Reduction of a Cone-Shaped Terrain Grounding Resistance by Remote Grounding

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***Abstract*— Tall structures such as wind turbines and mobile phone base stations are often installed in remote and hilly locations to gain more power or to have line of sight to end users. Those locations are usually very rocky and characterized by a low-conductivity soil. Moreover, these locations have a higher risk of being struck by lightning due to the geographical elevation and the height of the structure. A proper grounding with low resistance of such structure is of high importance. Recent studies showed that the grounding resistance of structures located on the top of mountains can be significantly higher than the grounding resistance of the same structure located on a flat ground. One of the practical methods to decrease the low frequency grounding impedance in a soil of high resistivity is to provide remote grounding to an area of lower soil resistivity, typically located at lower altitudes. In this paper, for the first time we analyze the influence of remote grounding considering a simplified cone-shaped geometry for an elevated terrain. It is shown that the remote grounding can be used to mitigate the increased resistance at the mountaintops.**

Keywords—Lightning; grounding resistance; hilly; elevated; irregular terrain; non-flat; vertical rod; FEM; remote grounding

I. INTRODUCTION

Tall structures are often installed in remote and hilly locations. For instance, wind turbines can be placed on mountains to obtain unobstructed access to wind and, thus, to have more power. Mobile phone base stations can also be installed on hills to improve line of sight to the end users (see Fig. 1). Tall structures on hills or mountains are more likely to be struck by downward lightning due to the geographical elevation [1,2] and the size of the tall structures themselves [3,4]. Additionally, tall structures have been observed to initiate upward lightning discharges [5]. The probability of incidence can be further increased for the case of wind turbines, presumably due to the removal of corona charge by the rotation of the blades [6].

These hilly areas are usually very rocky with low soil conductivity (0.001 S/m and lower), making the design of proper grounding a challenging task. The influence of a non-flat ground on the grounding resistance of structures was recently analyzed in [7]. It was shown [7,8] that the grounding resistance of structures located on the top of mountains can be significantly higher than the grounding resistance of the same structure located on a flat ground.

In the present study, we analyze one of the methods used to decrease the grounding resistance in a soil of high resistivity, which consists of providing a remote grounding to an area of lower soil resistivity, typically located at lower altitudes. The analysis is done for the case of a DC excitation and it is valid for a low frequency analysis of the grounding system. In order to get the full response of the grounding system (ground potential rise), one should obtain the impedance as a function of frequency. The impedance can either have inductive or capacitive behavior. For the case of the vertical rod this depends on the ratio of soil conductivity and length of the rod (see fig. 7 in [9]). In the cases of low conductivity soil (which is the main concern in this study), the vertical rod has capacitive behavior for the case of the rods up to several tens of meters. In most of the real cases the length will be below that value. In these cases, time domain response of the grounding system is governed by its low frequency response, since the impedance tends to decrease at higher frequency, and so does the energy spectrum of lightning. For such low conductivity soils, the response of the system is well represented by the resistance.

The aim of this paper is to investigate the use of a remote grounding to reduce the grounding resistance of structures located in hilly and low conductivity regions. If the structure of interest that needs to be properly grounded is located in an area of poor soil conductivity, one can provide a grounding path to a nearby area with more favorable conditions, either using overhead wires or buried cables [10,11]. For example, the Säntis telecommunication tower located on the top of Mount Säntis is grounded at its base, and also connected to a remote grounding via the cable car [10]. A buried wire would provide additional reduction of the resistance but it would be more expensive to install. It should be noted that this would only provide the reduction on the low frequency impedance of the system. Due to the inductance of the remote grounding cable [12,13], this influence at higher frequencies would be negligible. Proper grounding should be therefore designed as a combination of the grounding at the location of the structure (to reduce the high frequency response), and a remote grounding (to reduce the low frequency response), while minimizing the cost. In this paper we analyze only the DC resistance, which usually corresponds to the impedance up to about few tens of kHz.

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The paper is organized in the following order. The computational method is presented in Section II. In Section III, three different case studies are discussed. First, for the sake of completeness, we present the analytical solution for a vertical grounding electrode in a flat ground (II.A) as well as the worst-case scenario results from [8] for the case of a grounding at the tip of a cone-shaped mountain (II.B). We will also discuss the more realistic case of a vertical grounding rod located at the tip of a truncated cone-shaped mountain and we will analyze the reduction of the resistance with the use of a remote grounding along the mountain (II.C). Finally, in the third case, we will evaluate the influence of an inhomogeneous three-layer ground (II.D). Conclusions are given in Section IV.

a.) b.)

Figure 1. Telecommunication towers at top of the mountain: (a) Säntis Tower (Switzerland) instrumented for lightning measurements [15], (b) Hoher Kasten Tower (Switzerland)

II. COMPUTATIONAL METHOD

The single vertical rod simplified geometry is used here only to illustrate the concept of remote grounding. The grounding systems of either wind turbines (e.g. [14]), or mobile base stations are much more complex since strict standards impose grounding values of less than 10 Ω [16,17].

The low-frequency response of a grounding system is governed by Ohm's law and the current continuity equation. Ohm's law in differential form, also called point form, can be written as:

$$\vec{J} = \sigma \vec{E} \quad (1)$$

where σ is the conductivity of the medium at a given point and $\vec{J}$ is the current density.

The continuity equation in cases where the time derivative of the volume charge density can be neglected, can be written as:

$$\vec{\nabla} \cdot \vec{J} = 0 \quad (2)$$

Using (1) and expressing the electric field in terms of the electric potential for the considered low frequency regime, (2) can be rewritten as

$$-\vec{\nabla} \cdot \left(\sigma \vec{\nabla} \cdot \varphi\right) = 0 \quad (3)$$

In the analysis, the numerical simulations will be carried out using the AC/DC module of COMSOL [17]. In all of the simulations, a current source of 1 A is applied on the top surface of the considered vertical rod. The Dirichlet boundary condition φ = 0 V is set at the bottom of the domain and the Neuman boundary condition $\vec{J}_{normal} = 0$ on the surface of the cone-shaped mountain.

III. VERTICAL GROUNDING ROD

A. *Flat Ground*

The resistance of a vertical grounding rod can be obtained analytically. In case of a flat ground, it is given by [19-21]:

$$R_{flat} = \frac{\rho}{2\pi L}\left(\ln\left(\frac{4L}{a}\right) - 1\right) \quad (1)$$

in which ρ is the resistivity of the ground, L is the length of the grounding rod, and a is the radius of the grounding rod.

B. *Grounding in the Apex of a Cone-shaped Mountain*

The coefficient expressing the increase of the grounding resistance with respect to the flat-ground case in terms of the apex angle of a cone-shaped mountain, derived in [7] for the case of a hemispheric grounding system, is given by:

$$k = \frac{R_{cone}}{R_{flat}} = \frac{1}{(1 - \cos(\varphi))(1 + ctg(\varphi))} \quad (2)$$

This equation is valid for the case of a hemispheric grounding electrode at the tip of a cone-shaped mountain (for the geometry, see Fig 2. in [8]). In [8], it was shown that the same coefficient can be used for the case of a vertical rod as a good approximation. Fig. 2 presents the grounding coefficient (1) as a function of the apex angle. In the same figure, numerical simulations for the case of a vertical rod with different lengths are presented. It can be seen that the analytical formula provides acceptable results for vertical rods.

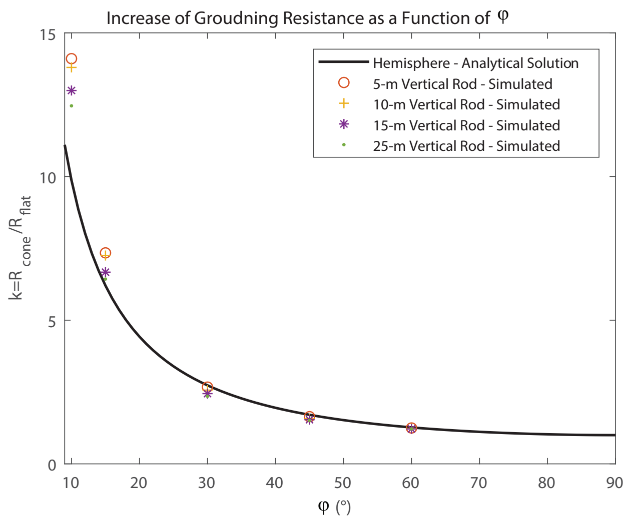

Figure 2. Coefficient of increase of grounding resistance as a function of the apex angle for different geometries. Adapted from [8].

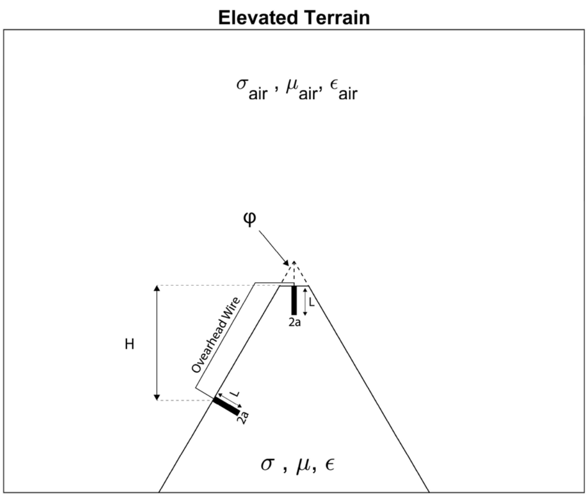

Figure 3. Geometry of problem. Grounding at the top of the cone and remote grounding connected with an overhead wire. Homogeneous soil.

C. Vertical Grounding Rod in a Truncated Cone-Shaped Ground with Remote Grounding

In this subsection, we will consider the geometry shown in Fig. 3. This simplified geometry of soil is used as a first approximation to investigate the influence of a non-flat terrain. Although real-case soil geometry varies from case by case, the considered simplified geometry allows to draw some general conclusions. The analysis is carried out for the case of a 5-m long vertical rod. The apex angle is chosen to be 25° and the top surface radius is 2 m. The soil resistivity is 2000 Ωm. We analyze three different cases: (i) Single grounding at the top of the cone, (ii) remote grounding using an overhead wire, at H=50 m below the top of the cone, and (iii) both groundings together.

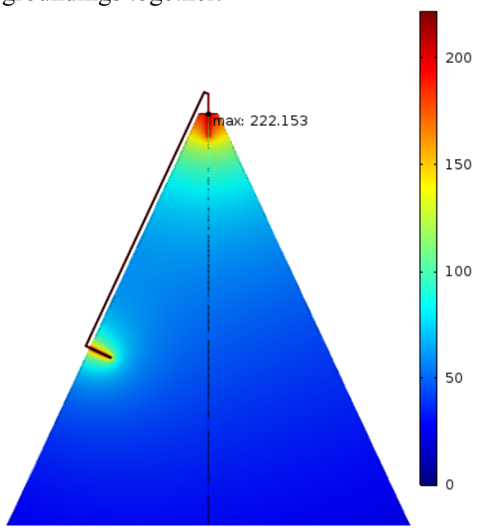

Figure 4. Ground potential rise of the structure excited by a 1-A current source. Homogenous soil.

The potential distribution is shown in Fig 4 for the case of a 1-A current excitation and considering both groundings. Table 1 presents the results for the grounding resistance. We can observe that for the same geometry of a vertical rod at the remote location, the resistance is reduced almost by a factor of 2. It is interesting to observe that this value is close to the value of the grounding resistance of a rod in a flat ground, since we moved to an area of greater effective volume of soil. The grounding resistance of the combined local and remote groundings is 222 Ω, which is very close to the equivalent resistance of the two grounding resistances assumed to be in parallel (201 Ω). This shows that, for the considered case, the coupling between the two groundings is low so that they can be considered, in a first approximation, uncoupled and in parallel. This observation depends of course on the distance between the two groundings, the size of the grounding systems, and the soil resistivity. Typically, as a rule of the thumb, grounding systems can be considered as uncoupled if the distance between them is more than about five times the biggest dimension of the grounding systems [22]. For these distances, a maximum reduction of the grounding impedance will be obtained. For lower distances, the reduction will be smaller due to mutual coupling effects between the two grounding systems.

TABLE 1. Grounding resistance for a homogeneous soil. ρ =2000 Ωm, L=5 m, a=10 cm, φ=25° and R_{flat}=274 Ω (eq. 1)

Grounding Resistance (Ω)		
Grounding at the top only	Remote grounding only	Both groundings
588	305	222

D. Vertical Grounding Rod in a Truncated Cone-Shaped Ground with Remote Grounding in an Inhomogeneous Soil

In this subsection, we evaluate the influence of an inhomogeneous soil with three layers of different ground conductivity. Mountaintops are usually very rocky and characterized by a very low soil conductivity. The conductivity generally increases at lower altitudes. There could also be localized areas of higher conductivity soil. Engineers can take advantage of such situations by selecting the remote grounding at locations characterized by low resistivities. In Fig 5, we present the considered simplified geometry of a three-layer mountain. The considered layers and their resistivities are shown in the figure. The remote grounding is located in the middle of the second layer at an altitude of H=50 m below top of the cone (see fig. 3).

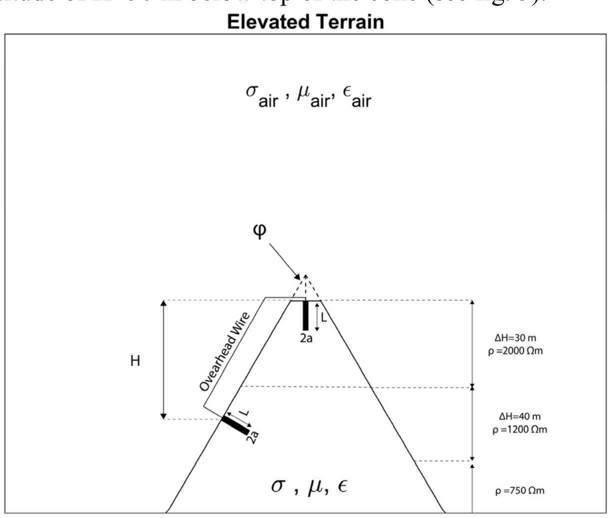

Figure 5. Geometry of the problem. Grounding at the top of the cone and remote grounding connected with an overhead wire. Inhomogeneous soil.

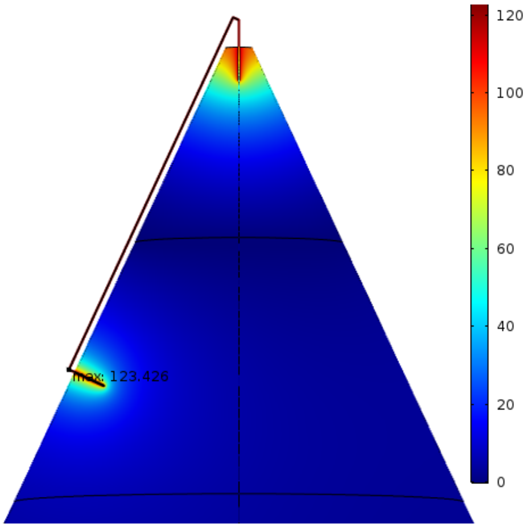

Figure 6. Ground potential rise of the structure excited by a 1-A current source. Three-layer soil.

The potential distribution is shown in Fig 6 for a 1-A current excitation and considering that both groundings are connected with an overhead wire. The value of the remote earth resistance compared to the resistance at the location of the structure is reduced by more than a factor of 3. The resistance of the remote grounding is the same as the one in the case of a flat ground (Eq. 1) with the electrical resistivity of the second layer. This is due to the higher conductivity of the soil in the remote grounding area which results in a more condensed distribution of the ground potential rise around the electrode (compare Figs. 4 and 6). In this case, the two grounding systems are nearly uncoupled and the value of the equivalent parallel resistance of the two grounding resistances is nearly identical to the simulated results.

TABLE 2. Grounding resistance for a three-layer soil. L=5 m, a=10 cm and φ=25°

Resistance (Ω)		
Grounding at the top only	Remote grounding only	Both groundings
502	164	123

IV. Conclusion

We analyzed the influence of a remote grounding to mitigate the increase of the resistance in the case of a structure located at the top of a hill or a mountain. The grounding resistance of such structures is relatively high because of the reduced conducting volume (compared to a flat ground), and also because of the low conductivity soil at mountaintops.

The presented analysis showed that the use of a remote grounding can result in a significant decrease of the grounding resistance. The decrease is essentially due to the increase in the conducting volume of the ground, and the choice of a region with lower ground resistivity as remote grounding.

Even though the analysis is carried out for the case of a vertical rod geometry, the presented analysis can be extended to any grounding geometry. Since the remote grounding wire has a high inductance at higher frequencies, it will not reduce the high frequency response of the grounding. The location of the remote grounding should be selected based on the local soil electrical properties.

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