

Optimization of Ground Resistance and Cost for Vertical and Horizontal GEM-encased Rods Buried in Homogeneous Soil

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Abstract— Grounding systems are fundamental components of protection systems for electrical systems and equipment, with a top priority assigned to their economic design. The ground resistance of ground-enhancement-material (GEM)-encased vertical and horizontal rods buried in a uniform soil is calculated based on the current sphere simulation technique (CSST). A relationship between ground resistance and the associated cost of rod installation is formulated to form an objective function for optimizing the ground resistance. For a vertical rod of 1.44 m in length and 16 mm in diameter, encased by GEM shell with diameter of 0.2 m and length of 1.5 m, the calculated ground resistance is 102% of that obtained by COMSOL. For a horizontal rod with the same dimensions, buried at a depth of 0.6 m, the optimal ground resistance is 108.6% of that of the vertical rod. However, the cost for the horizontal rod is almost 70% of that of the vertical rod at the optimal solution.

Keywords—current sphere simulation technique (CSST), ground enhancement material, optimization, multilayer, vertical and horizontal rods

I. INTRODUCTION

The precise analysis of various grounding system configurations is fundamental to the design of safe and cost-effective grounding systems. Proper design is a critical factor in electrical systems due to its role in protecting equipment and preventing failures in the electrical network, thereby ensuring operational continuity and enhancing safety for personnel around such equipment. Irregular and multi-layered configurations pose challenges that researchers continuously strive to address through the development of more accurate analytical methods. Additionally, studies on materials added to the soil, such as ground enhancement material (GEM), aim to improve soil resistivity and examine their impact on grounding system performance, including the calculation of the optimal amount of these materials to achieve maximum economic efficiency. This

contributes to the design of grounding systems that achieve the highest possible levels of economic efficiency with maximum safety.

Several literature reviews have been presented that focus on providing analytical methods for various electrical systems, particularly multi-layered systems, as well as systems that incorporate soil enhancement materials in their design. Additionally, these reviews explore the optimal cost of electrical systems in relation to achieving the highest possible efficiency.

A new method called the Current Sphere Simulation Technique (CSST) was developed [1] to accurately calculate ground resistance in various soil conditions. The CSST models conductors and rods by spheres, allowing for precise calculations in both homogeneous and two-layer soils. Compared to other methods, the CSST demonstrated high accuracy, with errors below 1%. The current sphere simulation technique was employed [2] to determine ground resistance by simulating the distribution of current within the grid components. A method for calculating the ground resistance of a vertical electrode embedded in homogeneous soil was introduced [3]. The ground resistance of substations buried in vertical-layered soil was assessed [4] using CDEGS software and the fall-of-potential method. The impact of an earthing-enhancing compound on lowering the tower footing resistance of a 500 kV transmission tower in rocky soil was assessed [5] using a commercial software named CDEGS, commonly used for analysis of grounding systems. A rod grounding system was studied [6] using three soil types (sandy, red loamy, and gray loamy) with enhancement materials such as waste-activated carbon, wood ash, and a developed mixture composed of both materials. Different types of enhancement materials were tested [7] and an optimization using a genetic algorithm and fuzzy ranking was used to determine the ideal mixture of material proportions. The CSST-based method was extended [8] to

calculate the ground resistance of a GEM-encased vertical rod buried in uniform soil. Optimization of grounding system designs, balancing both performance and cost using various algorithms like fuzzy algorithms, genetic algorithms, and multi-objective particle swarm optimization were studied [9]. Optimized substation grounding grid designs using a Genetic Algorithm. IEEE 80-2013 guidelines were applied [10], and a cost function was developed based on factors such as the number of conductors, burial depth, and rod length. MATLAB software was used for analysis to conclude that increasing the number of conductors and ground rods improved grid resistance and safety. Optimizing the switchyard grounding system by adjusting the grid dimensions and ground rod length was studied [11] based on IEEE Std 80-2000 guidelines and MATLAB-GUI for simulations.

To the authors' knowledge, the present paper introduces for the first time a calculation method to evaluate the effect of encasing GEM around grounding rod on reducing the ground resistance. Available in the literature empirical equation [7], [12] are for evaluating the ground resistance R_g with the use of GEM around rods, along with the use of a commercial packages such as ERICO [12]. This expresses the novelty of the present paper.

The paper organized as follows: Section (II) presents the proposed methodology based on the current sphere simulation technique for calculating the ground resistance of a GEM-encased rod buried either vertically or horizontally in a uniform soil. This is in addition to optimization of the rod grounding resistance and installation-cost using Pareto front algorithm. Section (III) is devoted to report the obtained results and their discussion. Section (IV) is to list the main conclusions of the present work.

II. METHODOLOGY

A. The current sphere simulation technique

The proposed methodology aims at evaluating the ground resistance of a GEM-encased rod buried either vertically or horizontally in homogeneous soil and stressed by an applied voltage V_{app} . Based on the CSST [1], the rod of length L_r is simulated by spheres along its axis with sphere diameter equal to the rod diameter d_r . The interface between the encasing GEM and the surrounding soil was simulated by two sets of spheres, one in the GEM side and the other in the soil side as shown in Figs. 1 and 2 for vertical and horizontal rods. The spheres in the GEM and soil sides have diameter D_1 . The diameter and length of the GEM shell around the rod are D_G and L_G , respectively as shown in Figs 1 and 2. Images of the simulation sphere are considered with respect to the soil surface.

The unknown simulation sphere currents are determined by satisfying the following boundary conditions [8] :

1. Dirichlet boundary condition for the equality of calculated rod potential V_{rod} to the applied voltage.

$$V_{rod} = V_{app} \quad (1)$$

2. Continuity of calculated potential at the GEM-soil interface.

$$V_{GEM} = V_{soil} \quad (2)$$

3. Continuity of calculated normal current density at the GEM-soil interface.

$$\sigma_{GEM} E_{n,GEM} = \sigma_{soil} E_{n,soil} \quad (3)$$

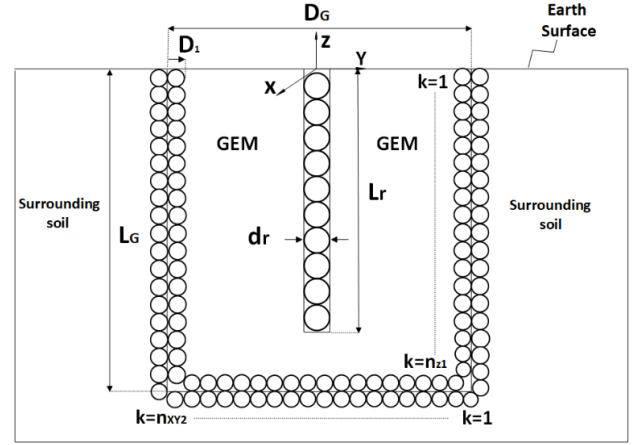


Fig. 1. Vertical view of the vertical rod encased by GEM with its spheres distribution

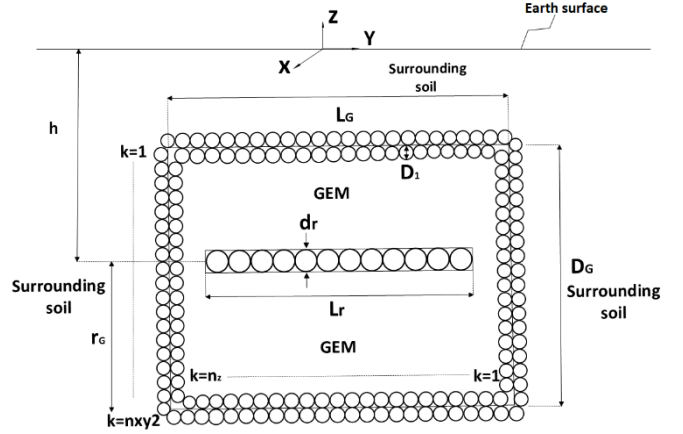


Fig. 2. Horizontal view of the horizontal rod encased by GEM with its spheres distribution.

where V_{GEM} and V_{soil} represent the calculated potential at the GEM-soil interface when seen from the GEM and soil sides, respectively, σ_{GEM} and σ_{soil} represent the GEM and soil conductivity values, respectively, $E_{n,GEM}$ and $E_{n,soil}$ represent the calculated normal electric field at the GEM-soil interface when seen from the GEM and soil sides, respectively.

Equations (1), (2), and (3) are satisfied at boundary points on the rod surface and the GEM-soil interface to form a matrix of $(N_t \times N_t)$ elements, where N_t represent the total number of spheres simulating the buried GEM-encased rod in soil as expressed by equations (4):

$$N_t = N_r + N_{GEM} + N_{soil} \quad (4)$$

where N_r is the number of spheres simulating the rod, N_{GEM} and N_{soil} are the number of simulation spheres of the GEM and soil sides, respectively.

The unknown currents associated with each sphere can be determined by solving the arranged matrix using MATLAB code. The total current flowing through the grounding rod is the sum of the currents conducted by the rod spheres. Consequently, ground resistance is calculated by dividing the applied voltage by the total current.

B. Optimization of Ground Resistance and Cost

Given that the economic factor is pivotal in any project and that designers always aim to achieve the highest possible efficiency at the lowest cost, The study examines the relationship between

the cost of excavation to create the required space for burying the grounding rod to encase it in GEM along with the cost of the rod itself and the cost of the surrounding GEM material, and the resulting ground resistance.

To simplify the study, the length of the GEM burial L_G was kept constant, while the excavation diameter D_G was varied to represent changes in the amount of the used GEM and the volume of required excavation.

It is worth to mention that the excavation extends along the z-direction for a distance $r_G + h$, where h is the depth of the GEM-encased rod from the earth surface and r_G is radius of the GEM shell around the rod as shown in Fig. 2.

To obtain the optimal size of the GEM (represented by the diameter D_G while keeping its length constant) that results in the lowest possible ground resistance at the lowest possible cost, the Multi-Objective Genetic Algorithm method was employed [13] after being supported by the Pareto front [14]. This approach enables the calculation of the utopia point, which determines the optimal diameter of the GEM shell to ensure the lowest cost for the minimum achievable ground resistance.

Minimization of a multi-objective function f_{obj} is aimed at minimizing simultaneously of two functions; the ground resistance function f_{R_g} and the cost function f_{cost} , so the target is to search for minimization of the multi-objective function

$$\text{minimize } f_{obj}(f_{R_g}, f_{cost}) \quad (5)$$

Subject to the following constrain

$$D_{G,min} \leq D_G \leq D_{G,max} \quad (6)$$

where $D_{G,min}$, $D_{G,max}$ are the minimum and maximum depths.

The function f_{R_g} expresses the dependency of the calculated R_g of the rod on the diameter D_G of the GEM encasing shell.

The cost depends on two parameters, the cost of used GEM, which is decided by the diameter D_G of the GEM shell and excavation cost. Thus, the cost function (f_{cost}) includes the following components.

$$f_{cost} = C_{GEM} + C_{exc} \quad (7)$$

$$C_{GEM} = c_G \times Vol_G, \quad C_{exc} = c_e \times Vol_{exc}$$

where C_{GEM} , C_{exc} are the costs of the GEM and excavation, respectively. The cost rates c_G , c_e are for GEM and excavation; Vol_G is the total volume of GEM; Vol_{exc} is the volume accommodating the rod, GEM and the soil above the GEM layer up to the ground surface.

To verify that the obtained cost values are optimal, the authors analyzed the Pareto front curves generated during the optimization process where all solutions are optimal, and the utopia point indicates the best optimal solution among those solutions. The total cost is that predicted from the Pareto front curve and that of the copper rod itself.

III. RESULTS AND DISCUSSIONS

Taking the average cost of excavation at 25 USD per cubic meter of soil [15]. Thus, the cost in USD of excavating the pit containing the rod-encasing GEM is equal to the volume of the pit multiplied by 25. The price of the copper rod of length 1.5m is 18.5 USD. The GEM price is 3,760 USD per cubic meter.

Table II presents the specifications of the investigated GEM-encased rod buried in soil either horizontally or vertically.

To verify the effectiveness of the proposed method, simulations of the above-described grounding rod were conducted using COMSOL software.

For vertical rod, the complete COMSOL mesh consists of 1,038,620 domain elements and 30,032 boundary elements against 469,800 domain elements and 22,242 boundary elements for the horizontal rod.

A. The vertical GEM-encased rod

Table III shows the calculated values of the current injected from the vertical rod into the soil through the surrounding GEM shell and the ground resistance R_g using both the proposed method and COMSOL software. Additionally, the ground resistance was calculated using approximate equations reported before [7], [12].

The results in Table III indicate that the differences between the resistance values calculated using the proposed method, compared to COMSOL and the approximate equations in [7], [12], are 1.72%, 27.17%, and 37.95%, respectively.

B. The horizontal GEM-encased rod

Table IV shows the calculated values of horizontal rod current and the ground resistance R_g using both the proposed method and COMSOL software. The ground resistance is also calculated using the approximate equation [12].

Table IV results indicate that the differences between the resistance values calculated using the proposed method, compared to COMSOL and the approximate equation in [12], are 3.04% and 5.56%, respectively.

It is worthy to mention that the ground resistance on using GEM is reduced from 64.44 Ω to 27.27 Ω for the vertical rod and from 63.14 Ω to 26.25 Ω for the horizontal rod.

The calculated resistance value for the horizontal rod is less than that for the vertical rod. This represents an advantage to the side of the horizontal rod. On the other hand, the horizontal rod is buried at a depth of 0.6 meters to make its installation cost higher compared to the vertical rod. However, the calculated resistance of the horizontal rod is less than that of vertical rod.

Fig. 3 shows the per-unit current distribution along the length of the horizontal and vertical rods. The current in the vertical rod increases gradually along the length toward its end. The current in the horizontal rod increases gradually toward the rod ends. The increase of the current toward the end of the rod either buried horizontally or vertically was attributed to the mutual effect among the simulation current spheres [1].

C. Optimization of ground resistance and cost

The diameter of the encasing GEM is assumed to lie in the range $D_{G,min} = 0.076 \text{ m}$ to $D_{G,max} = 1 \text{ m}$, where $D_{G,min}$ is the diameter of a simulated sphere and $D_{G,max}$ is selected value taking into account the high price of GEM and the depth of the GEM-encased rod.

Figs. 4 and 5 illustrate the Pareto curves for the vertical and horizontal rods, respectively along with the location of the utopia point on each curve. For the vertical rod, the utopia point is located at a diameter of 0.4 m with a ground resistance of 18.15 Ω and cost of 850.1 USD. For the horizontal rod, the utopia point is at a diameter of 0.331 m, a ground resistance of 19.71 Ω , and cost of 594.16 USD.

TABLE II. SPECIFICATIONS OF THE GEM-ENCASED ROD TO BE ANALYZED USING THE PROPOSED METHOD.

Rod length (L_r)	1.44 m
Rod diameter (d_r)	0.016 m
GEM pit length (L_G)	1.5 m
GEM pit diameter (D_G)	0.2 m
Horizontal rod depth (h)	0.6 m
GEM resistivity (ρ_{GEM})	2 $\Omega \cdot m$ [6]
Soil resistivity (ρ_{soil})	100 $\Omega \cdot m$
Applied voltage (V)	100 V

TABLE III: COMPARISON OF CURRENT FLOW AND GROUND RESISTANCE FOR VERTICAL ROD ENCASED WITH GEM

	Current (A)	Resistance R_g (Ω)
Proposed method	3.66	27.27
COMSOL	3.73	26.8
Approximate eq. [7]	-	34.68
Approximate eq. [12]	-	37.62

TABLE IV: COMPARISON OF CURRENT FLOW AND GROUND RESISTANCE FOR HORIZONTAL ROD ENCASED WITH GEM

	Current (A)	Resistance R_g (Ω)
Proposed method	3.81	26.25
COMSOL	3.63	27.05
Approximate eq. [12]	-	24.79

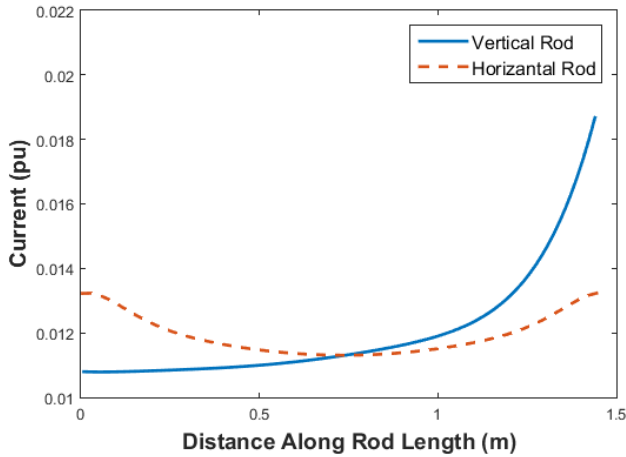


Fig. 3. Per-unit current distribution along the rod length for the vertical and horizontal rods.

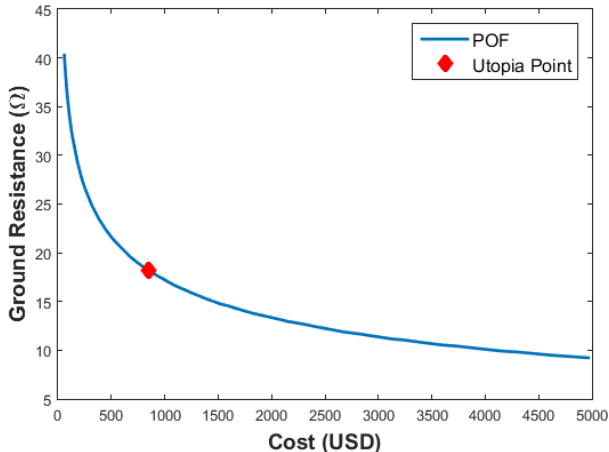


Fig. 4. Ground resistance-cost Pareto curve with utopia point for the vertical GEM-encased rod.

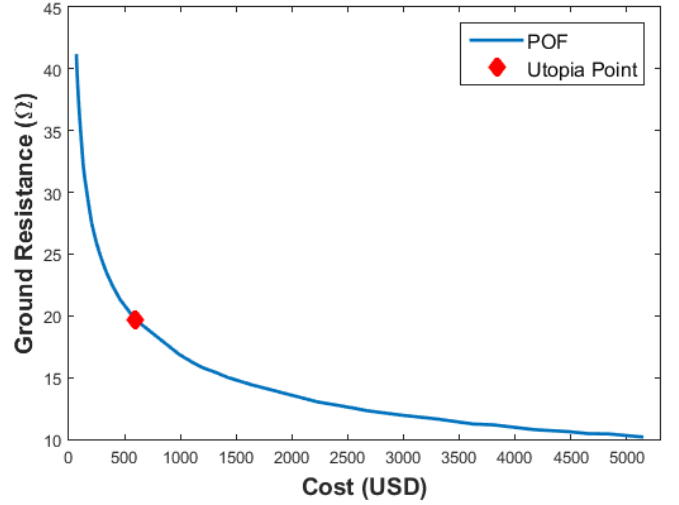


Fig. 5. Ground resistance-cost Pareto curve with utopia point for the horizontal GEM-encased rod.

The results show that the optimized ground resistance of the vertical rod is 92% of that for the horizontal rod. However, the cost of the vertical rod is 143% of that for the horizontal rod.

IV. CONCLUSION

The numerical method based on the Current Sphere Simulation Technique (CSST) discussed before in detail in [8] is applied to GEM-encased vertical and horizontal rods buried in uniform soil. The calculated results are compared with those obtained from the COMSOL software and other approximate equations presented before [7], [12].

To achieve cost-efficiency in the design of grounding systems, an optimization of the ground resistance value against the cost was performed by varying the diameter of the GEM shell within a range of 0.076m to 1 m. A Pareto curve is then plotted, showing the relationship between ground resistance and cost.

The results show that the optimal GEM diameter is 0.4 m for the vertical rod against 0.331m for the horizontal rod. The corresponding optimal ground resistance is 18.15 Ω for the vertical rod against 19.71 Ω for the horizontal rod. The corresponding optimal cost values are 850.1 USD for the GEM-encased vertical rod and 594.1 USD for the GEM-encased horizontal rod.

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