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Finite-difference modeling of dispersive soils validated via experimental evaluation of transient grounding signals

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ABSTRACT

In this paper, we develop a soil dispersion model into the FDTD algorithm for analyzing grounding systems. The model is constructed by inserting into frequency-domain Maxwell-Ampere equation a Padé approximant for $\boldsymbol{\sigma} + \boldsymbol{j}\omega\varepsilon$, in such way functions available in literature describing the frequency dependence of soil's parameters are properly represented. With adequate mathematical manipulations, time-domain equations for uptating electric field are obtained. The second contribution of this paper is the design and construction of a low-cost surge generator, which is used in the experiments as the voltage excitation source. The results show that the simulated signals are in excellent accordance with measurements.

1. Introduction

It is known that grounding systems are usually designed so that their steady-state parameters, such as ground resistances, are limited by a given threshold [1]. Meeting such kind of specification means that the designed system is efficient at draining currents to ground during low frequency events. However, grounding behavior is significantly different. High-frequency signals are present: the lightning surges [2] excite the grounding structures. For this reason several electrodynamic effects must be considered. First, the self and mutual inductances among the electrodes and cables become relevant. Second, because the displacement current becomes a more significant portion of the drained current to ground, this results on increased capacitive interaction between the electrodes and soil. Another important reason is that the soil in general is a dispersive material, that is, its electrical parameters vary with frequency [2]. In Ref. [3], it is shown that the soil's electrical conductivity and permittivity are strongly frequency-dependent over the frequency band that is representative of lightning signals ($0 - 2$ MHz). As a consequence, the effect of soil dispersion may significantly change the transient response of a grounding system [4]. This fact was observed in literature when comparing the experimental response of a grounding system subject to a high frequency signal to its theoretical response neglecting soil dispersion [5]. Therefore, it is important to take into account the effect of soil dispersion in the analysis of the transient behavior of a grounding system, aiming for a more realistic model and hence a comprehensive assessment of its performance upon critical high frequency events, such as lightning surges.

Motivated by those benefits associated with such a precise analysis, we evaluate the behavior of grounding systems considering the soil as a dispersive medium. The grounding systems were analyzed by means of field experiments, and each experiment is reproduced numerically with the Finite-Difference Time-Domain method (FDTD) [5]. A FDTD dispersive soil modeling technique is developed in this paper. The frequency-dependent curves of the soil's electrical conductivity and relative permittivity proposed by Visacro-Alipio [4] were fitted by Padé approximant for the term $\sigma + j\omega\varepsilon$, which is included in frequency-domain Maxwell-Ampère equation. The explicit FDTD updating equations for electric field were then obtained by employing appropriate mathematical manipulations. In field experiments, the excitation source is an own manufactured surge generator, of which two possible output signals are waveforms representing direct and subsequent lightning strokes. The parameters of these waveforms

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meet the specifications of standards IEC 60060-1 [6] and IEEE Std-4 [7].

Thus, the first contribution of this paper is to introduce for the first time a model for representing dispersive soils in FDTD for analyzing grounding systems. The second contribution is to provide a detailed description of the design and implementation processes of the surge generator used in our experiments.

2. Frequency-dependent electrical parameters

The interaction of electromagnetic fields with arbitrary media can be macroscopically described by Maxwell's equations and by material electromagnetic constitutive parameters: electric conductivity σ, electric permittivity ε and magnetic permeability μ. The electric permittivity is associated to the ability of a medium to become polarized when it is subjected to an external electric field. In this situation, the charges present in the medium are displaced and they form electric dipoles, which store energy in the form of electric potential energy. The stored energy depends on the frequency of the applied external field. While the charges are moving in response to the external field, energy is dissipated proportionally to the distance charges were displaced. In order to describe both the effects (energy storage and dissipation) for a medium subjected by a time-harmonic field of angular frequency ω, it is necessary to consider a complex permittivity given by

$$\overline{\varepsilon}(\omega) = \varepsilon'(\omega) - j\varepsilon''(\omega), \tag{1}$$

where the real part $\varepsilon'(\omega)$ is related to energy storage and imaginary part $\varepsilon''(\omega)$ is related to energy dissipation (losses due to the polarization process) [8–9].

Let us begin by considering the Maxwell-Ampère Law in frequency domain:

$$\nabla \times \overrightarrow{\mathbf{H}} = (\sigma_{DC} + j\omega\overline{\varepsilon}(\omega))\overrightarrow{\mathbf{E}}. \tag{2}$$

By substituting (1) in (2), we obtain

$$\nabla \times \overrightarrow{\mathbf{H}} = [\sigma_{DC} + j\omega(\varepsilon'(\omega) - j\varepsilon''(\omega))]\overrightarrow{\mathbf{E}} \Rightarrow \nabla \times \overrightarrow{\mathbf{H}} = [(\sigma_{DC} + \omega\varepsilon''(\omega)) + j\omega\varepsilon'(\omega)]\overrightarrow{\mathbf{E}}. \tag{3}$$

One may define the effective conductivity as $\sigma_{ef}(\omega) = \sigma_{DC} + \omega\varepsilon''(\omega)$ and the effective permittivity $\varepsilon_{ef}(\omega) = \varepsilon''(\omega)$. Then, (3) can be rewritten as:

$$\nabla \times \overrightarrow{\mathbf{H}} = \left(\sigma_{ef}(\omega) + j\omega\varepsilon_{ef}(\omega)\right)\overrightarrow{\mathbf{E}}. \tag{4}$$

As it can be seen, the effective conductivity σ_{ef} is composed of a constant term σ_{DC} and a frequency-dependent function $\omega\varepsilon''(\omega)$. In general, literature shows that $\sigma_{ef}(\omega)$ increases with frequency rise while $\varepsilon_{ef}(\omega)$ decreases [4], [9–12]. In (4), we see that the electric conductivity and the electric permittivity are both frequency-dependent, characterizing the dispersive medium. Thus, for presenting the proposed formulation, we set $\sigma(\omega) = \sigma_{ef}(\omega)$ and $\varepsilon(\omega) = \varepsilon_{ef}(\omega)$.

3. Finite-difference modeling of isotropic dispersive media

The constitutive relations for isotropic dispersive media are given by

$$\overrightarrow{D}(t) = \varepsilon(t) * \overrightarrow{E}(t) = \int_0^t \overrightarrow{E}(t-\tau)\varepsilon(\tau)\,d\tau\,,\ \overrightarrow{J}(t) = \sigma(t) * \overrightarrow{E}(t) = \int_0^t \overrightarrow{E}(t-\tau)\sigma(\tau)\,d\tau \text{ and } \overrightarrow{B}(t) = \mu\,\overrightarrow{H}(t). \tag{5}$$

From the relations given in (5), Maxwell's equations for dispersive media are given by:

$$\frac{\partial\overrightarrow{D}}{\partial t} + \overrightarrow{J} = \nabla \times \overrightarrow{H} \Rightarrow \frac{\partial\left(\varepsilon(t) * \overrightarrow{E}\right)}{\partial t} + \sigma(t) * \overrightarrow{E}(t) = \nabla \times \overrightarrow{H} \tag{6}$$

and

$$\frac{\partial\overrightarrow{B}}{\partial t} = -\nabla \times \overrightarrow{E}. \tag{7}$$

By applying the Fourier transform to (6) and by performing the proper algebraic manipulations, one may write:

$$(\sigma(\omega) + j\omega\varepsilon(\omega))\overrightarrow{\mathbf{E}} = \nabla \times \overrightarrow{\mathbf{H}}. \tag{8}$$

In this work, we use the expressions proposed by Visacro and Alipio in Ref. [4] to describe the frequency dependence of soil electrical resistivity and relative permittivity. These expressions are as follows

$$\rho(\omega) = \rho_{DC}\left\{1 + \left[1.2 \times 10^{-6} \cdot \rho_{DC}^{0.73}\right] \times \left[\left(\frac{\omega}{2\pi} - 100\right)^{0.65}\right]\right\}^{-1} \tag{9}$$

and

$$\varepsilon_r(\omega) = 7.6 \times 10^3 \left(\frac{\omega}{2\pi}\right)^{-0.4} + 1.3, \tag{10}$$

where ρ_{DC} is the soil resistivity for very low frequency ($f \approx 0$ Hz) and $\varepsilon_r(\omega)$ is the relative permittivity of the medium as function of ω. Equation (9) is valid for frequencies ranging from 100 Hz to 4 MHz, while (10) is valid for frequencies ranging from 10 kHz to 4 MHz. For expressing the relative permittivity below 10 kHz, Visacro and Alipio [4] suggested using the value given by (10) at 10 kHz. The electric conductivity and electric permittivity are obtained by $\sigma(\omega) = \rho(\omega)^{-1}$. and $\varepsilon(\omega) = \varepsilon_0\varepsilon_r(\omega)$, respectively.

The main goal is to obtain a Padé approximation [13, 14], for $\sigma(\omega) + j\omega\varepsilon(\omega)$ and include this approximation in the FDTD (Finite-Difference Time-Domain) method [5], [15]. Mathematically, we have

$$\sigma(\omega) + j\omega\varepsilon(\omega) \approx \frac{a_0 + a_1(j\omega) + a_2(j\omega)^2 + \ldots + a_\alpha(j\omega)^\alpha}{1 + b_1(j\omega) + b_2(j\omega)^2 + \ldots + b_\beta(j\omega)^\beta}. \tag{11}$$

In this work, we have observed that $\alpha = \beta = 1$ is sufficient for representing (9) and (10) with (11). Therefore, one has

$$\sigma(\omega) + j\omega\varepsilon(\omega) \approx \frac{a_0 + a_1(j\omega)}{1 + b_1(j\omega)}. \tag{12}$$

The complex coefficients a_0, a_1 and b_1 are obtained by using the least squares method [16], with which we solve a complex system of linear equations. The application of (12) into (8) leads to