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Influence of Electrode Spacing on Grounding Resistances in Electrical Networks for Effective Lightning Protection

Anedi Oko Ganongo*, Rodolphe Gomba, Nianga-Apila, Linné Lovel Atsembou Obita, Branham Jacques Lévi Makanga, Mathurin Gogom, Gilbert Ganga

Polytechnic Superior National School, Marien Ngouabi University, Brazzaville, Congo

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Abstract

This study aims to analyze the influence of inter-electrode spacing on grounding resistance in high-voltage transmission networks. A simplified analytical model is applied to a case study on the Djiri-Ngo 220 kV line (Republic of the Congo), considering two representative soil types: clayey and siliceous sand. The grounding resistance is calculated by varying the number of electrodes and their spacing. The results show that increasing electrode spacing reduces grounding resistance. In certain configurations, the improvement exceeding 50 % when the spacing is increased from 5 m to 25 m. A saturation threshold is identified, beyond which further increases in spacing yields diminishing returns. Electrode spacing proves to be a key design factor, sometimes more influential than the number of electrodes. The proposed parametric geometric analysis offers a practical and cost-effective strategy for grounding system design, emphasizing the importance of adapting configurations to local geotechnical conditions.

Keywords: electrode spacing, grounding resistance, lightning protection, soil resistivity, transmission line safety

1. Introduction

Electrical power networks, despite robustly designed and operated, remain vulnerable to disturbances that affect their performance and reliability. Among these, lightning strikes represent one of the most severe natural threats [1-2]. Due to their high-energy transient nature, lightning events can cause equipment damage, service interruptions, and widespread outages [3-5]. Given the increasing dependence of modern societies on uninterrupted power supply, improving protection strategies against lightning is both a technical and economic priority [6-7]. Conventional protective devices, such as spark gaps, overhead ground wires, and surge arresters, are widely used to mitigate lightning effects. However, the effectiveness depends critically on the quality of the grounding system. A low grounding resistance ensures efficient dissipation of lightning currents into the soil, thereby reducing the risk of insulation breakdown and equipment failure [8-9].

Research on grounding system design and performance improvement has evolved along two main directions: geometric parameters and material selection. Several authors have investigated geometric approaches, with [10-11] proposing design methods based on electrode length and radius relative to soil resistivity, finding that increasing electrode length can significantly reduce resistance. Concurrently, material selection is recognized as crucial for long-term performance, especially in tropical environments [12]. The use of locally available materials, such as charcoal has been recommended to enhance conductivity while reducing costs [13].

* Corresponding author. E-mail address: okoanedi@gmail.com

Recent investigations have further explored comparative configuration analysis and advanced material characterization. It has been demonstrated that vertical electrode arrangements generally provide lower grounding resistance than horizontal configurations in layered soil conditions [14]. Complementary studies enhancement materials under impulse conditions reported reduction exceeding 40% in steady-state resistance [15].

More recently, researchers have introduced a proportionality factor to model low-resistivity backfill materials, demonstrating improved system performance through electrode addition and material enhancement [16]. The impact of transient phenomena, such as lightning surges on power systems, is also extensively studied, further reinforcing the importance of grounding system design [17-18].

However, a critical research gap persists. Recent studies have demonstrated the superiority of vertical electrode arrangements and achieved significant resistance reduction using enhancement materials [14-15]. Their focus has primarily been on configuration type and material composition. These studies often assume a fixed or non-optimized spatial layout. Approaches based on electrode addition and material enhancement are well-established [10, 16]. Thus, the strategic adjustment of the inter-electrode spacing as a simple, cost-free, and highly effective parameter remains underexplored.

The purpose of this research is to address this gap through a parametric geometric analysis focusing on the distance between vertical electrodes. It aims to demonstrate that spacing is a key, and sometimes dominant, parameter in minimizing grounding resistance, thereby offering a simple and cost-effective design strategy. This approach is evaluated within the framework of international safety standards (e.g., IEEE Std 80, IEC 60364-5-54), which stipulate that grounding resistance should typically not exceed 10 Ω in electrical networks [13,19].

2. Methodology and Modeling

This section presents the theoretical framework and modeling approach used to analyze the behavior of grounding systems under lightning conditions. It first describes the propagation of lightning waves along transmission lines and the role of protective devices such as spark gaps. It then introduces analytical expressions employed to calculate the grounding resistance for single and multiple electrode configurations, taking into account soil properties and geometric parameters.

2.1. Lightning wave propagation

Fig. 1 illustrates a segment of an overhead transmission line equipped with two spark gaps installed at towers 2 and 3. These spark gaps provide a low-resistance path to the earth during transient overvoltages, such as those caused by lightning strikes.

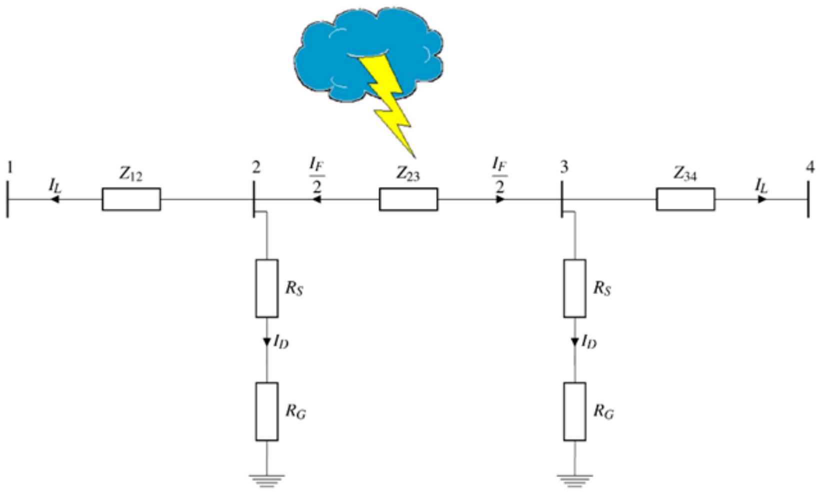

Fig. 1 220 kV transmission line segment with spark gaps and current division during a lightning strike

Under normal operating conditions, the line remains at nominal voltage, and the spark gaps, having a very high resistance ($R_S = \propto$), do not conduct current. When a lightning strike occurs, the resulting current pulse ($I_P/2$) propagates along the line in both directions. Near the impact point, the sudden overvoltage causes nearby spark gaps to activate, diverting part of the lightning current (I_D) to the ground, while the remainder (I_L) continues along the conductor.

To ensure system protection and operational continuity during such events, the grounding resistance (R_G) must be kept as low as possible, allowing the maximum share of lightning current to safely discharge into the earth. Minimizing this resistance requires careful consideration of soil electrical properties, which vary by region [17-18].

While this study focuses on the steady-state grounding resistance, it is important to briefly consider the system's transient behavior during lightning events. Modeling transient behavior is challenging; for instance, Muhammad et al. [20] demonstrated the influence of impulse generator characteristics on the measured response, and Abdullah et al. [21] developed non-linear equivalent circuits to capture effects such as soil ionization. Even though these phenomena fall beyond the scope of the present steady-state model, they underscore the importance of transient considerations in grounding system design.

In high-resistivity soils, the current may not spread effectively, leading to elevated potential gradients near the electrode surfaces. Moreover, electrode spacing can influence not only the steady-state resistance but also the transient impedance profile. However, these dynamic effects are not captured by the present low-frequency/DC model. A full characterization would require frequency-dependent or time-domain modeling, as discussed in the future work section.

2.2. Analysis and reduction of grounding system resistances

The design of an effective grounding system requires accurate prediction of its electrical resistance. This section presents the analytical framework used to model both single and multiple electrode configurations, forming the basis for the subsequent geometric optimization study. For a single vertical electrode of length (l) and radius (r) in homogeneous soil of resistivity (ρ), the self-resistance can be estimated using Dwight's formula [13, 15, 17]:

$$R_1 = \frac{\rho}{2\pi l}\left(\ln\frac{4l}{r} - 1\right) \tag{1}$$

While Dwight's formula is widely adopted, alternative formulations—such as Rudenberg's and Liew-Darveniza's—yield comparable results under similar assumptions of uniform soil resistivity, perfectly vertical electrodes, and negligible capacitive or inductive effects. These expressions establish the fundamental relationship among electrode geometry, soil properties, and grounding resistance.

Rudenberg's formula:

$$R_1 = \frac{\rho}{2\pi l}\left(\ln\frac{4l}{d}\right) \tag{2}$$

where d is the electrode diameter. This expression omits the correction term "- 1" used in Dwight's formula, which can slightly underestimate the resistance for shorter electrodes.

Liew-Darveniza formula:

$$R_1 = \frac{\rho}{2\pi l}\left(\ln\frac{r+l}{r}\right) \tag{3}$$

This expression offers an alternative geometric approximation for estimating the grounding resistance for a single vertical electrode. Based on the electrode length (l) and radius (r).

When the grounding resistance of a single vertical electrode remains too high due to the soil resistivity, a commonly adopted mitigation method consists of encasing the electrode with a low-resistivity backfill material, such as charcoal. The resistance of such a single vertical electrode embedded in homogeneous soil and surrounded by low-resistivity material can be estimated using the Fegan-Lee analytical expression:

$$R_m = \frac{1}{2\pi l}\left\{\rho_m \ln\left(\frac{r_m}{r}\right) + \rho\left[\ln\left(\frac{4l}{r_m}\right) - 1\right]\right\} \tag{4}$$

Recent experimental studies [22] have quantified that enhancement materials can reduce steady-state resistance by over 40% and significantly improve performance under lightning impulse conditions. In tropical environments, charcoal is frequently used due to its low cost and effective conductivity [10, 13, 15].

Grounding resistance is also reduced by increasing the electrode length or diameter, or by enlarging the hole intended for the low resistivity material [13, 15-16, 19]. In cases where a single electrode does not provide sufficiently low resistance, multiple vertical electrodes are installed.

In the absence of enhancement materials, and assuming uniform soil conditions, the equivalent resistance for *n* identical vertical electrodes arranged linearly with regular spacing *D* (where $D > l$) can be approximated by [17]:

$$R_n \approx \frac{1}{n}\left\{\frac{\rho}{2\pi l}\left(\ln\frac{4l}{r} - 1\right) + \frac{\rho}{\pi D}\left(\frac{1}{2} + \cdots + \frac{1}{n}\right)\right\} \tag{5}$$

where:

R_m : Resistance of single electrode with low-resistivity backfill material [Ω]

R_n : Equivalent resistance of n vertical electrodes in linear configuration [Ω]

ρ : Soil resistivity [Ω·m]

ρ_m : Backfill material resistivity [Ω·m]

l : Electrode length [m]

r : Electrode radius [m]

D : Inter-electrode spacing [m]

r_m : Radius of backfill cavity [m]

For a set of *n* identical vertical electrodes embedded in homogeneous soil with resistivity ρ, the total resistance is not simply the parallel combination of *n* independent electrodes. In reality, the potential zones surrounding each electrode overlap, which leads to mutual coupling effects. These interactions contribute to an increase in the overall system resistance. To account for this mutual influence, an analytical approximation of the equivalent resistance can be derived by including the contributions of interactions starting from the second electrode. This leads to the following expression:

$$R_n \approx \frac{1}{n}\left\{\frac{\rho}{2\pi l}\left(\ln\frac{4l}{r} - 1\right) + \frac{\rho}{\pi D}\sum_{k=2}^{n}\frac{1}{k}\right\} \tag{6}$$

This expression represents a practical variant of Eq. (5), in which the summation term is rewritten explicitly to facilitate implementation. By starting the sum from $k = 2$, the formulation avoids counting the self-resistance of the first electrode twice, which is already accounted for in the first term. This version is therefore better suited for numerical evaluation and comparative analysis.

In this equation, the first term corresponds to the ideal case of n independent electrodes in parallel, representing the resistance if no coupling exists between them. The second term introduces a correction due to mutual interaction, which accounts for the physical overlap of potential zones in the soil. This corrective term decreases as the spacing D increases, meaning that electrodes become electrically more independent when farther apart. As a result, the total resistance approaches the ideal parallel value when the spacing is sufficiently large.

As $D \to \propto$, the electrodes become electrically independent, and the equivalent resistance tends towards that of n parallel-connected electrodes:

$$\lim_{D \to \infty} R_n = \frac{R_1}{n} \tag{7}$$

This theoretical behavior confirms that increasing the spacing between electrodes effectively reduces grounding resistance, up to a threshold beyond which the performance gain becomes negligible.

However, as the literature does not provide an explicit formula to calculate the resistance of a grounding system consisting of multiple electrodes in a straight line, each surrounded by a low-resistivity material, Eq. (5) is applied in this study by considering the electrode radius r equal to the radius of the backfill cavity r_m. This approach models the geometric effect of the low-resistivity material, increasing the effective electrode radius, but it does not explicitly account for the electrical property (resistivity, ρ_m) of the backfill material itself. Consequently, for a given cavity radius ρ, this simplification yields the same resistance estimate regardless of the specific backfill material used, provided the geometric enhancement is identical. For designs where the electrical properties of the enhancement material are critical, more detailed models or numerical simulations incorporating ρ_m would be required.

3. Simulations and Results

To evaluate the practical effectiveness of the proposed parametric analysis, simulations are conducted on the Djiri-Ngo transmission line, part of the Congolese 220 kV network and previously studied in [15]. This 208 km line crosses two main types of soil: clayey sand and siliceous sand, which represent contrasting geotechnical conditions along the route. The nominal voltage of the line is 220 kV. The line's electrical parameters are as follows:

Linear capacitance: 9.033 *nF/km*

Linear resistance: 0.057 Ω*/km*

Linear reactance: 0.404 Ω*/km*

Tower reactance: 8.2 mΩ

For each soil type, the grounding system is initially modeled using a single vertical electrode surrounded by charcoal, applying the Fegan-Lee analytical expression (Eq. (4)). As this configuration does not produce sufficiently low resistance values, the number of electrodes is gradually increased up to 20, while maintaining the same electrode and backfill configuration. Since no closed-form expression is available for calculating the resistance of a multi-electrode system with each electrode individually surrounded by low-resistivity material, the approximation given by Eq. (5) is adopted.

The influence of inter-electrode distance on the total grounding resistance is examined by testing spacings of 5, 15, 20, and 25 meters. These values span a realistic range of installation constraints, from relatively compact to widely spaced configurations.

Resistance curves shown in Figs. 2 and 3 are plotted for each configuration. The parameters used in the calculations are summarized below:

Charcoal resistivity ρ_m =10 Ω·m

Clayey sand resistivity ρ =275 Ω·m

Siliceous sand resistivity ρ=1600 Ω·m

Hole radius r_m =1 m

Electrode length l =5 m

Electrode radius r =6 cm

Inter-electrode spacing (D): 5 m, 15 m, 20 m and 25 m

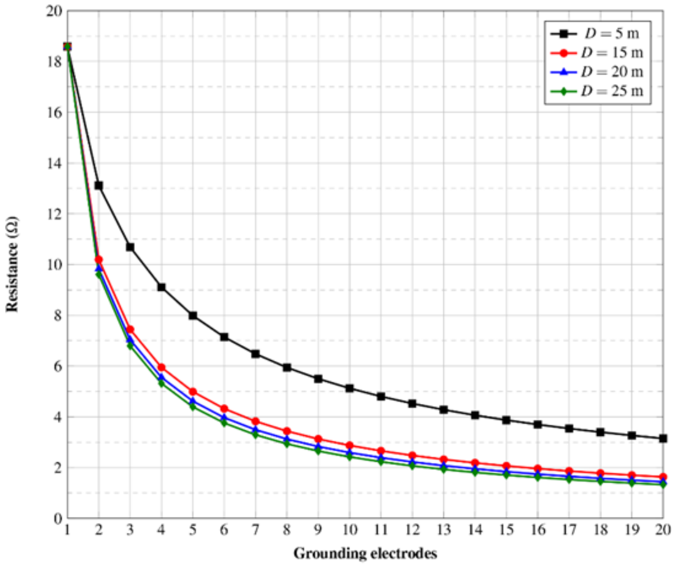

Fig. 2 Grounding resistances for clayey sand

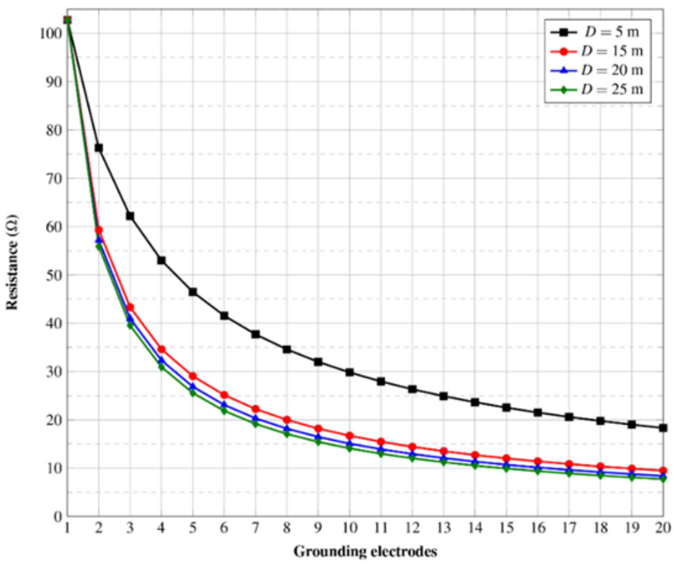

Fig. 3 Grounding resistances for siliceous sand

To highlight the improvement achieved by the proposed strategy, Tables 1 and 2 present a comparative summary of grounding resistance values for both soil types. The values are compared for the same number of electrodes but with varying spacing distances. The relative improvement is calculated with respect to the configuration having the smallest spacing (D = 5 m).

Table 1 Grounding resistances in clayey sand under different configurations

Electrodes number	Spacing (D)	Grounding resistance	Relative improvement
5	5 m	7.9874 Ω	–
5	15 m	4.9918 Ω	37.50 %
5	20 m	3.1235 Ω	42.19 %
5	25 m	2.9356 Ω	45.00 %
20	5 m	3.1474 Ω	–
20	15 m	1.6315 Ω	48.16 %
20	20 m	1.442 Ω	54.18 %
20	25 m	1.3283 Ω	57.79 %

Table 2 Grounding resistances in siliceous sand under different configurations

Electrodes number	Spacing (D)	Grounding resistance	Relative improvement
5	5 m	46.4722 Ω	–
5	15 m	29.043 Ω	37.5 %
5	20 m	26.8643 Ω	42.19 %
5	25 m	25.5571 Ω	45.00 %
20	5 m	18.3123 Ω	–
20	15 m	9.4922 Ω	48.16 %
20	20 m	8.3896 Ω	54.18 %
20	25 m	7.7281 Ω	57.79 %

4. Discussion

The analysis confirms that inter-electrode spacing is a decisive design parameter, at least as influential as the number of electrodes. For instance, in clayey sand, increasing the spacing from 5 m to 25 m for five electrodes reduced the resistance from 7.99 Ω to 2.94 Ω, representing a 45% improvement. Increasing spacing reduces mutual interference, allowing each electrode to dissipate current into a larger soil volume and improving utilization of the soil’s conductive capacity. However, spacing must be balanced with practical constraints such as land availability, installation complexity, and layout geometry.

Figs. 2 and 3 further illustrate that increasing the number of electrodes reduces grounding resistance, validating the classical principle that additional parallel paths enhance current dissipation. Notably, the benefit of adding electrodes diminishes when spacing is already large, indicating a geometric saturation effect. The optimal configuration is highly dependent on soil type, reflecting local geotechnical properties such as resistivity, moisture content, and mineral composition. Site-specific adaptation is therefore essential to ensure both effectiveness and cost-efficiency.

Beyond technical performance, the economic implications of geometric optimization are significant. For clayey soil, increasing the spacing from 5 m to 20 m (with three electrodes) reduces resistance from approximately 10.7 Ω to 7.0 Ω, a result comparable to adding three more electrodes at 5 m spacing (yielding 7.1 Ω). However, the associated costs differ substantially. Spacing adjustment primarily requires extending the trench length and the horizontal copper conductor, typically resulting in only marginal increases in material and labor costs. In contrast, adding electrodes incurs additional expenses related to electrode materials, backfill (e.g., charcoal), drilling, and installation. This comparison highlights that spacing adjustment is economically advantageous when land constraints permit.

While this study emphasizes geometric optimization through spacing, other parameters also influence grounding resistance. As highlighted by [10], electrode dimensions and backfill radius cavity are significant factors. Material enhancement approaches [22] offer complementary benefits, with reported reductions exceeding 40% in steady-state resistance under impulse conditions. Increasing the effective soil–electrode contact area improves conduction, suggesting that a multidimensional design strategy integrating geometric and material considerations yields optimal results.

The present analysis assumes steady-state resistance and homogeneous soil, which simplifies real field conditions. Transient effects from lightning, soil stratification, and imperfect installation are not modeled. Experimental studies [20] have shown that impulse generator characteristics significantly influence the measured transient response, while advanced non-linear models [21] demonstrate the notable influence of inductive and capacitive effects. These findings highlight the complexity of accurately characterizing lightning behavior in grounding systems. Nevertheless, the presented analytical approach remains valid for comparative studies and preliminary design, especially in contexts where detailed simulation tools are unavailable.

This observation is consistent with recent CDEGS simulations [23], which show that ground potential rise stabilizes beyond certain remote earth dimensions, suggesting fundamental geometric limitations in grounding system design. The proposed strategy is particularly suitable for tropical and developing regions, where cost constraints may limit the use of enhancement materials or advanced numerical modeling. The method offers a practical solution that requires no additional material and can be applied to retrofit or design grounding systems based on site constraints. Moreover, identifying the saturation point beyond which increasing distance yields negligible improvement prevents unnecessary layout expansion and cost.

Although not modeled in this study, numerical methods such as the finite element method (FEM), boundary element method (BEM), and method of moments (MoM) have been widely applied to simulate complex soil interactions, layered media, and transient phenomena [16]. These approaches yield more detailed results but often typically require significant computational resources and accurate soil characterization. In contrast, the present analytical formulation offers a simple yet physically grounded tool that engineers can apply in early-stage planning or feasibility assessments [2, 15].

5. Conclusion

This study developed and applied a parametric geometric analysis to evaluate the influence of inter-electrode spacing on grounding resistance in high-voltage transmission lines. The model was evaluated through a case study of the Djiri-Ngo 220 kV line in the Republic of the Congo, considering both clayey and siliceous sand.

The main conclusions of this work can be summarized as follows:

(1) The inter-electrode spacing (D) is a critical parameter. Increasing the spacing from 5 m to 25 m reduced the overall grounding resistance by over 50 % for a fixed number of electrodes, a level of improvement comparable to, and in some cases exceeding, those obtained by increasing the number of electrodes.

(2) A saturation effect was observed, whereby the marginal benefit of increasing the spacing diminishes beyond a certain threshold (observed around 20-25 m in this study). This finding supports the importance of balancing electrical performance with land-use and economic constraints.

(3) The proposed geometric optimization provides a highly cost-effective strategy, as it does not require additional enhancement materials. This makes it particularly suitable for resource-constrained environments where the use of low-resistivity backfilling may be economically constrained.

(4) Grounding system performance and the most effective configuration are strongly dependent on local soil resistivity. This underscores the necessity of site-specific adaptation rather than applying a one-size-fits-all design.

While the model is based on steady-state analysis and homogeneous soil assumptions, it offers a practical tool for preliminary design and planning. Future work will focus on incorporating transient lightning analysis, non-homogeneous soil models, and experimental validation to further enhance the model's robustness and applicability.

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Conflicts of Interest

The authors declare no conflict of interest.

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