Simulation of Transients with a Modal-Domain Based Transmission Line Model Considering Ground as a Dispersive Medium

Alberto De Conti and Maique Paulo S. Emídio

Abstract-- **In this paper, a modal-domain based transmission line model available in popular electromagnetic transient programs is adapted to evaluate the effect of frequency-dependent ground conductivity and permittivity in the calculation of transients on overhead power distribution lines. The calculation of the line parameters considering ground as a dispersive medium is performed in MATLAB making use of practical equations that are based on in situ measurements of ground conductivity and permittivity in a wide frequency range. The propagation function and characteristic impedance of the line are synthesized in the frequency domain as the sum of rational functions using the vector fitting technique. The poles and residues of the synthesized functions are written in a .pch file that is read by the Alternative Transients Program (ATP) as a JMarti model. Time domain simulations are performed considering both switching and lightning transients on single- and two-phase power distribution lines. The results indicate that the consideration of the ground as a dispersive medium leads to a distortion of the calculated transient voltages that can be relevant in the case of very low ground conductivity. However, such effect can be significantly reduced in line topologies that include multiple branches and grounding points. It is also shown that constant values of ground conductivity and permittivity are able to lead to results comparable to those obtained with frequency dependent conductivity and permittivity provided a suitable value of ground relative permittivity is selected.**

Keywords: **Transmission line modeling, modal domain, frequency-dependent ground parameters.**

I. INTRODUCTION

THERE has been an increasing interest in the simulation of electromagnetic transients in transmission lines considering the dispersive nature of the ground parameters. This is apparent not only from the number of publications describing new methodologies to measure and model the variation with frequency of the ground conductivity (σ) and permittivity (ε) presented in the last fifteen years or so [1-6], but also from the increasing amount of papers discussing the prospective effect of such variation on the transient response of grounding electrodes [7-11] and on the calculation of switching and lightning transients in power systems [12-19].

In spite of this trend, the transmission line models available in popular transient simulators rely on the use of Carson's integrals [20] or their approximation through the use of the complex ground return plane [21] for calculating the ground return impedance. Since both approaches are low-frequency approximations in which $\sigma >> \omega\varepsilon$ is assumed, the influence of the ground permittivity in the ground-return impedance is not taken into account properly. This feature, combined with the assumption of a constant value of ground conductivity, suggests the possibility of errors in the simulation of cases involving poor ground conductivities, high-frequency transients, or a combination of both.

In this paper, the transmission line model proposed by Marti [22] is adapted to include the effect of frequency dependent ground parameters in the time-domain simulation of electromagnetic transients in power distribution lines. The calculation of the line parameters is implemented in MATLAB, where the poles and residues necessary to fit the characteristic impedance and propagation function of each mode are determined in the frequency domain via the vector fitting technique [23]. The obtained poles and residues are then written in a .pch file that can be read by the Alternative Transients Program (ATP) and solved as a JMarti model.

This paper is organized as follows. Section II discusses the calculation of the ground return impedance of transmission lines considering different expressions under the assumption of constant or frequency-dependent ground parameters. Section III discusses the use of the J. Marti model available in ATP for calculating transients on power distribution lines considering ground as a dispersive medium. Results and analysis are presented in Section IV, followed by conclusions in Section V.

II. CALCULATION OF THE GROUND RETURN IMPEDANCE OF TRANSMISSION LINES UNDER DIFFERENT ASSUMPTIONS

A. *Ground Return Impedance*

The self and mutual terms of the ground impedance matrix of overhead transmission lines can be calculated with the equations proposed by Sunde [24]. Taking as reference the two-conductor line illustrated in Fig. 1, Sunde's equations read

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$$Z'_{g_{ii}} = \frac{j\omega\mu_0}{\pi}\int_0^\infty \frac{e^{-2h_i\lambda}}{\sqrt{\lambda^2+\gamma_g^2}+\lambda}d\lambda \tag{1}$$

$$Z'_{g_{ij}} = \frac{j\omega\mu_0}{\pi}\int_0^\infty \frac{e^{-(h_i+h_j)\lambda}}{\sqrt{\lambda^2+\gamma_g^2}+\lambda}\cos(r_{ij}\lambda)d\lambda \tag{2}$$

where

$$\gamma_g = \sqrt{j\omega\mu_0(\sigma + j\omega\varepsilon_r\varepsilon_0)} \tag{3}$$

in which μ_0=4π×10^{-7} H/m, ε_0=8.85×10^{-12} F/m, ω is the angular frequency in rad/s, and σ and ε_r are the ground conductivity and relative permittivity, respectively. The following approximations to (1) and (2) in logarithmic form have been proposed by Sunde [24] and Rachidi et al. [25], respectively

$$Z'_{ii,g} = \frac{j\omega\mu_0}{2\pi}\ln\left[\frac{1+\gamma_g h_i}{\gamma_g h_i}\right] \tag{4}$$

$$Z'_{ij,g} = \frac{j\omega\mu_0}{4\pi}\ln\left\{\frac{[1+0.5\gamma_g(h_i+h_j)]^2+(0.5\gamma_g r_{ij})^2}{[0.5\gamma_g(h_i+h_j)]^2+(0.5\gamma_g r_{ij})^2}\right\} \tag{5}$$

In [25] it is shown that (4) and (5) reproduce (1) and (2) for 0.01 ≥ σ ≥ 0.001 S/m with good accuracy. In Figs. 2 and 3, assuming two conductors with 5 mm radius, one located 10 m and the other 8.17 m above the ground, with r_{ij}=2 m (see Fig. 1), it is confirmed that (4) and (5) are also sufficiently accurate to reproduce (1) and (2) for σ=0.0001 S/m and different values of ε_r, at least for heights and distances between conductors that are typical of power distribution line configurations.

If $\sigma >> \omega\varepsilon_r\varepsilon_0$ is assumed in (3), then (1) and (2) reduce to

$$Z'_{g_{ii}} = \frac{j\omega\mu_0}{\pi}\int_0^\infty \frac{e^{-2h_i\lambda}}{\sqrt{\lambda^2+j\omega\mu_0\sigma}+\lambda}d\lambda \tag{6}$$

$$Z'_{g_{ij}} = \frac{j\omega\mu_0}{\pi}\int_0^\infty \frac{e^{-(h_i+h_j)\lambda}}{\sqrt{\lambda^2+j\omega\mu_0\sigma}+\lambda}\cos(r_{ij}\lambda)d\lambda \tag{7}$$

which are the equations proposed by Carson to represent the ground-return impedance of overhead lines [20]. They are implemented in popular transient simulators and for this reason are often used in the simulation of transients in power systems.

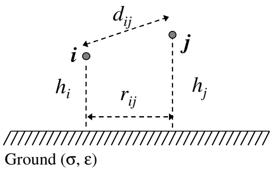

Fig. 1. Problem geometry.

For a relatively high ground conductivity of σ=0.01 S/m, it can be shown that Carson's integrals (6) and (7) are accurate up to few MHz, which is the frequency range of most power system transients. However, for a relatively poor ground conductivity of σ=0.001 S/m inaccuracies are observed in the phase angle of Carson's ground return impedance in frequencies of few hundreds kHz [25]. This is because for such frequencies and such value of ground resistivity the assumption σ>>ωε may no longer hold. In a worst case scenario involving poorer ground conductivities, the validity of Carson's integrals is even more limited. This is shown in Fig. 4, which illustrates the percentage error in the magnitude and phase angle of the ground impedance calculated with (6) for σ=0.0001 S/m, taking as reference Sunde's expression (1) for h_i=10 m, r=5 mm, and different values of ground relative permittivity. It is seen Fig. 4(a) that the percentage error in the magnitude and phase angle of the ground impedance can be very significant for frequencies above 100 kHz.

A simplified way to obtain the ground return impedance consists in using the well-known approximate formulas proposed by Deri et al. [21], which leads to

$$Z'_{g_{ii}} = \frac{j\omega\mu_0}{2\pi}\ln\left[\frac{h_i+\dot{p}}{h_i}\right] \tag{8}$$

$$Z'_{g_{ij}} = \frac{j\omega\mu_0}{2\pi}\ln\left[\frac{\sqrt{(h_i+h_j+2\dot{p})^2+r_{ij}^2}}{\sqrt{(h_i+h_j)^2+r_{ij}^2}}\right] \tag{9}$$

If σ>>ωε, the complex penetration depth reads [21]

$$\dot{p} = \sqrt{\frac{1}{j\omega\mu\sigma}} \tag{10}$$

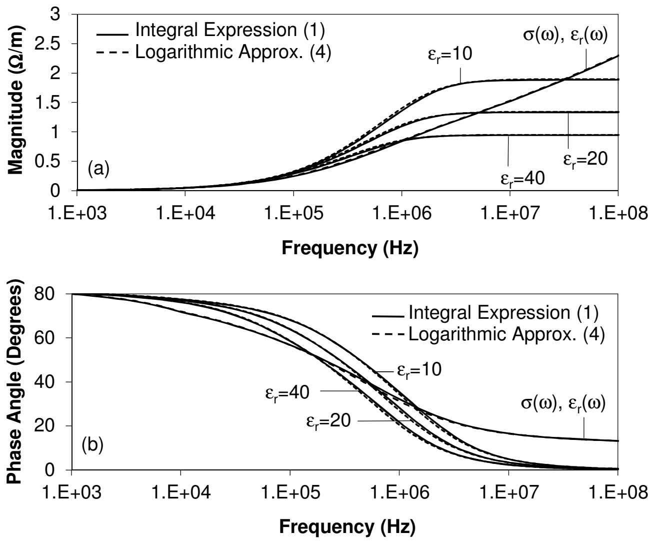

Fig. 2 – Comparison between Sunde's integral expression (1) and its logarithmic approximation (4) for constant σ=0.0001 S/m and different values of ε_r. Also included are curves obtained for frequency-dependent values of ground resistivity and permittivity according to (12) and (13), obtained for ρ_0=10000 Ω.m.

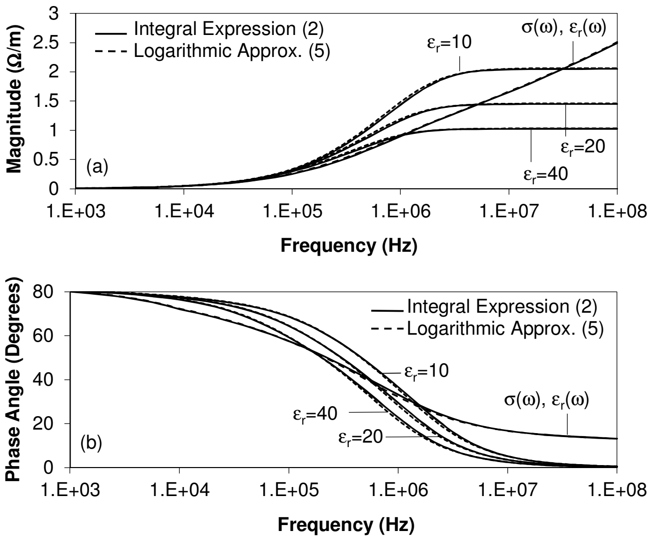

Fig. 3 – Same as Fig. 2, but for Sunde's integral expression (2) and its logarithmic approximation (5).

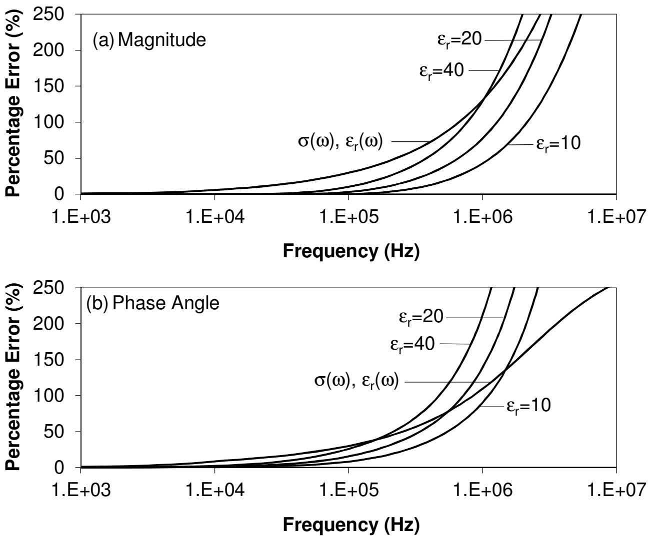

Fig. 4 – Percentage error in the (a) magnitude and (b) phase angle of the self term of the ground impedance calculated with Carson's expression (6), taking as reference the more general formula of Sunde (1) for σ=0.0001 S/m. Also included is the error curve obtained considering frequency-dependent values of ground resistivity and permittivity according to (12) and (13), calculated for ρ_0=10000 Ω.m.

In this particular case, the ground return impedance given by (8) and (9) reproduces with good accuracy Carson's formulas (6) and (7) [20]. In the more general case considering the explicit representation of the ground permittivity, the complex penetration depth is given by [29]

$$\dot{p} = \frac{1}{\gamma_g} = \frac{1}{\sqrt{j\omega\mu_0(\sigma + j\omega\varepsilon_r\varepsilon_0)}} \tag{11}$$

in which case (8) and (9) are equivalent to (4) and (5). In other words, the errors observed in Fig. 4 with the direct application of Carson's formula (6) become negligible if the complex penetration depth given by (11) is used instead of (10) in the simplified equations proposed by Deri et al. [21] to calculate the ground-return impedance. This procedure can be readily used to include the effect of the ground permittivity in the calculation of the series impedance of transmission lines, as done in, e.g., [12, 25, 29].

It is to be noted that the lack of explicit representation of the ground permittivity in (6) and (7) can be related either to assuming ε_r=0 (if the current propagation in the wire is neglected in the derivation of equations (6) and (7)) or to assuming ε_r=1 (if a lossless propagation constant is considered in the derivation of the aforementioned equations) [26-28]. For example, it is known that Sunde's equations (1) and (2) were derived neglecting propagation effects, which could be viewed as a shortcoming. However, for including propagation effects in (1) and (2) as well as in their approximate representations (4) and (5), it suffices to use the product $(\varepsilon_r - 1)\varepsilon_0$ instead of $\varepsilon_r\varepsilon_0$ in (3) and (11), as suggested in [26, 28]. Given that the differences observed in the calculated ground return impedance with assuming either $(\varepsilon_r - 1)\varepsilon_0$ or $\varepsilon_r\varepsilon_0$ in (3) are not significant for the transient studies performed in this paper, all calculations presented here consider Sunde's equations in their original form, which means to assume $\varepsilon_r\varepsilon_0$ in (3) and (11).

B. Ground Admittance

Several expressions have been proposed to include the ground admittance in the calculation of transmission line parameters [26]. It can be shown that at high frequencies the ground admittance can be used to explain the transition from a pure TEM propagation to a mixed TEM/TM/TE propagation [26]. However, different authors have come to the conclusion that for typical frequencies associated with power system transients and realistic values of ground conductivity and permittivity the effect of the ground admittance can be neglected without significant errors [13, 18-19]. For this reason, only the ground impedance is assumed in this paper to be affected by the non-perfectly conducting ground.

C. Frequency-Dependent Ground Parameters

The analysis in Section II-A assumes both σ and ε as constants. However, it is known that both parameters present a wide variation with frequency [1-6]. Therefore, it is expected that an accurate simulation of electromagnetic transients in transmission lines should consider the ground as a dispersive medium, in which the conductivity and permittivity vary with frequency. In fact, some authors suggest that the variation of σ and ε with frequency can affect switching and lightning transients in frequencies as low as tens of kHz, depending on the soil characteristics [2].

In recent years, different procedures have been proposed for measuring and modeling the variation of σ and ε with frequency [1-6]. In this paper, the soil model of Visacro and Alipio [4] is considered in the calculation of the ground-return impedance with (4) and (5). This soil model is based on measurements performed at 31 different sites in Brazil, where low-frequency resistivity values ranging from 60 to 9100 Ω.m were recorded. In all cases, a strongly frequency-dependent behavior was observed for both σ and ε.

By defining the relative resistivity as $\rho_r(\omega)=\rho(\omega)/\rho_0$, where $\rho(\omega)$ is the ground resistivity and ρ_0 is the ground resistivity at 100 Hz, Visacro and Alipio [4] proposed the following approximate expressions to represent the frequency-dependent behavior of $\rho_r(\omega)$ and $\varepsilon_r(\omega)$

$$\rho_r(\omega) = \{1+[1.2\times10^{-6}\rho_0^{0.73}]\cdot[(f-100)^{0.65}]\}^{-1} \qquad (12)$$

$$\varepsilon_r(\omega) = \begin{cases} 7.6\times10^3 f^{-0.4}+1.3 & f \geq 10\,\text{kHz} \\ \varepsilon_r(\omega)\big|_{f=10\,\text{kHz}} & f < 10\,\text{kHz} \end{cases} \qquad (13)$$

Equations (12) and (13) are able to represent with very good accuracy the behavior of the evaluated soil samples in the frequency range 100 Hz - 4 MHz [4]. Their use in the simulation of the transient response of grounding electrodes also leads to a better agreement between the predictions of a rigorous electromagnetic model with measured data [7-9]. This gives confidence about the accuracy and suitability of (12) and (13) to evaluate the frequency dependence of σ and ε in the simulation of transients in transmission lines.

Application examples of (12) and (13) are illustrated in the curves labeled as $\sigma(\omega)$ and $\varepsilon_r(\omega)$ shown in Figs. 2, 3, and 4, where a ground conductivity $\sigma_0(\omega)=1/\rho_0$ at low frequencies was assumed for ρ_0=10000 Ω.m. It is seen that the consideration of frequency-dependent ground parameters affects considerably both the magnitude and phase angle of the ground-return impedance.

III. Transmission Line Model of Marti Considering Dispersive Ground Parameters

The transmission line model proposed by Marti [22] is possibly the most popular model for the digital simulation of electromagnetic transients on overhead lines. It is a distributed-parameter model in which the variation of the line parameters with frequency is automatically considered in a frequency range determined by the user. The solution of the transmission line equations is performed in the modal domain, where a system of n coupled conductors is represented as n independent single-phase lines by means of a similarity transformation. For the computation of the voltages and currents in time domain, a constant and real transformation matrix calculated at a frequency determined by the user is considered [22].

In this paper, Marti's model is used for evaluating the effect of ground as a dispersive medium in the calculation of electromagnetic transients on overhead transmission lines. However, the J. Marti setup available in the LCC routine of ATPDraw considers the expressions of Carson and Deri et al. [20, 21] to calculate the line parameters. As in their original form such expressions do not explicitly consider the parameter ε, as discussed in Section II, and neglect the variation of σ with frequency, an alternative implementation of Marti's model was necessary to evaluate the effect of ground as a dispersive medium in the time domain simulation of electromagnetic transients. For such, the vector fitting technique [23] was used for synthesizing the characteristic impedance and the propagation function of the evaluated lines. For calculating the line parameters, the complex penetration depth given by (11) was used in the expressions proposed by Deri et al. [21], which is equivalent to considering Sunde's formulas (4) and (5). The variation of σ and ε with frequency is assumed to be governed by the soil model described in Section II-C.

A dedicated set of poles was used to represent each transmission line mode. This was necessary because for a poorly conductive ground the propagation function of the ground mode attenuates at a much lower frequency than the aerial modes. The lossless time delay associated with each mode was used in the synthesis, which typically comprised a frequency range from 0.1 Hz to 10^7-10^9 Hz, depending on the considered line length. The real transformation matrix necessary for the time domain simulations was calculated at the upper frequency of the assumed frequency range.

To include the effect of frequency dependent ground parameters in Marti's model, real poles and residues calculated in MATLAB with the vector fitting technique were written as a .pch file compatible with ATPDraw. Transient voltages and currents were then calculated at each time step by the ATP solver. A full code with a version of Marti's model extended to deal with complex poles was also written in MATLAB. The implemented code was used to double check the results obtained with ATP. In all cases discussed in Section IV, the results obtained via the .pch files simulated in ATP were seen to lead to results identical to those obtained by the MATLAB code using complex poles. For this reason, only the results obtained with the .pch files are presented.

IV. Results and Analysis

This section presents results of simulations of switching and lightning transients on overhead lines considering either frequency-dependent or constant ground parameters for different values of ε_r. Conductor heights and distances typical of power distribution lines are considered.

A. Single-phase distribution line

Fig. 5 illustrates voltages calculated at the receiving end of a 10-m high, single-phase overhead line with radius of 5 mm subjected to a lightning current impulse at the sending end. The injected current has a peak value of 12 kA, a front time of 0.3 µs (measured as the time from $0.3I_p$ to $0.9I_p$, where I_p is the current peak value), and a maximum steepness of 40 kA/µs [30, 31]. This current waveform is representative of subsequent strokes of negative downward lightning measured at Mount San Salvatore, Switzerland [32]. Three different line lengths were considered, namely 600, 1800 and 3600 m. In all cases, the line was grounded at both ends by means of a matching resistance of 497.6 Ω. Three different conditions were assumed to represent the ground parameters. One, whose corresponding .pch file is listed in Appendix A, assumed frequency-dependent parameters according to (12) and (13) for σ_0=0.0001 S/m. The other two cases assumed constant ground parameters with σ_0=0.0001 S/m calculated either with Carson's expressions or with Sunde's expressions for ε_r=40.

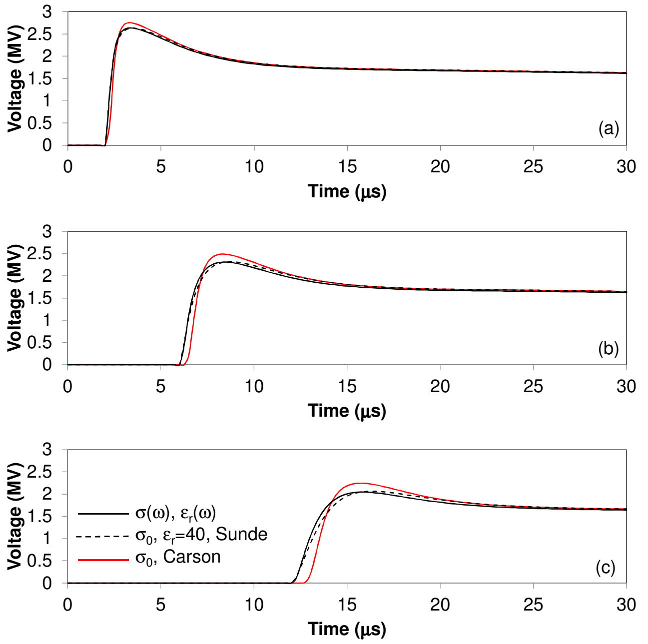

Fig. 5 – Voltages at the receiving end of a single-phase line with length of (a) 600 m, (b) 1800 m or (c) 3600 m assuming the injection of a lightning current at the sending end and considering σ_0=0.0001 S/m. Both line ends were connected to a matching resistance of 497.6 Ω.

Taking as reference the voltages calculated assuming frequency-dependent ground parameters, the results shown in Fig. 5 indicate peak values up to 15% higher if a constant conductivity is assumed in Carson's expressions. A noticeable difference is also observed in the propagation speed, which seems to be slower if Carson's expressions are considered. This observation is consistent with Fig. 6, which shows that the phase velocity associated with the use of Carson's formula approaches the speed of light slower than the remaining curves at high frequencies. Interestingly, a very good agreement is observed between the voltage waveforms calculated assuming ground as a dispersive medium and those obtained for constant σ with ε_r=40. Although not shown, a similar agreement was observed for ground conductivities above 0.0001 S/m. In any case, for σ=0.001 S/m or higher, the influence of frequency-dependent ground parameters and different values of ε was seen to be negligible on the calculated voltage waveforms.

B. Two-phase distribution line

Fig. 7 illustrates voltages calculated at the receiving end of an 1800-m long, two-phase distribution line consisting of two vertically stacked conductors with heights of 10 m and 8.17 m, respectively. In the calculations, a 1 pu voltage source with internal resistance of 150 Ω supplying a step waveform was connected to the sending end of the topmost conductor while the sending end of the other conductor was grounded and the receiving ends of both conductors were left open. This line topology is typical of rural lines used in Brazil and serves to illustrate the influence of different assumptions regarding the ground parameters on switching overvoltages. In the calculations, a 5-mm conductor radius was assumed together with σ_0=0.0001 S/m. The same conditions of the previous section were assumed for the calculation of the ground-return impedance, namely frequency-dependent ground parameters according to (12) and (13) for σ_0=0.0001 S/m, or constant ground parameters with σ_0=0.0001 S/m assuming either Carson's expressions or Sunde's expressions with ε_r=40. The .pch file obtained for the frequency dependent case (determined considering a maximum frequency of 10^7 Hz) is listed in Appendix B.

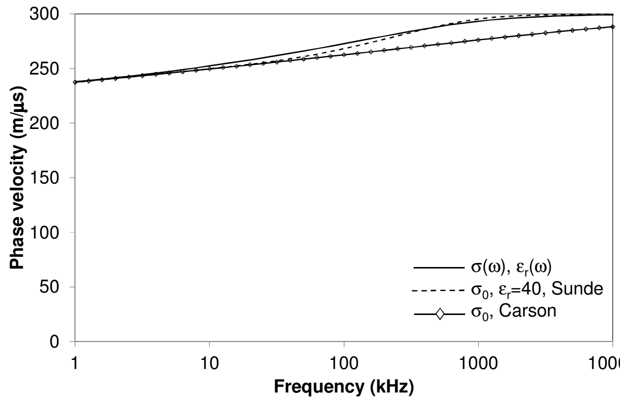

Fig. 6 – Phase velocity associated with a single-phase overhead line with height of 10 m and radius of 5 mm for σ_0=0.0001 S/m and different ground models.

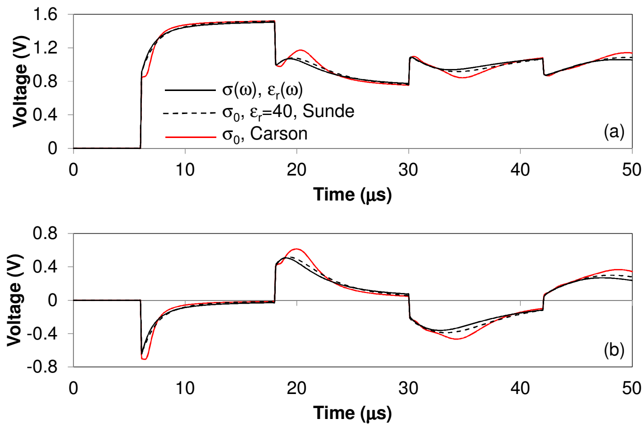

Fig. 7 – Voltages at the receiving end of an 1800-m long two-phase line assuming a 1 pu step voltage source with internal resistance of 150 Ω to energize the topmost conductor while the sending end of the other conductor was grounded and the receiving end of both conductors were left open: (a) voltages at the topmost conductor; (b) voltages at the bottom conductor. Ground conductivity σ_0=0.0001 S/m.

It is seen in Fig. 7 that the voltage waveforms calculated with Carson's expressions present again the largest deviation from the waveforms calculated considering frequency-dependent ground parameters according to (12) and (13). This is apparent if the voltages induced on the grounded conductor are analyzed, in which differences of about 20% are observed in the induced peak values. Also, it is seen that assuming σ_0=0.0001 S/m and ε_r=40 leads again to voltage waveforms in very good agreement with those calculated assuming frequency-dependent ground parameters. Although not shown, additional tests made for lateral distances up to 4 m between both conductors (parameter r_{ij} in Fig. 1), which could be considered representative of power distribution lines, were seen to lead to similar conclusions. Again, as expected, the differences between the calculated waveforms reduced significantly with increasing ground conductivity.

C. Two-phase distribution line with branches and grounding points

Most of the literature dealing with the influence of frequency-dependent ground parameters on switching and lightning transients on overhead lines disregards the presence of line branches and multiple grounding points. Since this condition is typical of power distribution lines, a final case is presented here in which the branched distribution line illustrated in Fig. 8 is subjected to the switching of a voltage source with internal resistance R_1=150 Ω supplying a step waveform. The configuration of the power distribution line is identical to the one considered in the previous section, consisting of a two-phase line with vertically-stacked conductors. The neutral conductor is grounded periodically with a grounding resistance R_2=80 Ω. This value is adopted by one of the major power utility companies in Brazil as the maximum acceptable value of grounding resistance in their distribution lines. Although the accurate modeling of distribution transformers would require a detailed pole-residue representation as well as the presence of surge arresters, the points A, B, C, and D in Fig. 8, which are left open, could be interpreted as the primary of distribution transformers installed to supply electrical energy to costumers in rural areas. Each transmission line block in Fig. 8 has a length of 150 m and is associated with a .pch file in ATP. As before, three different conditions were assumed in the calculation of the ground-return impedance, namely frequency-dependent ground parameters according to (12) and (13) for σ_0=0.0001 S/m, or constant ground parameters with σ_0=0.0001 S/m assuming either Carson's expressions or Sunde's expressions with ε_r=40. The .pch file obtained for the frequency dependent case (determined considering a maximum frequency of 10^8 Hz) is listed in Appendix C.

Fig. 9 shows the voltages calculated at points A, B, C, and D for the case illustrated in Fig. 8. It is seen that the presence of multiple branches and grounding points makes the results nearly independent on the ground-return impedance model, which is an interesting result that might suggest the suitability of simplified models for representing the ground parameters in certain types of analysis. Once again the results obtained assuming constant ground conductivity and ε_r=40 leads to voltage waveforms nearly coincident with the ones calculated assuming frequency-dependent ground parameters.

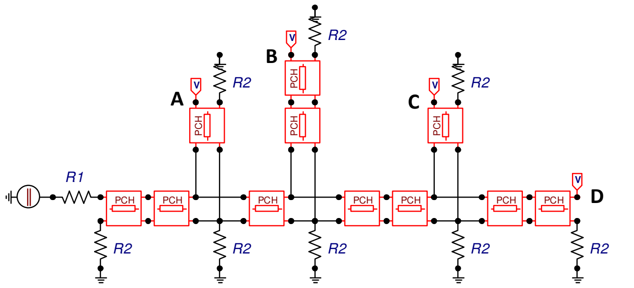

Fig. 8 – Circuit implemented in ATPDraw to simulate a branched distribution line. Each transmission line block is 150-m long, R_1=150 Ω and R_2=80 Ω.

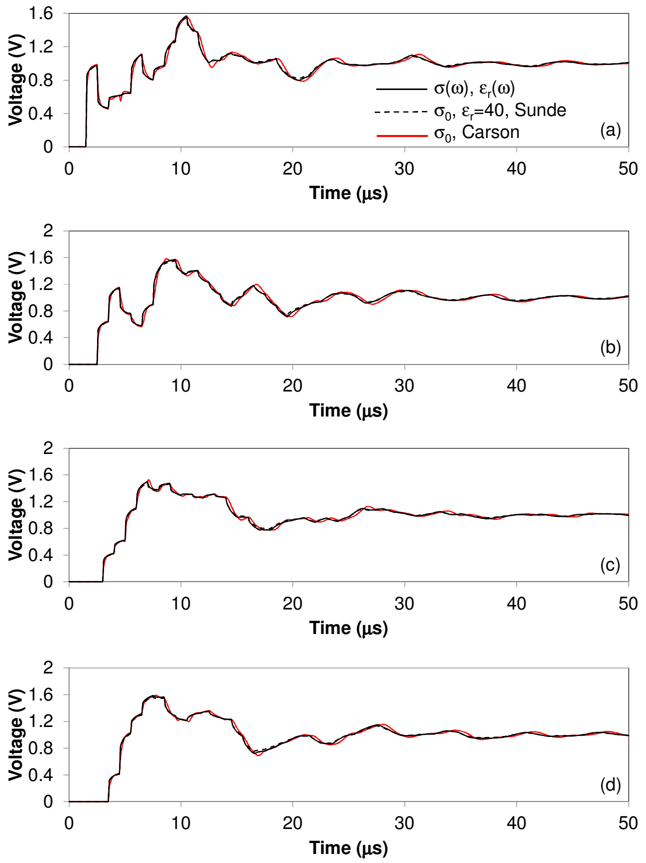

Fig. 9 – Voltages at points (a) A, (b) B, (c) C, and (d) D of the power distribution line of Fig. 8.

V. Conclusions

In this paper, a modal-domain based transmission line model was used to calculate lightning and switching transients considering frequency-dependent ground parameters. Tests performed in single- and two-phase power distribution lines indicate that the consideration of ground as a dispersive medium can be of some importance in the study of high-frequency phenomena on overhead lines located above a poorly conducting ground (e.g., σ< 0.001 S/m).

By taking as reference a specific soil model that includes the variation of the ground conductivity and permittivity with frequency, it is shown that assuming a constant value for σ together with a suitable value for ε is able to lead to voltage waveforms in good agreement with those obtained with the frequency-dependent ground model. On the basis of the analysis presented in this paper, the use of ε_r=40 together with the low-frequency value of the ground conductivity is recommended. In any case, it must be noted that additional analyses are necessary to assess to what extent this assumption holds for different soil models. If that is the case, a simple modification could be made in popular electromagnetic transient simulators to accommodate the possibility of adjusting a suitable value for ε_r in the calculation of the ground-return impedance of transmission lines.

Finally, the obtained results suggest that the presence of multiple branches and multiple grounding points is likely to reduce the relative importance of the assumed ground-impedance model in the simulation of transients in power distribution lines. In any case, a more definitive conclusion in this direction requires further studies involving more representative distribution line topologies, different soil models, and the investigation of other relevant transient phenomena.

VI. APPENDIX

A. PCH file of the 600-m long single-phase line of Section IV-A considering frequency-dependent ground parameters

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-1IN___AOUT__A                2.  0.00             -2 1
     12        4.97509680118310940000E+02
   4.89040461178831810E+03   6.51545858335469800E+03   9.35961378202711420E+03
   6.01139710016544090E+03   2.63495405613793850E+04   2.20748533525693900E+05
   1.95671607001609800E+06   1.67217292504247610E+07   7.40079955983188750E+07
   1.11848745691922260E+08  -5.57306595871959460E+05  -1.33388694775600860E+05
   3.23339052380764440E+00   7.88937973253849730E+00   2.53650703680675170E+01
   1.00735375837945360E+02   1.01584353861820910E+03   7.84889301241589780E+03
   5.92334022100264560E+04   3.95056738199622370E+05   2.30536640092842420E+06
   1.50274006472555360E+07   1.76533466748305010E+05   1.76533466748305010E+05
      9        2.00070758205234060000E-06
  -2.86006971760625270E+09   1.41665507916519280E+09   7.85117445818453280E+07
   6.09349532161832790E+05   1.13390858030871430E+07   7.17538648221284970E+05
   1.42939449550848920E+06   5.73560263846185760E+05   2.55616523355094360E+04
   2.04201565772296220E+10   4.72799999161449430E+09   5.64534931296067830E+08
   1.60496735912643490E+08   7.88819246550548520E+07   1.09885607834759540E+07
   1.04993484687795010E+07   2.10940636139622100E+06   3.23474779308710310E+05
  1.00000000
  0.00000000
```

B. PCH file of the 1800-m long two-phase line of Section IV-B considering frequency-dependent ground parameters

```
-1IN___AOUT__A                2.  0.00             -2 2
      7        3.55253283387668090000E+02
   5.27219799731382870E+05   5.96525869055192160E+04   3.51652379277314460E+03
   1.25376214549482480E+04   8.03574766479353180E+03   4.84814218458455980E+03
   3.54456926582515870E+03
   2.65592602606585250E+05   1.15751995068919150E+04   2.26931144121281530E+02
   6.30093547280099240E+01   1.79877012447671450E+01   5.59894863868208330E+00
   2.30847328455031290E+00
      8        6.00161386679394220000E-06
   4.89823645263483940E+08   2.38948878808848090E+06   3.42913213363709450E+05
   1.88987181593077660E+04   2.09539533277945470E+03   8.75141654430658780E+01
   9.36892396008977780E-01   1.19359700571623990E-02
   5.43630779248099450E+08   4.72519781140828950E+07   1.13606180526303220E+07
   1.96248871920381440E+06   3.67746433290539780E+05   4.28077013056875150E+04
   2.71205152918589370E+03   3.24632781453123090E+01
-2IN___BOUT__B                2.  0.00             -2 2
     16        6.24049532917474720000E+02
   5.34730260097013710E+03   6.07769973441367440E+03   7.05732368433331790E+03
   4.20194652521304400E+03   1.28549711811596330E+04   7.25362251106686310E+04
   4.15570328443056900E+05   2.91022415981091610E+06   1.24412995455677660E+07
  -1.62692694396426750E+07   7.06756743068040760E+07   1.59104622771032040E+08
   1.60729530707831050E+07   2.33115750180559250E+08  -3.06987211672537410E+04
  -1.54073656522314180E+04
   3.98246324225728590E+00   8.23968024585554030E+00   2.10222198408786340E+01
   6.79305585368173580E+01   3.64288866527566600E+02   1.94587866347706490E+03
   1.05518592569589930E+04   5.68208524525867110E+04   2.43360757661272710E+05
   9.00948709131590210E+05   9.62284225664496540E+05   3.80751224521444600E+06
   4.70549229097143280E+06   2.13077614834895580E+07   4.29050611052774470E+04
   4.29050611052774470E+04
     10        5.91005506627276220000E-06
   5.42029485526780950E+02   1.49590966931294950E+04  -4.79351422571950590E+02
   1.99721686964451250E+05   8.52060722736741300E+05   3.72060725713565840E+04
  -5.16093538375201050E+05  -2.62042446682419300E+06   1.03994367943618110E+06
  -1.91223367449165350E+05
   2.65076458732672040E+04   1.52927805642578750E+05   4.08697334562157570E+05
   5.30208391726890000E+05   1.33822761907975820E+06   3.28894697890176720E+06
   5.35479326034044850E+06   3.65129317464425040E+07   2.75746545196476800E+07
   2.75746545196476800E+07
  0.74172450  0.62822302
  0.00000000  0.00000000
 -0.67068771  0.77799217
 -0.00000000  0.00000000
```

C. PCH file of the 150-m long two-phase line of Section IV-C considering frequency-dependent ground parameters

```
-1IN___AOUT__A                2.  0.00             -2 2
      5        3.55623128676135760000E+02
   1.40366924312754850E+05   1.20280579296726370E+04   1.01033996388505820E+04
   5.79144374266837620E+03   3.97251078211775480E+03
   2.03879833688935610E+04   9.31246882518187820E+01   2.50169970605745960E+01
   6.71623531503889380E+00   2.38546185877424130E+00
      5        5.00103618968123590000E-07
   6.58093722985256200E+09   2.11127069118262040E+06   1.27876661948336260E+05
   3.74773839204539220E+03   4.27736359182266880E+01
   6.69525582727721880E+09   2.09728303229752210E+08   2.60552706830312460E+07
   2.35363219997971370E+06   9.14216626435442160E+04
-2IN___BOUT__B                2.  0.00             -2 2
     10        6.25233602197139250000E+02
   2.54382062355948330E+08   1.09120891224525930E+08   1.09851497441550920E+07
   1.42639674133274950E+07   2.94692618246592670E+06   3.00291081286946840E+05
   3.07688682057636800E+04   7.15373162912701990E+03   8.89594132964325040E+03
   6.71087897067659650E+03
   9.06949432833862120E+06   1.78709259622575830E+06   5.87765236367034840E+05
   2.70236454624685170E+05   5.00521462255167930E+04   5.95591089011073930E+03
   6.12149900566291420E+02   4.74398752824588290E+01   1.20395534102758270E+01
   4.21975457926969360E+00
      5        4.99640389937285710000E-07
  -9.87211106052957920E+07   7.67339900090667960E+08   1.13095461526605150E+07
   1.70281252045315550E+06   2.06398618397906680E+05
   3.20416100549760630E+09   1.23780467419306330E+09   9.55644856004598740E+07
   1.08002289264442010E+07   1.55435466974295470E+06
  0.74278792  0.62609170
  0.00000000  0.00000000
 -0.66952476  0.77974458
 -0.00000000  0.00000000
```

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