



Comparative Evaluation of Ground Resistance Measurement Techniques and FEM-Based Modeling under Grounding Electrode Configurations

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Abstract: Accurate estimation of ground resistance is essential for designing safe and reliable electrical grounding systems. This study investigates the performance of four representative electrode configurations—single rod, two parallel rods, three rods in a linear arrangement, and three rods in a delta arrangement—by combining experimental measurements with numerical modeling. The ground resistance values were measured using the 3-pole Fall-of-Potential (FOP) method and the 4-pole Wenner method and compared with results simulated via the Finite Element Method (FEM) implemented in the COMSOL Multiphysics Program. The analytical solutions were set under homogeneous soil conditions at the test site. The soil resistivity was first determined experimentally to establish the boundary conditions for the FEM model. The numerical model's accuracy was confirmed by simulation results that closely matched field measurements, with a relative error of less than 3%. Moreover, the results revealed that increasing the number of grounding rods effectively reduces total earth resistance. However, the reduction is nonlinear due to mutual coupling between the adjacent electrodes. The delta configuration provided the lowest resistance, followed by the three-rod linear arrangement. Overall, the study demonstrates that FEM analysis achieves high accuracy in predicting ground resistance under uniform soil conditions. The integration of numerical and experimental approaches supports the development of cost-effective and technically robust grounding designs for high-voltage and power distribution systems.

Keywords: Ground resistance; soil resistivity; electrode configuration; finite element method (FEM); grounding system design

1. Introduction

The design and performance of grounding systems are critical for the safe and reliable operation of electrical power networks, high-voltage installations, and communication infrastructures, etc [1]. Measuring ground resistance is important for ensuring safety and efficiency in electrical systems. The effectiveness of such systems is strongly influenced by two key factors, soil resistivity and electrode configuration, which vary widely with soil type, moisture content, temperature, and compaction. The measurement generally uses an earth tester with two main methods: the fall-of-potential method [2, 3],

which requires driving 3-4 metal rods into the ground, and the 4-pole Wenner method, which measures soil resistivity using four probes in a straight line, equally spaced. Although both techniques are widely applied in grounding studies, these serve distinct and complementary purposes in system design [4]. Numerous standards, such as IEEE Std. 81 [5], provide guidelines and analytical formulations for evaluating earth resistance under steady-state conditions.

However, in practical applications, especially under diverse soil conditions and complex electrode arrangements, grounding system behavior often deviates from simple theoretical assumptions. Previous studies have highlighted the limitations of analytical models when applied to heterogeneous soils and non-traditional electrode geometries [6-8]. For instance, investigations on ground resistance with copper-clad steel demonstrated significant variations in measured ground resistance depending on soil characteristics and electrode arrangements. Similarly, finite element method (FEM) simulations have been employed to evaluate the potential distribution and resistance of multiple vertical rods, showing close agreement with analytical solutions for homogeneous soil while offering improved accuracy for electrode arrangement models [9, 10]. Despite extensive research, comparative studies that systematically evaluate different electrode configurations using both measured methods and numerical FEM simulations remain limited [11, 12].

This paper examines the electrical performance of 4 practical grounding-electrode configurations: a single vertical rod, two rods connected in parallel, three rods arranged linearly, and three rods arranged in a triangular (delta) layout. The ground resistance of each configuration was determined through field measurements using both the three-pole fall-of-potential (FOP) and the four-pole Wenner techniques [13]. The experimental findings were then compared with numerical results from a finite-element analysis carried out in COMSOL Multiphysics. Linking field measurements to FEM simulations provides clearer insight into how electrode geometry influences earth resistance under realistic soil conditions, thereby supporting more efficient and reliable grounding-system design.

2. Methods

2.1 Theoretical Approach

The theoretical basis for grounding resistance is derived from classical electromagnetic field theory and soil resistivity models. For a uniform soil model, the steady-state ground resistance with improved agreement observed in refined formulations can be approximated by the Dwight-Sunde approximation [2, 3]:

$$R = \frac{\rho}{2\pi L} \left[\ln \left(\frac{8L}{d} \right) \right] - 1. \quad (1)$$

Where R is ground resistance (Ω), ρ is the soil resistivity ($\Omega \cdot m$), L is the electrode length (m), and d is the electrode diameter (m). This expression assumes homogeneous soil and neglects surface effects. In multi-rod systems, the mutual resistance effect is accounted for by potential superposition [14]. This theoretical framework supports the observed nonlinear reduction in resistance with increasing electrode count, which is further validated by FEM simulation results showing that mutual coupling reduces effectiveness. For soil resistivity, it was measured and calculated using the Wenner four-pin method as expressed:

$$\rho = 2\pi a R_E. \quad (2)$$

Where ρ is soil resistivity ($\Omega \cdot m$), a is the distance between pins (m), and R is the resistance value measured by the instrument (Ω). This model approximates realistic soil conditions and serves as a reference for validating both numerical simulations and field tests.

2.2 Experimental Measurement

Field measurements were conducted to validate the theoretical and simulation results. A Fluke 1625 earth ground tester was employed using the fall-of-potential (FOP) method, according to Fluke Manual [15]. In this method, the test electrode under study is energized, while two auxiliary probes are placed in line at predetermined distances. The potential probe measures the voltage drop at varying distances, while the current probe provides a stable reference current, as shown in Figure 1.

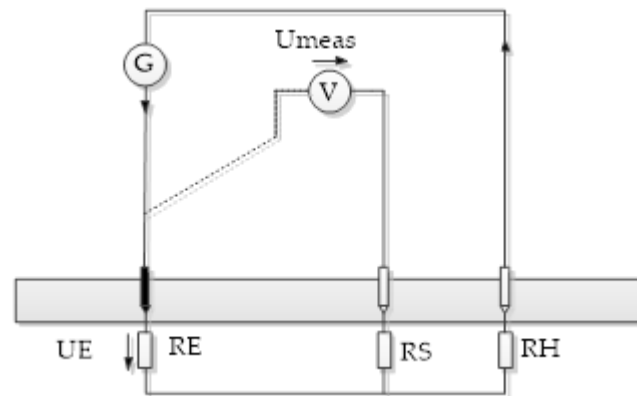


Figure 1. Earth electrode with auxiliary probes

For each grounding configuration, multiple measurements were performed by repositioning the potential probe to generate resistance–distance curves. The ground resistance was measured approximately 62% along the distance between the test electrode and the current investigation, in accordance with the 62% rule. To minimize errors due to soil inhomogeneity, measurements for all configurations were carried out on the same day under similar environmental conditions. Under the FOP testing, the high-performance ground tool and the IEEE standard. 81, the results are extremely reliable, highly accurate, and give complete control over the setup. In this measurement, the current probe is placed >20 m away from the earth electrode under test. An example of 3 straight grounding system configurations is shown in Figure 2.



Figure 2. Three-core copper-clad steel straight earth resistance measurement

Figure 3 shows the 4-pin configuration for measuring soil resistivity. The 4-pole Wenner method was used to measure soil specificity according to the Fluke 1625-2 Earth/Ground Tester manual [3]. Four equidistant probes are inserted into the soil on a straight line as shown in Figure 4. Then the current terminals (C1 and C2) of the advanced earth testing meter, Fluke 1625, are connected to the two outer probes, and the potential-probing terminals (P1 and P2) are connected to the two inner probes. The measurements R had been averaged from a 90-degree perpendicular axis 4-pole method. Then, the soil resistivity was calculated from the measured resistance using Equation 2.

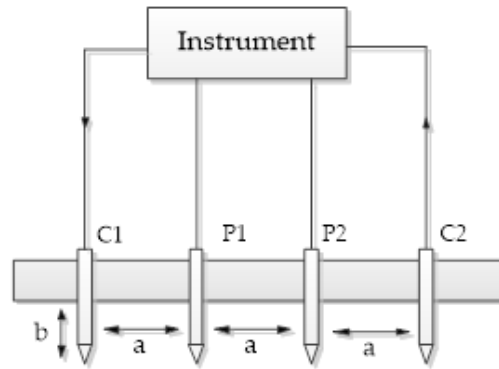


Figure 3. Connection diagram of the four-pole method.



Figure 4. Wenner four-pin method for soil resistance measurement.

2.3 Simulation approach

The grounding systems were examined through finite element modeling using COMSOL Multiphysics. In the simulation setup, the soil region was created as a large cylindrical volume in both radius and depth to ensure that the computed electric field was unaffected by the domain boundaries. Copper-clad steel rods representing the electrodes were positioned vertically and buried about 2.4 m below the ground surface, under conditions consistent with practical installation standards. The outer boundary of the soil model was set with a Neumann boundary condition, assuming zero normal current density ($\partial V/\partial n = 0$), which represents the absence of current flow across the air–soil interface, as depicted in Figure 5.

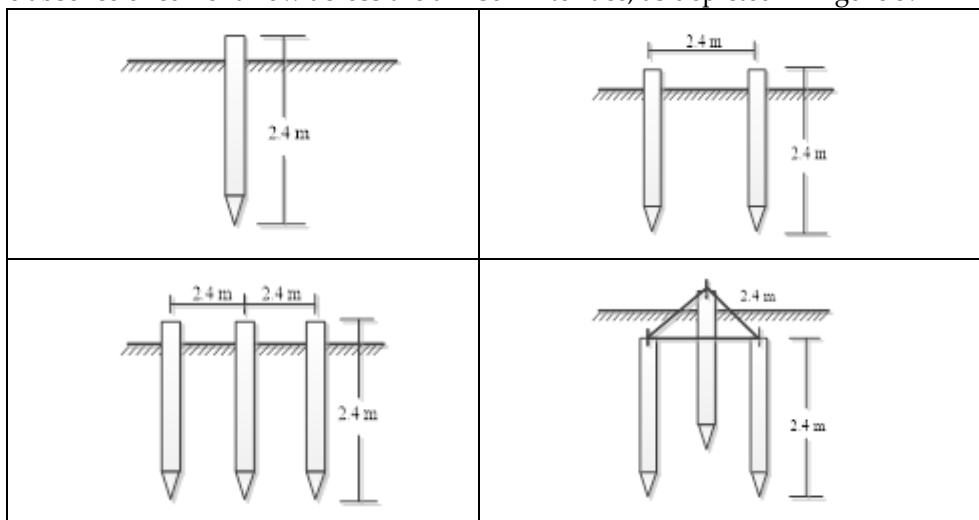


Figure 5. Copper Clad Steel Ground Rod Dia 5/8 X2.4 m at different arrangements.

Then, mesh refinement, as shown in Figures 6 and 7, was applied around the electrode surfaces to ensure numerical accuracy. Several electrode configurations were analyzed, including single-rod, 2 parallel rods, 3 straight ground rods, and 3 triangular arrangements, to examine the effects of electrode geometry and surface area on ground resistance.

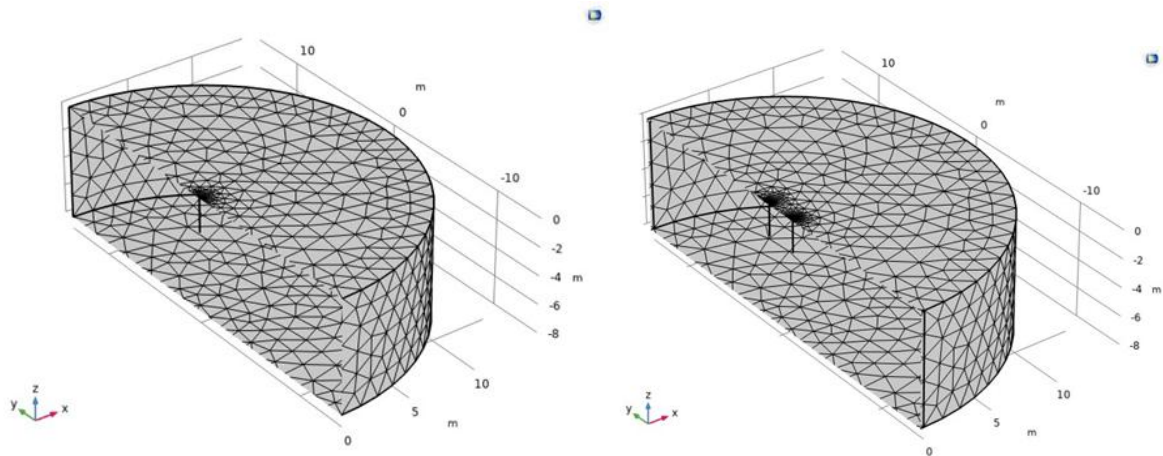


Figure 6. The mesh settings for 1 and 2 rods at the yz-plan cut section.

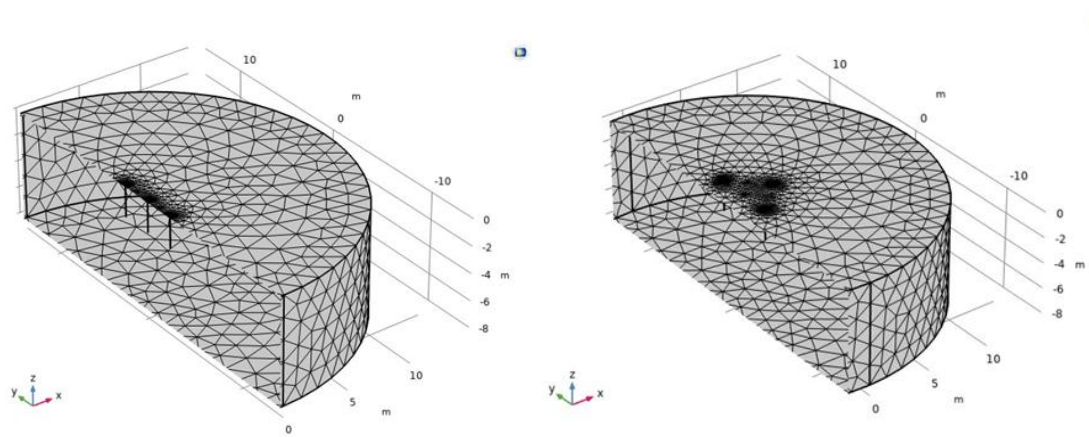


Figure 7. The mesh settings for 3 straight and 3 triangular rods at the yz-plane cut section.

The program parameters are listed in Table 1. The parameters included the precise dimensions of the copper-clad ground rod. The measured soil resistivity, calculated from equation 2, was $0.027 \Omega \cdot \text{m}$. The rod was set as the current source at 0.005 A and energized at 111 Hz , as per the Fluke 1625-2 manual. The soil domain was defined as a cylindrical volume extending 3 times the rod length deeper. The electrical current nodes within the AC/DC module and the frequency domain were used in the computation.

Table 1. Parameters setting for all electrode arrangements.

Parameters	Value
Rod diameter	0.008 [m]
Soil cylinder	$Z=-10-0 \text{ [m]}$
ρ_s	$0.027 \text{ }[\Omega \cdot \text{m}]$
I_{in}	0.005 [A]
f	111 [Hz]
Ground rod	rods 1,2,3-straight,3-delta

3. Results and Discussion

3.1 Simulation results

The 3D model was built in COMSOL Multiphysics, approximately following the same geometry as in the measurement methods. The vertical ground rod, 2.4 meters long with a 0.008 m radius, was plotted in a cylindrical volume.

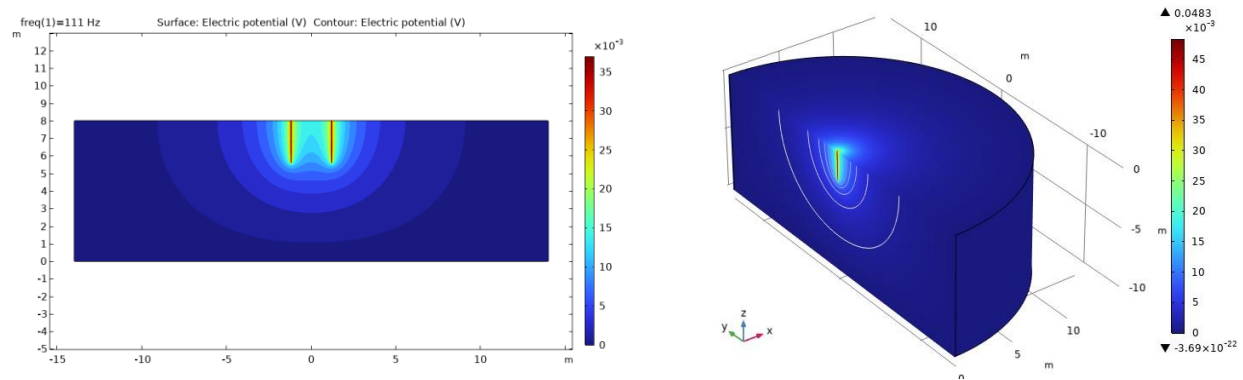


Figure 8. Simulation of electric field distribution (left) and electric field norm (right) for 1 ground rod

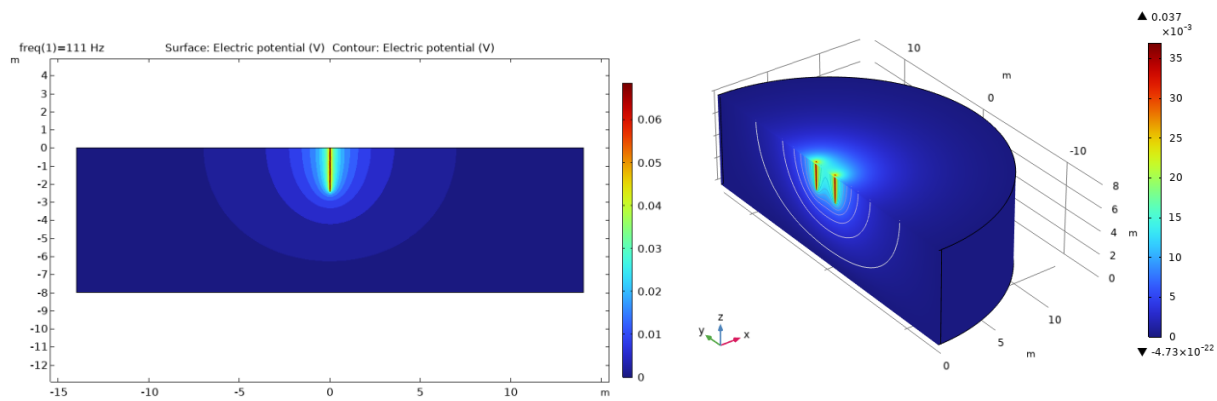


Figure 9. Simulation of electric field distribution (left) and electric field norm (right) for 2 ground rods.

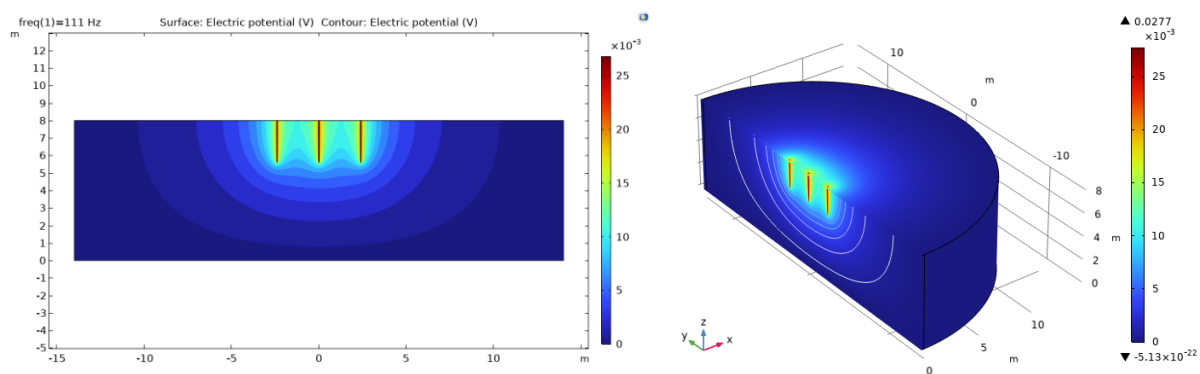


Figure 10. Simulation of electric field distribution (left) and electric field norm (right) for 3 straight ground rods.

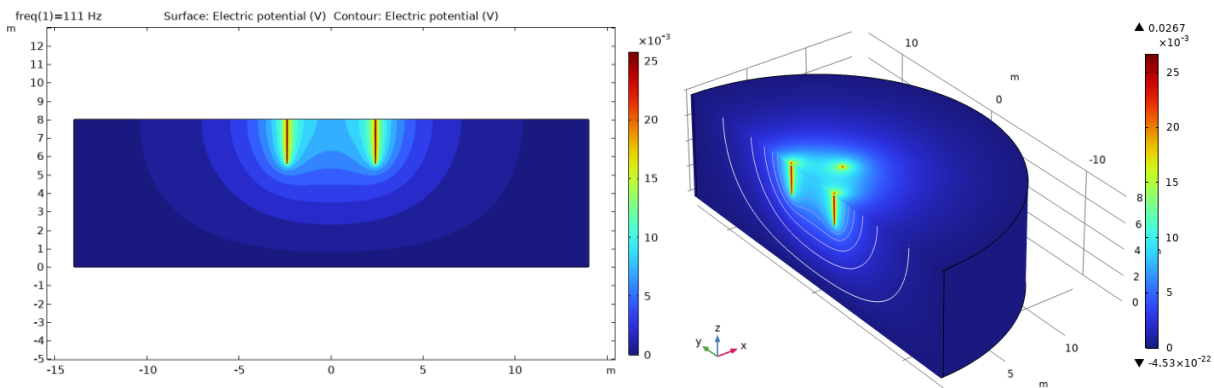


Figure 11. Simulation of electric field distribution (left) and electric field norm (right) for 3-delta ground rods.

The electrode geometry and the cut plane ($x=0$) were set along the center, the 2D potential and the 3D electric field norm are shown in Figures 8-11. The results obtained by simulating the distribution of voltage scattering in the approximate homogeneous ground are plotted. Given the different ground rod arrangement, there is clearly good dissipation. The potential gradient at the ground surface decreased with increasing number of electrodes, suggesting enhanced grounding performance and reduced surface voltage stress. Therefore, the number of ground rods and the rod arrangement are affected by the computed values. The comparison of ground resistance results between measurement and simulation is shown in Table 2. The results have good agreement in terms of the error percentage.

Table 2. Comparison table of ground rod resistance values from measurement and simulation.

Ground rod number	Measurement (Ω)	Simulation (Ω)	%Error
1	13.6	13.58	0.14
2	7.2	7.39	2.57
3-straight	5.71	5.62	1.57
3-delta	5.3	5.40	1.85

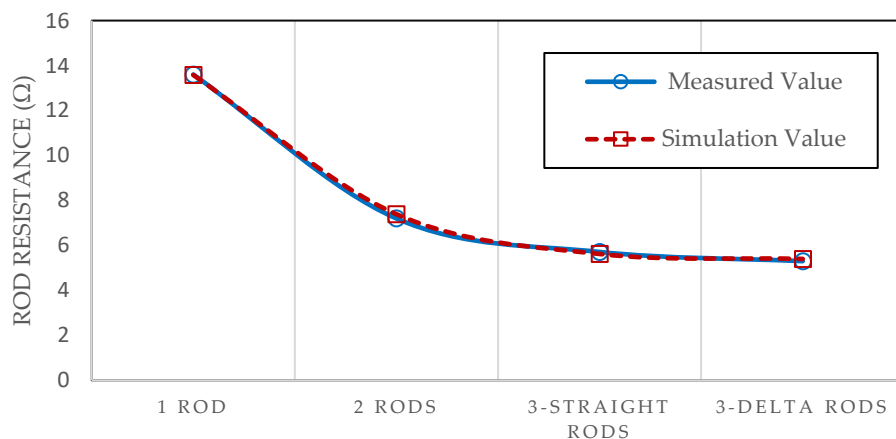


Figure 12. Resistance of ground rod for various arrangements.

Figure 12 shows the ground-rod resistance graph for various arrangements, evaluated both analytically and by measurement and by the FEM method. The outcomes derived from the simulation approach closely resemble the analytical results. The relative error was lower than 3%, which is very small and consistent within the experimental uncertainty range. Although all configurations show good agreement between measurement and simulation, the magnitude of the error varies across configurations. The two-rod

configuration exhibits the highest deviation (2.57%), which may be attributed to the influence of mutual resistance between electrodes and the limitations of the 62% rule under closely spaced conditions. In contrast, the single-rod configuration shows the lowest deviation, as it is less affected by interaction effects and more closely matches the assumptions of the analytical and numerical models.

4. Conclusions

This study conducted a comparative analysis of four grounding electrode configurations—single rod, two parallel rods, three rods in a linear arrangement, and three rods in a delta arrangement—assessed through field measurements and Finite Element Method (FEM) simulations. The experimental results from the 3-pole Fall-of-Potential (FOP) and 4-pole Wenner methods closely aligned with the FEM-based computations conducted in COMSOL Multiphysics. The difference between the simulation and the measurement was less than 3%, indicating that FEM is a reliable tool for predicting the design of a grounding system. The results show that adding more grounding rods greatly lowers the overall earth resistance. However, the rate of reduction is not linear because of the effects of mutual coupling between the rods. The effect of mutual coupling can be quantified by comparing the measured resistance with the ideal independent case. For the two-rod configuration, the theoretical value is 6.8Ω ($13.6/2$), while the measured value is 7.2Ω , corresponding to an efficiency loss of about 5.9% due to mutual resistance between electrodes. The three-rod delta arrangement had the lowest resistance of all the tested geometries, followed by the three-rod linear configuration, due to its larger average electrode spacing, which reduces mutual coupling and improves current dispersion. This shows how important electrode geometry is for current dissipation. The electric-field distributions from the simulation showed that multi-rod systems exhibit greater potential gradients, making grounding more effective. The results also suggest that multi-rod configurations improve grounding safety by reducing potential gradients and minimizing step and touch voltage risks. These results show that combining numerical FEM modeling with experimental methods is an effective approach for analyzing and improving grounding systems under practical conditions. However, the present findings are limited to homogeneous soil conditions, and the results may differ in multi-layer or high-resistivity soils. Future studies should focus on extending the analysis to multi-layer and non-uniform soil conditions. As well as evaluating the impacts of electrode spacing and depth optimization, and of transient phenomena such as lightning-induced currents, to expand the applicability of the suggested approach.

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