An Accurate Analysis of Lightning Overvoltages in Mixed Overhead-Cable Lines

R. Alipio, H. Xue, and A. Ametani

***Abstract*—An accurate investigation of lightning overvoltages on a typical mixed overhead-cable line is performed. The recently developed extended transmission line (TL) approach, frequency-dependent (FD) soil model and FD grounding system modeling method are also reviewed. The wave propagation characteristics of an overhead and a cable in frequency domain are studied using classical and extended TL approaches. Moreover, transient simulations using Numerical Laplace Transform (NLT) are carried out with different FD soil parameters and FD grounding behavior, and the influences of FD characteristics on the transient cable sheath voltages are made clear.**

***Keywords*: Overhead-cable line, transmission line approach, frequency-dependent soil, frequency dependent grounding, transient study.**

I. Introduction

THE use of underground cables for transmitting energy has been constantly increasing worldwide over the last few decades. According to [1], this stems from technical changes and strong competition in the cable sector, which have reduced prices. Furthermore, increased urbanization and public concerns have increased the difficulty and time taken to obtain consents for overhead (OH) lines. The use of short underground (UG) sections has also been common, either due to complaints from residents or due to physical restrictions regarding OH line terminating structures arriving the substation, resulting in mixed overhead lines with short underground sections [2].

The study of lighting overvoltages for a mixed overhead-cable lines is an important issue [3]. A lightning strike on the shielding wire of the OH line can propagate into the sheath circuit since the transmission tower and cable sheath often share the same grounding system at the transition site. Also, a back flashover can occur across OH line insulators or even a lightning strike can directly hit the phase conductors due to a shielding failure. In these cases, the lightning surge can directly propagate into the cable core, inducing voltages at the cable sheath. In systems comprising short sections, multiple reflections and superpositions can occur in a short period of time and cause severe overvoltages [4]. The sheath overvoltage requires careful studies to avoid failures of sheath voltage limiters and sheath interrupts [3].

Typically, the study of transients in power transmission systems, including mixed overhead-cable lines, is carried out using EMT-type programs (for instance in [4]-[5]), that adopt some assumptions that may lead to inaccurate results, especially considering lightning overvoltages and short underground sections. The cable models normally adopt Pollaczek's formula of earth-return impedance and disregards ground displacement currents along with the earth-return admittance. The soil electrical parameters are also usually assumed constant and frequency independent. However, recent studies show that both aforementioned approximations can lead to inaccuracies in transients' studies involving underground cables and frequency region of kHz up to MHz [6]-[10]. Furthermore, in most simulations, the sheath bonding and grounding is made through a simple lumped resistance, disregarding the frequency-dependent (FD) behavior of grounding system. It is to be noted that the level of the sheath overvoltage is highly dependent on the grounding performance at the transition site.

This paper assesses the influence of considering different modeling approaches in the computation of lightning overvoltages developed in short underground cable sections. The paper is organized as follows. The system under study, transmission line (TL) based parameters, FD soil model and grounding system are summarized in the Section II. In Section III, the wave propagation characteristics of overhead line and underground cable in frequency domain are investigated based on different approaches discussed in the Section II. Section IV performs the transient studies of a typical mixed overhead-cable line. Also, the influences of earth parameters, FD soil parameters and FD characteristics of grounding system on transient voltages of cable are made clear.

II. System Under Study and Modeling Guidelines

To focus on the fundamental aspects regarding the influence of several modeling approaches on the simulation of transient overvoltages developed in a mixed overhead-underground cable line, the single-phase equivalent circuit of 138 kV mixed line shown in Fig. 1 is considered. It consists of an overhead bare phase conductor (radius of 0.9155 cm and R_{dc} = 0.2076 Ω/km) positioned 12 m above ground, which, in the transition tower, is connected to an insulated cable that goes down vertically to the transition point between the overhead line and the underground section.

At the transition site, the transmission tower and the cable

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sheath of the underground section share the same grounding system, which consists of four counterpoise copper wires of 9.525 mm radius with burial depth of 0.5 m, each one with a total length of L = 60 m, as depicted in Fig. 2 (a).

At the receiving end of the underground section, the cable sheath is bonded to the substations grounding grid, which is a square grid of 60 m × 60 m and meshes of 5 m × 5 m, as shown in Fig. 2 (b). The grounding grid is buried 0.8 m deep in soil and its copper electrodes have a radius of 7 mm. The receiving end of the cable core is connected to a capacitance of 500 pF representing the substation entrance.

Next sections detail the models adopted for each component of the system shown in Fig. 1.

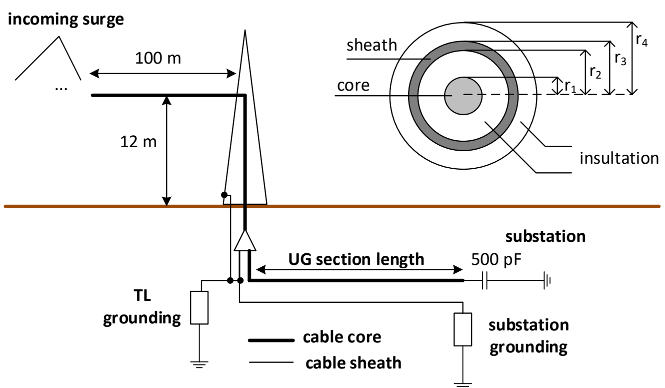


Fig. 1 System under study. Cable geometry: r_1=2.34 cm, r_2=3.85 cm, r_3=4.13 cm, r_4=4.84 cm. Core resistivity = 1.7×10^{-8} Ωm, lead sheath resistivity = 2.1×10^{-8} Ωm, inner insulation relative permittivity = 3.5 and outer insulation relative permittivity = 4.

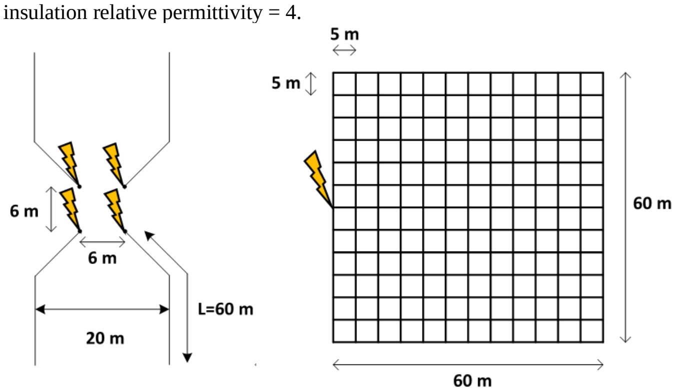


Fig. 2 Configuration of grounding systems: (a) transmission line grounding system, (b) substation grounding grid.

A. Calculation of Propagation Constants by TL Approaches

As discussed in [8], the TL approach is characterized by the extended TL approach and classical TL approach. For the extended TL approach, the generalized formulas of series impedance and shunt admittance of a multi-phase overhead or underground cable are given by

$$\mathbf{Z} = \mathbf{Z_i} + \mathbf{Z_e} \tag{1}$$

$$\mathbf{Y} = j\omega \mathbf{P}^{-1} \tag{2}$$

where $\mathbf{Z_i}$ is the internal impedance matrix of the cable and consists of the conductor and the insulator impedances [8], $\mathbf{Z_e}$ is the earth-return impedance matrix of the cable [8] and the potential coefficient matrix $\mathbf{P}$ is defined as

$$\mathbf{P} = \mathbf{P_i} + \mathbf{P_e} \tag{3}$$

where $\mathbf{P_i}$ and $\mathbf{P_e}$ are the internal and earth-return potential coefficient matrices of the cable [8].

If earth permittivity and $\mathbf{P_e} = 0$ are assumed in (1) and (2), then it is defined as classical TL approach which is the same as the formulas adopted into the original Cable Constants routine [8].

Then, the unknown modal propagation constants and current / voltage transformation matrices can be calculated by solving the eigenvalue and eigenvector of product of (1) and (2) without any difficulties. It should be noted that the classical and extended TL approaches based external electromagnetic characteristics of underground cables are studied using numerical electromagnetic analysis in [11], [12].

B. Frequency-Dependent (FD) Soil Model

Several experimentally-obtained formulas for modeling the frequency dependence of soil parameters have been proposed in the literature. In this paper, the Alipio-Visacro model (AV FD soil model) [13] is considered, which is based on the measured frequency response of 65 different types of soils with low-frequency resistivity values (ρ_0) ranging from 60 to 18000 Ωm. This model satisfies causality and is recommended by CIGRE [14] for lightning-related studies. It states that soil resistivity, $\rho_g(f)$, and permittivity, $\varepsilon_g(f)$, can be calculated at a given frequency f (Hz) by using:

$$\rho_g(f) = \rho_0\left(1 + 4.7\times10^{-6}\times\rho_0^{0.73}\times f^{0.54}\right)^{-1} \ (\Omega\text{m}) \tag{4}$$

$$\varepsilon_g(f) = 9.5\varepsilon_0\times10^4\times\sigma_0^{0.27}\times f^{-0.46} + 12\varepsilon_0 \ (\text{F/m}) \tag{5}$$

where ε_0 is the vacuum permittivity and $\sigma_0 = 1/\rho_0$.

C. Grounding Systems Modeling

In many applications, the grounding system is represented as a lumped resistance with value equal to the low-frequency (LF) grounding resistance (R_{LF}). However, when subjected to lightning currents, the grounding response presents certain complexities that make its behavior quite different from that presented at low frequencies [15], [16]. Due to the impulse nature of lightning currents, they present a large frequency content ranging from dc to several MHz. In this frequency range, the grounding system shows different behavior at different frequency intervals, exhibiting inductive or capacitive behavior, depending on the grounding electrodes arrangement and soil resistivity.

In this paper, the FD behavior of both transmission line and substations grounding systems is determined using the accurate hybrid electromagnetic model (HEM) [17]. This model solves Maxwell's equations numerically via the vector and scalar potentials using the thin wire approximation. The output of the calculations is the FD grounding input impedance $Z(j\omega)$, which is computed in the frequency range of interest in transient studies.

Fig. 3 shows the magnitude of the input impedance of the substation grounding system in the frequency range of 10 Hz to 1 MHz, assuming soils of (a) 200 Ωm, (b) 1000 Ωm, and (c) 5000 Ωm. It is observed, regardless of soil resistivity, that in the LF range the harmonic impedance is constant and frequency-independent, and equal to the LF resistance. As the frequency increases, the impedance shows different behaviors, depending on the soil resistivity. In the case of 200 Ωm soil, the impedance exhibits inductive behavior, and its value becomes larger than R_{LF}. For 1000 Ωm soil, it is seen a decay of the impedance in the frequency range of few kHz up to around 50 kHz due to the capacitive behavior, followed by an increase in the high-frequency (HF) due to predominant inductive effects. Finally, for the high-resistivity soil of 5000 Ωm, a strong capacitive behavior effect is observed, leading to lower values of impedance in comparison to R_{LF} in the whole analyzed frequency spectrum.

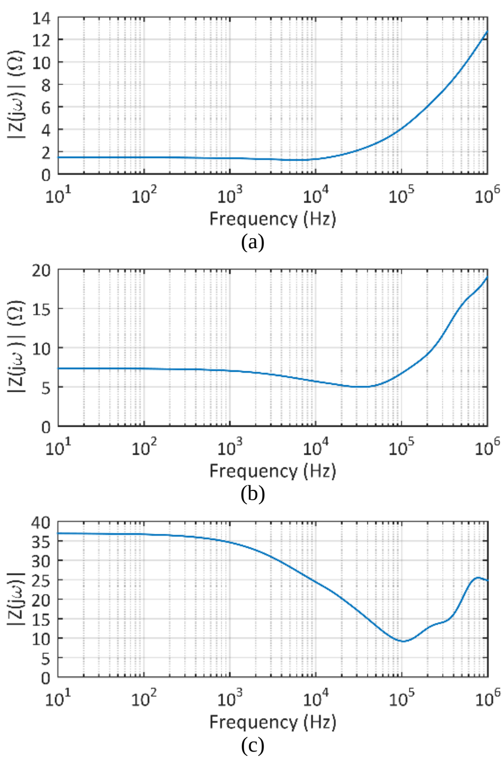


Fig. 3 Input impedance of the substation grounding system in frequency range of 10 Hz to 1 MHz, and soils of (a) 200 Ωm, (b) 1000 Ωm, and (c) 5000 Ωm.

III. Numerical Calculations in Frequency Domain

A. Modal Propagation Constants for Overhead Line

Fig. 4 shows the calculated modal propagation constants of an overhead line shown in Fig. 1 by adopting the extended and classical TL approaches. The influences of CS model and AV FD soil model on the calculated modal propagation constants are also investigated in Fig. 4.

As shown in Fig. 4 (a), it is clear that visible differences are observed for modal attenuation constants using classical and extended TL approaches at a high frequency region, i.e. $f = 1\,\text{MHz}$. The modal attenuation constants calculated by the classical TL approach increase monotonously. However, the results evaluated by the extended TL approach decrease as frequency increases due to the Sommerfeld-Goubau mode transition which has been thoroughly investigated in [18], [19]. Also, the AV FD soil model gives a more sensitive effect on the modal attenuation constants in the high frequency region in comparison to the results calculated by the CS model.

Fig. 4 (b) illustrates the modal phase velocities calculated by different TL approaches and soil models. The modal phase velocities are more sensitive to the results evaluated by the FD soil model and soils of higher resistivity. Also, the calculated modal phase velocities using the classical TL approach show a significant difference from the results evaluated by the extended TL approach above several hundreds of kHz.

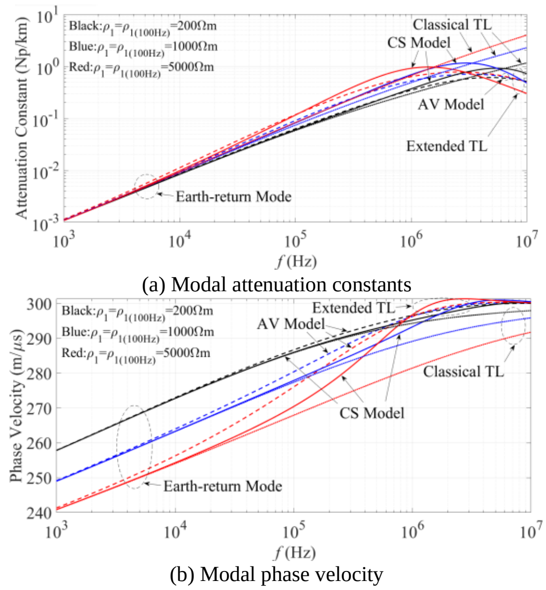
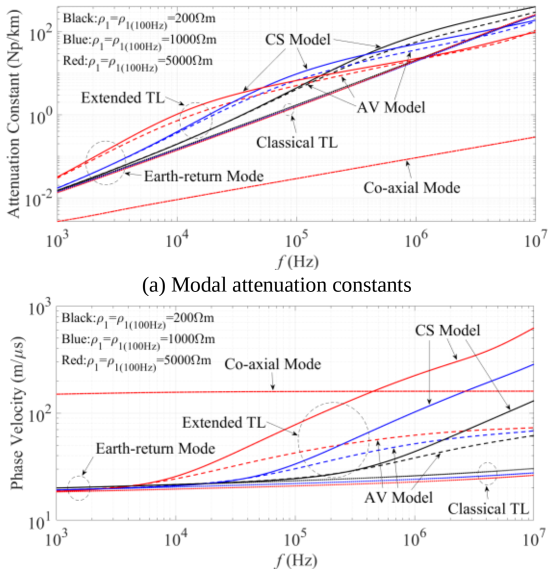


Fig. 4 Modal propagation constants evaluated by the extended and classical TL approaches for an overhead line.

B. Modal Propagation Constants for Underground Cable

Fig. 5 shows the modal propagation constants calculated by classical and extended TL approaches using CS and AV FD soil models. It should be noted that the variation of external parameters, i.e. soil resistivity and earth-return admittance, have no impact on the propagation constant of co-axial mode. Visible effects of FD soil model on attenuation constant of earth-return mode are also observed in Fig. 5 (a).

A more complicated phenomena of modal phase velocities are illustrated in Fig. 5 (b). If the CS model is adopted into the calculations, the phase velocity of earth-return mode may exceed the phase velocity of co-axial mode at certain frequency which depends on the value of earth resistivity. The phase velocity of earth-return mode exceeds the phase velocity of co-axial mode at $f = 464.2$ kHz with $\rho_1 = 5000\,\Omega$m, and at $f = 2.71$ MHz with $\rho_1 = 1000\,\Omega$m. However, this kind of characteristics of modal phase velocities is not observed if the FD soil model is used in the calculations. Therefore, the behavior of that the phase velocity of earth-return mode exceeds the phase velocity of co-axial mode is due to the inaccurate representation of soil with constant parameters. Moreover, it is suggested that the FD soil model should be adopted into the calculations of underground cable transients if the soil resistivity is large.



(a) Modal attenuation constants

(b) Modal phase velocity

Fig. 5 Modal propagation constants evaluated by the extended and classical TL approaches for an underground cable.

C. Modal Characteristic Impedance for Underground Cable

Fig. 6 illustrates the calculated absolute value of modal characteristic impedance of the cable shown in Fig. 1 using CS and AV FD soil models with two TL approaches. Again, no impacts of external parameters are observed for the characteristic impedance of co-axial mode. The FD soil model markedly influences the evaluated characteristic impedance of earth-return mode using extended TL approach at higher frequencies, and higher-resistivity soils. Together with the phenomena obtained in Fig. 5 (b), the monotonously increase of the characteristic impedance of earth-return mode as the function of frequency may due to the inappropriate characteristics of constant soil parameter at high frequencies, especially for higher-resistivity soils.

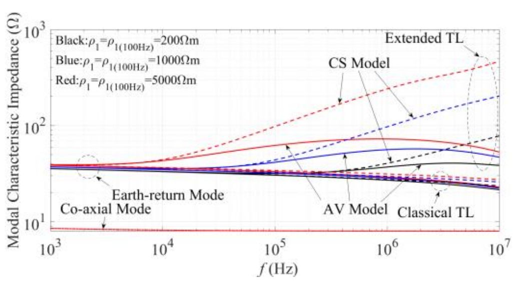


Fig. 6 Modal characteristic impedance evaluated by the extended and classical TL approaches for an underground cable.

IV. Transient Responses

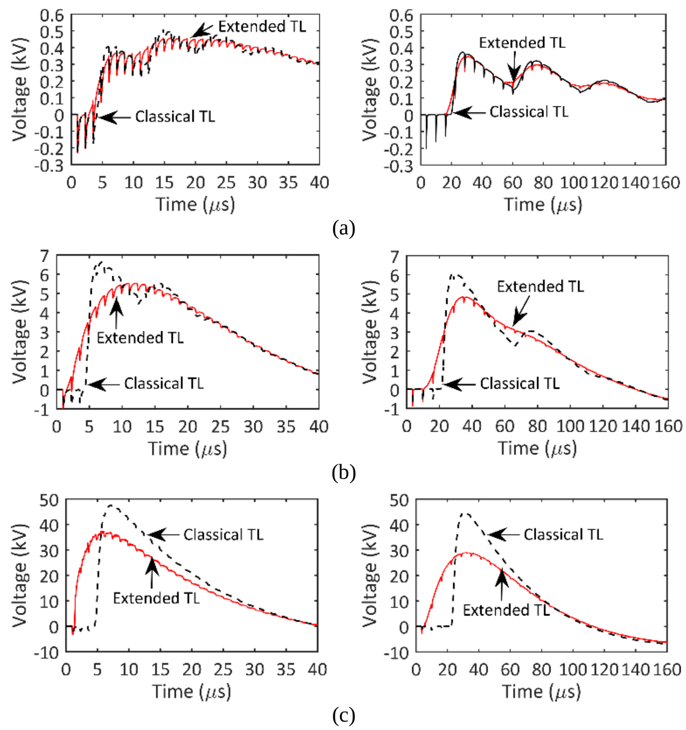
In this section, the transient sheath voltages at the receiving end of the underground section are computed, considering different modeling approaches for the system components. The incoming surge in Fig. 1 is represented by an impulse voltage of 1.2/50 μs and amplitude of 650 kV, which corresponds to the typical Critical Flashover Voltage (CFO) of a 138 kV line. The aerial bare conductor was impedance matched to avoid unwanted reflections.

The time domain responses were obtained via the Numerical Laplace Transform (NLT) [20]. The whole system was implemented in a frequency-domain code in a similar structure to the Frequency-domain Transient Program (FTP) presented in [21].

The influence of vertical cable is also checked, however, it has no significant effects on the transient simulations thus the vertical cable is not included into the following studies.

A. Influence of Cable Earth Parameters and Underground Section Length

Fig. 7 compares the sheath voltage at the receiving end of 100 m (left) and 500 m (right) underground sections, considering both extended and classical TL approaches, and different values of soil resistivity, namely (a) 200 Ωm, (b) 1000 Ωm, and (c) 5000 Ωm. The soil parameters are assumed frequency-independent (CS model) and the grounding systems are modeled as lumped resistances according to soil resistivity.



(a)

(b)

(c)

Fig. 7 Sheath voltage at the receiving end of a 100 m (left) and 500 m (right) underground section, considering both extended and classical TL approaches, and soil resistivity of (a) 200 Ωm, (b) 1000 Ωm, and (c) 5000 Ωm.

As a general comment, the voltages for the 100 m length section show a more oscillatory behavior due to the more sensitive effect of the multiple reflections. The spikes observed in the waveforms stem from the induced effects associated with the propagating wave along the cable core. Also, smoother waveforms are observed for higher resistivity soils due to the larger attenuation.

According to the results, for a given value of LF soil resistivity, increasing the length of the underground section slightly influences the peak value of the sheath voltage, being observed a small decrease with increasing the section length.

On the other hand, the soil resistivity value has a great influence on the sheath voltage, with a large increase in the peak value being observed with the increase of resistivity. This occurs because, for the same grounding systems, increasing the soil resistivity leads to a poor-quality grounding with higher values of grounding resistance. This reinforces the significant importance of bonding and grounding in reducing the sheath overvoltages.

Comparing the results obtained using the classical and extended TL, it is noted that the last leads to higher damper and faster propagating waves, especially for higher resistivity soils. These results are in line with those of Section III, which show that the attenuation constant and the phase velocity of a underground cable are greater when considering the extended TL compared to the classical one, in the frequency range of the analyzed transient. Finally, along the wave tail, the curves obtained using both extended and classical TL match each other, since the wave tail is associated with lower frequencies where the soil admittance effect is negligible.

B. Influence of Frequency Dependence of Soil Parameters

Fig. 8 shows the sheath voltage at the receiving end considering the extended TL approach and adopting both constant (CS model) and FD (AV model) soil parameters assuming (a) 200 Ωm, (b) 1000 Ωm, and (c) 5000 Ωm. An underground section of 500 m is assumed, and the grounding systems are modelled as lumped resistances according to soil resistivity.

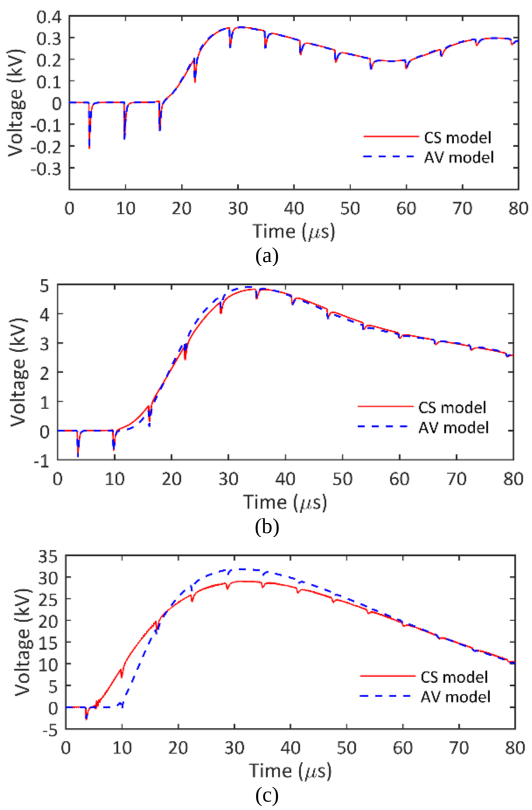


Fig. 8 Comparison of the sheath voltage at the receiving end of a 500 m underground section, considering constant (CS model) and FD soil parameters (AV model), and soil resistivity of (a) 200 Ωm, (b) 1000 Ωm, and (c) 5000 Ωm.

It is seen in Fig. 8 that for the 200 Ωm soil, the differences between the calculated curves are negligible. Increasing the soil resistivity, more noticeable differences are noted in the curves calculated considering or neglecting the variation of the soil parameters with frequency. For the 5000 Ωm soil, it is clearly observed that, considering the FD soil, the voltage wave propagates more slowly and is subject to less attenuation. Again, the results obtained in this section are in line with those of Section III, which shows a lower attenuation constant and phase velocity, assuming FD soil and extended TL approach. Furthermore, the results agree with recent findings detailed in [10], which indicate that the effects of FD soil parameters on the transient voltages are more noticeable for the short cables buried in high-resistivity soils.

Finally, it is important to emphasize that neglecting the frequency dependence of the electrical parameters of the soil leads to non-conservative results, that is, lower estimates of the peak value of sheath voltage, especially for high-resistivity soil. Such differences could be determinant for the occurrence or not of sheath insulation breakdown in certain conditions.

C. Influence of FD Behavior of Grounding Systems

Fig. 9 shows the sheath voltage at the receiving end considering the extended TL and FD soil parameters. An underground section of 500 m is assumed, and two different models are considered for the grounding systems: i) a lumped resistance with value equal to the LF grounding resistance (labeled “LF model”); and 2) a wideband model considering the FD characteristics of the grounding input impedance (labeled “WB model”).

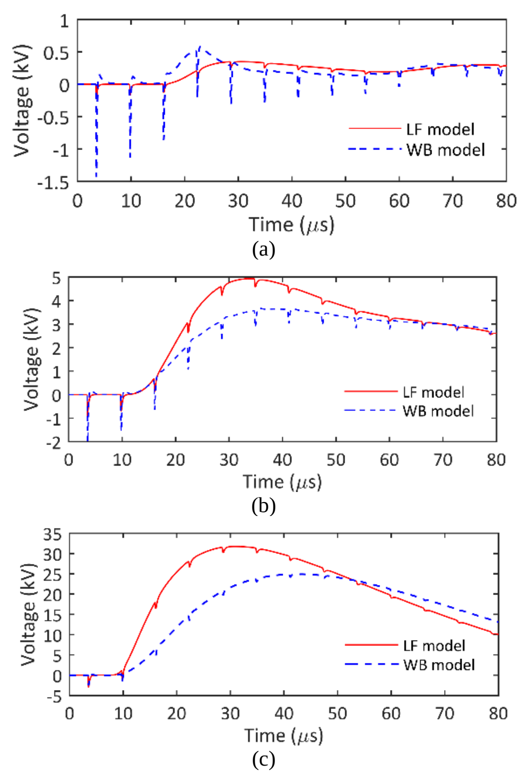


Fig. 9 Comparison of the sheath voltage at the receiving end of a 500 m underground section, representing the grounding systems as a lumped resistance (LF model) and FD impedance (WB model), and soil resistivity of (a) 200 Ωm, (b) 1000 Ωm, and (c) 5000 Ωm.

It is seen that the inclusion of the FD behavior of the grounding system has a significant impact on the results, and such impact depends on the value of soil resistivity. For the 200 Ωm soil, an increase of the sheath voltage peak value is observed when considering the wideband behavior of the grounding systems, in comparison with the representation via lumped resistors. This stems from the strong inductive effect observed for the substation grounding system buried in the soil of 200 Ωm, as shown in Fig. 9 (a), which leads to an increase in the grounding impedance with increasing frequency. Interestingly, the induced spikes in the waveform present much larger amplitudes for the WB model compared to the LF model. This is due to the high frequency content associated with these induced effects, which further enhance the inductive effects of grounding system.

In the case of 1000 Ωm and 5000 Ωm soils, an opposite behavior is observed, i.e., a reduction in the peak value of the sheath voltage is observed, when considering the WB model of the grounding system. This is because in the frequency region of the transient, the substation grounding system shows a capacitive behavior for the higher resistivity soils, especially for the 5000 Ωm soil, leading to lower values of grounding impedance in comparison with the LF resistance (LF model). Specifically, for the 1000 Ωm soil, the peak values of the spikes in the waveform considering the WB grounding model are higher compared to those considering the LF model. This is because for the 1000 Ωm soil and very high frequencies, the grounding grid shows an inductive behavior. All these results agree with the FD input impedances of the substation grounding grid shown in Fig. 3.

V. Summary and Conclusions

This paper presents an investigation of lightning overvoltages on a mixed overhead-cable line. From the presented analysis, the following main conclusions can be drawn.

- An abnormal phase velocity of earth-return mode of underground cable has been observed with increasing the frequency and for high-resistivity soils if their parameters are assumed constant. Thus, the FD soil parameters should be implemented in cable transient studies if the soil resistivity presents large values.
- Classical TL approach results in more oscillatory and less damped transient sheath voltages corresponding to the wave propagation characteristics in frequency domain.
- The effects of FD soil parameters on the transient voltages are more noticeable for short cable sections buried in high-resistivity soils. Neglecting the frequency dependence of the electrical parameters of the soil leads to non-conservative results, i.e. lower estimates of the peak value of the transient voltages at the cable sheath.
- The FD behavior of the grounding systems to which cable sheath is bonded markedly influences the sheath transient voltages. This influence depends on the soil resistivity, and if the grounding system exhibits inductive or capacitive behavior with increasing the frequency.

VI. References

[1] Working Group B1.07, Statistics of AC Underground Cables in Power Networks. CIGRE, 2007.

[2] Working Group B1.05, Coupling of Overhead and Underground Transmission Lines - Technical Recommendations for Brazilian Utilities (in Portuguese). CIGRE Brazil, 2016.

[3] A. Ametani, N. Nagaoka, Y. Baba, T. Ohno, and K. Yamabuki, Power System Transients: Theory and Applications, CRC Press; 2nd Edition, 2016.

[4] T. V. Gomes, M. A. O. Schroeder, R. Alipio, A. C. S. de Lima, and A. Piantini, "Investigation of overvoltages in HV underground sections caused by direct strokes considering the frequency-dependent characteristics of grounding," *IEEE Trans. Electromagn. Compat.*, vol. 60, no. 6, pp. 2002-2010, Dec. 2018.

[5] F. M. Gatta, A. Geri, S. Lauria, and M. Maccioni, "Statistical lightning simulations for a HV 'mixed' overhead-cable line: Preliminary studies," in *33rd International Conference on Lightning Protection (ICLP)*, 2016.

[6] T. A. Papadopoulos, D. A. Tsiamitros, and G. K. Papagiannis, "Impedances and admittances of underground cables for the homogeneous earth case," *IEEE Trans. Power Delivery.*, vol. 25, no. 2, pp. 961-969, Apr. 2010.

[7] A. P. C, Magalhaes, M. T. C de Barros and A. C. S. Lima, "Earth return admittance effect on underground cable system modelling," *IEEE Trans. Power Delivery*, vol. 33, pp. 662-670, 2018.

[8] H. Xue, A. Ametani, J. Mahseredjian and I. Kocar, "Generalized formulation of earth-return impedance / admittance and surge analysis on underground cables," *IEEE Trans. Power Delivery*, vol. 33, no.6, pp.2654-2663, 2018.

[9] N. Duarte, A. De Conti, and R. Alipio, "Transient analysis of buried cables considering a nodal admittance matrix approach," in *International Symposium on Lightning Protection (XV SIPDA)*, 2019.

[10] T. A. Papadopoulos, Z. G. Datsios, A. I. Chrysochos, P. N. Mikropoulos, and G. K. Papagiannis, "Wave propagation characteristics and electromagnetic transient analysis of underground cable systems considering frequency-dependent soil properties," *IEEE Trans. Electromagn. Compat.*, doi: 10.1109/TEMC.2020.2986821.

[11] H. Xue, A. Ametani and K. Yamamoto, "Theoretical and NEC calculations of electromagnetic fields generated from a multi-phase underground cable," *IEEE Trans. Power Delivery*, doi: 10.1109/TPWRD.2020.3005521.

[12] H. Xue, A. Ametani and K. Yamamoto, "A study on external electromagnetic characteristics of underground cables with considerations of terminations," *IEEE Trans. Power Delivery*, doi: 10.1109/TPWRD.2020.3037335.

[13] R. Alipio and S. Visacro, "Modeling the frequency dependence of electrical parameters of soil," *IEEE Trans. Electromagn. Compat.*, vol. 56, no. 5, pp. 1163-1171, 2014.

[14] Working Group C4.33, Impact of Soil-Parameter Frequency Dependence on the Response of Grounding Electrodes and on the Lightning Performance of Electrical Systems. CIGRE, 2019.

[15] S. Visacro, "A Comprehensive Approach to the Grounding Response to Lightning Currents," *IEEE Trans. Power Delivery*, vol. 22, no. 1, pp. 381-386, Jan. 2007.

[16] R. Alipio and S. Visacro, "Frequency dependence of soil parameters: effect on the lightning response of grounding electrodes," *IEEE Trans. Electromagn. Compat.*, vol. 55, no. 1, pp. 132-139, 2013.

[17] S. Visacro and A. Soares, "HEM: A model for simulation of lightning-related engineering problems," *IEEE Trans. Power Delivery*, vol. 20, no. 2, pp. 1206-1208, 2005.

[18] A. Ametani, Y. Miyamoto, Y. Baba and N. Nagaoka, "Wave propagation on an overhead multiconductor in a high frequency region", *IEEE Trans. Electromagn. Compat.*, vol. 56, no. 6, pp. 1638-1648, 2014.

[19] H. Xue, A. Ametani, J. Mahseredjian, Y. Baba, F. Rachidi and I. Kocar, "Transient responses of overhead cables due to mode transition in high frequencies," *IEEE Trans. Electromagn. Compat.*, vol. 60, no. 3, pp. 785-794, 2018.

[20] P. Gómez and F. A. Uribe, "The numerical Laplace transform: An accurate technique for analyzing electromagnetic transients on power system devices," *Int. J. Electr. Power Energy Syst.*, vol. 31, no. 2-3, pp. 116-123, 2009.

[21] N. Nagaoka and A. Ametani, "A development of a generalized frequency-domain transient program-FTP," *IEEE Trans. Power Delivery*, vol. 3, no. 4, pp. 1996-2004, 1988.