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Lightning Transients on Branched Distribution Lines Considering Frequency-Dependent Ground Parameters

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***Abstract*—This paper investigates the influence of considering frequency-dependent ground parameters in the calculation of lightning transients on a two-phase distribution line including the presence of branches. The analysis is focused on propagation effects along the line. It is shown that the influence of frequency-dependent ground parameters is only remarkable if a poorly-conducting ground is considered. It is also shown that the presence of line branches is likely to reduce the relative importance of considering the frequency variation of the ground parameters in the calculation of lightning transients.**

Keywords- transmission line modeling; frequency-dependent ground parameters; branched distribution lines; lightning overvoltages.

I. INTRODUCTION

There has been an increasing interest in the simulation of electromagnetic transients considering the variation of the ground conductivity and permittivity with frequency [1-14]. However, most of the available literature deals with line topologies in which the presence of branches and multiple grounding points is neglected. More recently, an attempt was made to investigate to what extent the consideration of frequency-dependent ground parameters would be important in the calculation of switching transients on a branched power distribution line [15]. In this paper, this analysis is extended to the study of direct lightning strikes over a power distribution line with complex topology, with focus on the influence of incorporating frequency-dependent ground parameters on the transmission line model.

II. MODELING ASSUMPTIONS

A. Transmission Line Parameters

The transmission line parameters are calculated assuming the ground-return impedance to be given by

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

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

where

$$\gamma_g = \sqrt{j\omega\mu_0[\sigma + j\omega(\varepsilon_r - k)\varepsilon_0]} \qquad (3)$$

In (1)-(3), ω is the angular frequency, σ is the ground conductivity, ε_r is the ground relative permittivity, h_i and h_j are the heights of conductors i and j, r_{ij} is the horizontal separation between the conductors, μ_0=4π×10^{-7} H/m, ε_0=8.85×10^{-12} F/m, and k is a constant that selects the desired ground-return model [15,16]. If k=1 in (3), equations (1) and (2) reduce to Nakagawa's equations [17]; if $k=\varepsilon_r$, equations (1) and (2) reduce to Carson's equations [18], in which it is implicitly assumed that ε_r is equal to the relative permittivity of the vacuum [16]. The fact that it is impossible to set values of ground relative permittivity other than unity in Carson's equations limits their application to cases in which $\sigma >> \omega\varepsilon$. In Nakagawa's equations it is possible to set any desired value to ε_r, which makes them applicable to studying high-frequency transients in transmission lines located above high-resistivity soils.

B. Soil Model

The considered soil model is the one proposed in [4]. It is based on measurements of the frequency response of 65 different types of soils in Brazil. This soil model describes the variation of the ground parameters with frequency as

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$$\sigma(\omega)=\sigma_0+\sigma_0\times h(\sigma_0)\left(\frac{f}{10^6}\right)^n \qquad (3)$$

$$\varepsilon_r(\omega)=\frac{\varepsilon'_\infty}{\varepsilon_0}+\frac{\tan(n\pi/2)\times 10^{-3}}{2\pi\varepsilon_0 10^{6n}}\sigma_0\times h(\sigma_0)\,f^{\,n-1} \qquad (4)$$

where $\sigma(\omega)$ is the frequency-dependent soil conductivity, in mS/m, σ_0 is the low-frequency soil conductivity determined at 100 Hz, in mS/m, $\varepsilon_r(\omega)$ is the frequency-dependent relative permittivity, $\varepsilon'_\infty/\varepsilon_0=12$ is the relative permittivity at higher frequencies, f is the frequency, $h(\sigma_0)=1.26\times\sigma_0^{-0.73}$, and $n=0.54$ (see [4] for details).

C. Transmission Line Model

All analyses consider the modal-domain transmission line model of Marti [19] extended to include frequency-dependent ground parameters as outlined in [15]. The transmission line parameters are calculated in MATLAB. The modal propagation functions and the modal characteristic impedances are fitted in the frequency domain from 1 Hz to 10 MHz using the vector fitting technique [20]. The resulting poles and residues are written in the form of a .pch file that is read and interpreted by the Alternative Transients Program (ATP) as a frequency-dependent line. Details of the implemented procedure can be found in [15].

III. Simulated Cases

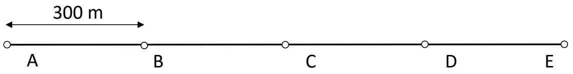
Fig. 1 illustrates the three basic cases considered in the analysis. The solid lines represent two-phase power distribution lines that are typically used in rural areas in Brazil. A vertically-stacked configuration is assumed in which the top and bottom conductors are at heights of 8.4 m and 7.2 m above the ground. The conductors are represented as solid copper wires of 5 mm radius, whose internal impedance is calculated with the traditional formulation using Bessel's functions. In practical conditions, the bottom conductor is expected to be grounded every 200 m or so. Here, it is not grounded to keep the analysis focused on the effect of frequency-dependent ground parameters on the wave propagation along the transmission lines. In all cases, all line terminations were left open, except at point A where both conductors were connected to ground by means of resistances of 480 Ω. This value approaches the characteristic impedances of both conductors if losses are neglected. Case 1 assumes a transmission line with length of 1200 m without any branches. Cases 2 and 3 add laterals with lengths L_n to Case 1, where n corresponds to the lateral number. All transmission line segments were simulated via .pch files in ATP as outlined in [15].

In all analyses, an ideal current source with a normalized peak amplitude of 1 A was considered. A lightning current waveform represented as a single Heidler function with virtual front time t_{d30}=0.2 μs (measured as the time from $0.3I_p$ to $0.9I_p$ divided by 0.6, where I_p is the current peak value) and time to half-value of 21 μs was assumed. This current waveform can be considered representative of fast subsequent stroke currents measured at short instrumented towers [21, 22]. This lightning current was injected by an ideal current source at points A or C indicated in Fig. 1.

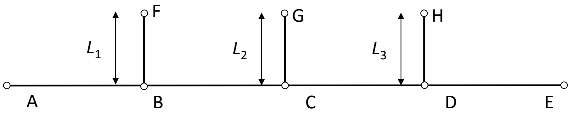
IV. Results and Analysis

A. Case 1

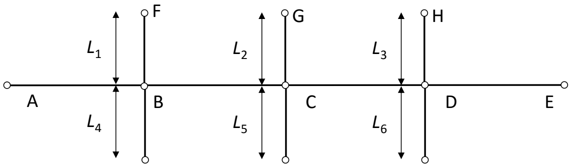
Fig. 2 illustrates voltages at points C and E for the injection of the lightning current at point A, considering a low-frequency ground conductivity of 0.001 S/m. The illustrated waveforms were obtained for the calculation of the transmission line parameters either with Carson's formula assuming a constant ground conductivity (curves labeled "σ_0, Carson") or with Nakagawa's equations assuming frequency-dependent ground parameters (curves labeled "$\sigma(\omega),\varepsilon_r(\omega)$, Nakagawa"). Fig. 3 repeats the analysis of Fig. 2 assuming a low-frequency ground conductivity of 0.0001 S/m. The .pch file associated with the 150-m long line segment considered as a building block for simulating the cases referring to frequency-dependent ground parameters with σ_0=0.0001 S/m can be found in the appendix of [15].



(a) Case 1



(b) Case 2



(c) Case 3

Figure 1. Investigated line topologies.

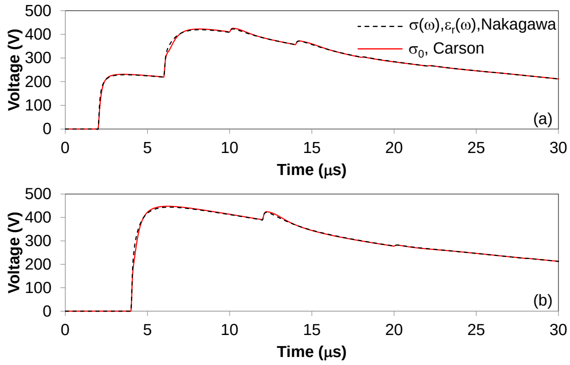


Figure 2. Voltages at points C and E for Case 1 [line illustrated in Fig. 1(a)] considering the current injection at point A and a low-frequency ground conductivity of 0.001 S/m.

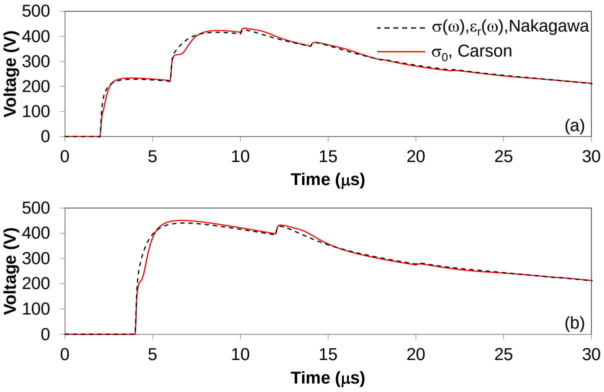


Figure 3. Same as Fig. 2, but for a low-frequency ground conductivity of 0.0001 S/m.

It is seen in Fig. 2 that for a ground conductivity of 0.001 S/m the differences between the calculated voltage waveforms are not significant. Although not shown, for a more conductive ground the observed differences become negligible. In Fig. 3, more noticeable differences are observed in the curves calculated considering or neglecting the variation of the ground parameters with frequency for a ground conductivity of 0.0001 S/m. Although the calculated peak values are not significantly affected, the observed waveform distortion could be determinant for the occurrence or not of insulation breakdown in certain conditions. Similar conclusions apply if the lightning current is injected at point C, as seen in Fig. 4, which shows the voltages calculated at points B, C, D and E for a low-frequency ground conductivity of 0.0001 S/m.

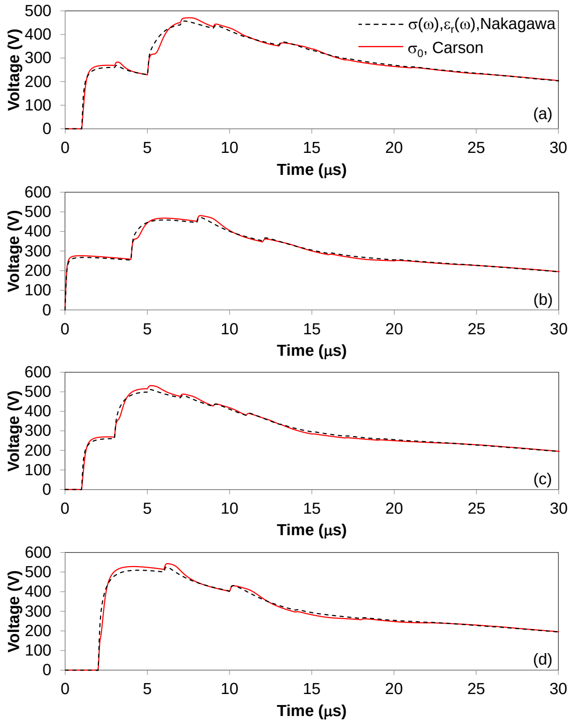


Figure 4. Voltages at points B, C, D, and E for Case 1 [line illustrated in Fig. 1(a)] considering the current injection at point C and a low-frequency ground conductivity of 0.0001 S/m.

B. Case 2

The analysis presented in this section considers Case 2, which corresponds to the distribution line with three laterals illustrated in Fig. 1(b). In the simulations, the laterals were assumed to have the following lengths: L_1=150 m, L_2=300 m, and L_3=450 m. Fig. 5 illustrates voltages calculated at points B, C, D, and E assuming the current injection at point A for a low-frequency ground conductivity of 0.0001 S/m, considering or neglecting the frequency variation of the ground parameters as before. Fig. 6 illustrates voltages calculated for the current injection at point C.

It is seen in Figs. 5 and 6 that the inclusion of laterals modifies the calculated waveforms in comparison with the results presented in the previous section, which were obtained for a transmission line without any branches. This is the result of the multiple reflections that take place at the various open-ended terminations. Another effect associated with the inclusion of laterals is the reduction of the peak voltages for both current injection points.

A comparison of the voltage waveforms calculated considering or neglecting the variation of the ground parameters with frequency shows that including this variation modifies the fine structure of the waveforms without changing their overall characteristics. The most notable differences between the calculated waveforms are observed at point E for the injection of the lightning current at point C, as illustrated in Fig. 6(d). However, even in this case the calculated peak voltages are not affected.

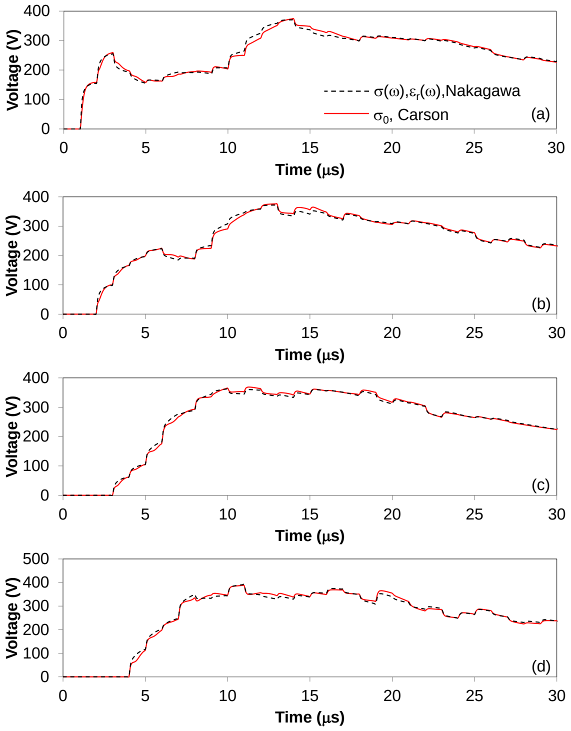


Figure 5. Voltages at points B, C, D, and E for Case 2 [line illustrated in Fig. 1(b)] considering the current injection at point A and a low-frequency ground conductivity of 0.0001 S/m.

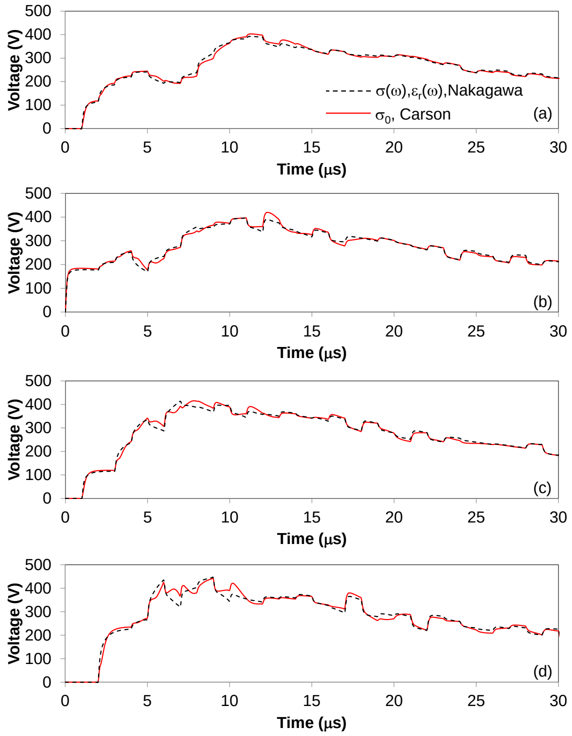


Figure 6. Same as Fig. 5, but for current injection at point C.

C. *Case 3*

The final set of results presented in this paper refers to Case 3, which corresponds to the distribution line with six laterals illustrated in Fig. 1(c). In the simulations, the following lengths were assumed for the laterals: L_1=L_4=L_6=150 m, L_2=300 m, L_3=450 m, and L_5=600 m. Fig.7 illustrates the voltages at points B, C, D, and E for the current injection at point A. Fig.8 does the same, but for the current injection at point C. In both cases, a low-frequency ground conductivity of 0.0001 S/m was assumed.

It is seen in Figs. 7 and 8 that the consideration of a total of six laterals reduces even further the calculated peak values. For example, for the current injection at point A the peak voltage at point E reaches about 450 kV in Case 1, 390 kV in Case 2, and 340 kV in Case 3. For the current injection at point C, the peak voltage at point E reaches about 525 kV in Case 1, 443 kV in Case 2, and 375 kV in Case 3. Again, as expected, this reduction is associated with the multiple reflections that take place in the branches.

Interestingly, in the presence of six laterals the calculated voltage waveforms are nearly model independent regardless of the assumed current injection point. This suggests that considering the frequency variation of the ground parameters might not be important in the calculation of the transmission line parameters if an analysis of lightning overvoltages on highly-branched distribution lines is to be performed.

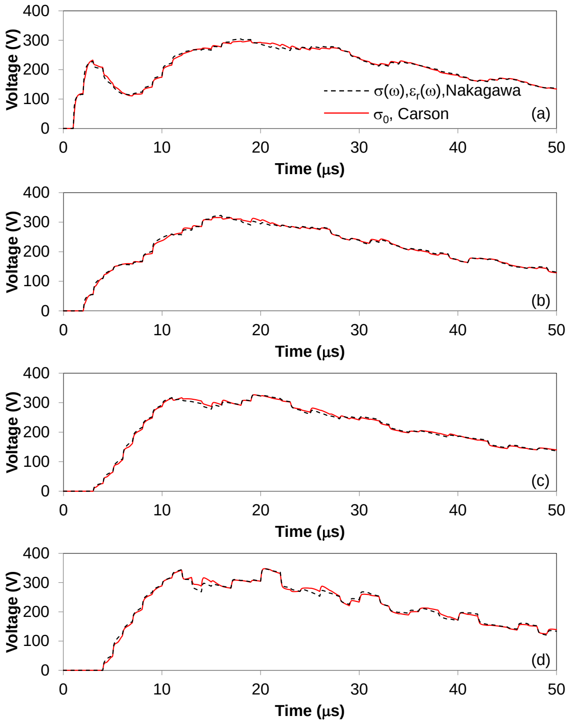


Figure 7. Voltages at points B, C, D, and E for Case 3 [line illustrated in Fig. 1(c)] considering curring injection at point A and a low-frequency ground conductivity of 0.0001 S/m.

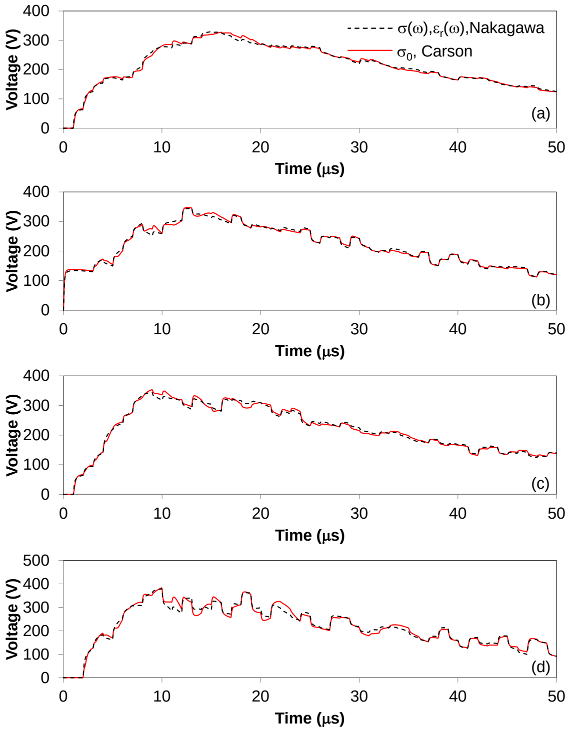


Figure 8. Same as Fig. 7, but for current injection at point C.

D. Discussion

The results presented in the previous sections indicate that the inclusion of line branches is likely to reduce the importance of considering the frequency variation of ground parameters in the calculation of transmission line parameters if lightning overvoltages are to be calculated on distribution lines. In fact, depending on the system topology the use of Carson's formula with constant ground parameters can lead to acceptable results even for a value of low-frequency ground conductivity as low as 0.0001 S/m.

It must be reminded that the considered lightning current has a virtual front time of 0.2 μs, which approaches the lower limit of front times of subsequent return-stroke currents measured at short instrumented towers. If slower lightning currents were considered, the differences observed between the voltage waveforms calculated assuming or neglecting the variation of the ground parameters with frequency would be even less significant. This happens because in this case the frequency content of the injected current would be more concentrated in the low-frequency range, and the reduction in ground resistivity and relative permittivity that is expected in the high-frequency region would be less relevant for the calculated results.

Finally, most of the results presented in this section refer to a ground conductivity of 0.0001 S/m at lower frequencies. As suggested in the results presented in Fig. 1, the consideration of a more conductive ground would reduce even further the differences observed if constant or frequency-dependent ground parameters are considered in the calculation of the transmission line parameters, especially in a line topology that include a great number of laterals.

V. CONCLUSIONS

This paper investigates the influence of considering a frequency-dependent soil in the assessment of lightning overvoltages on a typical two-phase distribution line. The analysis is focused on propagation effects along the line. It is shown that frequency-dependent ground parameters are of some relevance only for very low values of ground conductivity (e.g., 0.0001 S/m at low frequencies). It is also shown that the presence of multiple line branches is likely to reduce the relative importance of considering a frequency-dependent soil in the calculation of transmission line parameters even for a poorly-conducting ground, at least in terms of resulting lightning transients.

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