Transient Performance Analysis on Overhead Transmission Line Considering the Frequency Dependent Soil Representation

J. B. Gertrudes, M. C. Tavares and C. Portela

***Abstract* - This paper presents a transient study, analyzing the frequency-domain response and the time-domain response of overhead transmission line (TL) with the longitudinal and transversal parameters represented by models that take into account the influence of the earth's parameters frequency dependence. Usually, between 10^3 Hz and 10^6 Hz the earth's conductivity may have the same order of magnitude as the product of the signal angular frequency (ω) by the dielectric constant (ε_g) due to the dependence of these parameters with frequency. Therefore, the low frequency assumptions traditionally used - the soil conductivity considered as constant and $\omega.\varepsilon_g$ nil - can lead to incorrect models that does not adequately represent the transmission line's transient response. A practical example it is presented through a time-domain single-phase switching test (SFST) in order to compare the TL transient response with the frequency dependence soil representation and the regular representation with constant conductivity in the PSCAD program.**

***Index Terms* - Soil model, Line parameters, Frequency dependence, Electromagnetic transients.**

I. INTRODUCTION

A model of an electrical component describes with more or less degree of accuracy its response to a specific physical phenomena to which it was submitted. In the electromagnetic (EM) transient's studies on electrical power systems it is necessary the previous knowledge of the overvoltages levels during the occurrence of a specific disturbance. First, to define project details, supportability of the equipment to reduce the overvoltages levels (pre-insertion resistors, surge arresters, circuit breakers (CB)), and secondly, to define the criteria for the protection actuation in cases where the integrity of such equipments or system stability is called into question.

The authors wish to thank the financial support received from the research agencies FAPESP (The State of São Paulo Research Foundation) and CNPq (National Council for Scientific and Technological Development).

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Paper (ID 176) submitted to the International Conference on Power Systems Transients (IPST2011) in Delft, the Netherlands June 14-17, 2011.

The Brazilian electricity system is characterized by long corridors of transmission lines. The most common transients that can occur in the electric power network are due to switchings (energizations and rejections), different faults types, and fast transients of atmosferic origin due to the high incidences of lightning discharges that occur frequently in the country. So, the adequate modeling of each network component is extremely important for that studies, from planning to operation, may generate results as close as possible to the physical reality, with direct consequences in the security, reliability and economy of the electrical power systems.

This paper proposes transmission lines models for transients studies, that approximate as much as possible of physical reality, i.e. with minimum possible suppositions in relation to the soil representation for the transmission lines modeling, in the frequency range 0 to 2 MHz. This range covers the majority of the EM transients in electrical systems. From field measurements' results and developed models [1]-[2] it can be observed that, between 1 kHz and 2 MHz the earth's conductivity (σ_g) may have the same order of magnitude as the product of the signal angular frequency (ω) by the dielectric constant (ε_g) due to the dependence of these parameters with frequency. Therefore, the assumptions of low frequency traditionally used for the soil representation in the transmission lines modeling - constant conductivity (σ_g) and $\omega\varepsilon_g$ that can be negligible ($\sigma_g >> \omega\varepsilon_g$) - can lead to incorrect models that do not adequately represent the transmission line's response, in cases of fast transients phenomena (with frequency spectrum above 1 kHz) [3].

In order to quantify the importance of properly considering the frequency-dependent soil model it is presented a time-domain electromagnetic transient study for a single-phase switching test case. It is considered a power system with a single 440 kV three-phase transmission line represented by models that take into account the influence of the earth's parameters frequency dependence. The results are compared with those obtained with the line represented by the regular use models that consider just a constant conductivity as the earth's parameters .

II. TRANSMISSION LINE MODELING IN THE FREQUENCY DOMAIN

A multi-conductor transmission-line is a distributed circuit that, for a specific frequency, f, in complex representation of sinusoidal transversal voltages and longitudinal currents, in matrix formulation of the voltages and currents in a point of longitudinal line, coordinate x, and with some simplifying assumptions, satisfies the voltage-current relations:

$$\frac{d^2[V(x)]}{dx} = [Z][Y]\,[V(x)]\ ;\ \frac{d^2[I(x)]}{dx} = [Y][Z][I(x)] \qquad (1)$$

being:

[Z] - the longitudinal impedance matrix per unit length;

[Y] - the transversal admittance matrix per unit length;

[V] - the matrix of transversal voltages of the line cables, function of longitudinal coordinate x;

[I] - the matrix of longitudinal currents in the line cables, function of longitudinal coordinate x;

Traditionally, the basic equations of a transmission line are valid if some geometric and EM field behavior simplifying assumptions can be considered [4]. The geometric simplifying assumptions consist of considering that the soil surface is plane; line cables are horizontal and parallel among themselves and the soil surface; the distance between any pair of conductors is much higher than the sum of their radius; and the EM effects of structures, grounding systems, insulators and eventual counterbalancing wires are neglected. The influence in bundle positions of the temperature, resulting from load conditions (currents and electric charges), transients' and meteorological conditions (e.g. wind, ice, rain) are neglected. The conductors are considered in an average height in relation to ground surface in order to minimize the "*transients'*" bundle positions and possible not plane soil surface. This fact will affect the signal modulation throughout the span, in some frequency range. The constant meteorological conditions and temperature (75°C for phase conductors and 45°C for ground wires) are used for the presented tests cases.

When the mentioned and neglected effects are potentially important, they must be included in the transmission line modeling.

A. Longitudinal impedance matrix per unit lenght

The longitudinal impedance matrix per unit length [Z], including explicitly the eventual grounding wires, can be obtained (with acceptable small error) considering three parts, each of which makes a significant contribution. They are:

i) The matrix of internal longitudinal impedances per unit length associated with the EM field within the conductor, which are affected by skin effects and can be calculated with good accuracy with formulas based on Bessel functions.

ii) The matrix of the external longitudinal impedances per unit length associated with the EM field in air, which, with a reasonably small error for frequencies of up to about 1 MHz, can be obtained assuming ideal conductors and soil as a perfectly conducting plane and an almost stationary EM field.

iii) The matrix of the external longitudinal impedances per unit length correction in relation to ideal soil assumption, associated with the EM field in soil supposing ideal conductors. The following assumption is not valid if the soil magnetic permeability is sensibly different from the vacuum permeability, a case in which there is a mistake in applicability of the Carson formulation. Except for the above case, for uniform soil with a reasonably small error and frequencies up to about 1 MHz, Carson's integral formulation [5] can be applied substituting in such formulation σ_g by $\sigma_g + i\,\omega\varepsilon_g$ [6], [7]. More precisely, in Carson's or equivalent formulae $\gamma_g = \sqrt{i\,\mu_g\,\omega\,(\sigma_g + i\,\omega\,\varepsilon_g)}$ should be considered instead of $\gamma_g = \sqrt{i\,\mu_g \omega \sigma_g}$, where γ_g is the propagation coefficient of the earth .

In the same applicability conditions, with an additional usually acceptable error, it can be used the modified complex plane method – an asymptotic series development of the Carson integral formulation, (also substituting σ_g by $\sigma_g + i\,\omega\varepsilon_g$), that can be interpreted as an equivalent ideal soil at a complex depth, D', below real soil surface, being $D' = 1/\sqrt{(\sigma_g + i\,\omega\varepsilon_g)\,i\,\mu_g\,\omega}$. This assumption can be treated as a correction (or modified) of Dubanton/Deri's (**DERI-M**) approximated formulae [8], substituting the ideal soil equivalent depth, that, in such formulation, is $d = 1/\sqrt{\sigma_g\ i\ \omega\mu_g}$, by the D' value indicated above.

With the simplifying assumption of an equivalent ideal soil at a complex depth, D', parts (ii) and (iii) of longitudinal impedance per unit length can be obtained with a single expression. Such formulation is indicated below (3). However, the longitudinal and transversal ground impedance expressions can be evaluated directly by integrating the Carson's or equivalent formulations.

So, the transmission line longitudinal impedance matrix, per unit length, including explicitly the eventual grounding wires, may be obtained considering:

$$[Z\,] = [Z_{int}] + [Z_{ext}] + [Z_g\,] \qquad (2)$$

where:

[Z]- longitudinal impedance matrix, per unit length;

$[Z_{int}]$ – internal impedance matrix, per unit length (diagonal matrix);

$[Z_{ext}]$ - external impedance matrix, per unit length considering ideally soil surface;

$[Z_g]$ - ground impedance correction matrix, per unit length.

$$Z_{ext}(DERI-M)_{k,m} = \mathbf{Z}_{ext\,k,m} + \mathbf{Z}_{g\,k,m} = i\frac{\omega\mu_0}{2\pi}\ \ln\left(\frac{D'_{km}}{d_{km}}\right)_{k,m} \qquad (3)$$

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

where:

$D'_{k,m}$ - distance between the k^{th} conductor and image of the m^{th} conductor "reflected" in ground added to complex soil depth *D'*.

d_{km} - distance between the k^{th} and m^{th} conductor.

The location of the conductors in the tower is shown in Figure 1a for the 440 kV single three-phase transposed transmission line. For calculation of ground longitudinal impedance matrix $[Z_g]$ per unit length, considering the frequency dependence of soil parameters, two different procedures were used:

-The complex plane method was used (schematically represented in Figure 1b) considering an ideal soil at a complex depth, D', below real soil surface.

-Numerical integration of the Carson/Wise/Nakagawa's modified expressions presented in section C.

The ground admittance matrix per unit length is also evaluated from this procedure.

B. Transversal Admittance Parameters

Traditionally the shunt admittance matrix [Y] is calculated assuming ideal conductors and soil (ideal conducting plane) with almost stationary EM field behavior and the correlated simplifying assumptions described below. Including explicitly the eventual grounding wires, this leads to:

$$[\mathrm{Y_{ext}}] = \mathrm{i}\, 2\pi\omega\varepsilon [\mathrm{A}]^{-1}, \quad A_{k,m} = \ln\left(\frac{D_{km}}{d_{km}}\right) \tag{4}$$

where, ω is the angular frequency, ε the permittivity of the air, d_{kk} the radius of k^{th} conductor, d_{km} is the same as described above, D_{km} is the distance between the k^{th} and image of the m^{th} image conductors (without complex depth *D'*) and [A] is the well known potential-coefficient matrix.

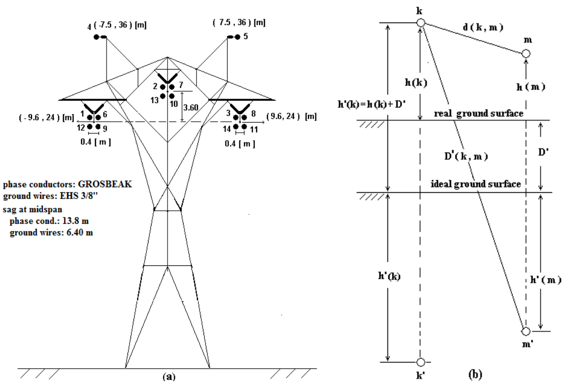

Figure 1– (a) Schematic representation of the 440 kV three-phase line and (b) Conductors k and m position supposing ideal soil surface at a complex depth D' below real soil surface.

If convenient, for the usual procedures of grounding wires connection , with acceptable small errors for frequencies of up to about 100 kHz, it is possible, with simple matrices manipulation, to consider grounding wires implicitly, considering longitudinal impedance, [Z], and transversal admittance, [Y], matrices referred only to equivalent phases' voltages and currents.

When the ground consists of a lossy medium, there should also be corrections to adjust shunt admittances [9], [10], [11]. In the next section it is presented some modified ground expressions based on the Carson/Wise/Nakagawa **(C/W/N-M)** modified expressions to include the frequency-dependent soil model in transmission lines' longitudinal and transversal parameters calculation.

C. Carson's modified ground impedance expressions to include the frequency dependent soil model on transversal and longitudinal transmission-line parameters

In the frequency range up to 2 MHz (where the frequency-dependent soil model is valid) the modified complex plane method (**DERI-M**) gives results close to those obtained with the Carson integral modified formulas (by replacing σ_g by σ_g+i $\omega\varepsilon_g$). The asymptotic error due to this procedure depends simultaneously on the frequency, conductors' radius, tower height and horizontal distance between conductors. In few cases the error is more than 10 % (especially for high-resistivity soils) and must be evaluated for each tower configuration.

In previous paper [12], following the same procedure and considerations to derive the Carson modified expression (i.e. considering the displacement currents in the ground) it was derived the Carson/Wise/Nakagawa modified formulations **(C/W/N-M)** [13], [14] to include the frequency-dependent soil model.

In the same applicability conditions the ground longitudinal impedance matrix and the ground transversal admittance matrix can be obtained by numerical integration of the following **(C/W/N-M)** modified expressions [15], [12].

The modified ground longitudinal impedance matrix correction term (LC) and the ground impedance matrix per unit length ($[Z_g$(C/W/N-M)]) is given by the following expressions

$$Z_{extk,m} + Z_g(C/W/N-M)_{k,m} = i\omega\frac{\mu_o}{2\pi}\left(\ln\left(\frac{D_{km}}{d_{km}}\right) + LC(\omega,\xi)\right)_{k,m} \tag{5}$$

$$LC(\omega,\xi) = 2\int_0^\infty \frac{\exp\{-(h_k+h_m)\}\xi}{\xi + \dfrac{\mu_0}{\mu_g}a_1}\cos(dl_{km}\,\xi)\,d\xi \tag{6}$$

The "correct" potential coefficients and transversal per-unit-length admittance matrix due to ground parameter are as follows

$$TC(\omega,\xi) = 2\int_0^\infty \frac{\left(\xi + \dfrac{\mu_g}{\mu}a_1\right)\exp[-(h_k+h_m)\xi]\cos(dl_{km}\,\xi)}{\left(\xi + \dfrac{\mu}{\mu_g}a_1\right)\left(\dfrac{\mu_g}{\mu}a_1 + \dfrac{\xi}{\tau^2}\right)}\,d\xi \tag{7}$$

$$P_{k,m} = \frac{1}{2\pi\varepsilon}\left(\ln(\frac{D_{km}}{d_{km}}) + LC(\omega,\xi)\right)_{k,m} \tag{8}$$

$$[Y_c(C/W/N-M)] = i\,\omega[P]^{-1} \tag{9}$$

where:

$D_{k,m}$ - distance between conductor *k* and "image" of conductor *m*;

$dl_{k,m}$ - horizontal distance between conductors *k* and *m*;

h_k, h_m - conductor height above ground;

μ, ε - air permeability and permittivity respectively.

μ_g, ε_g - ground permeability and permittivity respectively.

$\gamma_0 = i\,\omega\sqrt{\mu\,\varepsilon}$ (propagation coefficient in the air)

$\gamma_g = \sqrt{i\,\omega\mu_g(\sigma_g + i\;\omega\;\varepsilon_g)}$ (propagation coefficient in the ground)

$$a_1 = \sqrt{\xi^2 + \gamma_g{}^2 - \gamma_0{}^2} \tag{10}$$

$$\tau^2 = \frac{\gamma_0{}^2}{\gamma_g{}^2} \tag{11}$$

The frequency dependence of soil parameters affects essentially the earth's propagation coefficient in the **C/W/N-M** formulations and by EM coupling the matrices of longitudinal impedance and transversal admittance.

In this paper it is considered the type 3 frequency-dependent soil model given by [1]:

$$\sigma_g + i\,\omega\varepsilon_g = K_0 + K_1\omega^{\alpha_1} + i\,K_1 \tan\left(\frac{\pi}{2}\alpha_1\right)\omega^{\alpha_1} \tag{12}$$

In the modified expressions (C/W/N-M) the earth's propagation constant becomes

$$\gamma_g = \sqrt{i\,\omega\mu_g\left[\left(K_0 + K_1\omega^{\alpha_1} + i\,K_1 \tan\left(\frac{\pi}{2}\alpha_1\right)\omega^{\alpha_1}\right)\right]} \tag{13}$$

III. Modified Line Parameters for Test Cases

The line parameters were calculated in frequency domain (considering implicitly representation of ground wires), such as per unit length series impedances and transversal admittances. The ground wires were continuously grounded along the line and were considered implicitly in the longitudinal phase impedance and transversal phase matrix. Three different soil representations were used to calculate the line parameters and are presented in Table I. They are:

M1: considering constant earth conductivity, term $\omega\varepsilon_g$ that can be neglected assuming a low frequency approximation ($\omega\varepsilon_g << \sigma_g$). Corrections due to ground return applied to [Z] and no corrections applied to [Y] (usual calculation of [Z] and [Y]).

M2: considering earth's conductivity and the term $\omega\varepsilon_g$ frequency dependence, corrections due to ground return applied to [Z] and no corrections in [Y].

M3: considering earth's conductivity and the term $\omega\varepsilon_g$ frequency dependence, corrections due to ground return applied both to [Z] and to [Y]. It is used the Clarke transformation matrix to convert phase components into modal components 0, 1, and 2, which are used in this study for modal domain analysis.

Mode 0: homopolar mode or quasi-modes.

Mode 1: non-homopolar mode or quasi-modes.

Soils with high resistivity (HR) and low resistivity (LR) were analyzed. The resistivity 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 frequency.

TABLE I – Typical range limits of low and high-resistivity Brazilian's soils [2],[7]

Parameters	Low-resistivity soil models (LR)		High-resistivity soil models (HR)	
	M1	M2, M3	M1	M2, M3
K_0 $[\mu S/m]$	1700	1700	50	50
K_1 $[\mu S/m.s^{-1}]$	0	0.9	0	0.0021
α_1	0	0.62	0	0.82

A. *Results: Longitudinal Parameters*

In figure 2, the modal resistances per unit length for the ideally transposed line are presented, comparing M1 and M2 for the HR case presented in table 1. The models **M1** and **M2** are equivalent for frequencies below 100 Hz both for the homopolar mode and non-homopolar, respectively.

From 100 Hz to 1 MHz the maximum differences between the **M1** and **M2** varies from 20 % (LR soil) to 43 % (HR soil) for the homopolar mode and from 50 % (LR) and 85 % (HR) for the non-homopolar mode. In the frequency range corresponding to the spectrum of fast transients (1 MHz to 2 MHz), the differences are more accentuated (figure 3).

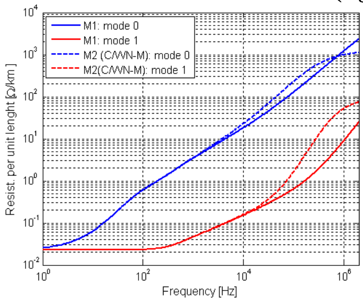

Figure 2 - Resistance per unit length comparing M1 and M2 for HR soils.

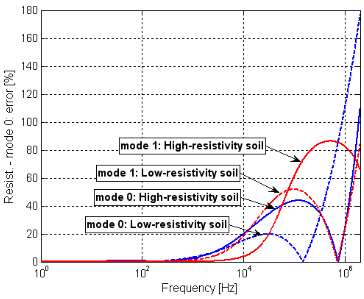

Figure 3 – Resistance difference between models M1 and M2

The modal inductance per unit length for the transposed line was analyzed, comparing **M1** and **M2** for the HR soils. The ground return affects essentially the homopolar mode inductance per unit length for frequencies above 1 kHz. The maximum value varies from 13 % at 100 kHz for LR soils to 33 % for HR soils at 1 MHz. In the Mode 1, the maximum difference between **M1** and **M2** does not exceed 5%.

B. *Results: Transversal parameters*

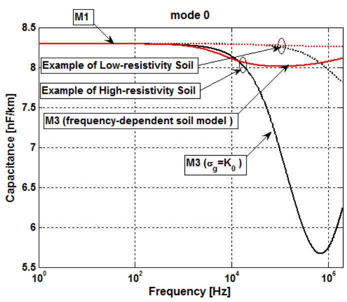

Figure 4 – Capacitances per unit length (homopolar mode), comparing M1, M2 and M3 for the LR and HR soils presented in Table 1.

In Figures 4 and 5 are presented the modal capacitances per unit length comparing three possibilities of soil representation: ideal soil (**M1**), **M2** (with constant conductivity and frequency independent), and **M3** (C/W/N-M) with soil model frequency-dependent. Notes that **M2** is a low-frequency approximation of **M3** (C/W/N-M).

In the homopolar mode (figure 4), similarly to the one-conductor case above the ground [12], in the range from 1 kHz to 2 MHz the maximum difference between **M1** and **M3** (with constant conductivity and frequency independent) varies from 5 % (LR) to 46 % (HR) (figure 5). Note that, when the frequency-dependent soil model is adequately represented, as in **M3,** the maximum differences in relation to **M1** is less than 0.5 % for LR soils and less than 3.5 % for HR soils. Similar results are obtained for the non-homopolar modes but the maximum difference does not exceed 2.5 %, in the worse case.

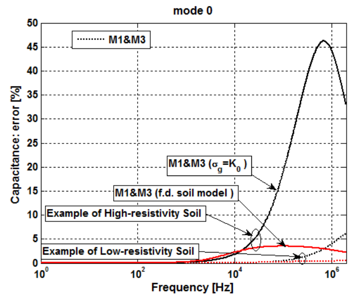

Figure 5 – Homopolar capacitance: error (difference) between M1 and M3 comparing LR and HR soils presented in Table 1.

Therefore, the frequency-dependent soil model representation for the TL transversal admittance is approximately equal to the ideal soil representation, due to the frequency dependence of the soil parameters. More precisely, due to the frequency dependence of the term $\omega\varepsilon_g$ (12), that is associated with the increases in soil conductivity when the signals frequency increase.

C. *Results: Transmission-line frequency domain response*

In figure 6 it is presented the non-homopolar atenuattion factor, considering different lengths of transmission line (30 km, 50 km, 300 km) and comparing the models **M1**, **M2** and **M3**.

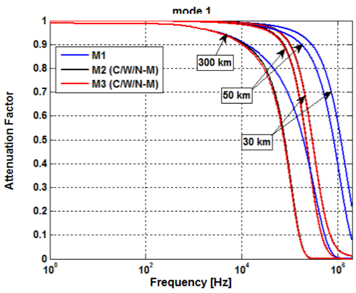

Figura 6 – Non-homopolar attenuation fator: Comparison between M1, M2 and M3(C/W/N-M) for HR soil.

It can be noted that, as expected, there are no significant differences between **M2** and **M3**. However, in the range from 10 kHz to 1 MHz (for 30 km length), the difference between M1 and M2 varies from 20 % (LR) to 60 % (HR).

A similar result can be observed for the homopolar mode with differences between **M1** and **M2** that vary from 10 % (LR) to 15 % (HR) in the range from 100 Hz to 1 kHz. The homopolar response showed a higher signals attenuation in comparision to the non-homopolar mode as the frequency increases. If line length increases the frequency range in which the signals is fully attenuated also increases.

In Figure 7 it is presented the voltage gain (30 km, receiving-end open and the transmission line without compensation). It is also compared **M1**, **M2** and **M3**. Note that, in general, for a given frequency **M1** is more conservative than **M2** (**M3**), ie, the voltage gain for **M1** is higher than for **M2** (**M3**). But the differences observed in the range of 10 kHz to 2 MHz are accentuated and may influence, for example, in determining the insulation levels or the short-circuit currents levels, depending on the signals-frequency involved in transients conditions and therefore on safety and reliability of electrical systems. A similar result can be observed for the homopolar mode, however, with lower voltage gain.

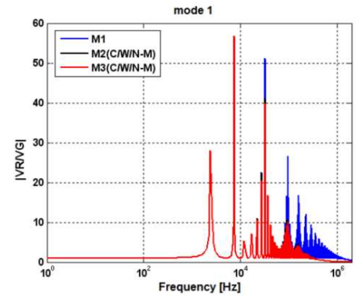

Figura 7 – Non-homopolar attenuation fator: Comparison between M1, M2 and M3(C/W/N-M) for the examples of HR soils.

D. *Transmission-line time-domain response*

In order to quantify the importance of properly considering the frequency-dependent soil model in transmission modeling it is presented a time-domain electromagnetic transient study for a single-phase switching test (SPST) case [15]. The soil model presented was included in the platform EMTDC/PSCAD and the matrices of longitudinal parameters have been updated considering the frequency dependent soil model and comparing M1 and M2. In the SPST, the rated line voltage (440 kV) was applied to the sending-end terminal with the receiving-end terminal open.

Initially the system is in the steady state and then the CB is opened at t = 54.2 milliseconds. The receiving-end voltage for the 4 different cases of LR and HR presented in Table 1 were simulated. The length of the transmission line is 100 km.

Figures 8 and 9 present the receiving-end voltage profiles VRa and VRb, comparing M1 and M2, for the LR and HR soils, respectively. After the transient the amplitudes are: VRa = 365 kV, VRb = 65 kV and VRc = 66 kV. Both models present the same values before the switching moment (t < 54.2 ms). The transient response VRc is similar to VRb with a short difference of 1 kV due to the configurations of conductors in the TL tower. During the transient time may be observed a higher damping in VRa in comparision with VRb and VRc and a distinct behaviour in the induced voltages VRb and VRc. The differences between **M2** and **M1** are important, especially for the induced voltages. Figures 10 and 11 show the differences between **M1** and **M2** in time-domain for the voltage profiles VRa and VRb, comparing the LR and HR cases, respectively. The maximum difference between **M1** and

M2 varies from 4 % (LR) to 5% (HR) in VRa and from 17 % (LR) to 14 % (HR) for the induced voltages (VRb and VRc).

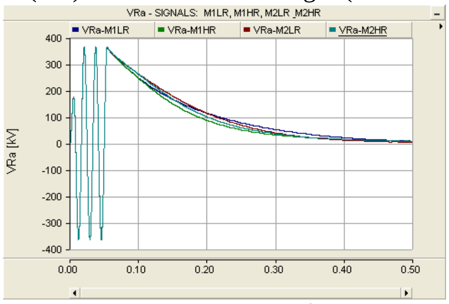

Figura 8 – Phase a receiving end voltage (VRa) for models M1 and M2 for LR and HR soils.

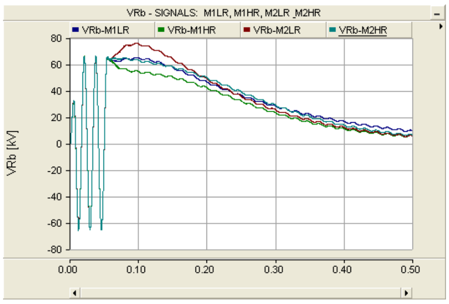

Figura 9 – Phase b receiving end voltage (VRb) for models M1 and M2 for LR and HR soils .

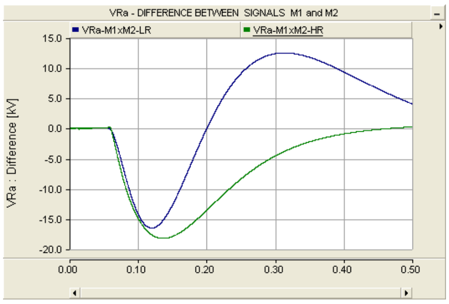

Figura 10 – Difference at receiving end phase a voltage (VRa) for models M1 and M2 for LR and HR soils.

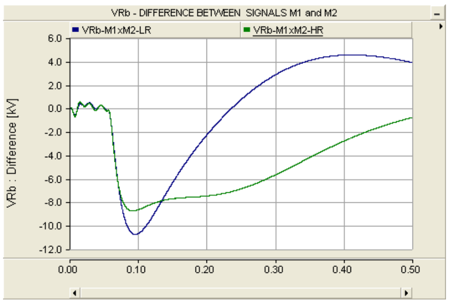

Figura 11 – Difference at receiving end phase b voltage (VRb) for models M1 and M2 for LR and HR soils.

IV. CONCLUSIONS

In the present paper the influence of the earth's conductivity and $\omega\varepsilon_g$ frequency dependence is considered for transmission line modeling in the frequency range up to 2 MHz. It is also presented a time-domain single-phase switching test in order to compare the transmission line's transient response when the frequency dependence soil representation is considered and the common representation with constant conductivity in the PSCAD program.

The inclusion of the frequency-dependent soil model affects essencially the TL longitudinal parameters per unit length and consequently the TL transient response. For the transversal parameters the results obtained with the frequency-dependent soil model are approximately equal to those obtained considering the soil as a perfectly-conducting plan. Therefore no modification for transversal line parameter needs to be implemented.

The differences for the TL models presented are important in the frequency range from 1 kHz to 2 MHz (corresponding to switching and fast transients' spectrum). The differences observed are greater for the HR soils.

From the SPST presented it can be observed an important difference between the common soil representation and the presented soil model for the induced voltages. The differences between the models presented also depend upon system configuration, line lengths and of the soil parameters representation. Therefore, further studies should be performed for an electric power system, operating under different conditions (including switching transients and fault transient, fast transients due to lightning discharges, etc.) to infer, for example, about the possible influence of the frequency-dependent soil model representation in insulation coordination and/or protection, among other studies involving signals with frequency spectrum in the range where the frequency dependence of soil parameters is important.

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