Frequency Dependence of Multilayer Soil Electrical Parameters: Effects on the Input Impedance of Grounding Systems

16th IET International Conference on AC and DC Power Transmission (ACDC 2020): ACDC 2020

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Keywords: Frequency dependence, Method of moment, Multi-layered soil, Grounding system, Input impedance.

Abstract

This paper presents an analysis of soil frequency dependence effect on input impedance of grounding system. It focuses on vertical grounding electrodes buried in multilayer soil structure. The proposed analytical formulae obtained from experimental results is used to predict the frequency dependence impacts of multilayer soil electrical parameters.To this aim, the precise full-wave method based upon the method of moment (MoM) is employed. The input impedance is calculated for different soil conditions described by the top layer height and the electrical parameters of soil for all layers. The contributions of this paper are: 1) considering frequency dependent of multilayer soil; 2) using the MoM-based approach, which is accurate and less time consuming, to evaluate transient behavior of grounding system. The effect of frequency dependence is more demonstrated for input impedance of electrodes that are buried in high resistivity soils in opposition with those buried in low resistivity soils and especially when these systems are subjected to high-frequency contents of lightning. This findings demonstrate that the frequency content of the impulse current, the soil electrical parameters and the grounding electrode length are the main factors affecting the lightning performance of grounding systems.

1 Introduction

Lightning current is a high frequency transient source in power systems. Owing to this fact, it is one of the main causes of faults and outages of AC/DC power transmission lines [1] and wind turbines. When a lightning strikes a power transmission line, the huge current with high-frequency content will flow into the grounding system and dissipate into soil. For the frequency ranges associated to lightning, the inductive behavior of electrodes can become more and more important with respect to its resistive behavior [2] and [3]. For instance, long vertical electrodes use in grounding grid of the wind turbines that might be buried in multilayer soil. In fact, high-frequency inductive behavior of the long vertical electrode of grounding system might cause in large peaks of the ground potential rise (GPR) at the feed point in cases when the lightning current has enough high-frequency content [4] and [5]. The owner naturally wishes to cut down on the use of copper where possible and use wires with smaller cross sectional areas in order to diminish costs. The exact modeling can be applicable for a conservative estimate of the upper bound of the impulse impedance of ground electrodes.

Proper design of the grounding system plays a vital role on voltage stresses inflicted on system equipment. Different issues in transient behavior of grounding system exist, such as high-frequency modeling of multi-layer and soil frequency-dependent electrical parameters, which need more research [7]. Electrical system components can be affected by the behavior of grounding systems since they are connected through ground terminations, surge arrester and shield wires. This is a significant issue for ensuring the appropriate electrical systems operation in regards to transient studies, protection, human safety, and electromagnetic compatibility [8]. Thus, exact evaluation of power system transient performance requires its relevant grounding system to be adequately considered as well.

So far, several techniques such as quasi-static methods and full-wave approaches have been employed for modeling of grounding systems [10]. However, these can't guarantee exact modeling when considering both multi-layer soil and soil frequency dependence together. Circuit-based methods, transmission line theory [12] are defined as quasi-static methods that generally fail in the prediction of high-frequency behavior of grounding systems. Finite difference time domain method (FDTD) [15], finite element method (FEM) [16], and the method of moments (MoM) [17] are classified as a full-wave or electromagnetic field approaches with the capability of exact appraisal of the grounding systems performance over a wide frequency range. The full-wave modeling of grounding system up to a few MHz would be required [18] and [19]. Due to the complex nature of the grounding system such as multilayer soil, frequency dependence electrical parameters, non-linearity and ionization, detailed modeling of the grounding system is a challenging issue.

Frequency dependence effect of multilayer soil electrical parameters is usually ignored in the modeling of grounding system, calculation of GPR and insulation coordination (IC) [21] and [4]. Opposing to its physical nature, electrical parameters are considered constant and equal to values measured at low-frequencies. Depending on the soil water content, the soil relative permittivity is assumed between 4 and 80 [3] and [23]. Due to high-frequency contents of lightning, this presumption can lead to imprecise results for grounding system subjected to lightning current [19]. Therefore, using a precise model of soil will help improving transient analysis of power systems. For instance, it gives us a better evaluation of the input impedance of tower-footing grounding system, GPR and back-flashover rate of the power transmission lines, which is a key factor in minimizing the cost of insulators, as well as the energy not supplied (ENS) [25]. This approach should be well suited to be employed in time domain, such as EMTP-like tools, which are usually used for the transient analysis of power systems [18] and [12].

Frequency dependence of soil electrical parameters has been inspected by experimental tests. Recently, an experimental methodology [26] was applied to measure the parameters of single layer soils from 60 to 9100 Ω.m in their natural environments, including different moisture. It was found that frequency dependence of soil electrical parameters could affect on input impedance of grounding system. Nevertheless, to the best of knowledge of authors, no rigorous full-wave method has been utilized yet for the inclusion of frequency dependence of multilayer soil electrical parameters into input impedance (harmonic impedance) [2].

Existing studies in the full-wave approach consider the constant electrical parameters of multilayer soil without evaluating the effect of the frequency-dependent parameters of the ground on the performance of the grounding system. This paper applies a precise full-wave approach based upon the method of MoM solutions of Maxwell's equations for analysing the behavior of grounding systems at the injected point, with the multilayer soil electrical parameters considered to be frequency dependent [26]. Also, multilayer soil is considered with different geometry of grounding system structure. Nonlinear behavior of soil has been neglected. This is of specific importance for the accurate computation of lightning generated overvoltages and for the implementation of grounding systems into circuit-based electromagnetic transient solvers [28]. Meoreover, it gives a more accurate demonstration of the input impedance of grounding systems.

This paper is organized as follows. Section II describes the theory and the formulations of grounding system modeling buried in multilayer soil using MoM. In Section III, frequency dependence of Multilayer Soil Electrical Parameters are evaluated. The problem specifications and the numerical results are discussed in Sections IV and V respectively. Conclusion remarks are presented in Section VI.

2 Full-Wave MoM for Multilayer Grounding Systems

Figure 1 shows a vertical electrode buried in multilayer soil structure. The vertical electrodes are used widely as a grounding system of power transmission lines and wind turbines. The electromagnetic model based on MoM [29] is applied for the calculation of the input impedance of a given grounding system at each frequency. The MoM solution of grounding electrodes generally requires the formulation of governing electromagnetic equations in the form of integral equations. As known, among the methods which are used for the analysis of grounding systems, MoM can be considered as the most efficient approach [3], because the thin wire approximation method reduces the original two-dimensional surface integration into an one-dimensional line integration [25, 30].

The multilayer soil structure is considered to have different resistivity and permittivity as shown in Figure 1. It is supposed

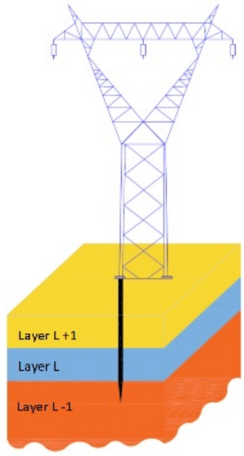

Figure 1: 3D model of vertical electrode buried in multi-layer soil

that the $e^{j\omega t}$ is time variation. A vertical electric dipole (VED) is placed in the lth layer and the observation point can be located in any layer. The thickness of each layer is d_l. The soil resistivity and permittivity of the lth layer are specified by ρ_l and ε_l, respectively.

To find the input impedance of vertical electrode over the wide range of frequency, the calculation of the Green's functions, explained by the Sommerfeld integrals in the spatial domain is needed. To this aim, the Green's functions are first obtained in the spectral domain, which can be represented in closed-form, in the source layer and these expressions are extended to the other layers. The spatial domain Green's functions are developed for the vector and scalar potentials. In the multilayer structures, the proposed Green's function formulations are different, because the scalar and vector potentials are not unique [31]. For the vector and scalar potentials, distinct sets of Green's functions can be selected to assure the same boundary conditions. In this paper, for the magnetic vector potential, the spatial domain Green's functions (1) is applied.

$$G_A = \begin{pmatrix} G_{xx} & G_{xy} & 0 \\ G_{xy} & G_{yy} & 0 \\ 0 & 0 & G_{zz} \end{pmatrix} \tag{1}$$

Further details about the derivation of spectral domain Green's functions are given in [10] and [32]. Inverse Fourier transform of its spectral domain counterpart is applied to find the spatial domain Green's function by (2)

$$G^{A,qe} = \frac{1}{2\pi}\int_0^{+\infty} \tilde{G}^{A,qe} u_\rho J_0\left(u_\rho \rho\right) du_\rho, \tag{2}$$

where $\tilde{G}^{A,qe}$ and $G^{A,qe}$ respectively, show the spectral domain and spatial domain Green's functions. The magnetic vector potential and the scalar potential defined by A and qe superscripts respectively. The ρ-component of the wave vector for the lth layer is u_ρ. The J_0 is the zero-order Bessel's function of the first kind. The radial distance in the cylindrical coordinate system is ρ. The static parts of the Green's functions in the spectral domain are the asymptotic terms for $u_\rho \to \infty$.

These are elicited by (3), which is the Sommerfeld identity and (4) to reach good results in the spatial domain. It should be emphasized that (3) can be solved using integration by part.

$$\int_0^{+\infty} \frac{e^{-ju_z|z|}}{ju_z} u_\rho J_0\left(u_\rho \rho\right) du_\rho = \frac{e^{-jar}}{r} \tag{3}$$

$$\int_0^{+\infty} e^{-ju_z|z|} J_1\left(u_\rho \rho\right) du_\rho = \frac{e^{-jar}}{\rho} \cdot \frac{|z| e^{-ja}}{\rho r} \tag{4}$$

where u_z is the z-component of the wave vector for the lth layer, r is the observation vector, and J_1 is the first order Bessel's function of the first kind. The more description of spectral domain Green's functions deriving and the appraisal of Sommerfeld's integral can be found in [10].

The mixed potential integral equation (MPIE) is caculated by enforcing the boundary condition for the electric current density, I, on the surface S placed in the multilayer soil as (5)

$$\hat{n} \times \left(E^s(r) + E^{\mathrm{i}}(r)\right) = 0, \quad r \text{ on } S, \tag{5}$$

where E^s and E^{i} are scattered and incident fields, respectively. The scattered field can be defined as (6)

$$E^s(r) = -[j\omega A(r) + \nabla\phi(r)], \tag{6}$$

where A, ω, and ϕ are the magnetic vector potential, angular frequency, and the electric scalar potential, respectively. The equations (7) and (8) are determined the magnetic vector potential and the electric scalar potential respectively.

$$A(r) = \int_S G^A\left(r|r'\right) \cdot I\left(r'\right) dS' \tag{7}$$

$$\phi(r) = \int_S G^{\mathrm{qe}}\left(r|r'\right) \rho_s\left(r'\right) dS', \tag{8}$$

where r', G^A, and G^{qe} are the source vector, the spatial domain Green's function for magnetic vector potential, and spatial domain Green's function for scalar potential respectively.

Equation (9) can express the relation between the electric current density $I(r)$ and the electric charge density $\rho_s(r)$.

$$\nabla \cdot I(r) = -j\omega\rho_s(r) \tag{9}$$

In the MoM solution, current distribution on the conductors is expanded in a finite series as (10)

$$I(r) = \sum_{n=1}^{N} I_n F_n(r), \tag{10}$$

where I_n is the vector of unknown coefficients to be determined. $F_n(r)$ is triangle shape basis function which is used to expand the electric current density on vertical electrode. By substituting from (6) to (10) in (5) and multiplying the resulting equation by $F_m(r)$, and then integrating over the space, I_n can be calculated from the resultant matrix equations (11).

$$[A][X] = [B], \tag{11}$$

where [A], [X], and [B] define, respectively, as the impedance matrix, the unknown vector, and the excitation vector in the MoM.

3 Multilayer Soil Frequency Dependence

Under the conditions imposed by impressed current, the behavior of soil electric parameters and the electrode length are main factors affecting the grounding systems response. A general procedure to analyse the grounding system performance against lightning considering frequency dependence of electrical parameters effects for single layer soil has been proposed [26], but to evaluate these effects on the multilayer grounding system input impedance and grounding system response has not yet to be researched.

The injected current in soil consists of capacitive and conductive components. The capacitive current density and conductive current density are given by equations of (12) and (13)

$$I_{Capacitive} = (2\pi f)\varepsilon \cdot E = (\omega) \cdot \varepsilon \cdot E \tag{12}$$

$$I_{Conductive} = \sigma \cdot E \tag{13}$$

where E is the electric field intensity. These are factor of major influence on soil behavior which is explained by ratio of conductive and capacitive currents (Eq. 14). So, in frequency domain, the ratio of conductive and capacitive currents expresses as

$$\frac{I_{Conductive}}{I_{Capacitive}} = \frac{\sigma}{2\pi f \varepsilon} \tag{14}$$

A description how this ratio are acted can be found in [11]. It has been found that as the frequency increasing, the resistance and permittivity of soil has a decreasing trend [26]. Additionally, it was realized that the decrease of soil resistivity and permittivity, resulting from the frequency dependent effects, is responsible for significant decrease of the grounding impedance, and this effect is more pronounced for soils with high resistivity [33]. Some laboratory measurements have been done to determine the frequency dependence of soil parameters, e.g. [26, 34]. For modeling the frequency dependence of multilayer soil electrical parameters, the analytical formulaes (15) and (17) are used as below [33]. Equation (16) is relation between conductivity and resistivity of soil at each frequency.

$$\rho(f) = \rho_0 \left\{1 + \left[1.2 \times 10^{-6} \cdot \rho_0^{0.73}\right] \cdot \left[(f - 100)^{0.65}\right]\right\}^{-1} \tag{15}$$

$$\sigma(f) = \frac{1}{\rho(f)} \tag{16}$$

$$\varepsilon_r(f) = 1.3 + [7.6 \times 10^3 f^{-0.4}], \tag{17}$$

where ρ_0 is the soil resistivity at 100 Hz. f is the frequency. Electrical parameters are frequency dependent. Over a specific frequency, the frequency dependence causes a reduction of the magnitude of input impedance of the grounding system along with an increase of the capacitive effect. As the soil resistivity ρ_0 increases, this frequency is decreased, and the capacitive

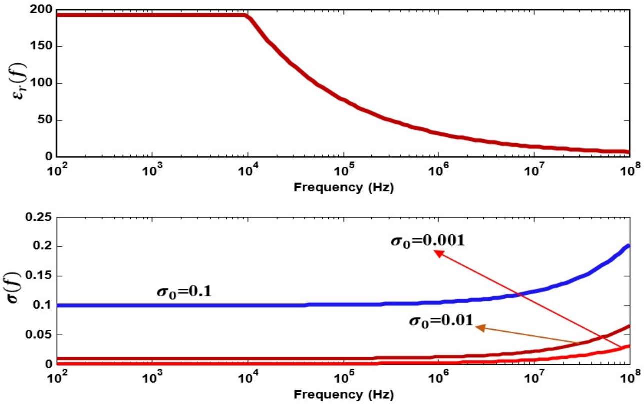

Figure 2: Frequency dependence of electrical parameters of soil for soils with low frequency conductivity σ_0 of 0.1, 0.01, and 0.001 S/m [11]

effect is raised. (See Figure 2)

4 Problem Specification

Figure 3 is used to explain the calculation of the input impedance of the grounding system buried in frequency dependence soil. Figure 3(a) shows a basis function of injected current. Figure 3(b) shows a multilayer structure of soil characterized by electrical parameters. To evaluate grounding system response, two types of soil structure, a) single layer; b) two layer, are considered with and without frequency dependence effects of the electrical parameters of soil. The MoM-Based model could be used to model electromagnetic phenomena in frequency domain and time domain. In our MoM modeling, we define the soil electrical parameters(resistivity and relative permittivity) as functions of frequency. In the simulations, a current of 1A is injected into the grounding system at each frequency. The excitation current spreads to an impressed half subsectional basis function located at top position feed point and the input impedance $Z(\omega)$ of the grounding system is computed as a function of frequency by (18)

$$Z(\omega) = \frac{V(\omega)}{I(\omega)} \tag{18}$$

where $V(\omega)$and $I(\omega)$ are, respectively, the electric potential phasor at the feed point in reference to the remote earth and the injected current phasor. The electric potential is calculated by integrating the electric field along a straight path starting from the electrode conductor surface to a point very far from the injection point in which the current approaches zero and could be physically considered as a voltage reference point. Various simulation cases are considered. The adopted values for the soil electrical parameters of for each case and configuration are given in Table I. Cases 1, 2 and 3 refer to a single layer soil, while cases 4, 5, 6 and 7 represent multilayer soil for which the depth of the first layer is set to h =1m. It is assumed that relative permittivity in modeling of grounding system considering constant parameters is equal to 10 for all cases.

5 Simulation Results

In this section, in order to analysis the electrical parameters frequency dependence effect of soil, single layer and multi

Table 1: Electrical Parameters of The Multilayer Soil

CASES	L	ρ_{01}	ρ_{02}	ε_{r1}	ε_{r2}
Case 1	3	10	10	10	10
Case 2	3	1000	1000	10	10
Case 3	24	1000	1000	10	10
Case 4	3	1000	100	10	10
Case 5	12	1000	100	10	10
Case 6	3	100	1000	10	10
Case 7	12	100	1000	10	10

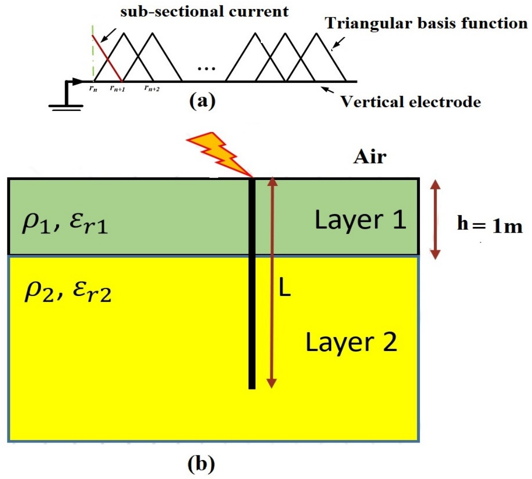

Figure 3: (a) Impressed-current excitation model for calculation of input impedance, (b) Vertical electrode buried in a soil.

layer soil structures of grounding systems are investigated. The MoM is used to simulate the response of buried electrodes. Relative permittivity and soil resistivity are used accordingly (15) and (17) for the case in which the soil is assumed to be frequency dependent.

5.1 Single layer soil

In case 1, a vertical electrode of length l = 3m is buried in a soil with resistivity ρ_0 and relative permittivity ε_r. We have considered an electrode radius of a = 15 mm, low-frequency resistivity of ρ_0= 10 Ω.m and a relative permittivity of ε_r = 10.

Figure 4 illustrates input impedance [magnitude, Phase] of the vertical electrode. The input impedance is calculated in frequency range of DC to 10 MHz for constant and frequency-dependent electrical parameters. As seen in Fig. 4, at higher frequencies and with low resistivity of soil, the inductive behavior is dominant for small electrodes.

In case 2, the vertical electrode with same length of l= 3m is evaluated (Figure 5). The soil is characterized by electric resistivity of ρ_0=1000 Ω.m and ε_r=10. The magnitude and the phase of the input impedance of grounding systems that further confirm the impact of the frequency dependence of soil electrical parameters on the performance of grounding electrodes. It is quite different from the previous case, in which the grounding electrode exhibits a inductive behavior over the frequency range of interest. Every increasing of length of electrode could be changed grounding system behavior from capacitive to inductive at same soil resistivity for each

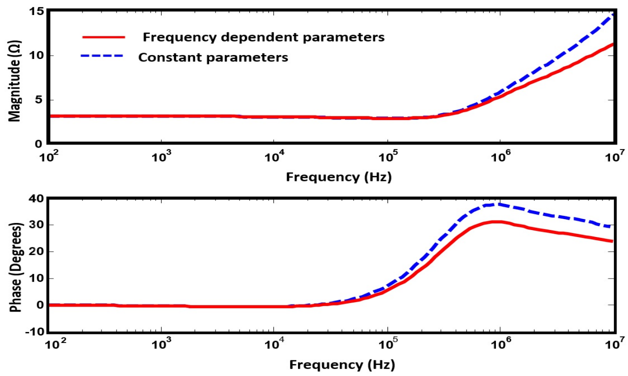

Figure 4: Input impedance of the vertical electrode of length l = 3 m. Red solid line: frequency dependent model and blue dashed line: constant parameters model. ρ_0=10 Ω.m, ε_r=10.

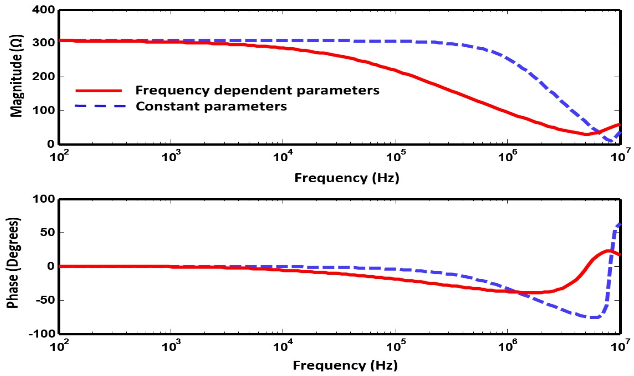

Figure 5: Input impedance of the vertical electrode of length l = 3 m. Red solid line: frequency dependent model and blue dashed line: constant parameters model. ρ_0=1000 Ω.m,ε_r=10.

layer. Also, if the vertical electrodes buried in soil with high resistivity , it is assumed that the length of electrodes are same, capasitive behavior of grounding system is more dominant at high frequency ranges.

In the case 3, Figure 6 presents the input impedance [magnitude, Phase] of the vertical electrode of length l = 24m that is buried in a soil with resistivity $\rho_0 = 1000$ Ω.m and relative permittivity $\varepsilon_r = 10$. At low frequencies, the impedance of vertical electrodes presents a resistive behaviour and assumes inductive behaviour at high frequencies. This behavior agrees with our anticipation of inductive behavior of grounding electrodes of long length buried in high resistive soils with respect to small and moderate grounding electrodes that usually reveal an capacitive behavior [2].

5.2 Multi-layer soil

In this section, to demonstrate the efficiency of presented method for evaluating the frequency dependence of multilayer soil electrical parameters effects on the input impedance of grounding systems that are buried in a multilayer soil, four case studies are considered. The vertical electrode is excited from its top by a 1A- current source and we consider four cases (4-7). The depth of the upper soil layer is set to h =1m. The adopted values for the soil electrical parameters for each case are given in Table I. The overall geometry of this grounding electrode is shown in Figure 3. Referring to (15) and (17), both resistivity and relative permittivity of the

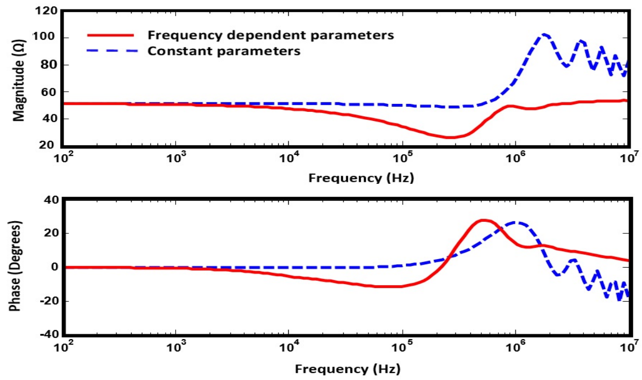

Figure 6: Input impedance of the vertical electrode of length l = 24 m. Red solid line: frequency dependent model and blue dashed line: constant parameters model. ρ_0=1000 Ω.m,ε_r=10.

soil are assumed to be frequency-dependent. The obtained simulation results are compared with calculated results using constant electrical parameters of soil.

In case 4, a vertical electrode with length of l=3m is considered. The soil is characterized by top layer resistivity of ρ_{01}=1000 Ω.m and down layer resistivity of ρ_{02}=100 Ω.m, and relative electric permittivity of ε_r=10. In case 5, the same vertical grounding electrode with a different length of l= 12 m is analyzed. Also, to analysis the frequency-dependence effect of soil electrical parameters, the same geometry of grounding system is considered. ρ_{01} and ρ_{02} are low-frequency resistivity of soil. simulation results confirm the effect of the frequency dependence of soil electrical parameters on the performance of grounding electrodes buried in multilayer soil with and without frequency dependent assumption. Further examination on Figure 7 and Figure 8 reveal that the inductive or capacitive behavior of grounding electrodes is mainly determined by the soil electrical parameters as well as the length of the electrode. The low-frequency value of magnitude of input impedance in case 4 is higher than case 5, but at high frequency range with increasing the length of electrode, the inductive behavior of case 5 is dominant. Also shown in Figure 7 and Figure 8 are the curves associated with the magnitude and the phase of the input impedance when soil electrical parameters are considered to be frequency dependent. It is clearly seen that the frequency dependence of the soil electrical parameters affects the performance of the grounding electrode so that its input impedance magnitude shows a lower value at high frequency compared to the case with constant parameter soils.

In case 6, a vertical electrode with length of l=3m is considered. The soil is specified by top layer resistivity of ρ_{01}=100 Ω.m and down layer resistivity of ρ_{02}=1000 Ω.m, and relative electric permittivity of ε_r=10. The same soil structure with a different electrode length of l= 12 m is analyzed in case 7. The magnitude and the phase of the input impedance of these grounding electrodes are shown in Figure 9 and Figure 10. As seen in Figure 9, at higher frequencies and for high resistive soil in down layer and based on small length of electrode, the capacitive behavior is dominant. In the case 6, low frequency resistance is larger than low frequency resistance of case 7. Moreover, it is interestingly observed that considering the frequency dependence of the soil resistivity

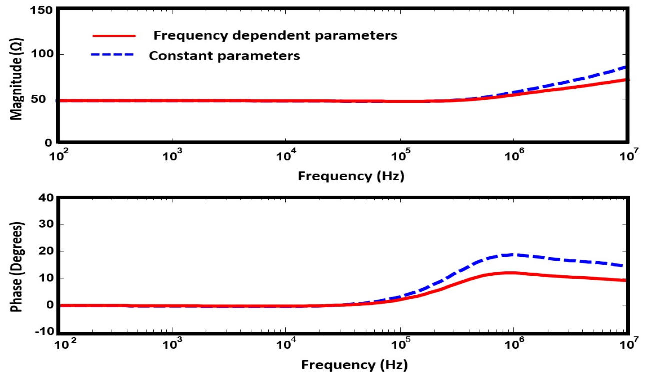

Figure 7: Input impedance of the vertical electrode of length l = 3m which is buried in two layer soil, ρ_{01}=1000 Ω.m, ρ_{02}=100 Ω.m and ε_r=10. Red solid line: frequency dependent model and blue dashed line: constant parameters model.

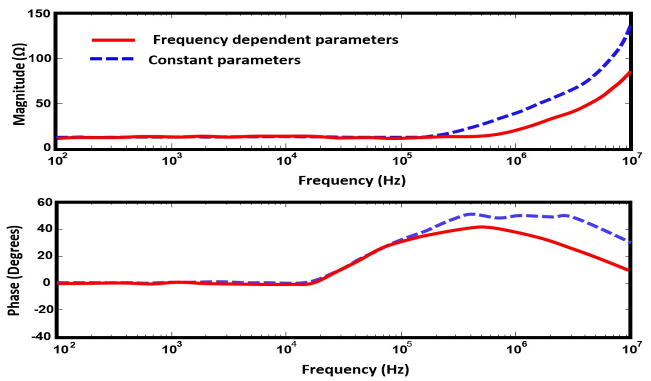

Figure 8: Input impedance of the vertical electrode of length l = 3m which is buried in two layer soil, ρ_{01}=100 Ω.m, ρ_{02}=1000 Ω.m and ε_r=10. Red solid line: frequency dependent model and blue dashed line: constant parameters model.

and relative permittivity leads to a more smooth variation of the input impedance at high frequencies. this is different from the oscillatory behavior (reported in [4]) obtained for soils with constant parameters. The frequency dependence of soil electrical parameters has a reduction effect on the magnitude of the grounding system impedance. Depending on the length of the electrode and the soil electrical parameters, in particular the soil resistivity, the grounding system might be dominan either inductive or capacitive. In case of inductive behavior, the input impedance at higher frequencies takes larger values than those of low frequencies. When the capacitive behavior is dominant, the input impedance at higher frequencies takes values less than those of low frequencies.

6 Conclusions

The MoM approach can be successfully applied to evaluate the behavior of grounding system buried in multilayer soil considering frequency dependency. Two types of grounding systems, namely a single layer and multilayer were studied. To this aim, the frequency dependence input impedance of vertical electrode with different geometry was obtained. Moreover, according to results, the frequency dependence of multi layer soil electrical parameters has a significant impact on the lightning performance of grounding electrodes. Therefore, in lightning-protection applications that require accurate results,

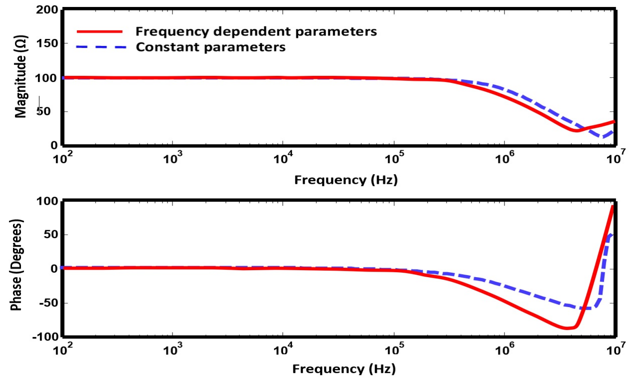

Figure 9: Input impedance of the vertical electrode of length l = 12m which is buried in two layer soil, ρ_{01}=1000 Ω.m, ρ_{02}=100 Ω.m and ε_r=10. Red solid line: frequency dependent model and blue dashed line: constant parameters model.

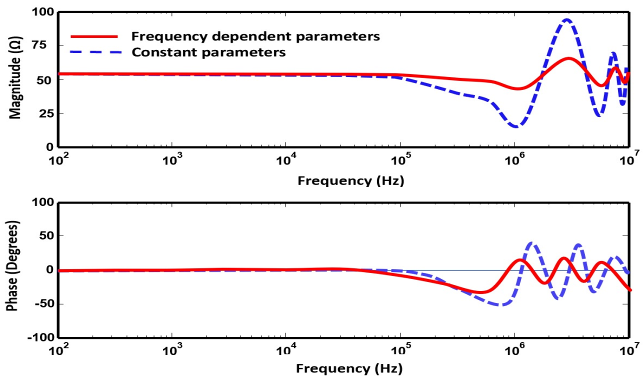

Figure 10: Input impedance of the vertical electrode of length l = 12m which is buried in two layer soil, ρ_{01}=100 Ω.m, ρ_{02}=1000 Ω.m and ε_r=10. Red solid line: frequency dependent model and blue dashed line: constant parameters model.

the frequency dependence of electrical parameters of soil should not be disregarded.

As expected, the frequency dependence of soil electrical parameters has generally a reduction effect on the magnitude of the grounding system input impedance. The results denote a very strong frequency dependence of soil resistivity and permittivity for multilayer soil and a significant impact on the response of ground electrodes subjected to lightning currents. These findings partially explain the fact that the frequency content of the impulse current, soil electrical parameters of layers and grounding electrode length are the main factors participating in transient behavior and lightning performance of grounding systems.

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