Title

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***Abstract*—Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Etiam lobortis facilisis sem. Nullam nec mi et neque pharetra sollicitudin. Praesent imperdiet mi nec ante.**

***Index Terms*—Earth conduction effects, electromagnetic transients, frequency-dependent soil models, overhead lines.**

I. Introduction

ELECTROMAGNETIC interference (EMI) between power transmission lines and pipelines sharing the same right-of-ways has been a topic of major concern for several decades now, due to the increasing industrialization, the more restrictive environmental regulations and the ever-increasing cost of rights-of-ways [1], [2], [3]. In general, there are three types of EMI, named as inductive (or electromagnetic) coupling, capacitive (or electrostatic) coupling, and conductive (or resistive) coupling [3], [4].

Therefore, in the presence of a neighboring pipeline, potentially hazardous voltages may be transferred to the interfered system and consequently a significant issue is to keep the voltage in all metallic parts within acceptable limits, since induced overvoltages may result in (a) safety hazards, due to electric shock to people coming in contact, (b) pipeline aging and insulation failures that subsequently can contribute to pipeline corrosion, (c) damages to the equipment and devices connected to the cables and the pipeline [3], [5], [6].

It is, therefore, imperative to assess the induced voltages on pipelines by overhead transmission lines. Most of these studies refer to cases during the normal operating condition or during faults at the mains frequency (50 Hz or 60 Hz). Recently, only a few works have presented preliminary EMI results about harmonic induction effects [7], [8] as well as the impact of transient surges on pipelines [2], [5], [6], [9], [10]. This is becoming more important for aboveground pipelines, where induced voltages from lightning and/or switching events are significant in comparison to 50-Hz faults [5], [6]. All these studies to predict the effects of transient EMI are based on electromagnetic transient (EMT) models and require the calculation of the per-unit-length self and mutual parameters (impedances and admittances) between all conductors of the arrangement. For their accurate estimation the influence of the imperfect earth is a crucial issue. The most known and widely adopted formulation has been proposed by Carson [11]. However, Carson's work is based on a series of assumptions regarding earth conduction effects; of those the most important are [12]:

- The influence of the imperfect earth is considered only on the line impedance, neglecting cable admittance earth conduction effects. This implies that earth behaves only as a conductor limiting the accuracy of such an approach to low-frequency applications, e.g., up to a few kHz. Many efforts to develop expressions for the series impedances have been reported in literature, with the most known proposed by Sunde, that extends [7] by including the influence of earth permittivity.
- The electrical properties of the soil, i.e., conductivity and permittivity are assumed to be constant; however, in reality they are frequency-dependent (FD) [13], [14], [15], [16], [17].

In order to develop more accurate earth models, aiming at the calculation of the earth conduction effects on both the series impedances and the shunt admittances was proposed by Wise [18], [19]. Accordingly, Kikuchi [20] by investigating the transition from quasi-TEM to surface wave guide propagation proposed also earth impedance and admittance formulas which under specific approximations result to those found by Wise. Later, Pettersson [21] approximated Kikuchi's and Wise's infinite integral expressions with logarithmic terms, thus providing an easily applicable and feasible formulation [22]. These approaches have been used to investigate the transient performance of overhead lines [22], [23], [24] as well as gas insulated buses [25]. Additionally, several models have been proposed for the prediction of the FD soil electrical properties [13], [14], [15], [16], [17]. However, most studies focus on overhead transmission line configurations [17], [26], [27], [28] and more recently on underground cable systems [29], [30], [31]. Therefore, the impact of earth conduction effects at high frequencies on configurations incorporating overhead transmission lines and pipelines has not been addressed in the literature.

II. Mathematical model

A. Earth impedance and admittance formulas

For the case of two thin wires situated in the topology of Fig. 1, Wise's generalized formulas, representing the influence of the conductive and displacement currents in all propagation media on the per-unit-length earth impedance ($Z_{e_{ij}}$) and earth admittance (Y_{e_i}) is given as (1)-(4) in integral form.

$$Z_{\varepsilon_j} = \frac{j\omega\mu_0}{2\pi}\left(\ln\frac{D_{ij}}{d_{ij}} + M_{ij}\right), \qquad (1)$$

$$Y_{\varepsilon_{ij}} = j\omega P_{e_{ij}}^{-1} = j\omega P_{pg_{ij}} + P_{g_{ij}}^{-1}, \qquad (2)$$

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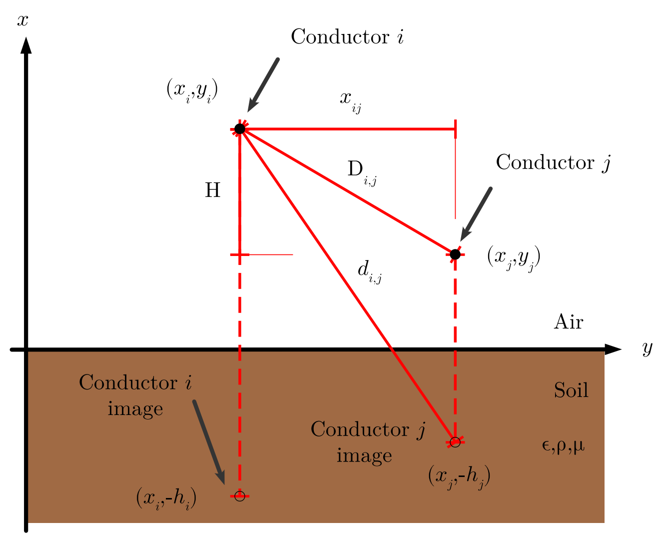

Fig. 1. Two parallel thin conductors above earth surface.

$$M_{ij} = \int_0^\infty \frac{2\mu_g e^{-h_i+h_i,a_0}}{a_g\mu_0 + a_0\mu_g}\cos(x_{ij}\lambda)d\lambda \approx \ln\frac{\sqrt{\left(h_i+h_j+\frac{2}{\sqrt{\gamma_g^2-\gamma_0^2}}\right)^2+x_{ij}^2}}{D_{ij}}, \tag{3}$$

$$P_{e_i} = P_{P_{g_j}} + P_{8_j} = \frac{1}{2\pi\varepsilon_0}\left(\ln\frac{D_{ij}}{d_{ij}} + Q_{ij}\right), \tag{4}$$

$$Q_{ij} = \int_0^\infty \frac{2\mu_g\gamma_0^2\mu_0\alpha_0 + \alpha_g\mu_g e^{-h_i+h_i}a_0}{a_g\mu_0 + a_0\mu_g\left(a_g\gamma_0^2\mu_g + a_0\gamma_g^2\mu_0\right)}\cos(x_{ij}\lambda)d\lambda \approx \frac{1}{(n^2+1)\pi\varepsilon_0}\ln\frac{\sqrt{h_i+h_j+\frac{n^2+1}{\sqrt{\gamma_8^2-\gamma_0^2}}+x_{ij}^2}}{D_{ij}}, \tag{5}$$

in which λ is the integration variable, $Z_{pg_{ij}}$,$P_{pg_{ij}}$ represent the influence of the perfectly conducting earth and $Z_{g_{ij}}$,$P_{g_{ij}}$ represent the influence of the imperfect earth, respectively. The EM properties of air, i.e., permittivity, permeability and conductivity, are denoted as ϵ_0, μ_0, (σ_0) and of earth $\epsilon_g = \epsilon_{rg}\epsilon_0$, $\mu_g = \mu_{rg}\mu_0$, σ_g, where ϵ_g is the relative permittivity and μ_g the relative permeability of the earth. Accordingly, the air and earth propagation constants are defined as $\gamma_0 = jk_0 = j\omega\sqrt{\mu_0\varepsilon_0}$ and $\gamma_g = \sqrt{\mathrm{j}\omega_0\left(\sigma_g + j\omega\varepsilon_0\varepsilon_{r_g}\right)}$, respectively, and $a_0 = \lambda$ and $a_g = \sqrt{\lambda^2+\gamma_g^2+k_0^2}$; $D_{ij} = \sqrt{H^2+x_{ij}^2}$, $d_{ij} = \sqrt{(h_i-h_j)^2+x_{ij}^2}$. The self impedance of conductor i is derived by replacing h_j with h_i and x_{ij} with the conductor outer radius r_i. In addition, by numerically approximating the integrals of (1)-(5) with logarithmic terms, Pettersson's simplified expressions are derived with $n = \sqrt{\varepsilon_{r_g} + \frac{\sigma_8}{j\omega\varepsilon_0}}$.

In the case of an overhead power line and an aboveground pipeline configuration, the total per-unit-length impedance and admittance matrices are derived by applying the generalized formulation of [31]. In particular, the self and mutual earth impedance and earth admittance are introduced, the influence of skin effect on the conductor self-impedances is taken into account and the insulation of the pipeline is expressed in the corresponding self-inductance and -capacitance.

B. Frequency-dependent soil model

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III. Propagation Characteristics

Under this section, the propagation characteristics of a system composed by a transmission line in close proximity with an aboveground metallic pipeline is investigated in detail. The different propagation modes, characteristic impedances, attenuation constants and phase velocities are analyzed in the frequency-domain using different formulations and soil models, with emphasis on the modes which are most affected by earth parameters.

A. System configuration

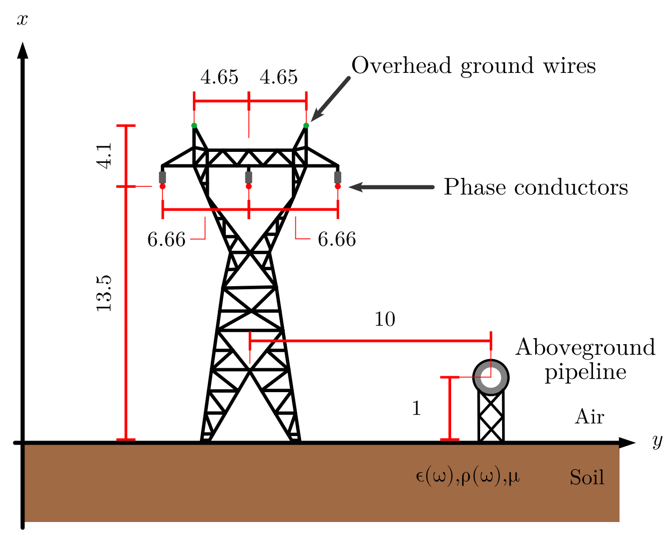

Fig. 2. Cross-section view of the system under investigation.

B. Modal analysis

- Mode #1 - Blue: Travels through conductor 5 (ground wire) - Returns through conductor 6 (ground wire).
- Mode #2 - Red: Travels through conductors 5 and 6 (ground wires) - Returns through conductors 1, 2, 3 (line phases).
- Mode #3 - Orange: Travels through all metallic conductors - Returns through infinite earth - This is the pure ground mode.
- Mode #4 - Purple: Travels through conductors 1, 2, 3, 5, 6 (line phases and ground wires) - Returns through conductor 4 (pipe).
- Mode #5 - Green: Travels through conductor 1 (line phase) - Returns through conductor 3 (line phase).

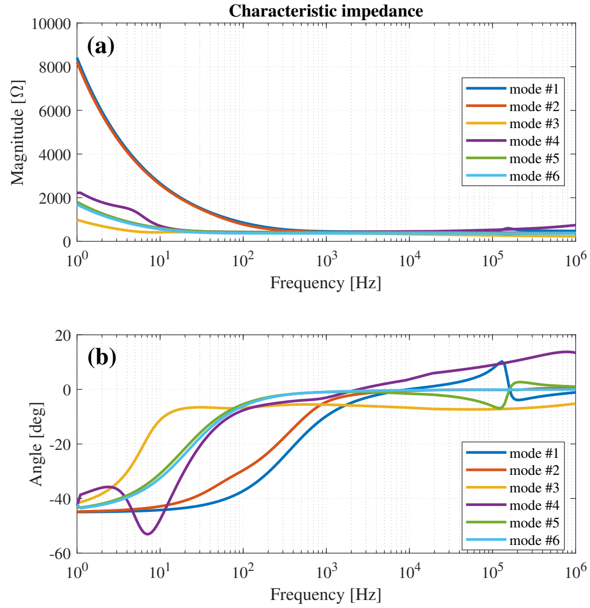

Fig. 3. Characteristic impedance magnitude (a) and angle (b), Wise's formula, constant soil parameters with $\rho = 1000\ \Omega$.m.

- Mode #6 - Cyan: Travels through conductor 2 (line phase) - Returns through conductors 1, 3 (line phases).

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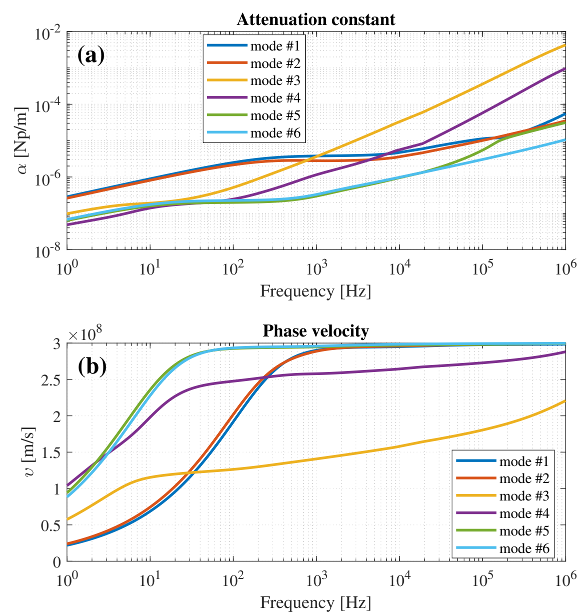

Fig. 4. Attenuation constant (a) and phase velocity (b), Wise's formula, constant soil parameters with $\rho = 1000\ \Omega$.m.

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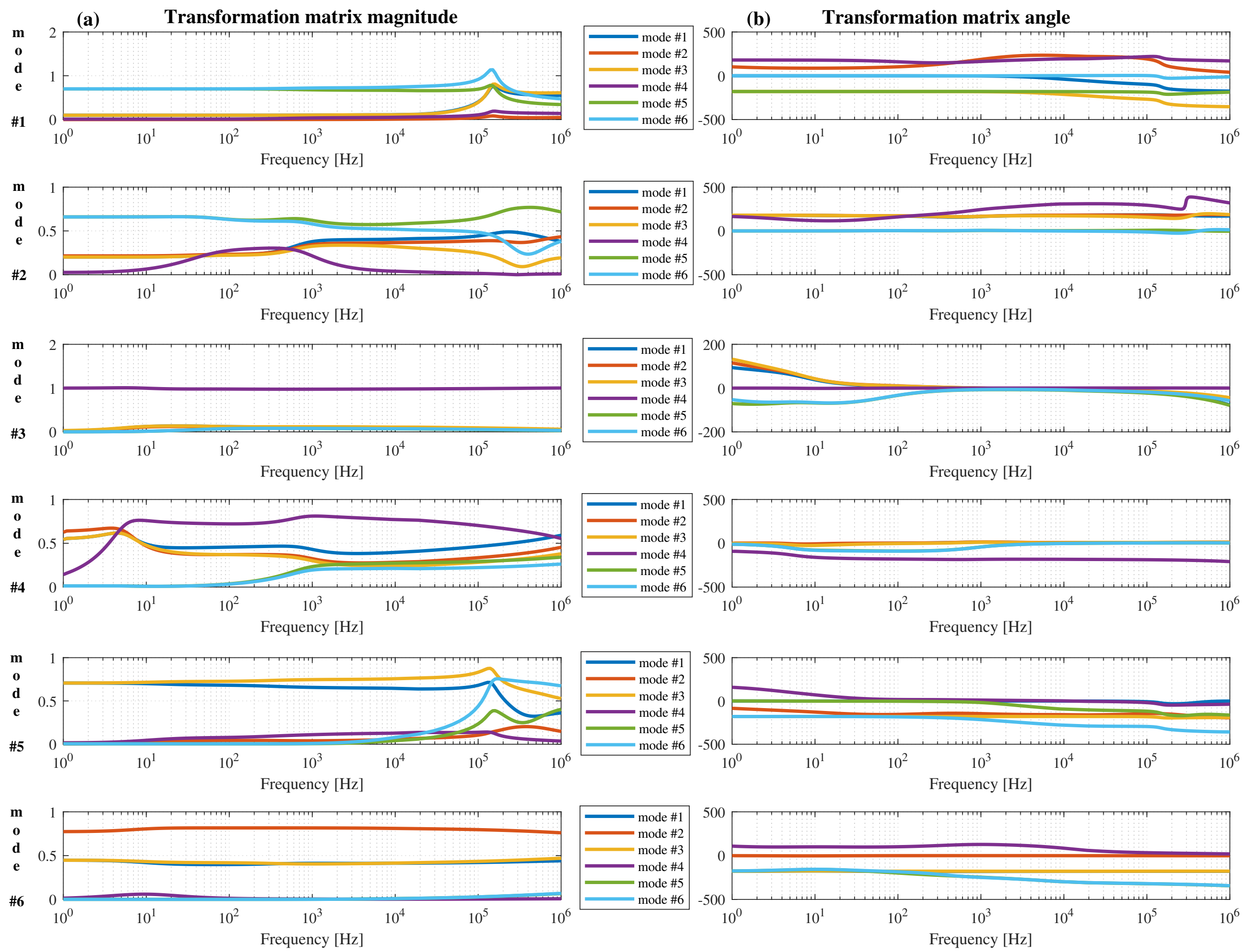

Fig. 5. Modal transformation matrix magnitude (a) and angle in degrees (b), Wise's formula, constant soil parameters with $\rho = 1000\ \Omega$.m.

C. Influence of earth admittance correction

The influence of earth impedance and admittance correction terms is assessed by comparing results obtained using Wise's formulas expressed in (3) and (5) to the classic Carson's equation, under which the soil permittivity constant is disregarded [11].

Soil parameters are assumed to be constant, and different resistivity values are employed, namely: 100 Ω.m, 1000 Ω.m, and 5000 Ω.m, covering a wide range of soils commonly found in real world installations [32]. Attenuation constants and phase velocities are evaluated accordingly, and to highlight the differences between each approach, normalized parameters are provided as the ratio with respect to Carson's results, or:

$$f_{norm} = \frac{\text{propagation characteristics}_{\text{ Wise}}}{\text{propagation characteristics}_{\text{ Carson}}}, \tag{6}$$

in which f_{norm} denotes the normalized propagation parameter of interest: attenuation constant or phase velocity, in p.u.

The propagation characteristics for mode #3 (pure ground mode) are represented in Figs. 6 and 7, whereas results for mode #4 (pipeline mode) are given in Figs. 8 and 9.

In general, ground mode waves attenuate more steeply and propagate slower than the pipeline (aerial) mode, which agrees with the finite earth resistivity yielding a lossy dispersive medium, in contrast to the insulating air within which the pipeline is installed.

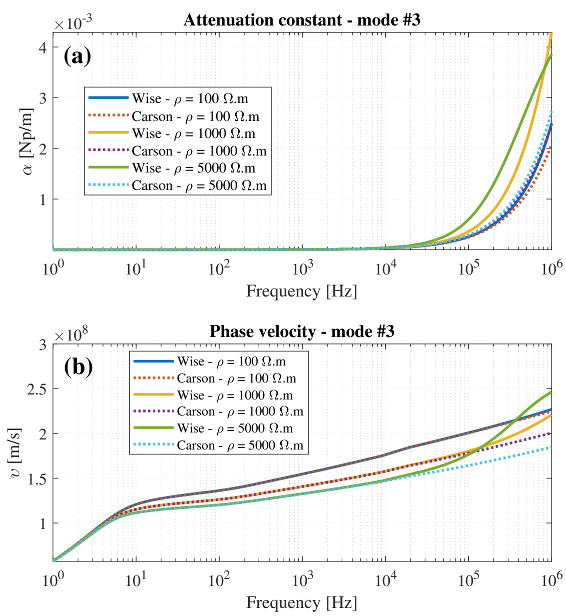

Fig. 6. Attenuation constant (a) and phase velocity (b) for mode #3 (ground mode), comparing Carson and Wise's admittance formulas, with constant soil parameters and different soil resistivities.

Results are essentially the same at the lower part of the frequency spectrum, however, after 10 kHz, discrepancies become more pronounced in Wise's model for increasing resistivity values. The influences of the soil resistivity in the propagation characteristics determined using Carson's formula

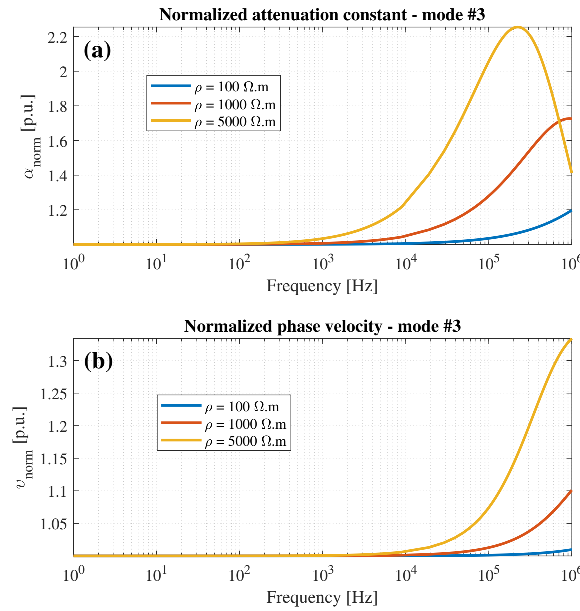

Fig. 7. Normalized attenuation constant (a) and phase velocity (b) for mode #3 (ground mode), comparing Carson and Wise's admittance formulas, with constant soil parameters and different soil resistivities.

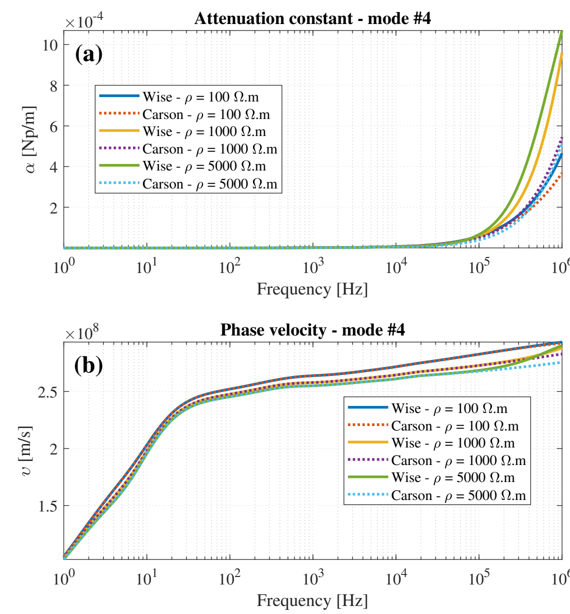

Fig. 8. Attenuation constant (a) and phase velocity (b) for mode #4 (pipeline mode), comparing Carson and Wise's admittance formulas, with constant soil parameters and different soil resistivities.

are nearly negligible, which not only agrees with previous reports in the literature [29], but it is also algebraically consistent with the potential coefficient definition in (4). Under Carson's model and electrostatic images theory, the term Q_{ij} in (4) equals to zero, nullifying the effect of imperfect earth on line admittances and, consequently, on propagation characteristics.

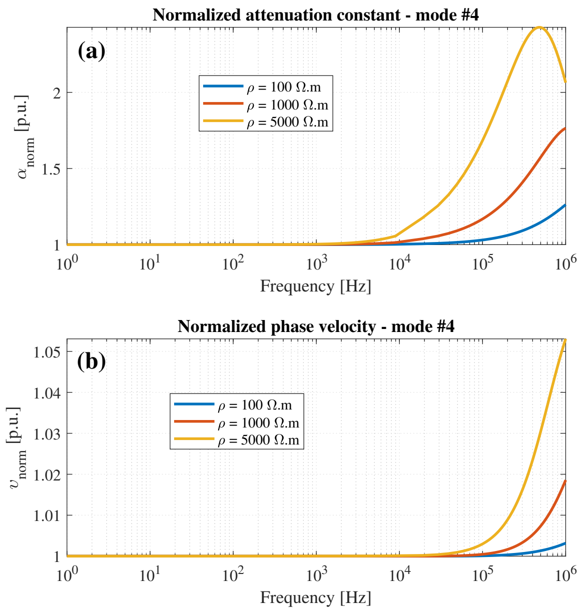

Fig. 9. Normalized attenuation constant (a) and phase velocity (b) for mode #4 (pipeline mode), comparing Carson and Wise's admittance formulas, with constant soil parameters and different soil resistivities.

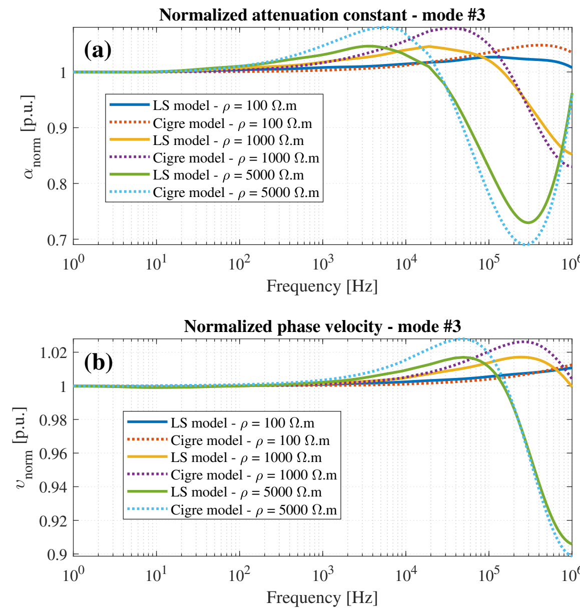

Fig. 10. Normalized attenuation constant (a) and phase velocity (b) for mode #3 (ground mode), comparing LS and Cigre frequency-dependence models, using Wise's formula and different soil resistivities.

On the other hand, Wise's formulation curves provide a clear perspective of how the earth admittance correction affects the attenuation constants and phase velocities of propagating waves, which is particularly evident from inspection of the normalized values for $\rho = 5000$ Ω.m. It can be seen that, in the worst case, Wise's attenuation constant more than doubles in relation to Carson's result, which corresponds to a discrepancy of over 100%. Similarly, phase velocities are increased when earth return admittances are accounted for, with discrepancies of around 5% (pipeline mode) to 30% (ground mode).

It can be generally concluded from above that neglecting earth return correction on line admittances may disregard important propagation effects taking place both on the interfering as well as the interfered installation, leading to innacurate induced voltage predictions, especially at higher frequencies, as demonstrated in Section IV.

D. Influence of soil model

To evaluate the influence of the soil parameters frequency-dependence on propagation characteristics, results obtained employing Wise's formula along with the Longwire-Smith (LS) and Cigre models are compared to the constant parameters (CP) model by means of normalized curves, taking the CP model as reference. Figs. 10 and 11 describe the normalized propagation parameters for ground mode and pipeline mode waves, respectively, considering different base resistivity values of 100 Ω.m, 1000 Ω.m and 5000 Ω.m.

As in the preceding section, the largest discrepancies occur for ground mode waves within the upper portion of the frequency spectrum and higher soil resistivities. In general, curves for both LS and Cigre models show the same trend, but with slightly increased magnitudes in the Cigre model.

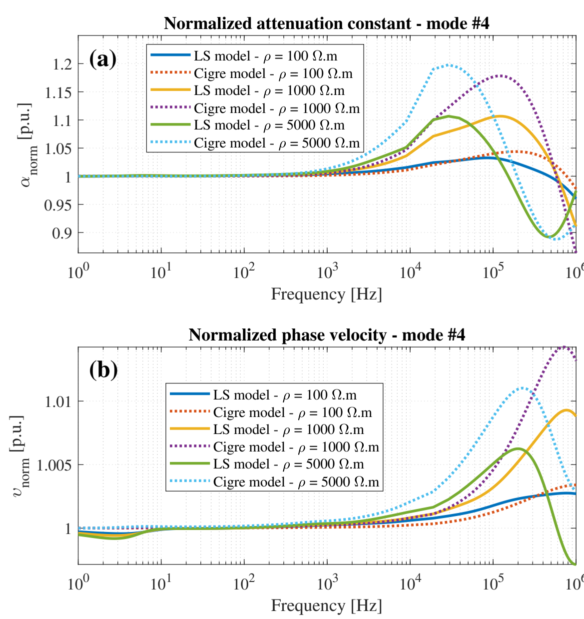

Fig. 11. Normalized attenuation constant (a) and phase velocity (b) for mode #4 (pipeline mode), comparing LS and Cigre frequency-dependence models, using Wise's formula and different soil resistivities.

IV. Pipeline induced voltages

A. Frequency-domain responses

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B. Transient responses

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V. Conclusions

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References

[1] G. C. Christoforidis, D. P. Labridis, and P. S. Dokopoulos, "Inductive interference on pipelines buried in multilayer soil due to magnetic fields from nearby faulted power lines," *IEEE Trans. Power Del.*, vol. 47, no. 2, pp. 254–262, 2005.

[2] A. G. Martins-Britto, C. M. Moraes, and F. V. Lopes, "Transient electromagnetic interferences between a power line and a pipeline due to a lightning discharge: An emtp-based approach," *Electric Power Systems Research*, vol. 197, p. 107321, 2021.

[3] CIGRE, "Guide concerning influence of high voltage ac power systems on metallic pipelines," *CIGRE Working Group 36.02*, 1995.

[4] F. P. Dawalibi and R. D. Southey, "Analysis of electrical interference from power lines to gas pipelines. i. computation methods," *IEEE Trans. Power Del.*, vol. 4, no. 3, pp. 1840–1846, 1989.

[5] I. Cotton, K. Kopsidas, and Y. Zhang, "Comparison of transient and power frequency-induced voltages on a pipeline parallel to an overhead transmission line," *IEEE Trans. Power Del.*, vol. 22, no. 3, pp. 1706–1714, 2007.

[6] K. Kopsidas and I. Cotton, "Induced voltages on long aerial and buried pipelines due to transmission line transients," *IEEE Trans. Power Del.*, vol. 23, no. 3, pp. 1535–1543, 2008.

[7] J. Yong, B. Xia, H. Yong, W. Xu, A. B. Nassif, and T. C. Hartman, "Harmonic voltage induction on pipelines: Measurement results and methods of assessment," *IEEE Trans. Power Del.*, vol. 33, no. 5, pp. 2170–2179, 2018.

[8] D. Boteler, C. A. Charalambous, and K. Lax, "New insights into calculations of ac interference at fundamental and harmonic frequencies taking account of the phase relationships of the currents," *IEEE Trans. Power Del.*, 2021.

[9] G. D. Peppas, M. P. Papagiannis, S. Koulouridis, and E. C. Pyrgioti, "Induced voltage on a above-ground natural gas/oil pipeline due to lightning strike on a transmission line," in *2014 International Conference on Lightning Protection (ICLP)*, 2014, pp. 461–467.

[10] D. Caulker, H. Ahmad, and M. S. M. Ali, "Effect of lightning induced voltages on gas pipelines using atp-emtp program," in *2008 IEEE 2nd International Power and Energy Conference*, 2008, pp. 393–398.

[11] J. Carson, "Wave propagation in overhead wires with ground return," *Bell Syst. Tech. J.*, p. 539–554, 1926.

[12] T. Papadopoulos, Z. Datsios, A. Chrysochos, P. Mikropoulos, and G. Papagiannis, "Wave propagation characteristics and electromagnetic transient analysis of underground cable systems considering frequency-dependent soil properties," *Bell Syst. Tech. J.*, vol. 63, no. 1, pp. 259–267, 2021.

[13] C. Longmire and K. Smith, "A universal impedance for soils," *DNA 3788T, Mission Research Corp., Santa Barbara, CA*, 1975.

[14] R. Alipio and S. Visacro, "Modeling the frequency dependence of electrical parameters of soil," *IEEE Transactions on Electromagnetic Compatibility*, vol. 56, no. 5, pp. 1163–1171, 2014.

[15] Z. G. Datsios and P. N. Mikropoulos, "Characterization of the frequency dependence of the electrical properties of sandy soil with variable grain size and water content," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 26, no. 3, pp. 904–912, 2019.

[16] D. Cavka, N. Mora, and F. Rachidi, "A comparison of frequency-dependent soil models: Application to the analysis of grounding systems," *IEEE Transactions on Electromagnetic Compatibility*, vol. 56, no. 1, pp. 177–187, 2014.

[17] CIGRE, "Impact of soil-parameter frequency dependence on the response of grounding electrodes and on the lightning performance of electrical systems," *CIGRE WG C4.33*, 2019.

[18] W. Wise, "Propagation of high frequency currents in ground return circuits," *Proc. Inst. Radio Eng.*, vol. 22, p. 522–527, 1934.

[19] ——, "Potential coefficients for ground return circuits," *Bell Syst. Tech. J.*, vol. 27, p. 365–371, 1948.

[20] H. Kikuchi, "Wave propagation along an infinite wire above ground at high frequencies," *Electrotech. J. Jpn.*, vol. 2, p. 73–78, 1956.

[21] P. Pettersson, "Image representation of wave propagation on wires above, on and under ground," *IEEE Transactions on Power Delivery*, vol. 9, no. 2, pp. 1049–1055, 1994.

[22] T. Papadopoulos, A. Chrysochos, C. Traianos, and G. Papagiannis, "Closed-form expressions for the analysis of wave propagation in overhead distribution lines," *Energies*, vol. 13, p. 4519, 2020.

[23] M. D'Amore and M. Sarto, "Simulation models of a dissipative transmission line above a lossy ground for a wide-frequency range. i. single conductor configuration," *IEEE Transactions on Electromagnetic Compatibility*, vol. 38, no. 2, pp. 127–138, 1996.

[24] T. Papadopoulos, G. Papagiannis, and D. Labridis, "A generalized model for the calculation of the impedances and admittances of overhead power lines above stratified earth," *Electr. Power Syst. Res.*, vol. 80, p. 1160–1170, 2010.

[25] A. Ametani, Y. Miyamoto, , and Y. Babaand N. Nagaoka, "Wave propagation on an overhead multiconductor in a high-frequency region," *IEEE Transactions on Electromagnetic Compatibility*, vol. 56, no. 6, pp. 1638–1648, 2014.

[26] A. C. S. de Lima and C. Portela, "Inclusion of frequency-dependent soil parameters in transmission-line modeling," *IEEE Transactions on Power Delivery*, vol. 22, no. 1, pp. 492–499, 2007.

[27] M. Tomasevich, Y. Mashenko, and A. C. S. Lima, "Impact of frequency-dependent soil parameters in the numerical stability of image approximation-based line models," *IEEE Transactions on Electromagnetic Compatibility*, vol. 58, no. 1, pp. 323–326, 2016.

[28] M. A. O. Schroeder, M. T. C. de Barros, A. C. S. Lima, M. M. Afonso, and R. A. R. Moura, "Evaluation of the impact of different frequency dependent soil models on lightning overvoltages," *Electr. Power Syst. Res.*, vol. 159, p. 40–49, 2018.

[29] T. Papadopoulos, Z. Datsios, A. Chrysochos, P. Mikropoulos, and G. Papagiannis, "Modal propagation characteristics and transient analysis of multiconductor cable systems buried in lossy dispersive soils," *Electr. Power Syst. Res.*, vol. 196, p. 107249, 2021.

[30] H. Xue, A. Ametani, Y. Liu, and J. De Silva, "Effect of frequency-dependent soil parameters on wave propagation and transient behaviors of underground cables," *Int. J. Electr. Power Energy Syst.*, vol. 122, p. 106163, 2020.

[31] A. Ametani, "A general formulation of impedance and admittance of cables," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-99, no. 3, pp. 902–910, 1980.

[32] J. He, R. Zeng, and B. Zhang, *Methodology and Technology for Power System Grounding*. Singapore: John Wiley & Sons Singapore Pte. Ltd., 2013.