[J/(Kg*k)]	Basic
Surface Emissivity	EpsilonRad-iso	0.5	1	Basic
Density	rho	8940	Kg/m^3	Basic
Thermal Conductivity	K-iso	400	W/m*k	Basic

Table 2. Specifications of soil layer

Property	Variable	Value	Unit	Property Group
Relative Permittivity	EpsilonR-iso	1	1	Basic
Electrical Conductivity	Sigma-iso	5e-3	[S/m]	Basic
Heat Capacity	Cp	820	[J/(Kg*k)]	Basic
Surface Emissivity	EpsilonRad-iso	0.7	1	Basic
Density	rho	2600	Kg/m^3	Basic
Thermal Conductivity	K-iso	3	W/m*k	Basic

Table 3. Specifications of rock layer

Property	Variable	Value	Unit	Property Group
Relative Permittivity	EpsilonR-iso	1	1	Basic
Electrical Conductivity	Sigma-iso	3.33e-4	[S/m]	Basic
Heat Capacity	Cp	820	[J/(Kg*k)]	Basic
Surface Emissivity	EpsilonRad-iso	0.7	1	Basic
Density	rho	3500	Kg/m^3	Basic
Thermal Conductivity	K-iso	3	W/m*k	Basic

After determining the physics of the different parts of the software, the desired voltages will be applied. After the software has identified the different parts of the software, the network needs to be elementalized and problem-solving, according to Figures 3 and 4.

Once the physics of the different parts has been determined, the applied voltages and software patches are ready to be resolved. We then begin to consider the Cut Line in accordance with Figures 5 to 7, which are defined in three ways: from the center of the network to the end of the cube, from the beginning to the end of the cube, and from the center of the network to the depth of the ground.

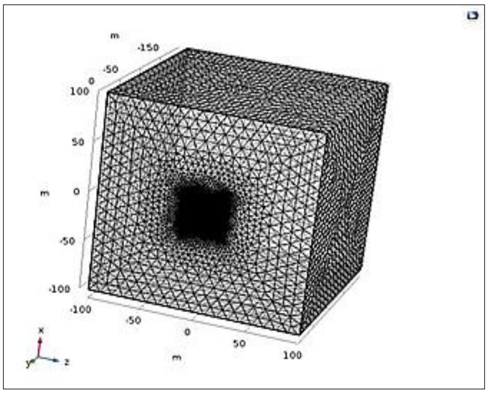

Figure 3. Soil State Meshing

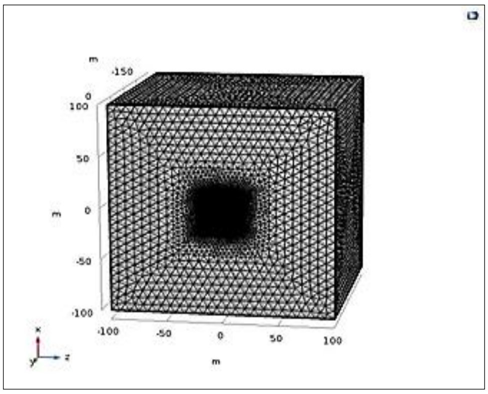

Figure 4. Rock State Meshing

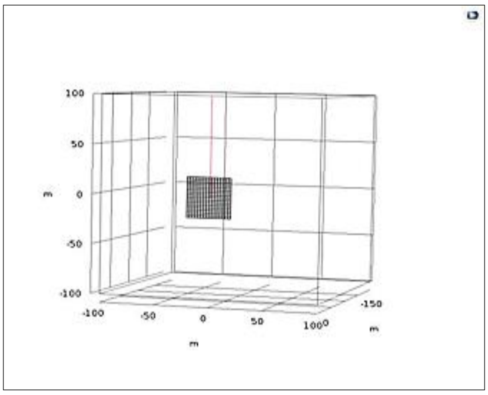

Figure 5. Cut Line 3D

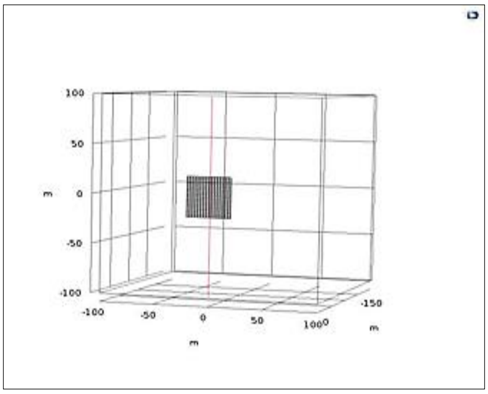

Figure 6. Cut Line 3D

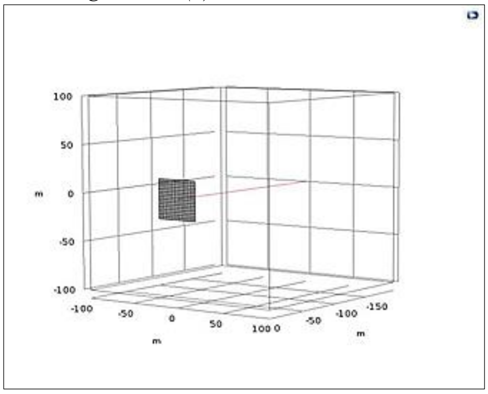

Figure 7. Cut Line 3D

Finally, we define cut planes in two states according to Figures 8 and 9: perpendicular to the ground grid and to its surface.

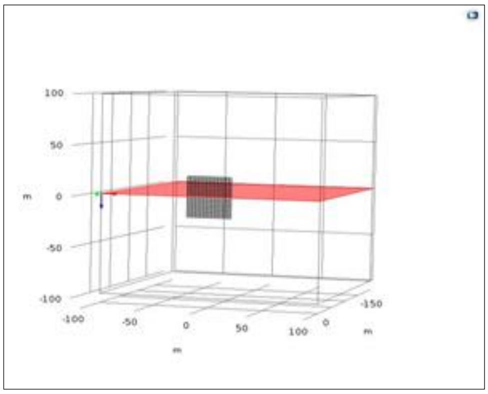

Figure 8. Cut Plane 3D

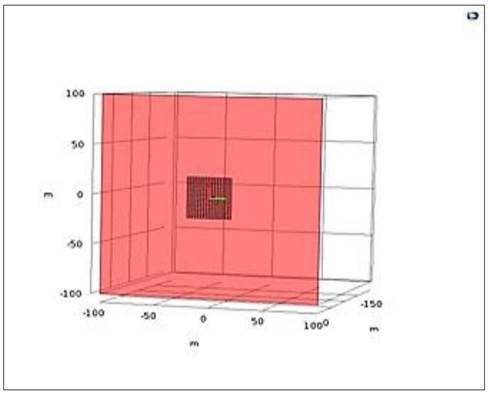

Figure 9. Cut Plane 3D

3. Finite Element Simulation

Figures 10 and 11 show the voltage distribution around the ground grid for the homogeneous soil state, along with the potential points in Figure 12.

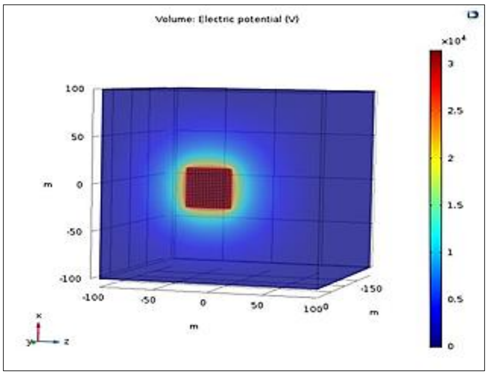

Figure 10. Voltage Volume

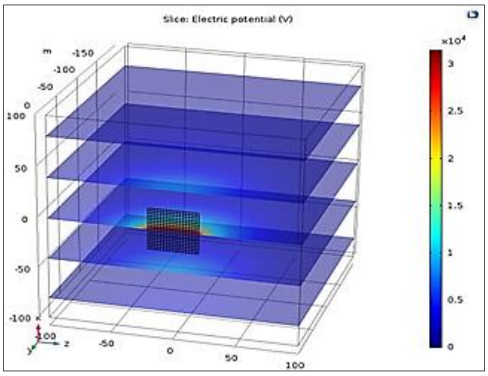

Figure 11. Slice of Cut Plane

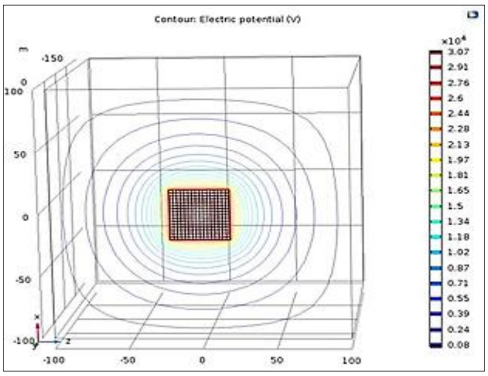

Figure 12. Contour of Voltage

Show the voltage distribution around the ground grid in Figures 13 and 14 for the non-homogeneous soil state, along with the potential points in Figure 15.

4. Simulation Result and Discussion

The output diagrams were examined in two homogeneous and heterogeneous soil states and compared with each other.

Figure 16 is for soil mode, and Figure 17 is for soil and rock mode. In the ground state diagram, the voltage at the bottom of the earth grid drops to 29100 volts, but in the rock state, the voltage drops to 28580 volts. The soil and rock have had a higher voltage drop in all similar locations. Obviously, the state of soil and rock is more dangerous because it has a higher voltage drop and, as a result, a greater potential difference, thus increasing the step and surface voltage. As shown in the diagrams, the highest voltage drop and the maximum potential difference are at the end of the ground grid. So, the closer we get from the center of the grid to the end of the grid, the more voltage we get, the more a step higher and more dangerous it is.

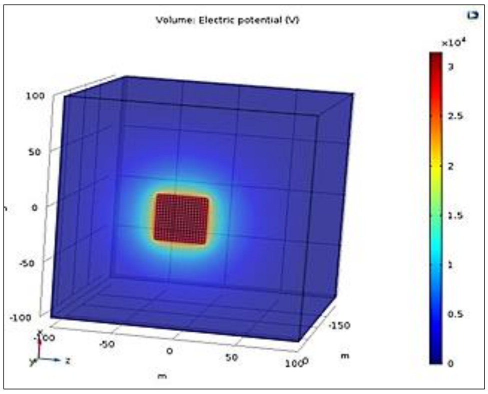

Figure 13. Voltage Volume

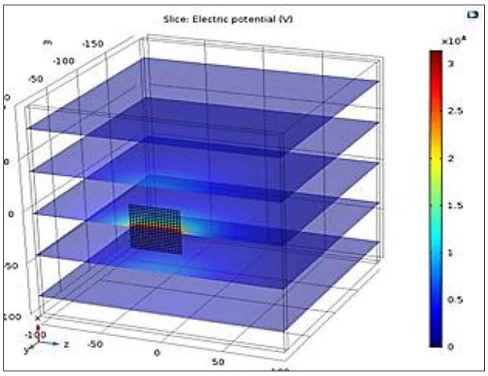

Figure 14. Slice of Cut Plane

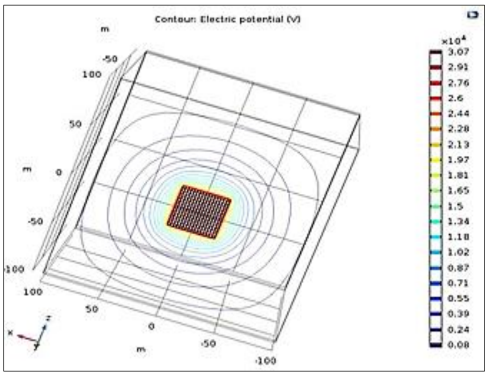

Figure 15. Contour of Voltage

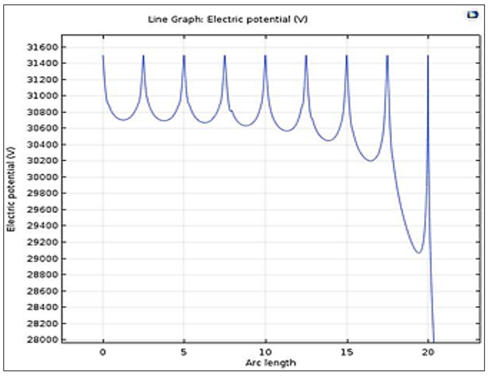

Figure 16. Electric potential diagram of soil state

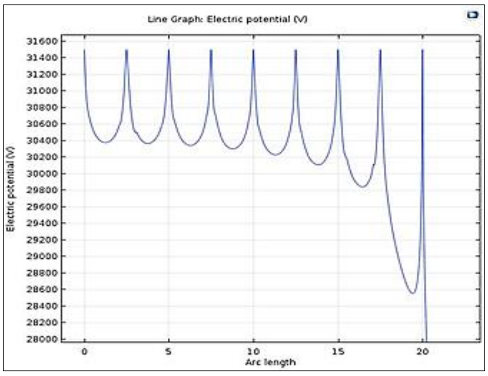

Figure 17. **Electric potential diagram of rock state**

Table 4 examines the step potential of both homogeneous and non-homogeneous states.

Table 4. **Comparison of step potential in two homogeneous and non-homogeneous states**

	Internal edge of the grid (v)	external edge of the grid (v)	Grid Center (v)
Monolayers	5500	2300	750
Double layer	6500	2800	1100
Percentage of change	%18.18	%21.73	%46.66

Figure 18 is for soil mode, and Figure 19 is for soil and rock mode. As can be seen, in the soil state 50 m away from the grid, the voltage is 6000 V, but in the soil and rock state, the voltage is 5200 V. Up to 100 meters away, the soil state diagram and rock are below the soil state diagram. This means that the diagram of the soil and rock shows a higher voltage drop, resulting in a higher voltage difference. The highest voltage difference is near the grid, so we have the highest voltage near the grid and the most dangerous point. After 100 meters, the voltage difference reaches its minimum and approaches zero.

As can be seen in Figures 20 and 21, we have a large field increase at the beginning and end of the network. In the soil state diagram, the increase in fields after the beginning and end of the post is close together, and their value is low, but in the soil and rock state, the increase is greater. For example, at a 90-meter distance in soil mode, the field is 5000 v/m, but in soil and rock conditions, it reaches 26000 v/m. At the next peak in the soil state, the field value is approximately 5000 v/m, but in the soil and rock state, the value is reduced to 7000 v/m. This means that in the case of soil and rock, the difference in the electric field is much greater and more dangerous. The most dangerous points are the beginning and the end of the post, where we have a very high field increase. Table 5 examines the step potential of both homogeneous and non-homogeneous states.

As can be seen in Figures 22 and 23, the electric field in the first diagram increases abruptly to 3 meters and then decreases with a very slight slope. In the second diagram, the electric field increases up to 3 meters and decreases with a slight slope. However, within 6 meters of the rock layer, the electric field makes a sharp drop, as can be seen in the diagram, and then drops with a slight slope. As we know, the voltage and the electric field are directly related, so the maximum voltage difference falls within 6 meters of the rock layer, making it the most dangerous spot. According to the graphs, the influence of the rock layer on the grid patterns and the step and surface voltage values are clearly visible.

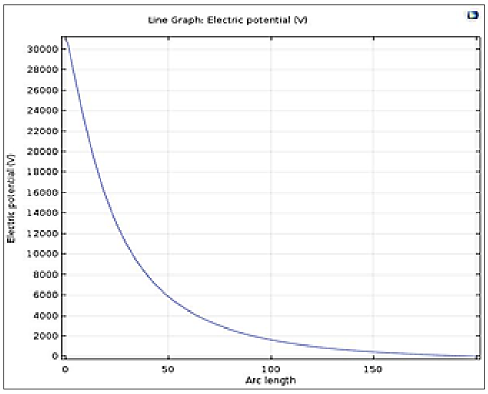

Figure 18. **Electric potential diagram of soil state**

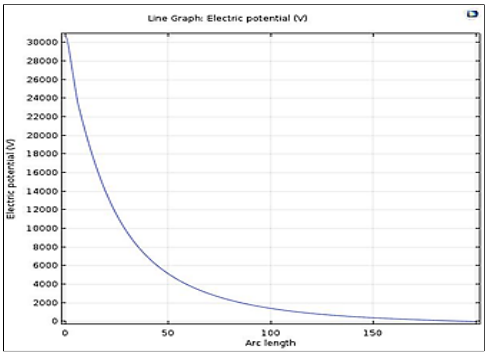

Figure 19. **Electric potential diagram of rock state**

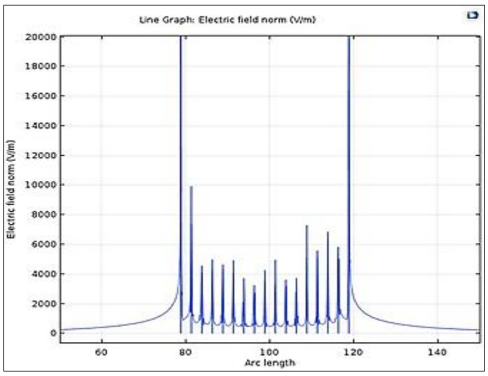

Figure 20. **Electric field norm diagram of soil state**

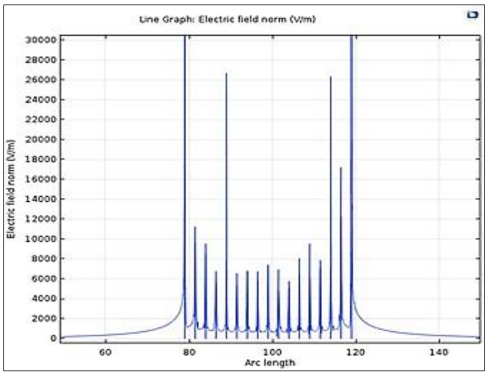

Figure 21. **Electric field norm diagram of rock state**

Table 5. Comparison of step potential in two homogeneous and non-homogeneous states

	Internal edge of the grid (v)	external edge of the grid (v)	Grid Center (v)
Monolayers	60000	61000	500
double layer	76700	78450	700
Percentage of change	%27.83	%28.6	%40

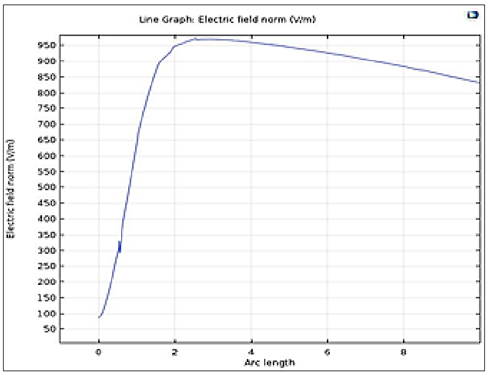

Figure 22. Electric field norm diagram of soil state

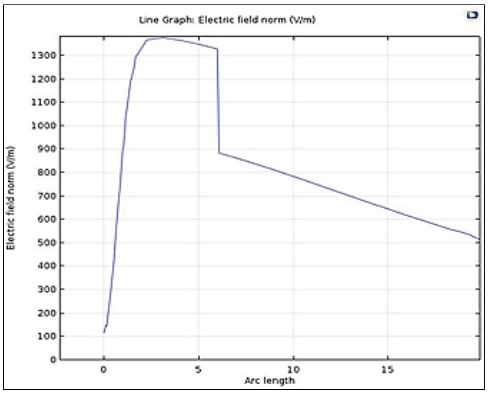

Figure 23. Electric field norm diagram of rock state

5. Comparison

To strengthen the study, we included a comparative analysis of different grounding improvement techniques used in non-homogeneous soils:

Table 6. Comparative analysis

Technique	Advantages	Disadvantages
Traditional Grounding Grid	Simple and cost-effective	Less effective in high-resistivity soils
Deep Grounding Electrodes	Better dissipation of fault currents in rocky soils	Requires deep drilling, increasing costs
Artificial Backfill Materials (e.g., Bentonite, Coke Breeze)	Reduces resistivity, enhancing performance	May degrade over time, requiring replenishment

The results show that deep grounding electrodes and artificial backfill materials are more effective in heterogeneous soil conditions, particularly in areas with rocky sublayers.

6. Sensitivity Analysis

A sensitivity analysis was conducted to evaluate how variations in soil resistivity due to moisture, temperature, and composition impact the performance of the grounding system. The methodology and results are detailed below:

<u>Methodology:</u>

• The simulation was performed using COMSOL Multiphysics version 6.3.0.290 by altering soil resistivity values to represent different environmental conditions.

• Three cases were considered:

1. Dry Soil Condition: Higher resistivity (100 Ω·m)

2. Normal Soil Condition: Base resistivity (50 Ω·m)

3. Wet Soil Condition: Lower resistivity (20 Ω·m)

• The impact on step voltage, touch voltage, and ground potential rise (GPR) was observed.

<u>Results & Discussion:</u>

• Dry Soil Condition: Increased step and touch voltage, higher GPR, and reduced current dissipation capability.

• Normal Soil Condition: Balanced grounding performance with acceptable safety limits.

• Wet Soil Condition: Lower step and touch voltage, improved grounding efficiency, but potential risk of rapid resistivity fluctuations with seasonal changes.

This analysis confirms that soil resistivity significantly affects grounding performance, and careful design considerations should be made for varying environmental conditions.

7. Mesh Selection and Accuracy

• The mesh density was determined through a convergence study, where progressively finer meshes were tested until results stabilized.

• Initial Mesh: Coarse mesh to ensure basic accuracy.

• Refined Mesh: Gradually increase elements in high-gradient areas (e.g., near electrodes) to enhance precision.

• Final Mesh: A trade-off between computational efficiency and result accuracy was achieved when step voltage variation remained below 1% between successive refinements.

• The mesh contained approximately [Extra Fine] elements, optimized for computational efficiency while maintaining solution accuracy.

8. Conclusion

As it was proved, the presence of a rock layer in the high-pressure post ground increased the electrical potential patterns and the electric field, causing the step voltage and contact voltage at the high-pressure post to be high and dangerous for equipment and persons inside the post, because the electric field is sharply reduced by impacting the rock layer; in other words, the presence of a rock layer causes the rock layer to act as an insulator when the leakage current enters the earth, and this current floats on the rock surface. A small amount of this current may come back to the post, which shows itself as electrifying equipment and causing problems for the high-pressure post and staff there. For this reason, it is important to check beforehand that the low-pressure soil is homogeneous or heterogeneous before the earth and the earth system are built. If it was inhomogeneous, first modify the low ground using existing methods to obtain standard specific resistance and important parameters of the low ground, and then build the ground system. The post surface can also be covered with a highly resistant layer such as pebble or asphalt to facilitate the movement of machinery in the post area, increasing the tolerable voltages (step and contact) in the post area. Sites with low rocky ground and low soil depth can be used as semiconductor belts for sleeping ground grids.

9. References

[1] Keller, K. (2010). Electrical Safety Code Manual: A Plain Language Guide to National Electrical Code, OSHA and NFPA 70E. Butterworth-Heinemann, Oxford, United Kingdom. doi:10.1016/C2009-0-20021-3.

[2] Zipse, D. W. (1999). Are the National Electrical Code and the National Electrical Safety Code hazardous to your health? 1999 IEEE Industrial and Commercial Power Systems Technical Conference (Cat. No.99CH36371), 9. doi:10.1109/icps.1999.787239.

[3] Ackerman, A., Sen, P. K., & Oertli, C. (2013). Designing Safe and Reliable Grounding in AC Substations With Poor Soil Resistivity: An Interpretation of IEEE Std. 80. IEEE Transactions on Industry Applications, 49(4), 1883–1889. doi:10.1109/tia.2013.2256092.

[4] 80-2013. (2013). IEEE Guide for Safety in AC Substation Grounding. doi:10.1109/IEEESTD.2015.7109078

[5] Ma, J., Dawalibi, F. P., & Southey, R. D. (2002). Effects of the changes in IEEE std. 80 on the design and analysis of power system grounding. Proceedings. International Conference on Power System Technology, 2, 974–979. https://doi.org/10.1109/icpst.2002.1047544.

[6] 81-2012. (2012). IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Grounding System. doi:10.1109/IEEESTD.2012.6392181.

[7] Sullivan, J. A. (2002). Evaluation of mesh and touch voltage at substations. IEE Proceedings: Generation, Transmission and Distribution, *149*(2), 201–209. doi:10.1049/ip-gtd:20020078.

[8] Permal, N., Osman, M., Ariffin, A. M., & Ab Kadir, M. Z. A. (2021). The impact of substation grounding grid design parameters in non-homogenous soil to the grid safety threshold parameters. IEEE Access, *9*, 37497–37509. doi:10.1109/ACCESS.2021.3063018.

[9] Kosztaluk, R., R, D., & Gervais, Y. (1984). Field Measurements Of Touch And Step Voltages. IEEE Transactions on Power Apparatus and Systems, PAS-103(11), 3286–3294. doi:10.1109/tpas.1984.318571.

[10] Babikir Adam, E. E., & Sathesh. (2021). Survey on Medical Imaging of Electrical Impedance Tomography (EIT) by Variable Current Pattern Methods. Journal of ISMAC, 3(2), 82–95. doi:10.36548/jismac.2021.2.002.

[11] Sverak, J. G. (1998). Progress in step and touch voltage equations of ANSI/IEEE Std 80 - Historical perspective. IEEE Transactions on Power Delivery, *13*(3), 762–767. doi:10.1109/61.686972.

[12] Gil, H. J., Kim, H. K., & Kill, G. S. (2010). Study of touch and step voltages with grounding grid using electrolytic tank and analysis program. International Journal of Safety, 9(2), 1-5.

[13] Vycital, V., Ptacek, M., Topolanek, D., & Toman, P. (2019). On minimisation of earthing system touch voltages. Energies, *12*(20), 3838. doi:10.3390/en12203838.

[14] Cooray, V., Cooray, C., & Andrews, C. J. (2007). Lightning caused injuries in humans. Journal of Electrostatics, *65*(5-6 SPEC. ISS.), 386–394. doi:10.1016/j.elstat.2006.09.016.

[15] Sverak, J., Dick, W., Dodds, T., & Heppe, R. (2007). Safe Substation Grounding-Part I. IEEE Transactions on Power Apparatus and Systems, *PAS-100*(9), 4281–4290. doi:10.1109/tpas.1981.316934.