Computing Tower-Footing Grounding Impedance and GPR curves of Grounding Electrodes Buried in Multilayer Soils

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***Abstract*—Grounding systems are essential to dissipate fault currents into soil to guarantee safe conditions to personnel and equipment. In this context, several approaches have been employed to calculate tower-footing grounding impedance either in the frequency or time domain. In the Transmission Line Model (TLM), vertical or horizontal electrodes are represented by distributed parameters along its length. and its impedance are calculate by analytical equations. However, for counterpoise electrodes there are no analytical formulae to estimate its tower-footing grounding impedance. To tackle this issue, numerical methods have been employed to assess the tower-footing grounding impedance in any various arrangements. In this article, a comparison between the grounding impedance obtained by the TLM and numerical Method of Moments (MoM) is carried out in order to verify the accuracy of the numerical method. Then, grounding impedances of counterpoise electrodes and the Grounding Potential Rising (GPR) are calculated for different configurations of a multi-layer soil. It can be noted that grounding impedance of counterpoise electrodes as well as the peaks of the GPR curves are strongly modified by the presence of multi-layer soil and electrode length.**

***Index Terms*—electromagnetic transients, transmission tower, tower-footing grounding impedance, multi-layer soils**

I. Introduction

Tower-footing grounding system is employed to provide a path for surge currents when a lightning strikes either at the top of transmission towers or at the shield wires, which may cause outages in electric power systems by the backflashover (BF) mechanism. Furthermore, it has to guarantee a safe reduction of the step potential around transmission tower base for protecting personnel who are in the vicinity and equipment [1], [2].

Modeling grounding impedance is fundamental for transient analysis in power systems. In most electromagnetic transient Programs (EMT)-type simulation tools, for the assessment of voltage surges due to lightning strikes, the tower-footing grounding impedance is represented commonly by: (i) a lumped resistor, which is a good approximation at low frequencies (below 100 kHz) [3], [4] or by (ii) a lumped equivalent circuit determined by quasi-static calculations [5].

Some researchers show the influence of ground resistance in the calculation of the overvoltages in transmission towers, where it is verified that the higher the resistance of grounding the greater the voltage surge waves [4], [6], [7]. However, tower-footing grounding impedance depends on the frequency, where the capacitive and inductive effects of the electrodes become significant and must be taken into account for an accurate transient analysis [3]. For more precise analysis, frequency dependence of the soil parameters (permittivity and resistivity) and soil ionization must be considered [8], [9]. In low resistivity soil, short horizontal or vertical electrodes are commonly employed for tower-footing grounding systems. However, in a soil of moderate or high resistivity, long counterpoise electrodes are connected to the tower feet to provide a low impedance to avoid BFs in power systems [10].

For the precise estimation of the tower-footing grounding impedance, several empirical, analytical, and numerical methodologies have been proposed in the technical literature, such as:

- Models based on Transmission Line Modeling (the so-called TLM) [11];
- Models based on circuit theory using lumped electric circuits [5];

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- Numerical models that solve Maxwell's equations using method of moments (MoM) [12], finite difference time domain (FDTD) [13], [14] and finite element method (FEM) [15].

Counterpoise electrodes are largely employed for grounding conductors at transmission towers running along the transmission line axis. In (EMTP)-type simulation tools, for most of the electromagnetic transient analysis, the grounding impedance of the counterpoise electrodes is usually represented by pure resistance, which is not adequate behaviour depending on the frequency range. Additionally, it is considered that the counterpoise electrodes are buried in homogeneous ground with frequency-independent electrical parameters of soil. However, organic matter, humidity, salinity varies along the layers of soil and these factors affect the resistivity (ρ), permeability (μ), permittivity (ϵ) of the soil [16]. A few number of paper have dealt studies of grounding electrodes buried in a multilayer soil and their influence on the transient response.

The objective of this paper is to compute the impedance of grounding electrodes buried in a generic multi-layer soil. First, the grounding impedance of vertical and horizontal electrodes are calculated by a commercial software (FEKO) that solves Maxwell's equations using numerical Method of Moments (MoM) and the classical TLM. In order to verify the accuracy of the MoM, a comparison between the grounding impedance of these electrodes is carried out for different soil resistivities in a frequency range from 100 Hz up to 5 MHZ. Next, the grounding impedances of counterpoise electrodes buried in a multilayer soil are computed by MoM. Finally, the Grounding Potential Rising (GPR) is computed for each multi-layer soil configuration when a lightning strikes directly at grounding counterpoise electrodes. It is verified that when another layer of soils is considered, the impedance of counterpoise electrodes as well as the GPR peaks are strongly affected and these facts have to be taken into account for a precise electromagnetic analysis.

II. Transmission Line Modelling

A cylindrical electrode, buried vertically or horizontally in a given soil, can be modeled as a short transmission line, using the Transmission Line Model (TLM). In this model, electrical parameters of the electrode are distributed along its length and the equations that model a generic transmission line are used to calculate the impedance of the electrode, seen from the sending end and with an open-circuit receiving end. This impedance is also called harmonic impedance. In Fig. 1a, a horizontal electrode of length d and diameter $2a$ is buried in a soil of resistivity ρ, at a burial depth of h.

Considering that the metallic electrode is represented by its distributed parameters, in per-unit-length, the current flowing an element of length Δx surrounded by a soil characterized by ρ_s, ε_s and μ_s, can be described as presented in 1-b. The current in this element presents two components: a longitudinal current I_L along the electrode and a transversal current I_T seen as a leakage spread along the surrounding soil. The longitudinal current comprises the losses and also establishes an intern

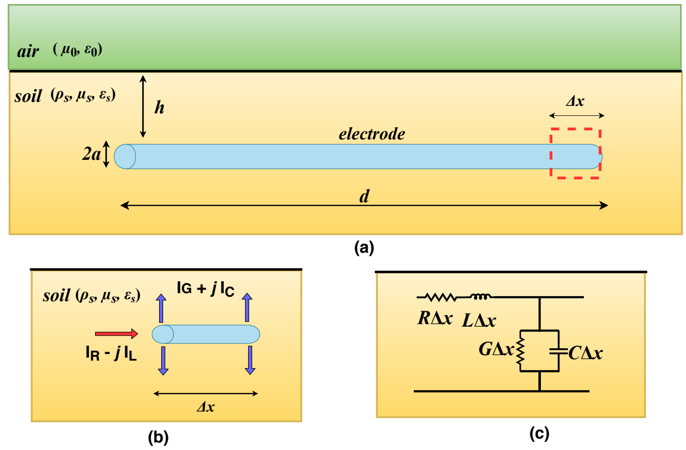

Fig. 1: (a) Horizontal electrode buried in a homogeneous soil; (b) Longitudinal and transversal currents in a segment Δx of the electrode; (c) Equivalent circuit representation of a segment Δx of the electrode.

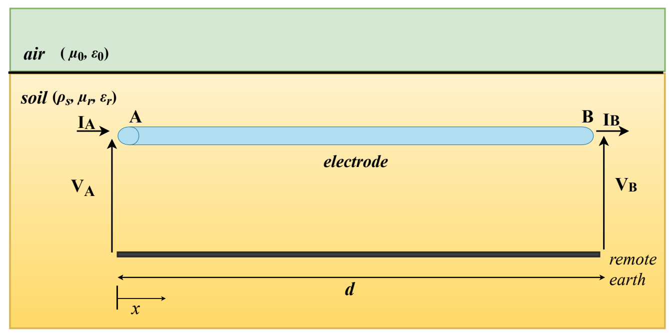

Fig. 2: Horizontal electrode seen as a short transmission line.

magnetic field inside the electrode and around its structure. These effects are comprised by a series RL branch formed by a resistance R and inductance L. These parameters are related to the voltage drop along the electrode as the longitudinal current flows. The transversal current is responsible for generating an electric field in the soil around the electrode, characterized by ρ_s and ε_s. This fact produces a current flowing through soil, which is associated to the losses in the soil (seen as a dielectric material) associated to a potential difference between the conductor and surface air/soil. These effects are comprised by a shunt admittance formed by transversal conductance G in parallel to the capacitance C, forming the branch GC that takes into account the leakage current I_T. The equivalent circuit of the electrode is depicted in Fig.1c. In Fig.1c, the segment Δx of the horizontal electrode is represented by a longitudinal impedance, which comprises the series resistance **R** [Ω/m] and inductance **L** [H/m] in per-unit-length, respectively and by the shunt admittance, which comprises the transversal conductance **G** [S/m] and capacitance **C** [F/m], per-unit-of-length, respectively [17]. The horizontal electrode, as well as the vertical electrode, is interpreted as a short transmission line of length d as shown in Fig. 2.

In Fig. 2, **A** and **B** are, respectively, the sending and receiving end of this short transmission line. The current $I_A(s)$ and voltage $V_A(s)$, as a function of the current $I_B(s)$ and voltage $V_B(s)$ at the receiving end, are calculated in the frequency domain by equations (1) and (2).

$$V_A\left(x\right) = cosh\left(\gamma x\right) V_B\left(x\right) + Z_C sinh\left(\gamma x\right) I_B\left(x\right) \quad (1)$$

$$I_A\left(x\right) = \left(1/Z_C\right) sinh\left(\gamma x\right) V_B\left(x\right) + cosh\left(\gamma x\right) I_B\left(x\right) \quad (2)$$

Equations (1) and (2) are known as the transmission line hyperbolic equations and describe the exact behavior of voltages and currents at terminals of a single-phase transmission line (or electrode) at steady state. The variables $\gamma(s)$ [m^{-1}] and $Z_C(s)$ [Ω] are the propagation function and the characteristic impedance of a transmission line given by

$$\gamma\left(\omega\right) = \sqrt{\left(R + j\omega L\right)\left(G + j\omega C\right)} \quad (3)$$

$$Z_C\left(\omega\right) = \sqrt{\frac{R + j\omega L}{G + j\omega C}}. \quad (4)$$

In (3) and (4), $\omega = 2\,\pi\,f$ is the angular frequency, where f is the frequency [Hz]. In frequency domain, considering that the horizontal (or vertical) electrode is a open circuit at the end B ($x = d$, $I_B(s) = 0$), the grounding impedance, also named harmonic grounding impedance, can be calculated by [2], [12]:

$$Z_0\left(\omega\right) = Z_C coth\left(\gamma\left(\omega\right) d\right) \quad (5)$$

Many authors have proposed different distributed parameter approaches for representing grounding electrodes in the literature [2], [11], [12], [18], [19]. Based on Fig.1, for the horizontal electrode, the series resistance R_h and inductance L_h and shunt conductance G_h and capacitance G_h parameters are defined by [19]

$$\begin{gathered} R_h = \frac{\rho_c}{\pi a^2}, \quad L_h = \frac{\mu_s}{2\pi}\left[ln\left(\frac{2d_h}{\sqrt{2ha}}\right) - 1\right], \\ C_h = \pi\varepsilon_s\left[ln\left(\frac{2d_h}{\sqrt{2ha}}\right) - 1\right]^{-1}, \quad G_h = \frac{1}{\epsilon_s\rho_s}C_h \end{gathered} \quad (6)$$

For the vertical grounding electrode, the series resistance R_v and inductance L_v and shunt conductance G_v and capacitance G_v are defined by [18]

$$\begin{gathered} R_v = \frac{\rho_c}{\pi a^2}, \quad L_v = \frac{\mu_s}{2\pi}\left[ln\left(\frac{2d_v}{a}\right) - 1\right], \\ C_v = 2\pi\varepsilon_s\left[ln\left(\frac{4d_v}{a}\right) - 1\right]^{-1}, \quad G_v = \frac{1}{\epsilon_s\rho_s}C_v \end{gathered} \quad (7)$$

In (6) and (7), μ_s is the permeability of the conductor and ε_s is the relative permittivity of the soil.

However, in transmission towers counterpoise electrodes are employed to connect tower feet to ground. It consists of 4 long electrodes buried below the surface of the ground, running along the axis of the phase conductors in the transmission line as depicted by Fig.8.

The counterpoise conductors provide low impedance path to the earth, especially in soils of medium and high resistivity, especially in a high keraunic level area where transmission lines are built. A low tower-footing grounding impedance will reduce the probability of an outage due BF. There are no analytical formulae to estimate the tower-grounding impedance of for counterpoise electrodes buried in homogeneous or stratified soil. Then, an alternative to tackle this issue is employing electromagnetic software with numerical methods to compute tower-footing impedance of complex grounding system. Furthermore, in these software specific characteristics of soil, such as frequency dependence on its parameters or many layers of ground can be considered. In the next section, numerical results are presented considering simple electrodes as well as counterpoise electrodes in homogeneous and 2 and 3-layer stratified soils.

III. Methodology applied

The impedance curves of the grounding electrodes in this article are computed for a wide frequency range, from 100 Hz up to 5 MHz, employing the Method of Moments (MoM) integral formulation of Maxwell's equations implemented in the computational electromagnetic software FEKO. To compute the grounding impedance curves, the calculation region must be bounded by a volume (domain) in the software. In this case, a Perfect Electric Conductor (PEC) region formed by a hemisphere attached to a cone is employed to bound the simulation domain as depicted by Fig.3.

This calculation region can be divided in two sections: one is the ground domain where the vertical, horizontal or counterpoise arrangement is buried in a given soil, characterized by μ_s, ε_s and ρ_s, and bounded by PEC hemisphere of radius R. The other is formed by air and it is bounded by the PEC cone of height H and base radius R. The H and R set for the simulations are 1 m and 100 m respectively for the simulation.

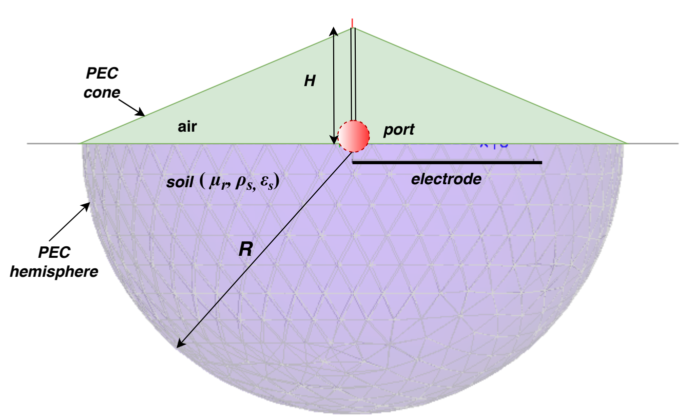

Fig. 3: Simulation model in FEKO to compute the impedances of cylindrical electrodes (not in scale).

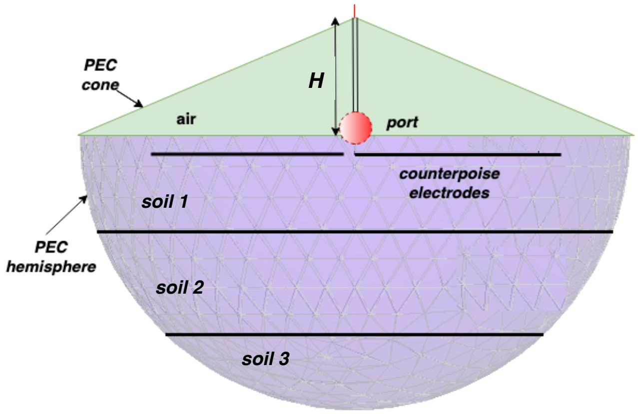

Fig. 4: Simulation model in FEKO to compute the impedances of counterpoise electrodes in a generic multi-layer soil. (not in scale).

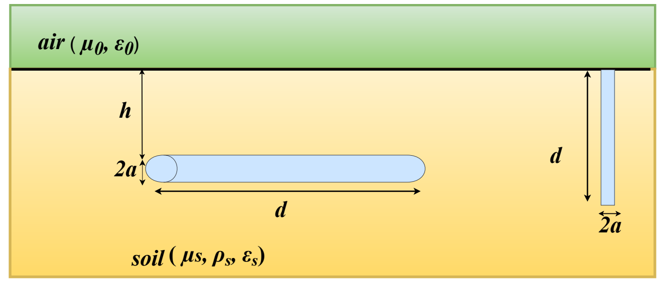

Fig. 5: Horizontal and vertical electrodes considered for the simulations.

A description how these values are computed can be found in [20]. The closed path for the current is formed by grounding electrode, through soil, passing the PEC hemisphere + cone structure and then to the cone top. An electromagnetic port, voltage source of 1 V, is defined between the top of metallic cone and the top of the cylindrical electrode. In this port, a specified voltage source gives the potential difference between the positive side of the port relative to the negative side. In this case, a current flows out of one side to the other side by a return path closed through structure and then through the grounding electrode. The impedance seen from the port is the grounding impedance, which is computed for multi-layer soils and grounding systems.

To compute the counterpoise grounding impedance, the same calculation region is employed but the ground is formed by a generic multi-layer soil, as depicted in Fig.4.

IV. Numerical Results

Numerical results are divided into three sections. In section IV-A, the impedance of vertical and horizontal electrodes are calculated by TLM and MoM, employing the topology in Fig.3, for several homogeneous soil. A comparison between grounding impedances computed by TLM and MoM is performed in order to validate the numerical method. In section IV-B, grounding impedances of the counterpoise electrodes are computed for homogeneous and multi-layers soils, employing the topology in Fig.4. In section IV-C, the GPR curves are calculated when a lightning strikes directly at the counterpoise electrode system buried in multi-layer soil. All grounding impedances are calculated in a frequency range that varies from 100 Hz up to 5 MHz, and the frequency dependence on the electrical parameters of soil (permissivity and resistivity) and soil ionization are not taken into account.

A. Calculation of grounding impedance for vertical and horizontal electrodes

The grounding impedances for vertical and horizontal electrodes are computed by TLM and MoM as a function of frequency for different soil resistivities. Fig.5 shows the horizontal and vertical electrodes buried in a generic soil with its geometrical parameters. The parameters of the electrodes are: length d = 1 m, burial depth h = 1 m and radius a = 12.5 mm. The electrical parameters of the soil are: relative permeability $\mu_s = \mu_0 = 0.4\pi$ μH/m, relative permittivity ϵ_s = 10 and resistivities ρ of 100, 500 and 1,000 Ωm.

Figs 6 and 7 show the impedances (magnitude and phase) obtained by MoM and TLM in dashed and solid lines respectively. Figs. 6 and 7 show that magnitudes of the grounding impedance are affected by distinct orientations of the electrodes. In low frequencies, the magnitude of the grounding impedance is purely resistive which is a constant value for this range (less than 100 kHz). It can be seen that grounding impedance assumes either inductive or capacitive behavior, depending on the frequency.

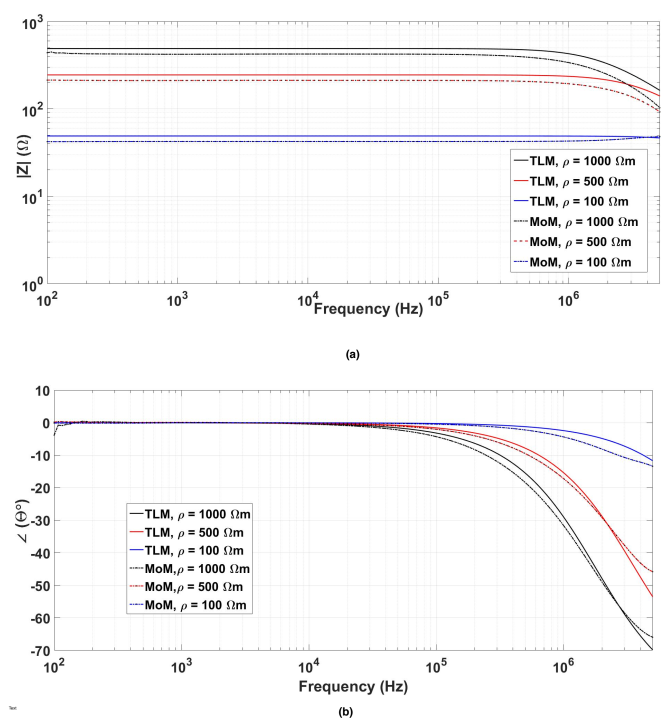

Fig. 6: Grounding impedances of a 1-m horizontal electrode for several soil resistivities: [(a) Magnitude and (b) Phase].

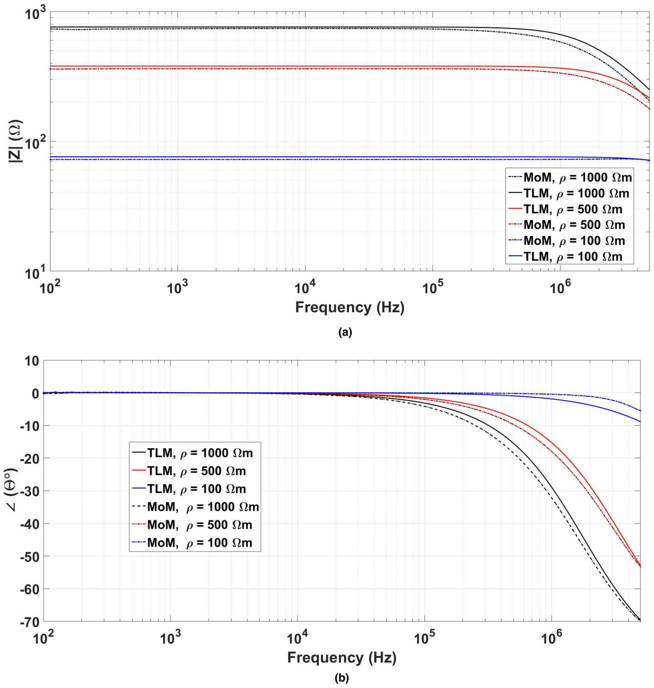

Fig. 7: Grounding impedances of a 1-m vertical electrode for several soil resistivities: [(a) Magnitude and (b) Phase].

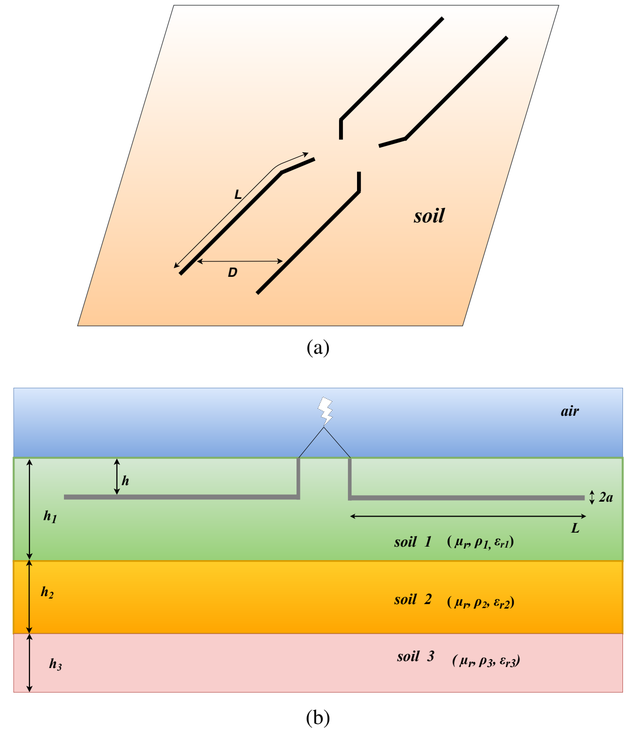

Fig. 8: Counterpoise electrodes: [(a) Top view and (b) buried in a generic 3-layer soil (side) view].

This pure resistance is employed in many electromagnetic transient simulations when lightning strikes at the transmission tower top are studied. However, lightning current is characterized by frequency content from zero to some megahertz, which the grounding impedance must take into account the high-frequency behavior of grounding systems for an accurate analysis [3], [21].

B. Calculation of the grounding impedance of counterpoise electrodes

A generic representation of the counterpoise electrodes is presented in Fig.8. A a precise computation of grounding impedance of counterpoise buried in a multi-layer soil is carried out in this section, employing the topology in Fig.4, where the same values of H = 1 m and R = 100 m are employed. A generic 3-layer soil which counterpoise electrodes are buried is depicted in Fig. 8a.

In Fig. 8b, h is the burial depth of the counterpoise electrodes, h_1, h_2 and h_3 are the thickness of each layer. D is distance between tower-feet, L is the total length of the electrode and a is the radius of the transversal section of the conductor. Each soil layer has a homogeneous ground with ρ_i. The values of geometrical parameters are: h = 0.50 m, h_i = 1 m, D = 3 m, a = 12.5 mm. The electrical parameters of soil are: ρ_1 = 1,000 Ωm , ρ_2 = 100 Ωm , ρ_3 = 10 Ωm and ϵ_{r1} = ϵ_{r2} = ϵ_{r3} = 10, as adopted by [21].

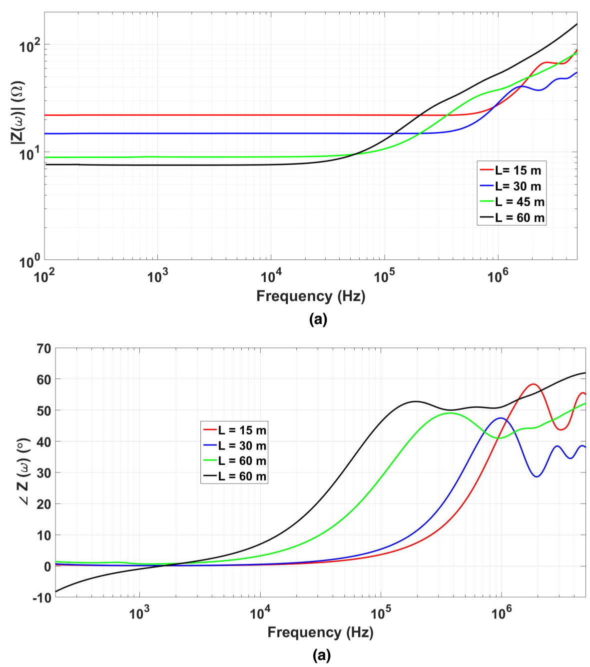

Fig. 9: Impedances of the counterpoise electrodes buried in a homogeneous soil for different lengths: [(a) Magnitude and (b) Phase].

The impedance of the counterpoise is computed for 4 different lengths L = 15, 30, 45 and 60 m. Considering the counterpoise electrodes buried in a homogeneous soil of ρ_1 =

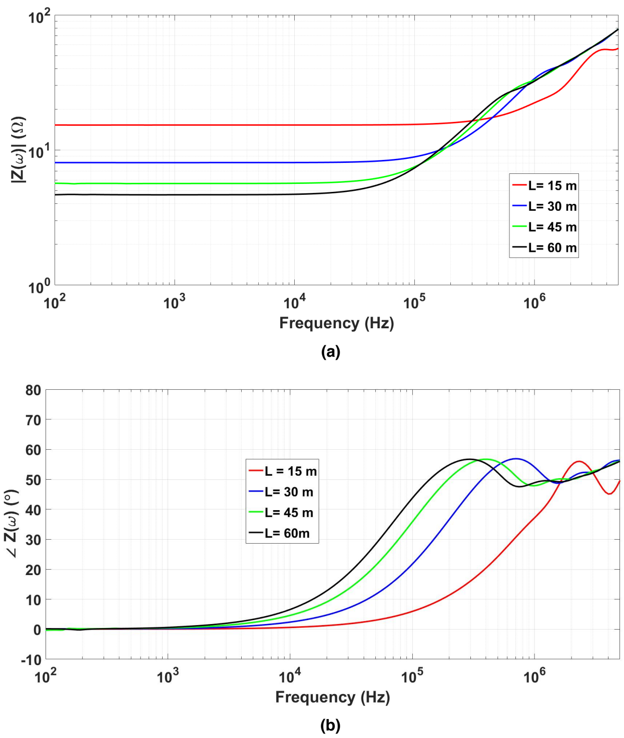

Fig. 10: Impedances of the counterpoise electrodes buried in a 2-layer soil for different lengths: [(a) Magnitude and (b) Phase].

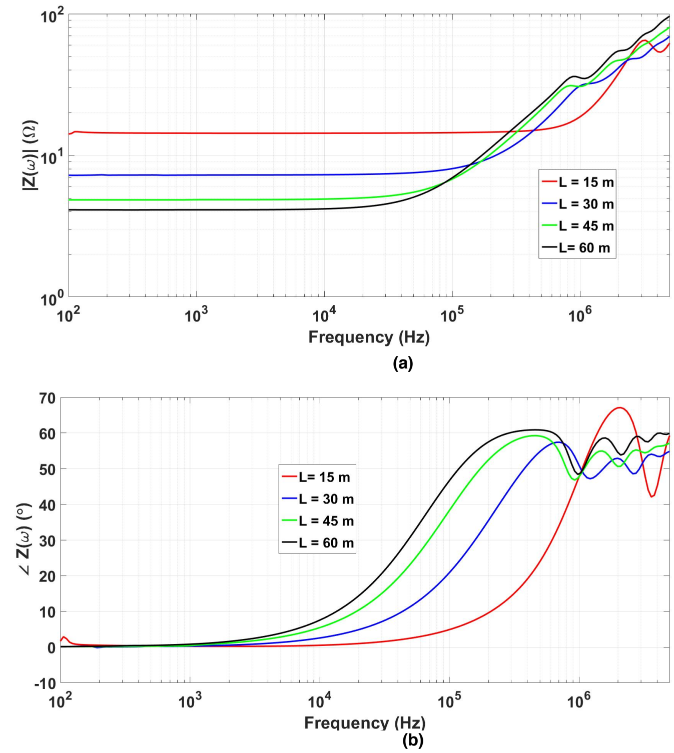

Fig. 11: Impedances of the counterpoise electrodes buried in a 3-layer soil for different lengths: [(a) Magnitude and (b) Phase].

1,000 Ωm, the grounding impedance for different length, as a function of the frequency is depicted in Fig. 9. Considering that tower-footing counterpoise electrodes are buried in a 2-layer soil, where ρ_1 = 1,000 Ωm and ρ_2 = 100 Ωm compose the ground. The counterpoise impedances are presented in Fig.10. Finally, the tower-footing grounding impedances for the counterpoise buried in a 3-layer soil, composed by ρ_1, ρ_2 and ρ_3, are shown in Fig.11.

It can be noted that a presence of another layer of soil affects the grounding impedance of the counterpoise electrodes as well as the total length (L) for a large frequency range. First, at low frequency range, the grounding impedances present frequency-independent resistive behaviour ($|Z| \approx$ R), where R is the DC resistance to ground [12], [19]. The value of R depends on the electrode length (L), where the higher length the lower R. At high frequencies, the counterpoise impedances increases due to dominantly inductive behaviour after a switching frequency. This switching frequency (SF) also depends on the electrode length, which SF decreases for higher L. The DC resistances calculated for the different soils are depicted in Table I. Comparing the DC resistance of the counterpoise electrodes in the conditions, it may be noted for longer electrodes, the DC resistance R_{DC} decreases. Adding another layer of soil also affects the counterpoise impedances, where the lowest values are obtained for a 3-layer soil.

TABLE I: Resistance R_{DC} at low frequencies

	R_{DC} (Ω)		
L (m)	1-layer	2-layers	3-layers
15	22	15.3	14.38
30	14.93	8.06	7.26
45	8.96	5.65	4.85
60	7.61	4.67	4.12

C. *Calculation of the GPR curves*

In this section, the GPR curves for the grounding counterpoise electrodes buried in a homogeneous, 2 and 3-layer soil are analyzed for a lightning striking in these structures, as depicted by Fig.8a. All geometrical and electrical parameters are the same of the previous section. The GPR is defined as the product of the grounding electrode impedance, in relation to a remote earth, and the current that flows through that electrode impedance. This is a procedure required to determine if the step and touch voltages are in accordance with specific standards for grounding systems as defined in [22]. The lightning current is modelled by a 1.20/50 μs double exponential function injected at the center of the tower-footing counterpoise electrodes approximated by I(t) = $I_0(e^{-\alpha\, t} - e^{-\beta\, t})$ with I_0= 1.037 kA, α = 1.47.10^{4}s^{-1} and β = 2.47.10^{6}s^{-1} [23]. The GPR curves for homogeneous, 2 and 3-layer soil are

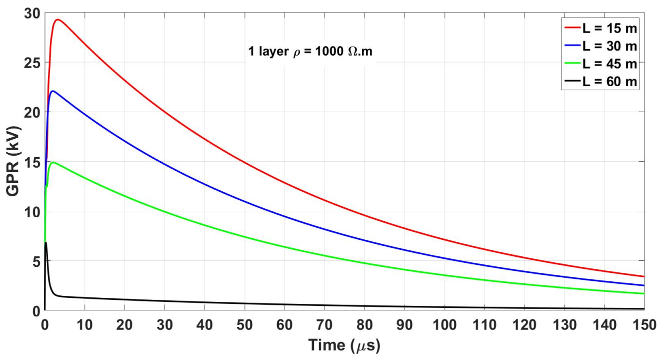

Fig. 12: GPR curves of the counterpoise electrodes buried in a homogeneous soil for different lengths (L).

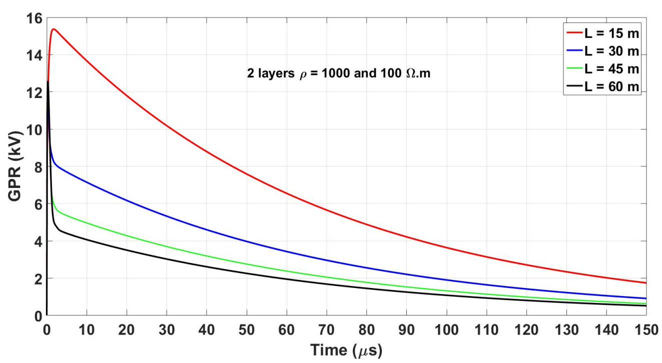

Fig. 13: GPR curves of the counterpoise electrodes buried in a 2-layer soil for different lengths (L).

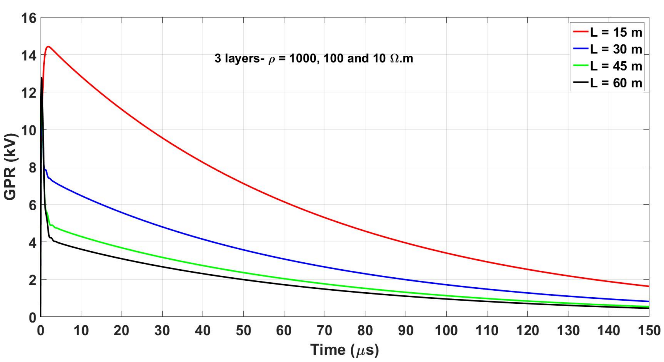

Fig. 14: GPR curves of the counterpoise electrodes buried in a 3-layer soil for different lengths (L).

depicted in Figs.12-14.

In Figs. 12-14, it can be noted that the voltage peak of the GPR curves decreases when the electrode length (L) increases. The wave-shape is also modified as the length (L) increases. The grounding impedance is strongly affected by a presence of more layers of soil where this condition has to be considered for a precise electromagnetic analysis.

V. Conclusions

This paper has presented the impedances of cylindrical and counterpoise electrodes buried in different configurations of soil over a large frequency range. The grounding impedance of vertical and horizontal electrodes buried in homogeneous soil was calculated using Method of Moments (MoM) and compared with TLM simulations. Results have shown a good agreement between the TLM and MoM over this frequency range. Further, the impedance of counterpoise electrodes were calculated for homogeneous and stratified soils, in frequency domain, for different electrode lengths (L). It can be seen that at low frequencies, the impedance of counterpoise electrodes present a resistive behaviour and assumes inductive or capacitive behaviour at high frequencies, depending on the soil resistivity.

These impedances curves also depend on the electrode length, and the magnitude of DC resistance decreases for longer electrodes. The frequency where the impedances change from inductive to capacitive behaviour, depends on the electrode length (L) and it is noted that larger counterpoise electrodes will present dominantly inductive behaviour. Furthermore, adding another layer of soil reduces the DC resistance for a fixed electrode length as depicted. In the time domain, the GPR wave-shapes are strongly affected by electrode length as well as by adding another layers of soil. For stratified soil, the GPR peaks are reduced as well as is its damping wave-shape.

References

[1] V. Kostić and N. Raičević, “Grounding system impedance measurement using shifted frequency method,” in *2015 IEEE 5th International Conference on Power Engineering, Energy and Electrical Drives (POWERENG)*. IEEE, 2015, pp. 197–200.

[2] S. Bourg, B. Sacepe, and T. Debu, “Deep earth electrodes in highly resistive ground: frequency behaviour,” in *Proceedings of International Symposium on Electromagnetic Compatibility*, Aug 1995, pp. 584–589.

[3] K. Sheshyekani, S. H. Hesamedin Sadeghi, R. Moini, F. Rachidi, and M. Paolone, “Analysis of transmission lines with arrester termination, considering the frequency-dependence of grounding systems,” *IEEE Transactions on Electromagnetic Compatibility*, vol. 51, no. 4, pp. 986–994, 2009.

[4] P. Yadee and S. Premrudeepreechacharn, “Analysis of Tower Footing Resistance Effected Back Flashover Across Insulator in a Transmission System,” *International Conference on Power Systems Transients*, 2007. [Online]. Available: http://www.ipst.org/techpapers/2007/ipst_2007/papers_IPST2007

[5] F. M. Gatta, A. Geri, S. Lauria, and M. Maccioni, “Equivalent lumped parameter II-network of standard grounding systems under surge conditions,” in *2010 30th International Conference on Lightning Protection, ICLP 2010*, 2017.

[6] O. E. Gouda, G. M. Amer, and T. M. El-Saied, “Factors affecting transient response of grounding grid systems,” in *2008 5th International Multi-Conference on Systems, Signals and Devices, SSD’08*, 2008.

[7] B. Marungsri, S. Boonpoke, A. Rawangpai, A. Oonsivilai and C. Kritayakornupong, “Study of Tower Grounding Resistance Effected Back Flashover to 500 kV Transmission Line in Thailand by using ATP/EMTP,” *World Academy of Science, Engineering and Technology International Journal of Electrical and Computer Engineering*, vol. 2, no. 6, pp. 1061–1068, 2008.

[8] R. Alipio and S. Visacro, “Frequency dependence of soil parameters: Effect on the lightning response of grounding electrodes,” *IEEE Transactions on Electromagnetic Compatibility*, vol. 55, no. 1, pp. 132–139, 2013.

[9] D. Cavka, N. Mora, and F. Rachidi, "A Comparison of frequency-dependent soil models: Application to the analysis of grounding systems," *IEEE Transactions on Electromagnetic Compatibility*, vol. 56, no. 1, pp. 177–187, 2014.

[10] S. Visacro and F. H. Silveira, "Lightning Performance of Transmission Lines: Requirements of Tower-Footing Electrodes Consisting of Long Counterpoise Wires," *IEEE Transactions on Power Delivery*, vol. 31, no. 4, pp. 1524–1532, 2016.

[11] R. Velazaquez and D. Mukhedkar, "Analytical Modeling of Grounding Electrodes Transient Behavior," *IEEE Power Engineering Review*, vol. PER-4, no. 6, pp. 43–44, 1984.

[12] L. Grcev, "Modeling of grounding electrodes under lightning currents," *IEEE Transactions on Electromagnetic Compatibility*, vol. 51, no. 3 PART 1, pp. 559–571, 2009.

[13] Y. Baba, N. Nagaoka, and A. Ametani, "Modeling of thin wires in a lossy medium for FDTD simulations," *IEEE Transactions on Electromagnetic Compatibility*, vol. 47, no. 1, pp. 54–60, 2005.

[14] M. Tsumura, Y. Baba, N. Nagaoka, and A. Ametani, "FDTD simulation of a horizontal grounding electrode and modeling of its equivalent circuit," *IEEE Transactions on Electromagnetic Compatibility*, vol. 48, no. 4, pp. 817–824, 2006.

[15] Y. Liu, N. Theethayi, and R. Thottappillil, "An engineering model for transient analysis of grounding system under lightning strikes: Nonuniform transmission-line approach," *IEEE Transactions on Power Delivery*, vol. 20, no. 2 I, pp. 722–730, 2005.

[16] A. Elzowawi, A. Haddad, H. Griffiths, and D. Clark, "Investigation of soil ionization propagation in two-layer soil samples," in *2015 50th International Universities Power Engineering Conference (UPEC)*. IEEE, 2015, pp. 1–5.

[17] S. Visacro, "A comprehensive approach to the grounding response to lightning currents," *IEEE Transactions on Power Delivery*, vol. 22, no. 1, pp. 381–386, Jan 2007.

[18] L. Grcev and M. Popov, "On high-frequency circuit equivalents of a vertical ground rod," *IEEE Transactions on Power Delivery*, 2005.

[19] L. Grcev and S. Grceva, "On hf circuit models of horizontal grounding electrodes," *IEEE Transactions on Electromagnetic Compatibility*, vol. 51, no. 3, pp. 873–875, Aug 2009.

[20] B. Salarieh, H. De Silva, and B. Kordi, "Wideband emt-compatible model for grounding electrodes buried in frequency dependent soil."

[21] H. Karami and K. Sheshyekani, "Harmonic Impedance of Grounding Electrodes Buried in a Horizontally Stratified Multilayer Ground: A Full-Wave Approach," *IEEE Transactions on Electromagnetic Compatibility*, 2018.

[22] IEEE, "Ieee recommended practice for determining the electric power station ground potential rise and induced voltage from a power fault," *IEEE Std 367-2012 (Revision of IEEE Std 367-1996)*, pp. 1–168, May 2012.

[23] W. Jia and Z. Xiaoqing, "Double-exponential expression of lightning current waveforms," in *The 2006 4th Asia-Pacific Conference on Environmental Electromagnetics*, Aug 2006, pp. 320–323.