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The influence of soil electrical parameters on the electric field due to power line communications: Measurements of frequency-dependent soil parameters

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ABSTRACT

The contribution of the present work is to demonstrate the influence of soil electrical parameters (conductivity and permittivity) on the electric field generated by power line communications (PLC). Soil samples were collected from beneath the high-voltage transmission lines under investigation and analyzed in the laboratory using a simplified method of measuring scattering parameters. These were converted into ABCD parameters in order to obtain the characteristic impedance and then the complex permittivity as a function of frequency. The employed methodology to find the soil electrical parameters as a function of the frequency was compared to the Smith and Longmire model, which is appropriate for modeling in the frequency range of PLC signals. The results obtained by both models for calculating the electrical parameters were applied to the electric field equations developed by D'Amore. Although high-voltage transmission lines generally use narrowband PLC for control system operations, the present work implemented both narrow and broadband analyses.

1. Introduction

One of the most analyzed aspects of PLC systems is the phenomenon of electromagnetic compatibility, which has been investigated from a variety of viewpoints [1,2]. Firstly, it is important to recognize that the radiated electric field of a PLC system depends on how the circuit has been set up [3,4]. Vertical or horizontal circuits present their own characteristics in a wave propagation study. One further aspect is the fact that the presence of the earth cannot be neglected in the electrical parameter model of the transmission line. Thus, broadband PLC systems must incorporate the ground admittance for high frequency signals and/or poor conductive ground [5,6]. Indeed, several important results were provided by Carson [7], Sunde [8], Kikuchi [9], Wait [10] and D'Amore [11] concerning the problem of wave propagation in overhead wires above lossy grounds. In general, the employed soil electrical parameters are constant values. However, it is well known that changes occur due to the frequency, and therefore soil sample analysis is able to provide important design orientations. These play a significant role in the calculation of electric fields generated by transmission lines. Recently, Cavka [12] presented a comparison of several models regarding the frequency dependence of soil electrical parameters. The results of this work are mainly applied to grounding system calculations. Of all the mentioned models, Smith and Longmire provide the only expressions appropriate for predicting values in the PLC frequency range, since the model presents curve fitting equations for a frequency range of 100 Hz to 200 MHz. However, this paper contains slight modifications in comparison to the original work [13], since the input parameter is conductivity rather than moisture content. Other similar works have also investigated soil electrical parameters with frequency dependence in order to obtain an accurate analysis of grounding systems [14,15]. Another field of investigation concerning soil frequency dependence was developed by Alipio [16], who evaluated the electric fields generated by grounding electrodes in the soil with electrical parameters as a function of the frequency. It may be noted that soil frequency dependence is still a current theme and should therefore be taken into account when calculating soil electrical parameters. To the best of the authors' knowledge, the use of microwave network analysis through impedance matrix to obtain soil electrical parameters has not been considered elsewhere. Therefore, compared with other previously published studies, the present work demonstrates a simplified method for investigating the electric field generated by high-voltage transmission lines, working as carrier channels. However, it is essential to present the main aspects for calculating the electromagnetic fields.

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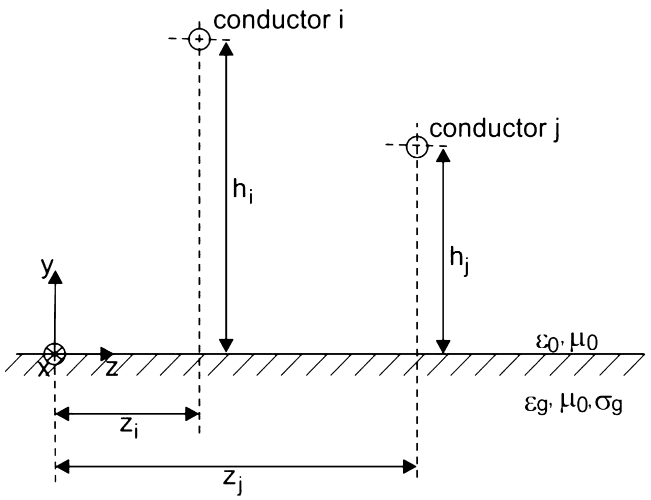

Fig. 1. General configuration of a multiconductor transmission line.

2. Electric field – formulation

The electric field can be expressed as a function of *Hertz* potentials. Eq. (1) shows the electric field **E** (V/m) as a function of the electric *Hertz* potential Π_e (V/m) and the magnetic *Hertz* potential Π_h (A/m) [17].

$$\mathbf{E} = -\gamma^2 \boldsymbol{\Pi} e + \nabla(\nabla \cdot \boldsymbol{\Pi} e) - i\mu\omega\nabla \times \boldsymbol{\Pi} h \tag{1}$$

It should be said that γ (m^{-1}) represents the complex propagation constant and μ (H/m) the permeability of the medium, respectively. Considering the conductor cables as thin wires of infinite length, located at a height h over lossy ground, it is possible to express the *Hertz* potentials as a function of the geometrical and electrical characteristics of the system compounded by the transmission line, the air and the soil itself.

To clarify this, Fig. 1 illustrates a general configuration of a transmission line above lossy ground where the soil has permittivity ε_g (F/m) and conductivity σ_g $(\Omega\,\mathrm{m})^{-1}$.

A brief review of the electric and magnetic *Hertz* potentials is presented below by Eq. (2a) and Eq. (2b), respectively [18].

$$\boldsymbol{\Pi} e = -\frac{j\omega\mu_0}{4\pi k_0^2} I_0 e^{-j\gamma x}\left(\int_{-\infty}^{\infty} e^{-u_0|y-h|}\frac{e^{-j(z-z_i)\lambda}}{u_0}d\lambda + \int_{-\infty}^{\infty} R_E(\lambda)e^{-u_0(y+h)}\frac{e^{-j(z-z_i)\lambda}}{u_0}d\lambda\right) \tag{2a}$$

$$\boldsymbol{\Pi} h = -\frac{j\omega\mu_0}{4\pi k_0^2} I_0 e^{-j\gamma x}\int_{-\infty}^{\infty} R_H(\lambda)e^{-u_0(y+h)}\frac{e^{-j(z-z_i)\lambda}}{u_0}d\lambda \tag{2b}$$

In Eqs. (2a) and (2b), λ is an auxiliary constant of integration and the variables R_E and R_H represent the soil reflection coefficients for the electric and magnetic *Hertz* potentials, respectively, and are represented by Eq. (3a) and Eq. (3b) [19]:

$$R_E(\lambda) = -1 + u_0\frac{2k_0^2}{k_0^2-\gamma^2}\left(\frac{1}{u_0+u_g} - \frac{\gamma^2}{k_g^2u_0 + k_0^2u_g}\right) \tag{3a}$$

$$R_H(\lambda) = -\frac{\gamma\lambda}{j\omega\mu_0}\frac{2k_0^2}{k_0^2-\gamma^2}\left(\frac{1}{u_0+u_g} - \frac{k_0^2}{k_g^2u_0 + k_0^2u_g}\right) \tag{3b}$$

In Eqs. (3a) and (3b), u_0 and u_g are auxiliary variables as a function of the system propagation constant γ as well as of the air and soil propagation constants k_0 and k_g, respectively, which are presented in Eq. (4a) and Eq. (4b) [20]:

$$k_0 = \omega(\mu_0\varepsilon_0)^{1/2} \tag{4a}$$

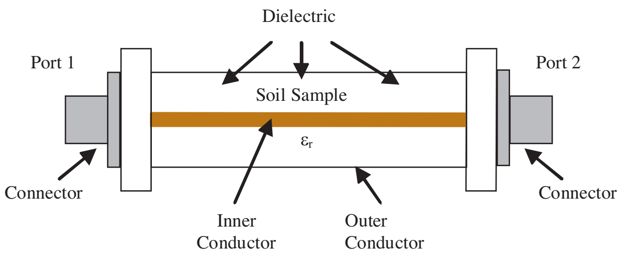

Fig. 2. Longitudinal sketch of a coaxial line filled inside with a soil sample.

$$k_g = k_0\left(\frac{\varepsilon_g}{\varepsilon_0} - \frac{j\sigma_g}{\omega\varepsilon_0}\right)^{1/2} \tag{4b}$$

The term inside the root in Eq. (4b) is the relative complex permittivity. It may be noticed that soil electrical parameters influence the electric field through the soil reflection coefficients R_E and R_H, which are inserted in the *Hertz* potential equations.

The next step consists of demonstrating how soil permittivity and conductivity may be encountered by network analysis methods with soil samples collected under actual transmission lines.

3. Methodology and theory

Through the use of a two-port device made with specific dimensions, it is possible to fill the inside with dielectric material. Fig. 2 shows a longitudinal sketch of a coaxial line filled inside with a soil sample.

The coaxial line filled with the soil sample being tested is connected to a vector network analyzer (Agilent E5071B) through which a transmission measurement is carried out for a specific frequency range. Using the impedance parameters from this measurement, the characteristic impedance Z_0 can easily be calculated. Fig. 3 shows the measurement set-up.

Measurements are grouped into a common file and then processed by a specific procedure developed as a function of the coaxial line characteristics.

From the countless basic publications it is possible to encounter the characteristic impedance Z_0 of a coaxial line with relative complex permittivity $\varepsilon_r = \varepsilon'_r - j\varepsilon''_r$ given by [21]:

$$Z_0 = \frac{\eta_0}{2\pi\sqrt{\varepsilon_r}}\ln\left(\frac{D}{d}\right) \tag{5}$$

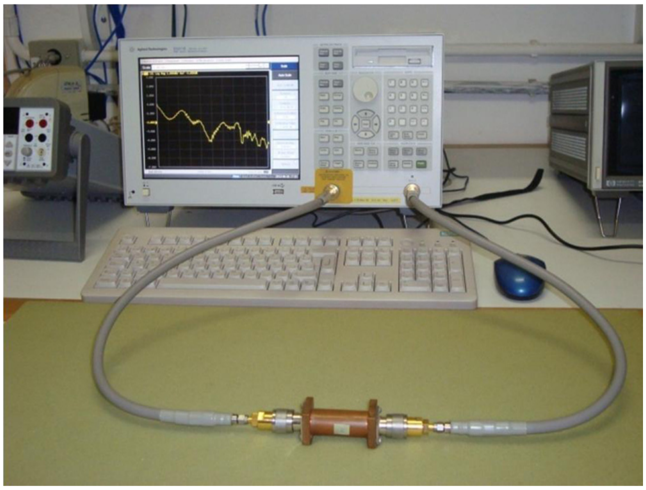

Fig. 3. Setup for a coaxial line filled with a soil sample as the dielectric material.