Earth Conductivity and Permittivity Data Measurements –Influence in Transmission Line Transient Performance

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Abstract-- In this work some procedures to measure and model soil electromagnetic behavior in frequency domain are presented. The soil samples were collected at Cachoeira Paulista, Brazil, southeastern region (22º 41.2 S, 44º59.0 W). The proposed model takes into account the earth conductivity and permittivity frequency dependence. Some procedures to reduce noise signals in the field measurement values are presented. The parameters of an actual 440 kV single three-phase transmission line were evaluated in frequency domain (considering the proposed soil model and the common representation with a constant conductivity and no permittivity), such as longitudinal line parameters, attenuation factor, phase velocity, and transfer function. It was possible to identify regions where not considering the proposed model could result in severe error.

Keywords: Soil model, Line parameters, Frequency dependence, Electromagnetic transients keywords.

I. INTRODUCTION

One of the essential requirements for studies and adequate simulation of transient phenomena in power systems is the adequate representation of ground effect. Most used procedures assume that the ground may be considered frequency independent, having a constant conductivity (σ) and an electric permittivity (ε) that can be neglected ($\omega\varepsilon << \sigma$). These three assumptions are quite far from reality and can originate an inadequate soil model for some applications, especially, fast transients phenomena as atmospheric discharges. It is necessary to have a proper knowledge of soil electromagnetic behavior in the frequency domain.

In [1-5] a new soil model is presented. This model satisfies the physical coherence conditions concerning the relation between conductivity (σ) and permittivity (ε) in the frequency domain, with results analyzed in 68 samples of the Amazon region. The physical model, with a small number of parameters, reproduces, within measurement accuracy and small heterogeneity effects, the measured results, assuring consistent physical behavior. The results presented in the paper were obtained in ten soil samples collected at Cachoeira Paulista, Brazil, southeastern region. The soil parameters obtained from soil samples in São Paulo State are coherent with results obtained previously from the Amazon Region. This coherence gives more confidence to field measurement procedures and to the proposed physical model because the samples were collected from sites 2000 km far from one another, with distinct geological characteristics. As an example of the importance of properly considering the soil modeling, an actual 440 kV single three-phase transmission line was represented considering the proposed soil model and the common representation with a constant conductivity and null permittivity. Some line parameters were evaluated in frequency domain, such as attenuation factor, phase velocity and transfer function. It was possible to identify regions were not considering the proposed model could result in severe error.

II. SOIL ELECTROMAGNETIC BEHAVIOR

Except for high electric field, where significant soil ionization occurs, soil electromagnetic is essentially linear, but with electric conductivity (σ) and electric permittivity (ε), strongly frequency dependent. The magnetic permeability, μ, is, in general, almost equal to vacuum permeability, μ_0.

For a slow variation of electromagnetic entities, hysteresis type behavior may occur. For direct current or very slow variation of electromagnetic entities, humidity migration phenomena, including electrosmosis and effects of temperature heterogeneity may take place. These phenomena cannot be dealt with only by means of local soil parameters.

For switching transients, the important frequency range goes up to 10 kHz, and it is shown that the homopolar mode has some discrepancies due to the soil representation used. For fast protection operation, such as fault detection, the important frequency range goes up to 100 kHz, and the soil model applied results in very different line parameters. For fast transients, namely those associated to lightning, the soil electromagnetic behavior is important in a reasonably wide frequency range, typically from 0 to 2 MHz. In this wide frequency range, apart from slow phenomena and hysteresis type phenomena, as commented above, soil behavior is typically of minimum phase shift type [2]. The model results are a sum of minimum phase shift parcels that apply to immittance type magnitude. In order to analyze the frequency behavior of conductivity (σ) and permittivity (ε) it is convenient to consider $W = \sigma + i\,\omega\,\varepsilon$ ($\omega = 2\,\pi$ f, being f the frequency) as an immittance [1-5]. In fact,

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apart geometric factor, W may be associated to the admittance of a volume element (sample soil). The function W may be interpreted as equivalent to the admittance of a continuous distribution of "infinitesimal" R-C (series resistor-capacitor) parallel circuits, with a relative density distribution associated to α.

For all soil samples modeled in this paper, it is accurate enough to consider two parcels for $\sigma + i\,\omega\varepsilon$, one constant (in most cases real), and the other of type (4) or of type (5), frequency dependent, described in [1-5]:

$$W = K_0 + K_1\,\omega^{\alpha} + i \cdot K_2\,\omega^{\alpha} \quad [\mathrm{S/m}] \tag{1}$$

$$\frac{K_2}{K_1} = \tan\left(\frac{\pi}{2}\,\alpha\right) \tag{2}$$

Where K_0, K_1, K_2 and α are constant and frequency independent. A variant form of relation (1) is

$$W = K_0 + K_2^{1M}\left[\operatorname{cotan}\left(\frac{\pi}{2}\,\alpha\right) + i\right]\left(\frac{f}{1\,\mathrm{MHz}}\right)^{\alpha} \tag{3}$$

Where: $K_0 = \sigma\ (\omega \to 0) \approx \sigma\ (100\ \mathrm{Hz})$ (4)

$$K_1^{1M} \approx \Delta\sigma = \sigma\ (1\ \mathrm{MHz}) - \sigma\ (100\ \mathrm{Hz}) \tag{5}$$

$$K_2^{1M} = \omega\,\varepsilon\ (1\ \mathrm{MHz}) \tag{6}$$

$$\frac{K_2^{1M}}{K_1^{1M}} = \frac{K_2}{K_1} = \tan\left(\frac{\pi}{2}\,\alpha\right) \tag{7}$$

α is a parameter of frequency dependence parcel of $\sigma + i\,\omega\varepsilon$. For all samples, α is the dominant parameter of the relative shape of a frequency dependent parcel, W, of $\sigma + i\,\omega\varepsilon$. For $\alpha \to 0$ such a parcel corresponds to a "pure" conductor (σ frequency independent, ε null). For $\alpha \to 1$, such a parcel corresponds to a "pure" dielectric. In all samples, for a frequency dependent parcel, a is in the range $0 < \alpha < 1$.

The two parcels of the second member of (3) are related to two different physical mechanisms and are statistically independent. In a few cases, there is a net hysteresis effect that can be modeled with an imaginary part of the constant parcel.

III. FIELD MEASUREMENTS PROCEDURE

Field measurements procedure has been chosen after extensive measure tests, with alternative procedures. The basic aspects related to collecting the sample are due to the necessity of [1-5]:

- Assuring maintenance and natural soil consistence and humidity, with sample material "identical" to natural soil characteristics.
- Avoiding influence of small depth surface effects, such as sun, wind and vegetation. These effects may originate an important dispersion, in time and space and special measurements difficulties. To consider such effects correctly, special methods, considering statistical distribution with space and time correlation, may be required. In most applications the error resulting of neglecting such effects is relatively small.
- Avoiding important effects of local soil heterogeneity.

For reasonably consistent soils, a cutting and collecting procedure is applied, obtaining samples with a cuboid shape (1.2 m x 0.2 m x 0.2 m), which are covered with a net, paraffin and a wood box. The procedures to collect the samples are illustrated in Figs. 1 to 3.

Figure 1 – Digging the hole and preparing the sample (photo: sample 1 – Cachoeira Paulista – 01/08/2002)

Figure 2 – Cuboid sample cut and covered with paraffin and net (photo: sample 3 – Cachoeira Paulista – 01/08/2002)

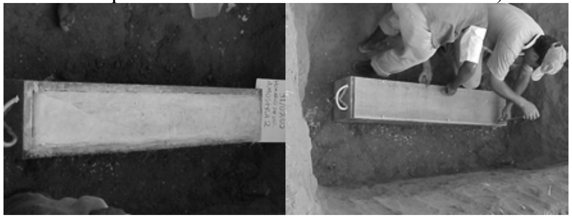

Figure 3 – Soil sample being protected by the wood box (photo: sample 2 – Cachoeira Paulista-31/07/2002)

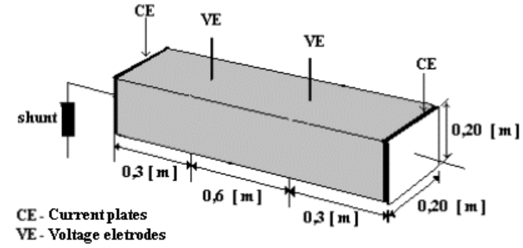

Figure 4 – Schematic representation of a soil sample for measurement of $\sigma + i\,\omega\varepsilon$ in frequency domain.

Two current copper plate electrodes (CE) were adapted at sample extremities (with adjusted pressure) and two copper cylindrical voltage electrodes (V_E) were inserted, with exemplificative geometry as in Fig. 4.

Through an oscillator with variable frequency f, it was imposed the sinusoidal voltage at the circuit. From the amplitude voltage at shunt terminal (V_R), which is related to the current, the amplitude voltage between electrodes (V), and the phase displacement (φ) between V_R and V, and geometric factors, it was possible to calculate $\sigma + i\,\omega\varepsilon$.

In some cases, especially for frequencies below 100 kHz, noise signals difficult a visual identification (or with oscilloscope cursors) of measurement amplitudes and phase (φ). To solve this problem it was necessary to filter the signals in order to reduce the harmonic content and facilitate the reading (see Figs. 5 and 6). In Fig. 5 an example of oscilloscope measured voltage (V) and current (V_R) in a soil sample for f = 1 kHz is presented. The presence of high frequency noise can be observed. The noise was an order of magnitude higher than the basic signal (at frequency 1 kHz). To solve the problem, a linear low-pass filter with cut frequency at 150 kHz was applied in order to reduce the harmonic content of field measurement. In Fig. 6 filtered signals are presented. The filter displaces equally both voltage signals V and V_R, keeping the phase displacement (φ) between them unchanged. Similar procedures were implemented in all the frequency range.

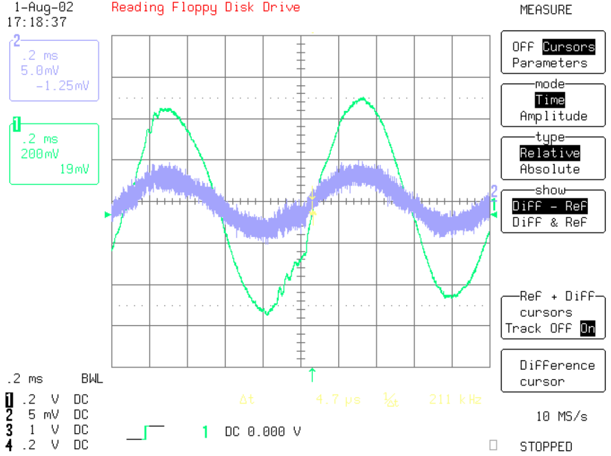

Figure 5 – Example of measured voltage and currents in a soil sample for f = 1 kHz

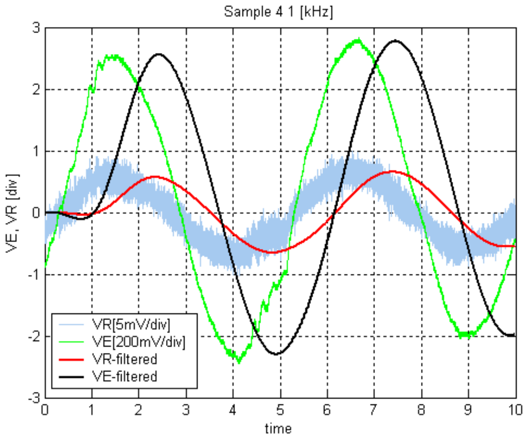

Figure 6 – Filtered signals of voltage and current in a soil sample for f = 1 kHz

The model parameters are chosen according to a minimum difference criterion between measured values and a physical model sample, with a minimum of adjusted numerical parameters (K_0, K_1, α), and considering error analysis. The measurements were carried out in a frequency range from 100 Hz to 2 MHz. In Fig. 7 the adjusted curves for all soil sample measurements are presented.

The measured soil samples at Cachoeira Paulista have high conductivity at lower frequencies (compared with common ranges in several other Brazilian soils), varying from 743.5 μS/m to 5800 μS/m, and the effects of soil frequency dependence become significant above of 10 kHz. In sample soils where the conductivity at lower frequencies is smaller than the measurement site case, frequency dependence is more prominent and become noticeable around 1 kHz.

IV. TRANSMISSION LINE PERFORMANCE

The schematic representation of the 440 kV single three-phase transposed line used in the simulations is shown in Fig. 8a. In order to implement the soil model, line parameters were calculated using the approximated formula, which includes earth effect in longitudinal impedance as being equivalent to having an ideal ground surface at a depth D' (complex) below physical ground surface [7], as illustrated in Fig. 8b.

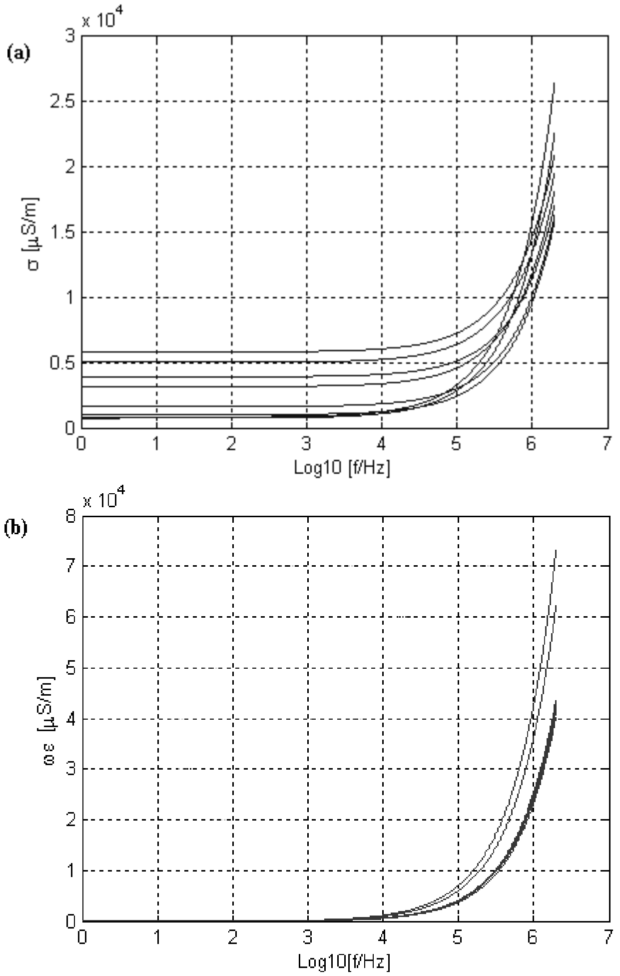

Figure 7 – Conductivity (a) and permittivity (b) of all soil samples collected at Cachoeira Paulista SP

Either in Deri's development [7] or in Carson's formulation [9] there is no imposition to have real soil conductivity. In fact, in linear conditions, in complex formulation of Maxwell's equations, e. g. referred to electromagnetic variables of the form $X\, e^{\pm i \omega t}$, the medium is characterized, only, by the parameters $\sigma + i \omega \varepsilon$ and $i \omega \mu$. So, in a formalism that complies with constraints of analytical functions of complex variables, as it is the case of integral Carson's formula and Deri's formula, it is enough to deal with those two parameters, or in other words, to substitute σ by $\sigma + i \omega \varepsilon$, to pass from the assumption of $\varepsilon = 0$ to the assumption of generic value of ε without the need of repeating the mathematical analytical manipulation. The Carson's series, however, are not, directly, and separately, analytical functions of complex variable, and the direct substitution of σ by $\sigma + i \omega \varepsilon$ must be avoided, some preliminary manipulation of series formalism being necessary. It must be said that, with presently available tools, there is no important reason to avoid the direct use of the integral Carson's formulas, naturally with adequate mathematical manipulation and precautions. Naturally, it is adequate to remember that the

Carson's integral formulas, and Deri's formula, are not "exact" (in the sense of resulting only from Maxwell's equations), and this implies in an accepted error associated to the assumed hypothesis in which formula may be considered reasonably accurate. However, that applies also if it is assumed that $\varepsilon = 0$.

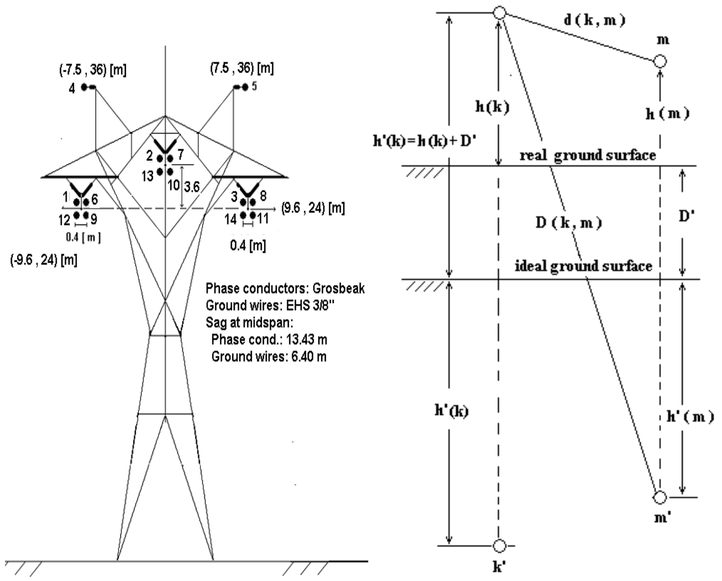

Figure 8 – (a) Schematic representation of the 440 kV three-phase line; (b) – Conductors k and m position supposing an ideal ground surface at a complex depth D'

The transmission line's longitudinal impedance matrix, per unit length, may be obtained considering:

$$Z^0\,(k,m) = Z_{int}\,(\,k,m\,) + Z_{ext}\,(\,k,m\,) \qquad (8)$$

where: k, m = 1, 2, ..., n (total number of conductors);

Z^0 - longitudinal impedance matrix element, per unit length;

Z_{int} – internal impedance, per unit length, of conductor k, for k = m, 0 for k ≠ m;

Z_{ext} - external impedance, per unit length, between conductors k and m;

$$D' = \frac{1}{\sqrt{(\sigma + i\omega\varepsilon)\cdot\omega\cdot\mu_0}} \qquad (9)$$

$$h'_k = h_k + D' \qquad (10)$$

$$Z_{ext} = i\frac{\omega\mu_0}{2\pi}\ln\frac{D_{k,m}}{d_{k,m}} \quad k, m = 1, 2, ..., n \qquad (11)$$

$$Z_{int} = \sqrt{\frac{i\,\omega\mu}{\sigma}}\,\frac{1}{2\pi R_1}\,\frac{I_0(\rho_1)K_1(\rho_0) + K_0(\rho_1)I_1(\rho_0)}{I_0(\rho_1)K_1(\rho_0) + K_0(\rho_1)I_1(\rho_0)} \qquad (12)$$

$$\rho_0 = R_0\sqrt{i\,\omega\mu\sigma} = R_0\sqrt{\omega\mu\sigma}\cdot e^{i\frac{\pi}{4}} \qquad (13)$$

$$\rho_1 = R_1\sqrt{i\,\omega\mu\sigma} = R_1\sqrt{\omega\mu\sigma}\cdot e^{i\frac{\pi}{4}} \qquad (14)$$

Where I_0, I_1, K_0, K_1 are the modified Bessel functions, R_0 and R_1 are the internal and external conductors' radius respectively.

Some line parameters were evaluated in frequency domain, such as the line resistance and inductance per unit length, the attenuation factor, the phase velocity and the transfer function. The 440 kV single three-phase transmission line was represented considering the proposed soil model (soil 2) and the common representation with a constant conductivity and null permittivity (soil 1). The conductivity of the studied soils were chosen to be equal at low frequency, in order to compare the obtained results, taking into account that traditional measurement of soil resistivity is done at low frequencies. The values presented in Table I were chosen to represent boundary conditions. More details of statistical distribution characteristics can be found in [5]. The measured values were within the range presented in Table I, but were not near extreme values.

Table I - Soil parameters used in the simulation

Parameters	Case 1 – High conductivity soil		Case 2 – Low-conductivity soil	
	Soil 1	Soil 2	Soil 1	Soil 2
K_0 [μS/m]	1700	1700	50	50
K_1 [μS/m.s^{-1}]	0	0.9	0	0.0021
α	0	0.62	0	0.82

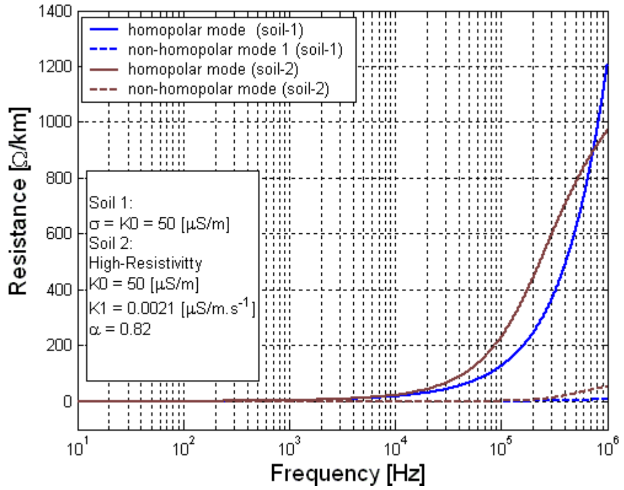

Figure 9 - Resistance per unit length comparing the both soil models – High resistivity soils

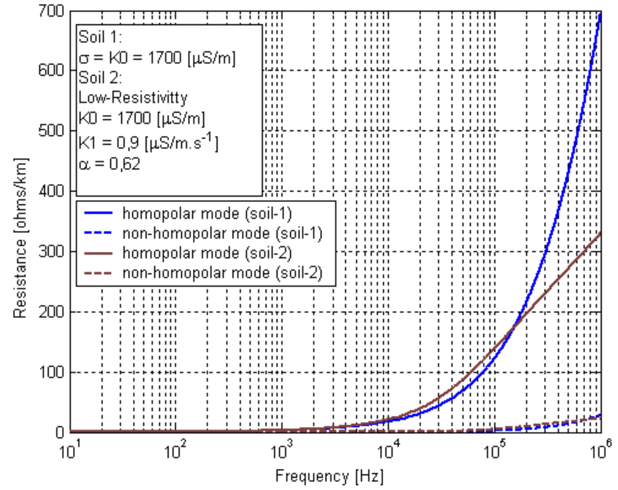

Figure 10 - Resistance per unit length comparing the both soil models – Low resistivity soils

V. RESULTS

The resistance per unit length for the transposed line using both soil models (soil 1 and 2) is presented for two different cases: considering high-resistivity soils (Fig. 9) and low-resistivity soils (Fig. 10). The difference between the resistance per unit length for the two soil models (soil 1 and soil 2) is important, namely for the homopolar mode (11 % for low-resistivity and 45 % high-resistivity 100 kHz). For fast transients, for which important frequency range may include frequencies above 10 kHz, the difference between the two soil models may also be important for non-homopolar modes (e. g., for 100 kHz) There is an order of magnitude difference in resistance per unit length, between the two soil models, for non-homopolar modes.

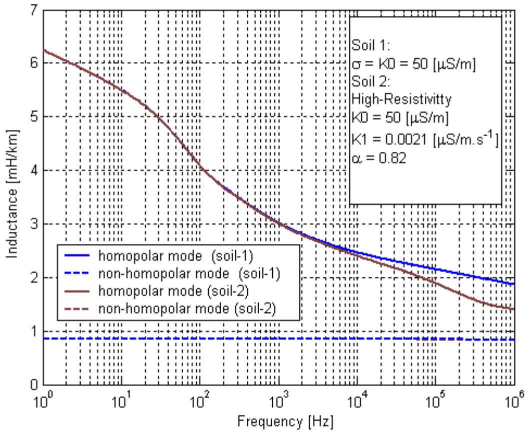

Figure 11 –The line inductance per unit length comparing the both soil models - High resistivity soils

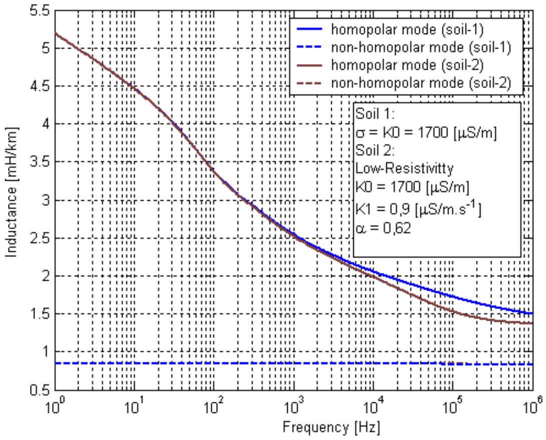

Figure 12 –The line inductance per unit length comparing the both soil models - Low resistivity soils

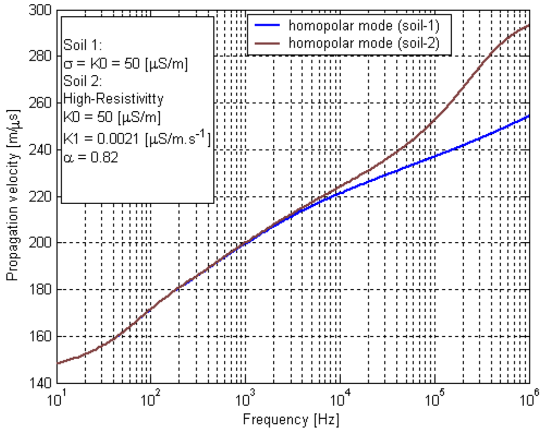

Figure 13 – Propagation velocity using both soil models - High resistivity soils

The inductances per unit length are presented comparing both soil models. The differences for homopolar mode are 13 % for low-resistivity soils (Fig. 12) and 17 % for high-resistivity soils (Fig. 11) at 100 kHz.

The propagation velocity (v), and attenuation factor ($e^{-\alpha \cdot l}$) were calculated using both soil models. They are described below and represented in Figs. 13 to 16 respectively, where:

$$\gamma = \alpha + i\,\beta = \sqrt{z \cdot y} \tag{15}$$

$$v = \frac{\omega}{\beta} \tag{16}$$

The attenuation factors for three different propagation distances, l, representing, by example, the distance between the fault location and the observation point, were calculated, specifically 30 km, 50 km and 300 km, for both models. As presented on Figs. 15 and 16, the difference between both models is more significant for frequencies above 1000 Hz. For long distances, even though the relative error for the attenuation factor is relevant, the attenuation factor is very low for not so high frequencies, around 10 kHz. For shorter distances, as 30 km or 50 km, the discrepancy at the attenuation factor is more noticeable. For 10 kHz, the difference between the models is 13 % for 30 km and 26 % for 50 km (Fig. 15). According to the presented results, if a signal with dominant frequency spectrum near 10 kHz is applied at 30 km from one line extremity, the signal arriving at such extremity will be lower than what is calculated with the line modeled with constant parameters.

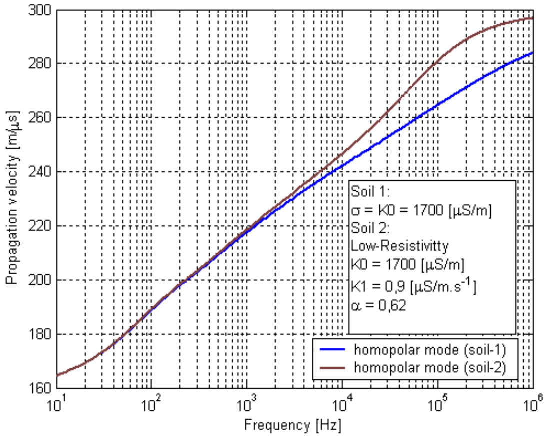

Figure 14 – Propagation velocity for homopolar mode using both soil models - Low resistivity soils

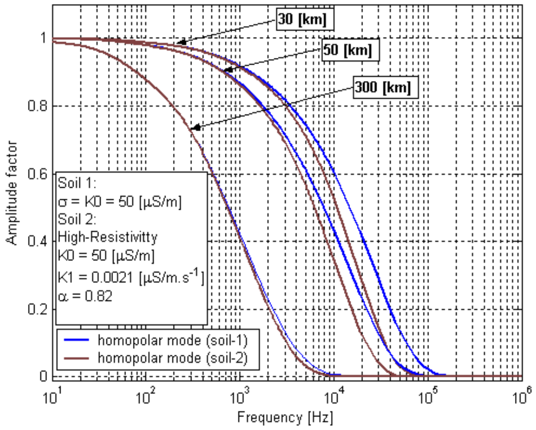

Figure 15 - Attenuation factor for homopolar mode using both soil models - High resistivity soils

The frequency response ($|V_R|/|V_G|$) was calculated using both soil models and considering the line without compensation and with open receiving-end. The relations between the receiving-end (V_R) and sending-end voltage (V_G) are given by (17):

$$\frac{|V_R|}{|V_G|} = \frac{1}{\cosh(\gamma(\omega)\cdot l)} \qquad (17)$$

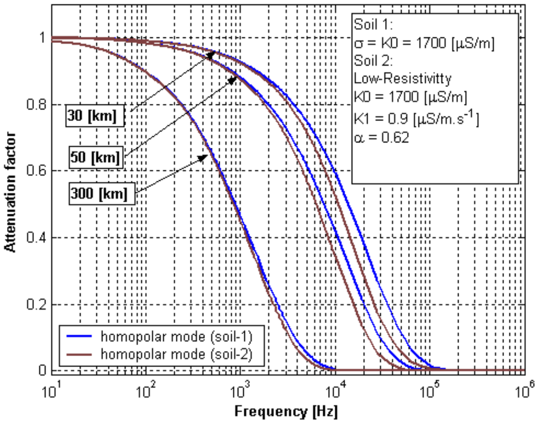

Figure 16 - Attenuation factor for homopolar mode using both soil models - Low resistivity soils

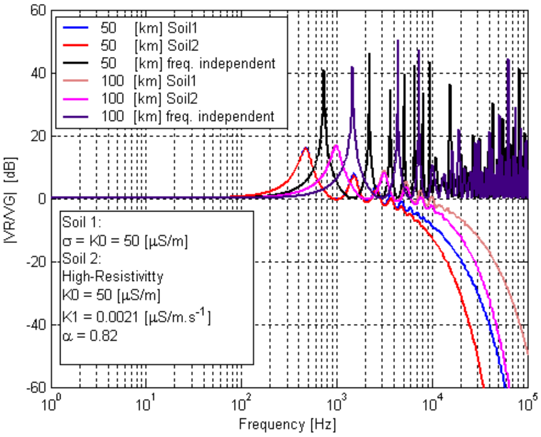

Figure 17 – Frequency response - High resistivity soils: 50, 100 km line length

Analyzing the frequency response or transfer function (Fig. 17), it is possible to identify resonance displacement and amplitude attenuation for different soil model. Currently with non-linear loads in the system, the effect of the ground can also be important for the harmonic analysis (filter projects for attenuation and rejection) and consequently for power quality.

VI. CONCLUSIONS

In the present paper some basic aspects of soil modeling have been presented and it was shown that:

- It is essential to choose a soil model that satisfies the physical coherence conditions concerning the relations between the conductivity (σ) and the permittivity (ε) in the frequency domain.
- The soil behavior is, typically, of minimum phase shift type.

The usual assumptions of ground conductivity frequency independent and ground electric permittivity, e. g. of the order of 10 to 30 times vacuum electric permittivity and frequency independent, are too far from reality for most soils. This procedure can originate an inadequate soil model becoming necessary to know the soil electromagnetic behavior in frequency domain. As presented, the soil electromagnetic parameters σ and ε are strongly frequency dependent in high frequencies.

For transmission lines, according to specific conditions, and the phenomena being studied, it may be quite important to correctly model the soil, considering frequency dependence [8]. The difference obtained between the two models for the longitudinal resistance was important for frequencies above 1 kHz for homopolar modes, and for frequencies above 100 kHz for non-homopolar modes. The conditions in which such a difference can be important include the following examples:

- Fast transients, for which important frequency range may include frequencies above 10 kHz. In this case, the difference between an accurate soil model and usual assumptions may be important also for non-homopolar modes. Typical cases in which frequency range much above 10 kHz (for some conditions above 1 MHz) is important are: transients originated by lightning; front of wave aspects of transients associated with short-circuits, fast protection operation, based in shape of front wave arriving at measurement point for fast fault location, transients in gas-insulated substations.

From the presented results, it is expected that for transient phenomena with dominant frequency spectrum until above 10 kHz the distinct homopolar mode response may have quite important effects, not restricted to higher attenuation. For example, the overvoltage shape, namely in the wave front, may be quite different, with important consequences in insulation coordination.

The ground parameters obtained with measurement results in Cachoeira Paulista are coherent with the results and ground electric behavior presented in [1-5].

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