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WIRE ANTENNA MODEL FOR TRANSIENT ANALYSIS OF SIMPLE GROUNDINGSYSTEMS, PART I: THE VERTICAL GROUNDING ELECTRODE

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Abstract—The paper deals with the transient impedance calculation for simple grounding systems. The mathematical modelmodel is based on the thin wire antenna theory. The formulation of the problem is posed in the frequency domain, while the corresponding transient response of the grounding system is obtained by means of the inverse Fourier transform. The current distribution induced along the grounding system due to an injected current is governed by the corresponding frequency domain Pocklington integro-differential equation. The influence of a dissipative half-space is taken into account via the reflection coefficient (RC) appearing within the integral equation kernel. The principal advantage of the RC approach versus rigorous Sommerfeld integral approach is simplicity of the formulation and significantly less computational cost.

The Pocklington integral equation is solved by the Galerkin Bubnov indirect boundary element procedure thus providing the current distribution flowing along the grounding system. The outline of the Galerkin Bubnov indirect boundary element method is presented in Part II of this work.

Expressing the electric field in terms of the current distribution along the electrodes the feed point voltage is obtained by integrating the normal field component from infinity to the electrode surface.

The frequency dependent input impedance is then obtained as a ratio of feed-point voltage and the value of the injected lightning current. The frequency response of the grounding electrode is obtained multiplying the input impedance spectrum with Fourier transform of the injected current waveform.

Finally, the transient impedance of the grounding system is calculated by means of the inverse Fourier transform. The vertical and horizontal grounding electrodes, as simple grounding systems, are analyzed in this work. The Part I of this work is related to the vertical

electrode, while Part II deals with a more demanding case of horizontal electrode.

1. INTRODUCTION

Grounding systems, such as buried vertical or horizontal electrodes and large grounding grids are important part of safety and electrical equipment protection in industrial and power plants.

The principal task of such grounding systems is to ensure the safety of personnel and prevent damage of installations and equipment, i.e., the configuration of grounding systems should avoid the values of transient step and touch voltages which determines the health hazard. The secondary purpose of grounding systems is to provide common reference voltage for all interconnected electrical and electronic systems.

Local inequalities of this reference potential and disturbances distributed along the grounding systems are a source of malfunction or even destruction of various components electrically connected with grounding systems. In particular, the induced transient voltages may cause serious damage of electronic equipment with low-signal levels sensitive to various types of electromagnetic interfaces.

Consequently, the analysis of the space-time distribution of transients along the grounding systems is necessary. One of the most important parameters arising from the transient analysis of a grounding system is the transient impedance.

In general, the transient response of any linear system could be obtained directly, by solving the time domain equations, or by frequency domain approach and inverse Fourier transform. The former approach is valid as far as the soil ionization effect can be neglected.

While the stationary behaviour of grounding systems is well investigated the transient analysis has been performed to a significantly less extent. Until now, there have been some studies dealing with the transient analysis of grounding systems based on analytical approaches, transmission line models and electromagnetic models [1–5].

Analytical approaches can be referred to as the network concept being based on the empirical approach, and the lumped circuit theory, respectively. However, these models approaches in definitely suffer from too many approximations. In particular, the calculation of the equivalent electrical network parameters, due to conductive or inductive coupling is rather difficult, in particular for the grounding systems of complex geometry.

A number of conventional approaches for transient analysis of grounding systems are usually related to the transmission line method (TLM) [2, 3]. TLM approach is, however, valid for long horizontal conductors, but not convenient for modelling vertical and especially interconected conductors. Moreover, the effect of the air-earth interface has often been neglected assuming the conductors to be buried at a very large depths [6]. Finally, TLM approach is not valid for low values of ground conductivity and it also neglects the effect of mutual coupling amoung the parts of the grounding system generating some errors.

The rigorous electromagnetic field approach to the analysis of the grounding system is based on wire antenna theory and is considered to be the most accurate approach [4, 5, 7]. This model is based on solving the corresponding thin electric field integral equation (EFIE) for half-space problems.

According to this approach the grounding system of interest is represented by a corresponding configuration of straight thin wire antennas buried in the surrounding soil. The soil is represented as a linear and homogeneous half-space characterized by its electrical parameters.

Through this rigorous approach the effect of an imperfectly conducting half-space is taken into account by the Sommerfeld integrals, appearing in the integral equation kernel. This approach, however, suffers from too long computational time for the evaluation of broadband frequency spectrum, consesquently, the rigorous approach is often regarded as too complex for practical applications, especially for large grounding grids and it should be avoided wherever is possible [8]. A useful study on validity of quasistatic theory compared to full wave theory was presented in [8]. One possible way of avoiding the computation of Sommerfeld integral is the use of modified image theory (MIT) [5, 9]. The MIT approach takes into account only the electrical properties of the soil, but not the burial depth as a parameter and it is stated to be valid up to 1 MHz.

This work deals with the transient impedance calculation of the vertical and horizontal grounding electrode, respectively, as simple grounding systems geometries. However, the approach can be readily extended to more complex geometries related to more realistic grounding systems.

The first part of this work deals with the vertical grounding electrode, while consideration of a more demanding case of horizontal electrode is taken up in Part II.

The analysis method presented in this paper is based on the Pocklington integro-differential equation formulation [4, 7] arising from the antenna theory, and also proposes a simplified reflection coefficient approach for the treatment of the half-space problem (instead of analytically demanding and numerically time consuming Sommerfeld integral approach [4, 5, 7–11]) is also proposed.

The current along the vertical grounding electrode is obtained by solving the corresponding integro-differential equation via the indirect scheme of the Galerkin-Bubnov Boundary Element Method (GB-BEM) [7, 9–11] and some illustrative numerical results are presented.

Further contribution of this work is a convenient procedure for the feed-point voltage evaluation. Firstly, the near electric field is expressed in terms of the current induced along the vertical electrode. The feed point voltage can be obtained by integrating the normal electric field from the electrode surface to infinity. The integration is avoided by utilizing the weak formulation of the problem.

The input impedance of the grounding electrode, i.e., the transfer function of the linear system, is defined as a ratio of evaluated voltage and injected lightning current at the feed point.

The frequency response of the grounding electrode is obtained multiplying the input impedance spectrum with Fourier transform of the lightning current waveform.

Finally, the transient impedance of the gounding electrode is computed by means of the inverse Fourier transform.

Some illustrative numerical results for the input impedance spectrum and transient impedance are presented in the paper.

2. INTEGRAL EQUATION FOR THE INDUCED CURRENT ALONG THE ELECTRODE

The geomatry of interest is a vertical straight wire of length L and radius a, buried in a lossy medium at depth d shown in Fig. 1. The wire is assumed to be perfectly conducting and the wire dimensions satisfy the well known thin wire approximation [4, 7, 8, 11], so the current along the wire is z-directed only.

The starting point in the mathematical model is the assessment of the current distribution induced along the vertical electrode due to a time-harmonic excitation and for a number of frequencies within a frequency band of interest. This current distribution is goverened by the Pocklington integro-differential equation. This integro-differential equation can be derived by expressing the electric field in terms of the Hertz vector potential and by satisfying the boundary conditions for the tangential field components at the electrode surface.

The complete electric field induced in the vicinity of the straight thin wire of finite length buried in an imperfectly conducting half-space

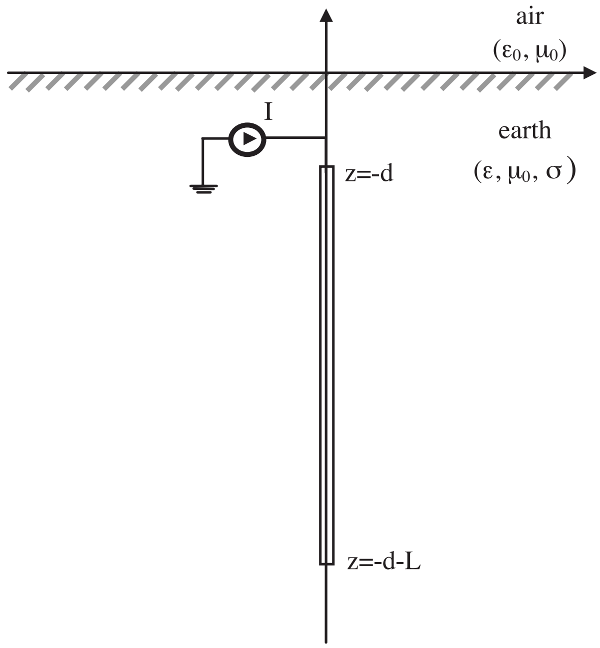

Figure 1. Vertical grounding electrode energized by a current source I_g.

can be expressed in terms of Hertz vector potential Π [7]:

$$\vec{E} = \nabla(\nabla\vec{\Pi}) + k_1^2\vec{\Pi} \tag{1}$$

where k_1 is the phase constant of a lossy ground:

$$k_1^2 = -\omega^2\mu\varepsilon_{eff} \tag{2}$$

and ε_{eff} denotes the complex permitivity of the lossy ground:

$$\varepsilon_{eff} = \varepsilon_r\varepsilon_0 - j\frac{\sigma}{\omega} \tag{3}$$

where ε_r and σ are the relative permitivity and conductivity of the ground respectively, and ω denotes the operating frequency.

A corresponding integral equation formulation for the vertical grounding electrode using the both Sommerfeld and RC approach is presented in Subsections 2.1 and 2.2, respectively.

2.1. Sommerfeld Integral Approach

For the case of vertical grounding electrode energized by a current source I_g the vector equation (1) can be written as a set of two scalar equations for the normal x-component and tangential z-component of the electric field due to the vertical electrode:

$$E_x^V(x,z) = \frac{\partial^2 \Pi_z^V}{\partial x \partial z} \tag{4}$$

$$E_z^V(x,z) = \left[\frac{\partial^2}{\partial z^2} + k_1^2\right] \Pi_z^V \tag{5}$$

where superscript V denotes the vertical electrode.

The vector potential z-component is given by [7]:

$$\Pi_z^V = \frac{1}{j4\pi\omega\mu\varepsilon_{eff}} \int_{-d-L}^{-d} \left[g_0^V(x,z,z') - g_i^V(x,z,z') + k_2^2 V_{11}\right] I(z')dz' \tag{6}$$

where $I(z')$ is the unknown current distribution along the vertical straight wire, $g_0(x,z,z')$ denotes the free space Green function of the form:

$$g_0^V(x,z,z') = \frac{e^{-jkR_{1vI}}}{R_{1v}} \tag{7}$$

while $g_i(x,z,z')$ arises from the image theory and is given by:

$$g_i^V(x,z,z') = \frac{e^{-jk_2 R_{2v}}}{R_{2v}} \tag{8}$$

where k_2 is the phase constant of free space:

$$k_2^2 = \omega^2 \mu \varepsilon_0 \tag{9}$$

and R_{1v} and R_{2v} are the distances from the wire in the ground and from its image in the air to the observation point in the lower medium, respectively.

The attenuation effect of the lossy ground is taken into account by the Sommerfeld integral term V_{11} [4]:

$$V_{11} = 2\int_0^\infty \frac{e^{-\mu_1(h-z)}}{k_2^2\mu_1 + k_1^2\mu_2} J_0(\lambda\rho)\lambda d\lambda \tag{10}$$

where $J_0(\lambda\rho)$ is zero-order Bessel function of the first kind, while μ_1, μ_2 and ρ are given by:

$$\mu_1 = \left(\lambda^2 - k_1^2\right)^{1/2}, \quad \mu_2 = \left(\lambda^2 - k_2^2\right)^{1/2}, \quad \rho = |z - z'| \tag{11}$$

The Pocklington integro-differential equation for the vertical straight wire buried in a lossy ground can now be obtained by enforcing the boundary conditions for the tangential electric field components on the perfectly conducting (PEC) wire surface. The total tangential electric field on the PEC wire surface at $x = a$ vanishes, i.e.,

$$E_z^{exc,V}(a,z) + E_z^{sct,V}(a,z) = 0 \tag{12}$$

where $E_z^{exc,V}$ denotes the excitation function and $E_z^{sct,V}$ is the scattered field along the electrode surface.

Combining the relations (5) to (12) leads to the Pocklington integro-differential equation for the vertical grounding electrode:

$$\begin{aligned} E_z^{exc,V} &= -\frac{1}{j4\pi\omega\varepsilon_{eff}} \int\limits_{-d-L}^{-d} \left[\frac{\partial^2}{\partial z^2} + k_1^2\right] \\ &\quad \cdot \left[g_0(z,z') - g_i(z,z') + k_2^2 V_{11}\right] I(z')dz' \end{aligned} \tag{13}$$

Solving the integral equation (13) the current distribution along the electrode is obtained.

2.2. Reflection Coefficient Approach

The repeated evaluation of the Sommerfeld integral (10) at several frequencies, by which the earth-air attenuation effect is taken into account, is rather difficult and time consuming task [4, 7–12].

Therefore, this work deals with a reflection coefficient (RC) approach which principal advantage versus rigorous Sommerfeld integral approach is simplicity of the formulation and significantly less computational cost.

For convenience, the integro-differential equation (13) can be written in the form:

$$E_z^{exc} = -\frac{1}{j4\pi\omega\varepsilon_{eff}} \int\limits_{-d-L}^{-d} G^V(z,z') I(z,z') dz' \tag{14}$$

where $G(z,z')$ is the total Green function given by:

$$G^V(z,z') = \left[\frac{\partial^2}{\partial z^2} + k_1^2\right] \left[g_0^V(z,z') - g_i^V(z,z') + k_0^2 V_{11}\right] \tag{15}$$

According to the RC approximation [7] the rigorous Green function simplifies into:

$$G^V(z,z') = \left[\frac{\partial^2}{\partial z^2} + k_1^2\right]\left[g_0(z,z') + \Gamma g_i(z,z')\right]$$
$$= \left[\frac{\partial^2}{\partial z^2} + k_1^2\right] g^v(z,z') \tag{16}$$

where Γ is the corresponding reflection coefficient [6] for the TM polarization:

$$\Gamma = \frac{\frac{1}{\underline{n}} - \sqrt{\frac{1}{\underline{n}}}}{\frac{1}{\underline{n}} + \sqrt{\frac{1}{\underline{n}}}} \tag{17}$$

and $\underline{n}$ is given by:

$$\underline{n} = \frac{\varepsilon_{eff}}{\varepsilon_0} \tag{18}$$

Finallly, the resulting Pocklington integro-differential equation for the vertical straight wire buried in a lossy half-space is given by:

$$E_z^{exc,V} = -\frac{1}{j4\pi\omega\varepsilon_{eff}} \int\limits_{-d-L}^{-d} \left[\frac{\partial^2}{\partial z^2} + k_1^2\right] \left[g_0^V(z,z') + \Gamma g_i^V(z,z') I(z') dz'\right] \tag{19}$$

In this paper, the integro-differntial equation (19) is solved by means of the indirect Galerkin-Bubnov scheme of the Boundary Element method (GB-BEM). An outline of the applied numerical method is available in Part II of this work. Solving the integral equation (19) the equivalent current distribution is obtained.

2.3. Imposed Boundary Conditions

In the analysis of the grounding electrodes, the excitation function is not given in the form of electric field, as the wire is not illuminated by the plane wave [4]. Thus, the left-hand side of the equation (19) vanishes along the perfectly conducting (PEC) wire surface, i.e.,

$$E_x^{exc} = 0 \tag{20}$$

and the integro-differential equation (19) becomes homogeneous.

The vertical electrode is energized by the injection of an arbitrary waveform current pulse produced by an ideal current generator with one terminal connected to the grounding electrode and the other one in the remote soil.

Thus, the excitation is given in the form of the current flowing into the electrode. This current source is included into the integral equation scheme through the simple boundary condition applied at the top of the electrode:

$$I(-d) = I_g \tag{21}$$

where I_g denotes the actual current generator.

In the frequency domain the unit current generator is always chosen, as its time domain counterpart is Dirac impulse.

3. THE EVALUATION OF THE INPUT IMPEDANCE SPECTRUM

The calculation of the vertical electrode input impedance is more demanding than in the antenna case, primarily because the input terminals are placed between electrode point and remote soil, and the tedious integration on the infinite integral cannot be avoided.

By solving the integral equations (19) the equivalent current distribution along the vertical electrode is obtained and the input impedance can be computed. It is worth noting that this input impedance depends only on the grounding system geometry and on the electrical properties of the surrounding soil.

The input impedance is simply defined by ratio [4]:

$$Z_{in} = \frac{V_g}{I_g} \tag{22}$$

where V_g and I_g are the values of the voltage and the current at the driving point, respectively.

The feed-point voltage is obtained by integrating the normal electric field component from the remote soil to the electrode surface, i.e.,

$$V_g = -\int_{\infty}^{a} \vec{E} d\vec{s} \tag{23}$$

Thus, the problem of obtaining the input impedance is related to the calculation of the feed-point volatge. The spectrum of input impedance is obtained by repeating this procedure in the wide frequency band.

For the given geometry of the vertical electrode integral (23) becomes:

$$V_g = -\int_{\infty}^{a} E_x^V(x, z) dx \tag{24}$$

Since only the Π_z component of the Hertz vector potential exists the E_z component of the electric field is given by:

$$E_x^V(x,z) = \frac{\partial^2 \Pi_z^V}{\partial x \partial z} = \frac{1}{j4\pi\omega\varepsilon_{eff}} \int_{-d-L}^{-d} I(z') \frac{\partial^2 g^V(x,z,z')}{\partial x \partial z} dz' \tag{25}$$

Numerical treatment of the expression (25) can be simplified by featuring the weak formulation of the problem [7, 9–11]. Namely, utilizing the property of Green functions for the source and image wire, respectively:

$$\frac{\partial g_0^V(x,z,z')}{\partial z} = -\frac{\partial g_0^V(x,z,z')}{\partial z'} \tag{26}$$

$$\frac{\partial g_i^V(x,z,z')}{\partial z} = \frac{\partial g_i^V(x,z,z')}{\partial z'} \tag{27}$$

and performing the integration by parts it follows:

$$\begin{aligned} E_x^V(x,z) =& -\frac{1}{j4\pi\omega\varepsilon_{eff}} \frac{d}{dx} \left[I(z') g^V(x,z,z') \Big|_{z'=-d-L}^{z'=-d} \right. \\ & \left. - \int_{-d-L}^{-d} \frac{\partial I(z')}{\partial z'} g_0^V(x,z,z') dz' + \int_{-d-L}^{-d} \frac{\partial I(z')}{\partial z'} \Gamma g_i^V(x,z,z') dz' \right] \end{aligned} \tag{28}$$

Obviously, the mixed second-order differential operator is removed from the integral equation kernel G^V.

Furthermore, substituting the equation (25) into (24) the following expression for the feed point voltage is obtained:

$$\begin{aligned} V_g =& -\frac{1}{j4\pi\omega\varepsilon_{eff}} \int_a^\infty \frac{d}{dx} \left[I(z') g^V(x,z,z') \Big|_{z'=-d-L}^{z'=-d} \right. \\ & \left. - \int_{-d-L}^{-d} \frac{\partial I(z')}{\partial z'} g_0^V(x,z,z') dz' + \int_{-d-L}^{-d} \frac{\partial I(z')}{\partial z'} g_i^V(x,z,z') dz' \right] dx \end{aligned} \tag{29}$$

which simply leads to the expression:

$$V_g = \frac{1}{j4\pi\omega\varepsilon_{eff}} \left[I(-d) g^V(x,-d,z) - \int_{-d-L}^{-d} \frac{\partial I(z')}{\partial z'} g_0^V(x,z,z') dz' \right.$$

$$+ \int_{-d-L}^{-d} \frac{\partial I(z')}{\partial z'} g_i^V(x,z,z')dz' \Bigg|_{x=a}^{x=\infty} \Bigg] \tag{30}$$

in which the tedious numerical integration over infinite domain is avoided.

The desired input impedance of the vertical grounding electrode is finally defined by the relation:

$$Z_{in} = \frac{1}{j4\pi\omega\varepsilon_{eff}I_g}\Bigg[I(-d)g^V(x,-d,z) - \int_{-d-L}^{-d} \frac{\partial I(z')}{\partial z'} g_0^V(x,z,z')dz'$$

$$+ \int_{-d-L}^{-d} \frac{\partial I(z')}{\partial z'} g_i^V(x,z,z')dz \Bigg|_{x=a}^{x=\infty} \Bigg] \tag{31}$$

Calculating this relation in a wide frequency range gives the frequency spectrum of the input impedance.

4. CALCULATION OF THE TRANSIENT IMPEDANCE

The transient impedance, an essential parameter in grounding system design, is defined as a ratio of time varying voltage and current at the driving point [4]:

$$z(t) = \frac{v(t)}{i(t)} \tag{32}$$

where $i(t)$ represents the excitation function, i.e., the injected current at a top of the vertical electrode, as shown in Fig. 1.

This injected current represents the lightning channel current usually expressed by the double exponential function:

$$i(t) = I_0 \cdot (e^{-\alpha t} - e^{-\beta t}), \quad t \geq 0 \tag{33}$$

where pulse rise time is determined by constants α and β, while I_0 denotes the amplitude of the current waveform.

The Fourier transform of the excitation function is defined by integral [13]:

$$I(f) = \int_{-\infty}^{\infty} i(t)e^{-j2\pi ft}dt \tag{34}$$

Integral (34) can be evaluated analytically [11]:

$$I(f) = I_0 \cdot \left(\frac{1}{\alpha + j2\pi f} - \frac{1}{\beta + j2\pi f} \right) \tag{35}$$

The frequency components up to few MHz are meaningfully present in the lightning current Fourier spectrum with strong decreasing importance from very low to highest frequencies.

Multiplying the excitation function $I(f)$ with the input impedance spectrum $Z_{in} fj$ provides the frequency response of the grounding system:

$$V(f) = I(f) Z_{in}(f) \tag{36}$$

Applying the Inverse Fourier Transform (IFT), a time domain voltage counterpart is obtained. IFT of the function $V(f)$ is defined by the integral [13]:

$$v(t) = \int_{-\infty}^{\infty} V(f) e^{j2\pi ft} d\omega \tag{37}$$

As the frequency response $V(f)$ is represented by a discrete set of values the integral (37) cannot be evaluated analytically and the Discrete Fourier transform, in this case the Fast Fourier Transform algorithm, is used, i.e.,

$$v(t) = \mathrm{IFFT}(V(f)) \tag{38}$$

Implementation of this algorithm inevitably causes an error due to discretization and truncation of essentially unlimited frequency spectrum. The discrete set of the time domain voltage values is defined as [13]:

$$v(n\Delta t) = F \cdot \sum_{k=0}^{N-1} V(k\Delta f) e^{jk\Delta f n\Delta t} \tag{39}$$

where F is the highest frequency taken into account, N is the total number of frequency samples, Δf is sampling interval and Δt is the time step.

Finally, the transient impedance of the vertical grounding electrode is computed from relation (32). The transient impedance should be recalculated for each excitation function while the input impedance spectrum depends only on geometry of the grounding system and on characteristics of the surrounding soil.

5. NUMERICAL RESULTS

Figure 2 shows the current distribution induced along the grounding vertical electrode of length $L = 1\,\mathrm{m}$ and radius $a = 5\,\mathrm{mm}$ for two

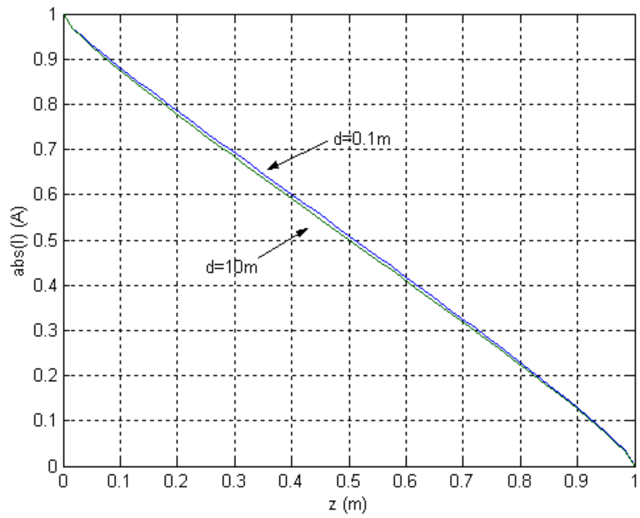

Figure 2. Current distribution along a grounding electrode ($L = 1\,\mathrm{m}$, $f = 1\,\mathrm{MHz}$, $\rho = 5400\Omega\mathrm{m}$).

different burial depths. As results clearly demonstrate, the influence of the burial depth to the induced current is negligible.

Figures 3 and 4 show the frequency spectrum of the input impedance for the grounding electrode of length $L = 1\,\mathrm{m}$ and $L = 2\,\mathrm{m}$, respectively, and radius $a = 5\,\mathrm{mm}$, buried in the ground at depth $d = 0.5\,\mathrm{m}$ with $\varepsilon_r = 10$. The specific resistance of the ground is $\rho = 5400\Omega\mathrm{m}$.

The results clearly demonstrate the influence of the electrode length to the input impedance.

The transient response of the vertical grounding electrode is evaluated using the relation (39). To avoid the discretization error, both the frequency range and the number of frequency samples have to be increased until satisfactory convergence is achieved. Although amplitude of the signal almost vanishes for the frequencies higher then 1 MHz, satisfactory results are obtained for frequency range of $F = 100\,\mathrm{MHz}$ and $N = 2^{16}$ samples as higher frequencies contain some significant information for the early time response. Grounding electrode is excited by the double exponential current pulse with parameters $I_0 = 1.1043\,\mathrm{A}$, $\alpha = 0.07924 \cdot 10^6\,\mathrm{s}^{-1}$, $\beta = 4.0011 \cdot 10^6\,\mathrm{s}^{-1}$. Figures 5 to 7 show different curves of the transient impedance of the vertical electrode for the case of variable wire length, burial depth and ground specific resistance. Radius of all electrodes is $a = 5\,\mathrm{mm}$.

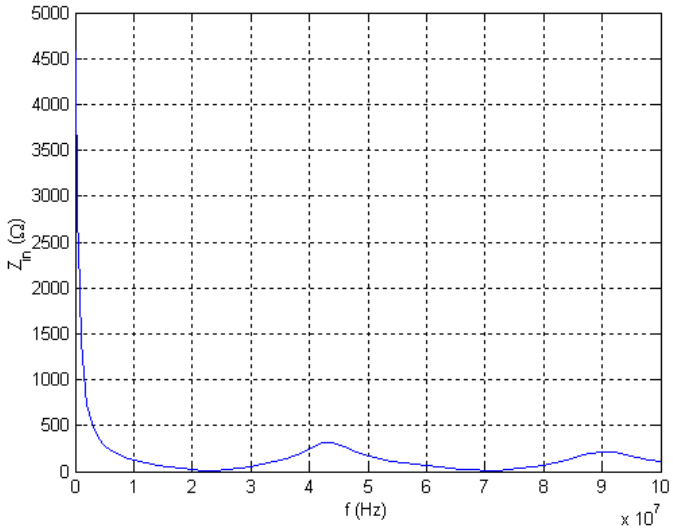

Figure 3. Input impedance spectrum ($L = 1\,\mathrm{m}$, $d = 0.5\,\mathrm{m}$, $\rho = 5400\Omega\mathrm{m}$).

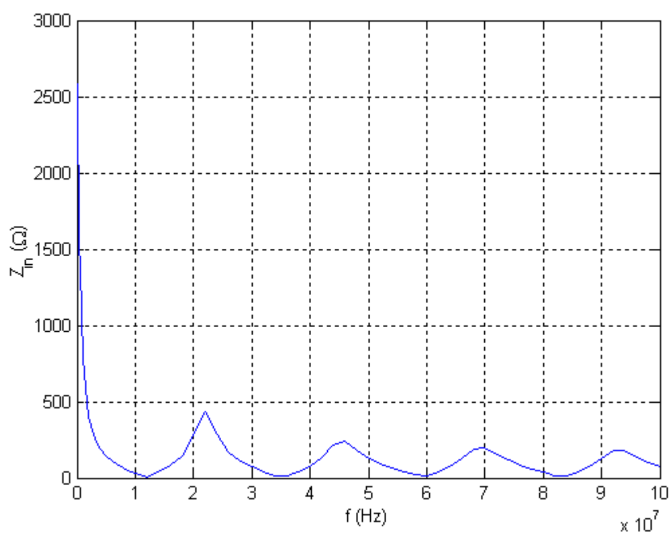

Figure 4. Input impedance spectrum ($L = 2\,\mathrm{m}$, $d = 0.5\,\mathrm{m}$, $\rho = 5400\Omega\mathrm{m}$).

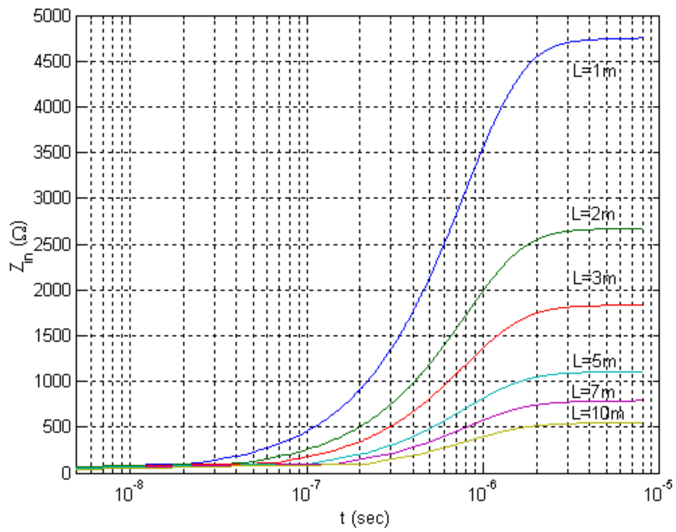

Figure 5. Transient impedance of the vertical grounding electrode with $d = 0.5\,\mathrm{m}$, $\rho = 5400\Omega\mathrm{m}$ computed for various wire lengths.

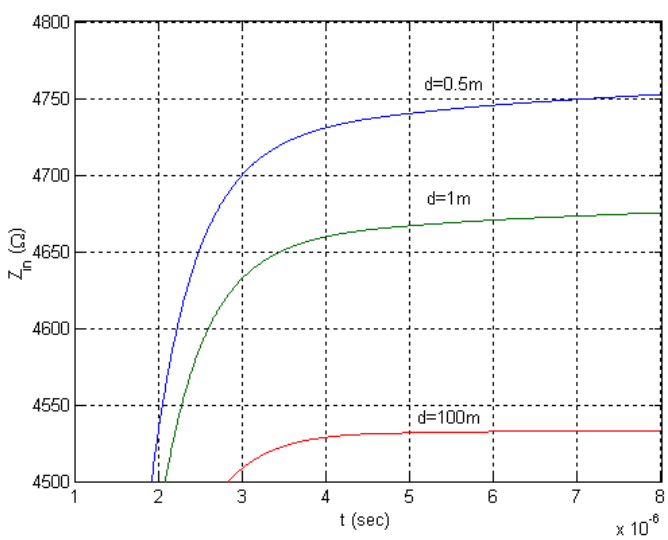

Figure 6. Transient impedance of the vertical electrode with $L = 1\,\mathrm{m}$ and $\rho = 5400\Omega\mathrm{m}$, computed for various burial depths.

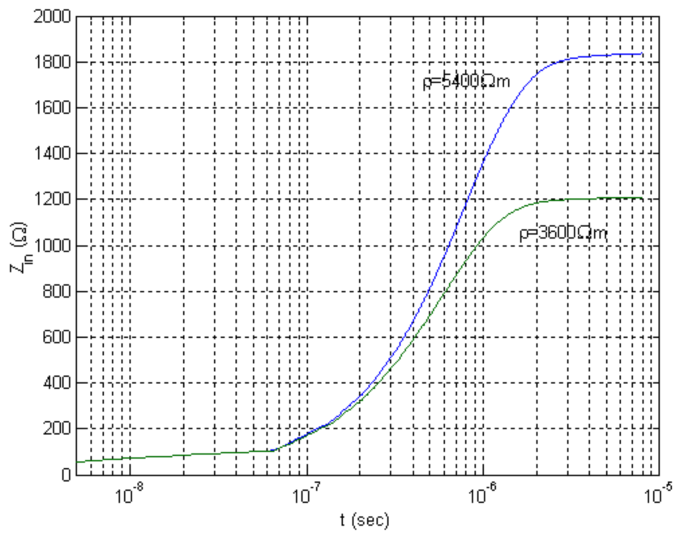

Figure 7. Transient impedance of the vertical grounding electrode with $L = 3\,\mathrm{m}$ and $d = 0.5\,\mathrm{m}$ computed for various values of the ground resistance.

It can be observed that the transient impedance values vary from zero towards the certain steady state value. Obviously, the transient impedance values are highly sensitive to the variations of electrode length, burial depth and properties of the ground resistance. As the current distribution along the electrode shows the low sensibility to the variations in burial depth, the high influence of the burial depth changes to the transient impedances obviously arise from the calculation of electric field. It is expectable, as the field is normal to the electrode but tangential to the interface of two different media.

6. CONCLUDING REMARKS

The transient impedance calculation of the vertical grounding electrode based on the antenna theory approach is presented in this work. The analysis is carried out in the frequency domain and the time domain results are obtained by using the inverse Fourier transform.

The vertical grounding electrode is represented by the straight end-fed wire antenna, buried in a lossy medium.

First step in the analysis is the evaluation of the equivalent current distribution along the electrode. The current distribution is governed by the Pocklington integro-differential equation.

The influence of the nearby air-earth interface is taken into account by the reflection coefficient appearing within the integro-differential equation kernel. The integro-differential equation is solved by the indirect Galerkin-Bubnov variant of the boundary element method (GB-BEM).

Electric field components at an arbitrary point in the lossy medium can be in principle evaluated directly from the previously calculated current distribution. Input impedance is obtained by analytically integrating the electrical field from the electrode surface to the infinity.

The frequency response of the grounding electrode is obtained by multiplying the analytically evaluated Fourier transform of the current pulse with the input impedance spectrum.

Finally, the transient impedance of the grounding wire is computed using the Inverse Fast Fourier Transform (IFFT). Obtained numerical results show that the transient impedance of the vertical grounding electrode is significantly influenced by the variation of electrode length, its burial depth and the specific resistance of the ground.

This procedure shows some advantages over rigorous approaches based on Sommerfeld integrals, primarily in simplicity and computational efficiency. The method presented in this work for the case of vertical grounding electrode is readily applicable to horizontal electrodes and complex grounding systems consisting of interconnected conductors.

An extension of the reflection coefficient approach to the analysis of the horizontal grounding electrode is presented in Part II of this work.

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