Paper accepted for presentation at 2009 IEEE Bucharest Power Tech Conference, June 28th - July 2nd, Bucharest, Romania

Analysis of the propagation characteristics of buried cables in imperfect earth.

Theofilos A. Papadopoulos, *Student Member, IEEE,* Dimitris A. Tsiamitros, *Member, IEEE*, and Grigoris K. Papagiannis, *Member, IEEE*

***Abstract*— The influence of the imperfect earth on the propagation characteristics of underground single bare conductors and single core insulated cables arrangements is investigated in this paper. The propagation characteristics are derived through the per-unit-length parameters of the conductors, using new expressions for the earth impedance and admittance correction terms. The influence of the earth electromagnetic and geometric configuration properties are thoroughly analyzed and the results are compared to the corresponding ones obtained by other approximate approaches. Finally, the buried conductor parameters calculated by the proposed method are used in a model, simulating typical fast transients.**

***Index Terms*— buried conductors, power cables, transient analysis.**

I. Introduction

THE extensive use of underground systems either for power transmission or telecommunication purposes during the last decades, necessitates the accurate modeling of underground arrangements. One topic of major importance is the detailed representation of the influence of the involved media and especially of the earth. In transmission line modeling the influence of the imperfect earth is generally taken into account by means of proper correction terms.

Pollaczek [1] first, suggested such earth correction terms for the series impedances of underground cable systems, assuming a resistive, homogeneous earth behaving as a conductor. Sunde [2] extended the original Pollaczek's formulas taking also into account the influence of earth permittivity on the earth return impedances. Additionally to the above well known approaches, several other simpler approximations have been reported in the literature and have been systematically discussed in [3].

However, the accuracy of all these models is limited to the low frequency range, since they neglect the influence of the imperfect earth on shunt admittances [4], [5]. A more rigorous model at the high frequency (HF) region, for the calculation of the per-unit-length (pul) earth impedance and earth admittance has been proposed by Vance [6] for the case of a single conductor. Recently, in [3] and [7] the earth impedance and earth admittance formulas of Sunde and Vance respectively have been adopted in order to create a suitable model for the simulation of fast travelling wave transients.

T. A. Papadopoulos, D. A. Tsiamitros, G. K. Papagiannis* are with the Power Systems Laboratory, Dept. of Electrical & Computer Engineering, Aristotle University of Thessaloniki / Greece, GR 54124, P.O. Box 486 (* corresponding author's e-mail: grigoris@eng.auth.gr).

978-1-4244-2235-7/09/$25.00

Scope of this paper is to present analytic expressions for the calculation of the earth correction terms for the series impedances and the shunt admittances of underground systems. The analysis of this work is focused on the single conductor case, although it can be easily applied to multiconductor arrangements.

The new expressions are used to investigate the influence of the earth admittance on the wave propagation characteristics of a single core underground insulated cable and of a bare conductor arrangement. Several earth topologies and burial depths are assumed, in order to investigate the influence of the frequency dependent behavior of earth on the propagation characteristics of the underground conductors.

The accuracy of the proposed model in both arrangements is validated by comparing the obtained results with the corresponding ones, resulting from [2] and [7].

Finally, the underground cable parameters, derived by the proposed methodology are used in fast electromagnetic transient simulations to examine their impact on the transient responses of cable systems.

II. Impedance and Admittance Formulas

A. Problem formulation

The fundamental equations describing the EM field propagation, generated by a dipole in inhomogeneous media, belong originally to Sommerfeld [8].

Based on his work, Wise [9] – [10] and Kikuchi [11] proposed the same analytic formulas, for the calculation of both impedance and admittance earth correction terms of conductors or cables located in the air above a lossy homogeneous earth. These formulas have a generalized form, since they include all EM properties of all involved media and are functions of the unknown propagation constant γ_x.

Their model can be properly transformed to the underground cable problem formulation by simply changing the medium in which the EM field is generated. Therefore, replacing the air terms with the corresponding ones of earth and vise versa, the problem under study is shown in Fig. 1 and the earth mutual impedance and admittance expressions have the form of (1) and (2) respectively.

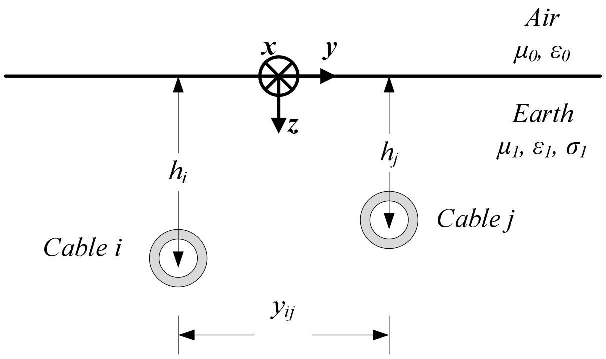

Fig. 1: Geometric configuration of two insulated underground conductors in homogeneous earth.

$$Z'_{e_{ij}}(\gamma_x)=\int_0^\infty \frac{A'(u)}{IdS}\times\left[\int_{-\infty}^{\infty} J_0\left(u\sqrt{x^2+y_{ij}^2}\right)e^{-\gamma_x x}dx\right]du\,, \qquad (1)$$

$$Y'^{-1}_{e_{ij}}(\gamma_x)=\int_0^\infty \frac{B'(u)}{IdS}\times\left[\int_{-\infty}^{\infty} J_0\left(u\sqrt{x^2+y_{ij}^2}\right)e^{-\gamma_x x}dx\right]du\,, \qquad (2)$$

where IdS is the moment of the dipole, u is the integral variable and functions $A'(u)$ and $B'(u)$ are expressed from the topology of the problem and are given in the Appendix.

A basic difficulty in the calculation of (1) and (2) is the presence of the unknown propagation constant γ_x. To overcome this, a common approximation is to assume that in the quasi-TEM field propagation, the propagation constant γ_x can be set equal to zero. This practically means that cables are electrically short and the contribution of the earth correction term for the conductor admittance is neglected, limiting the solution of the problem to frequencies lower than some hundreds of kHz [4], [5].

At high frequencies a better approximation is to set $\gamma_x \approx jk_x = j\omega\sqrt{\mu_1\varepsilon_1}$ [6]. This is equivalent to assume a lossless propagation along the conductor, although the propagation constant will be recalculated more accurately at a second step through the pul parameters. The mutual earth impedance and admittance formulas take their final form in (3) and (4) respectively.

pul mutual earth impedance

$$Z'_{e_{ij}}=\frac{j\omega\mu_1}{2\pi}\int_0^{+\infty} F(\lambda)\cos\left(y_{ij}\lambda\right)\cdot d\lambda\,, \qquad (3a)$$

$$F(\lambda)=\frac{e^{-\alpha_1|h_i-h_j|}}{\alpha_1}-\frac{e^{-\alpha_1(h_i+h_i)}}{\alpha_1}+\frac{2\mu_0 e^{-\alpha_1(h_i+h_j)}}{a_1\mu_0+a_0\mu_1}\,. \qquad (3b)$$

pul mutual earth admittance

$$Y'_{e_{ij}}=j\omega P^{-1}_{e_{ij}}\,, \qquad (4a)$$

$$P_{e_{ij}}=\frac{j\omega}{2\pi\left(\sigma_1+j\omega\varepsilon_1\right)}\int_0^{+\infty}\left[F(\lambda)+G(\lambda)\right]\cos\left(y_{ij}\lambda\right)\cdot d\lambda\,, \qquad (4b)$$

$$G(\lambda)=\frac{2\mu_0\mu_1\alpha_1\left(\gamma_1^2-\gamma_0^2\right)e^{-\alpha_1\left(h_i+h_j\right)}}{\left(a_1\mu_0+a_0\mu_1\right)\left(a_1\gamma_0^2\mu_1+a_0\gamma_1^2\mu_0\right)}\,, \qquad (4c)$$

where $a_k=\sqrt{\lambda^2+\gamma_k^2+k_x^2}$, $\gamma_k^2=j\omega\mu_k\left(\sigma_k+j\omega\varepsilon_k\right)$ for k=0, 1 and λ is the new integral variable.

The self earth impedances and admittances are derived from (3) and (4) respectively, by replacing y_{ij} with cable outermost radius and h_j with h_i.

The complex semi-infinite integrals of the earth correction terms are evaluated numerically, using the integration scheme of [12], which has been proved to be very efficient numerically for the type of integrands involved.

B. Transmission line modeling

The pul equivalent circuits of the single bare and insulated conductor cases, involved in the Transmission Line equations are represented in Figs. 2a and 2b respectively [3], [13].

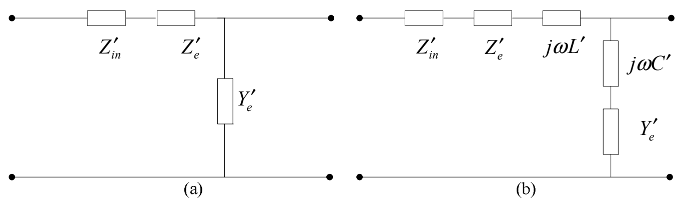

Fig. 2: Pul equivalent circuits of underground conductors. (a) Single bare conductor, (b) single core insulated cable.

For insulated cables, the impedance earth correction term of (3) is added to the internal impedance of the conductor, due to the skin effect and to the inductance of the insulator, due to the magnetic field penetration. The admittance earth correction term of (4) is added to the capacitive admittance of the insulation.

For bare conductors, the total impedance is the sum of the earth and the internal impedances, while the shunt admittance is expressed only by the term of (4).

C. Remarks on the expressions

Observing (3) and (4) the following remarks can be noticed:

The generalized expression of (3) transforms to the existing formula of earth impedances for underground power cables, proposed by Sunde [2], simply by setting k_x equal to zero. Additionally, if the influence of the earth permittivity is neglected then (3) reduces to the corresponding formula of Pollaczek [1].

The quantities in the integral formulation of the pul parameters in (3) and (4) relate each to specific properties of the EM field. The first term in the integral of $F(\lambda)$ expresses the primary field, if the conductor was placed in an unlimited homogenous medium with the EM properties of earth, as shown in the Sommerfeld wave equations [8]. The remaining two terms of $F(\lambda)$ and the $G(\lambda)$ function represent the effect of the conduction and displacement currents of the secondary field respectively, due to the presence of the air-earth interface.

The above remarks can be noticed, considering for simplicity the single bare conductor case, i. e. for h_j equal to h_i. Ignoring the internal impedance term, which for frequencies above some tens of kHz is a valid approximation

[7], the propagation constant of the bare conductor γ_b is defined through the pul parameters in (5).

$$\gamma_b = \sqrt{Z_e \cdot Y_e} = \gamma_1 \sqrt{\frac{\int_0^{+\infty} F(\lambda) d\lambda}{\int_0^{+\infty} \left[F(\lambda) + G(\lambda) \right] d\lambda}}, \tag{5}$$

Assuming air with EM properties equal to those of earth, the calculated propagation constant γ_b becomes equal to γ_1, since $G(\lambda)$ and the last two terms of $F(\lambda)$ vanish.

If we assume that h_i tends to infinity, i.e. the conductor is located in infinite depth, again γ_b equals to $\gamma_1 = \sqrt{j\omega\mu_1(\sigma_1 + j\omega\varepsilon_1)}$, since the air-earth interface is practically neglected, due to the exponential type of the above mentioned terms.

Finally, neglecting $G(\lambda)$ and the first two terms of $F(\lambda)$, the proposed model reduces to the model proposed by Petrache *et al.* [7]. In this model, the earth return impedance is similar to that of [2], however it is independent of the burial depth, neglecting the air-earth interface and is evaluated numerically using a logarithmic approximation. The calculation of the earth admittance is based on an estimation of the propagation constant [6], where it is taken equal to the propagation constant of earth γ_1, assuming earth as an infinite medium.

III. System Under Study

The propagation characteristics of a single bare conductor and of a single core insulated cable arrangement, shown in Fig. 3, are examined. The same conductor core is used in both configurations, while additionally the insulated cable contains an outer insulation. Conductors are assumed to be buried in variable depth in earth with varying resistivity and permittivity. The relative permeabilities of all involved media are assumed to be equal to unity.

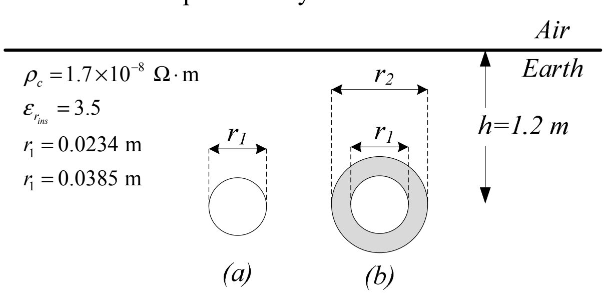

Fig. 3: Examined underground single conductor configurations. (a) Single bare conductor, (b) Single core insulated cable.

IV. The Bare Conductor Case

A. Influence of conductor's depth

First, the influence of the burial depth on the bare conductor propagation characteristics is investigated, using the proposed model.

The characteristic impedance magnitude and phase constant for $\rho_1 = 1000\ \Omega\cdot\text{m}$ is shown in Figs. 4 and 5b, while the attenuation constant for $\rho_1 = 100\ \Omega\cdot\text{m}$ is shown in Fig. 5a. In both earth topologies earth relative permittivity is 10 and the conductor is located at 0.5, 1.2 and 5 m in earth.

In order to compare and verify the accuracy of the results by the proposed model, in Figs. 4 – 5 the corresponding terms obtained by Petrache *et al.* [7] are also presented. Note, that for the bare conductor case the propagation constant terms of [7] identify to those of earth.

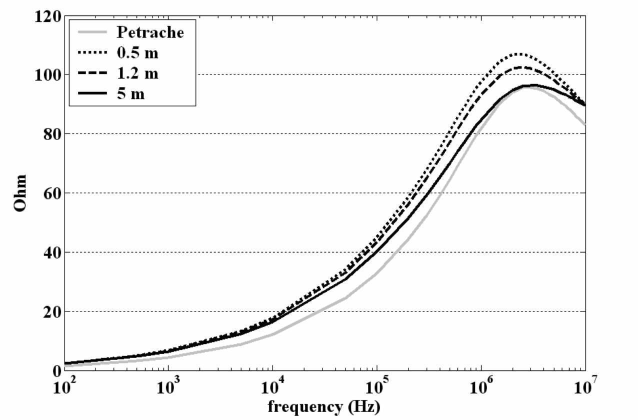

Fig. 4: Characteristic impedance magnitude for different burial depths.

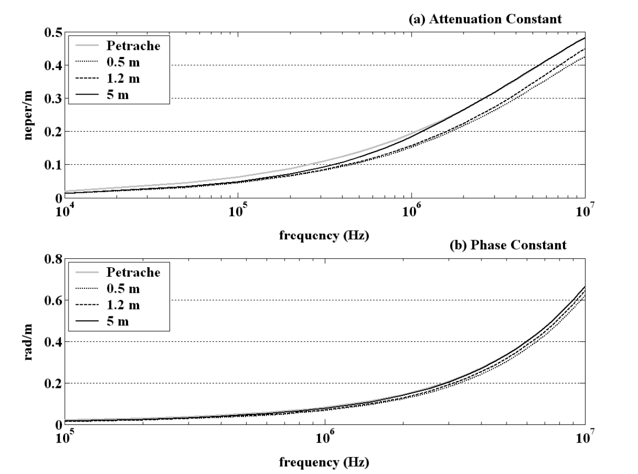

Fig. 5: (a) Attenuation constant for ρ_1=100 Ω·m, (b) Phase constant for ρ_1=1000 Ω·m and different burial depths.

Small differences are recorded between the two models. However as the burial depth increases the differences are further reduced. In all cases the calculated propagation constant terms get lower values to the corresponding ones, obtained by [7]. For burial depths higher than 5 m, the influence of the air medium, especially in the MHz frequency region is negligible and the propagation constant terms of the proposed model are identical to the corresponding of earth. This is the reason, why researchers like Vance ignored the burial depth in the calculation of the pul earth parameters [14].

The above results are in total agreement with the fundamental assumptions of the quasi-TEM propagation in inhomogeneous media [15], verifying also the validity of the proposed expressions.

B. Influence of earth EM properties

Next, the sensitivity of the propagation characteristics against earth resistivity in Figs. 6-7 and earth permittivity in Figs. 8-9 respectively is investigated, assuming the conductor buried in 1.2 m.

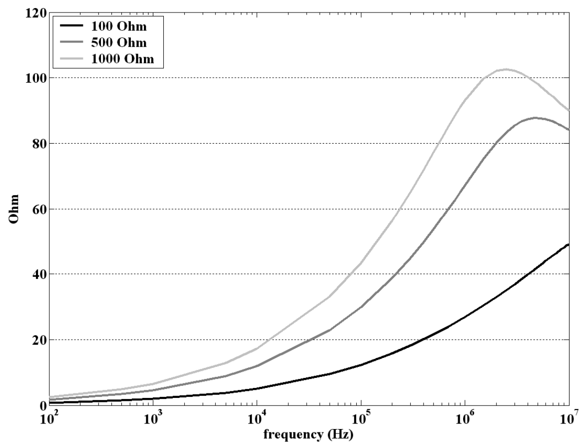

Fig. 6: Characteristic impedance magnitude for different earth resistivities. Earth relative permittivity is 10.

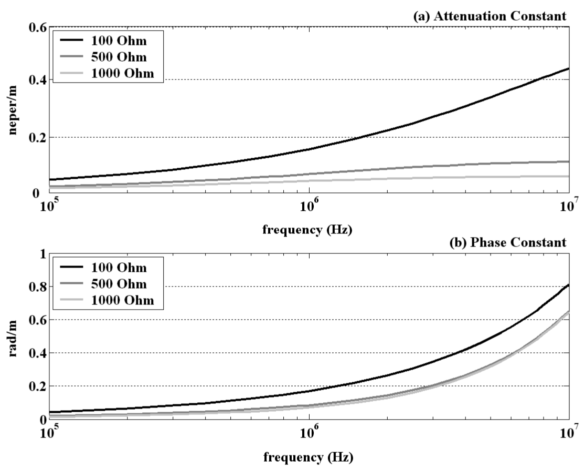

Fig. 7: (a) Attenuation and (b) phase constants for different earth resistivities. Earth relative permittivity is 10.

It is shown in Figs. 6 – 7 and 8 – 9, that the propagation characteristics of the bare conductor are very sensitive to earth resistivity and earth permittivity. The magnitude of the characteristic impedance is a non monotonic function of the frequency, since at the MHz frequency region and for earth cases with high resistivities, a maximum peak point is recorded. The value of the peak point and of the corresponding frequency decrease, as the earth permittivity increases, while the frequency of the peak value increases as the earth resistivity decreases.

The attenuation and phase constants in Figs. 7a – 9a and 7b – 9b respectively vary proportionally to the corresponding EM properties of the earth. Therefore, the attenuation constant decreases in the whole frequency range as earth resistivity and earth permittivity increases, while the phase constant reduces as the earth resistivity increases or the earth permittivity decreases.

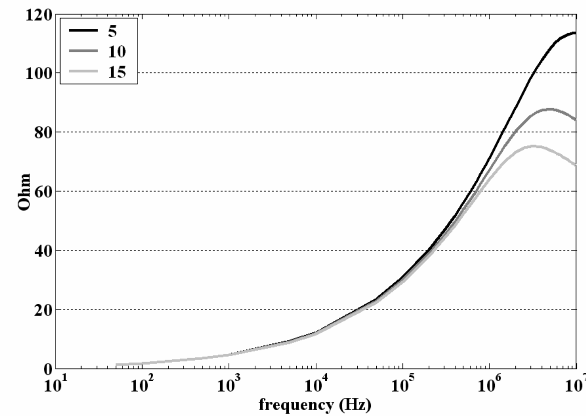

Fig. 8: Characteristic impedance magnitude for different relative earth permittivities. Earth resistivity is 500 Ω·m.

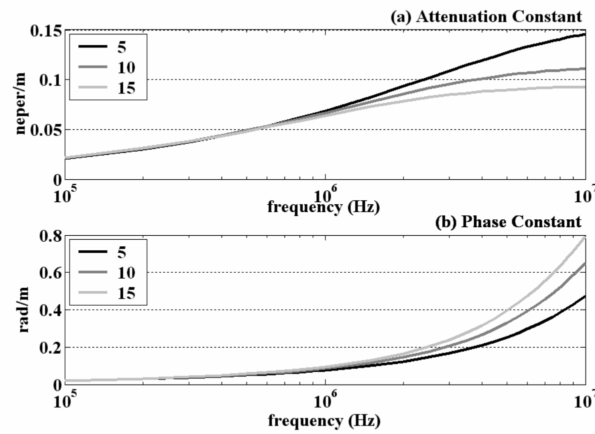

Fig. 9: (a) Attenuation and (b) phase constants for different relative earth permittivities. Earth resistivity is 500 Ω·m.

V. The Insulated Cable Case

A. Comparison with other approaches

The propagation characteristics of the single insulated underground cable are calculated first using the proposed model.

Next, the earth models of Petrache *et al.* [7] and Sunde [2] are used in the analysis. Sunde's model [2] neglects the influence of the imperfect earth on the admittances, while in this work the semi-infinite integral of the earth impedance correction term is numerically evaluated using the integration scheme of [12].

In Fig. 10 the characteristic impedance magnitude of the single core cable of Fig 3b, calculated by the three models, is presented for cases of $\rho_1 = 100\ \Omega\cdot\mathrm{m}$ and $\rho_1 = 1000\ \Omega\cdot\mathrm{m}$. In both earth topologies it is assumed that $\varepsilon_{r1} = 10$ and $d = 1.2$ m.

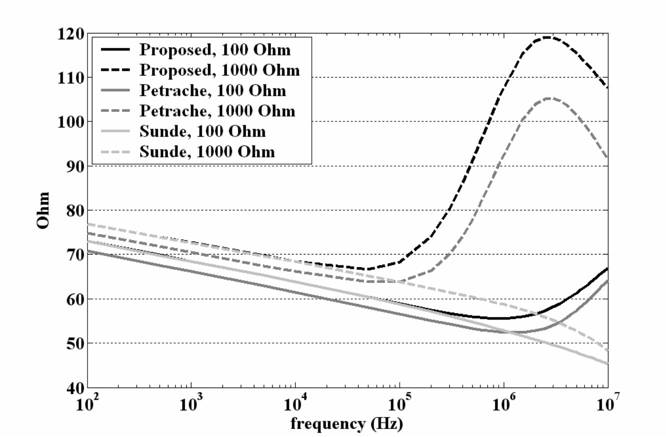

Fig. 10: Characteristic impedance magnitude for different methods and earth resistivities.

In Figs. 11a and 11b the attenuation and phase constants are shown, for $\rho_1 = 1000\ \Omega \cdot \mathrm{m}$. The corresponding terms of the propagation constants of the earth and the insulator, defined respectively as $\gamma_1 = \sqrt{j\omega\mu_1\left(\sigma + j\omega\varepsilon_1\right)}$, $\gamma_{ins} = j\omega\sqrt{\mu_{ins}\varepsilon_{ins}}$ are also plotted in these figures to show the differences resulting by each approach, since the propagation characteristics are expected to be between these boundary values [5].

Results show that the proposed model and the model of [7] are in very good agreement, as expected considering the previous results for the bare conductor case. Differences are recorded in the magnitude of the characteristic impedance, due mainly to the approximations in the approach of [7]. However, both models present the same behavior in all propagation parameters in all examined cases.

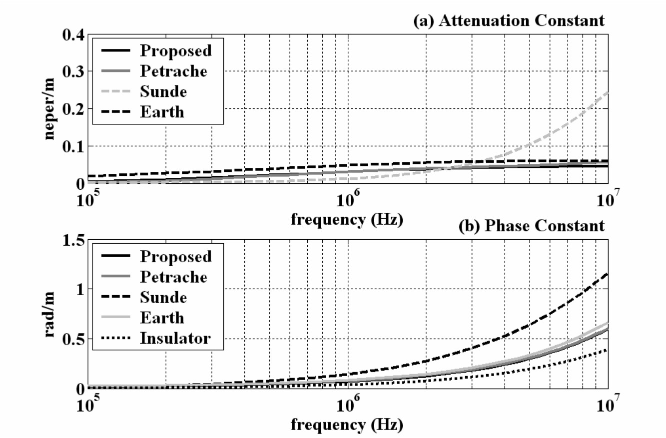

Fig. 11: (a) Attenuation and (b) phase constants for the two methods. Earth resistivity is 1000 Ω·m.

Results by Sunde's model for the characteristic impedance show a completely different behavior in the MHz frequency region, being monotonic decreasing functions with frequency. Significant differences are also recorded in the propagation constant terms, since curves corresponding to Sunde's model tend to higher values than those of the propagation constant of earth in the MHz region.

On the contrary, the propagation constant calculated by the proposed model is between the corresponding values for the earth and the insulator media, which is in agreement with the fundamental assumptions of the quasi-TEM propagation in inhomogeneous media [5]. The differences between the proposed and Sunde's models appear in the frequency region of kHz, where earth begins to behave also as an insulator and the admittance earth correction term cannot be disregarded.

B. Influence of conductor depth

The influence of the imperfect earth on the insulated cable propagation characteristics is further examined.

First, the insulated cable is assumed to be buried at variable depths in earth, where the latter has EM properties $\rho_1 = 500\ \Omega \cdot \mathrm{m}$ and $\varepsilon_{r1} = 10$. The attenuation and phase constants are presented in Figs. 12 (a) and (b) respectively.

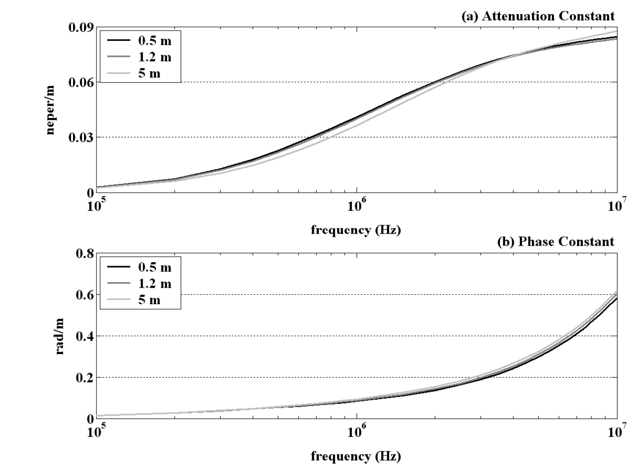

Fig. 12: (a) Attenuation and (b) phase constants for different burial depths.

As the burial depth increases, the attenuation constant takes slightly lower values for frequencies up to 5 MHz, while for higher frequencies results follow a different order. This type of behavior is due to the complex influence of the EM properties of both the imperfect earth and the cable insulation. However, the phase constant in the whole frequency spectrum increases as the burial depth increases, similar to the bare conductor case.

C. Sensitivity to earth EM properties

Next, the cable is located at 1.2 m and earth is assumed with resistivity $500\ \Omega \cdot \mathrm{m}$ but with variable permittivity. The curves of Figs. 13(a) and 13(b) show that the propagation constant is affected significantly by earth permittivity, following the same type of behavior as in the bare conductor case.

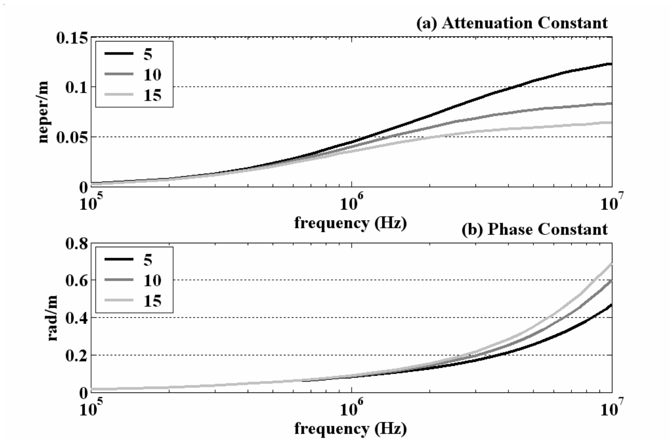

Fig. 13: (a) Attenuation and (b) phase constants for different earth permittivities. Earth resistivity is 500 Ω·m.

Finally, the influence of earth resistivity in Figs. 14 (a) and 14 (b) is examined, comparing the results of the proposed model to the corresponding obtained by Sunde's model.

As shown the attenuation constant calculated with Sunde's model is slightly affected by the EM properties of the soil almost up to 2 MHz, as also observed in [3] for the pul parameters. As frequency increases higher values of the attenuation constant are recorded for the topology with earth resistivity $1000\,\Omega\cdot\mathrm{m}$. On the contrary, the proposed model behaves in a completely different way. For frequencies below 1.5 MHz, the proposed model is strongly affected by earth resistivity resulting in higher attenuation as ρ_1 increases. For frequencies in the MHz region the opposite behavior of the attenuation constant is observed. This is due to the fact the earth acts differently depending on the frequency. At high frequencies as the earth resistivity increases, earth shows strong dielectric properties [8], considering the variation with frequency of earth propagation constant γ_1.

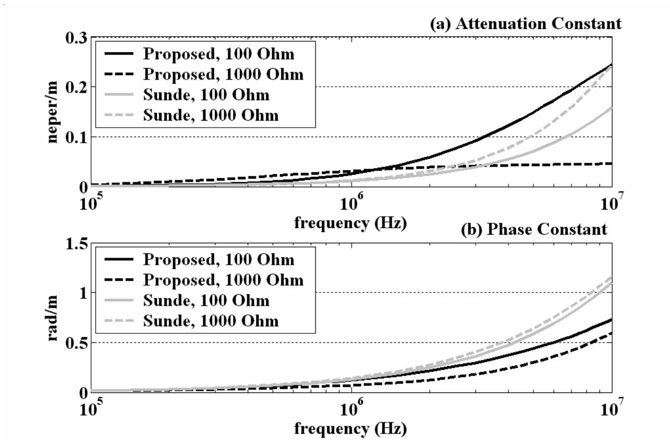

Fig. 14: (a) Attenuation and (b) phase constants for different methods and earth resistivities.

VI. Transient Responses

Of vital importance is the investigation of the impact of the earth EM properties on the actual voltages and currents resulting from a transient simulation. Therefore, the test case of the insulated cable of Fig. 3b has been implemented in ATP-EMTP [16], using the time domain, distributed parameter traveling wave transmission line model. A double exponential voltage source with a magnitude of 1 p.u. and time constants 1.2/50 μs is connected at sending end *S* of the conductor, while the receiving end *R* is terminated at a 10 Ω resistance. The cable is buried at 1.2 m, the line length is 100 m and earth has relative permittivity 10.

The pul parameters of the cable model are calculated at 4 different discrete frequencies, namely 10 kHz, 100 kHz, 500 kHz and 1 MHz and the corresponding transient voltages are presented in Fig. 15, assuming earth with $\rho_1 = 100\,\Omega\cdot\mathrm{m}$. As it can be observed the voltage rippling, caused by reflections at the line end, reduces as frequency increases, due to the increased attenuation across the cable line.

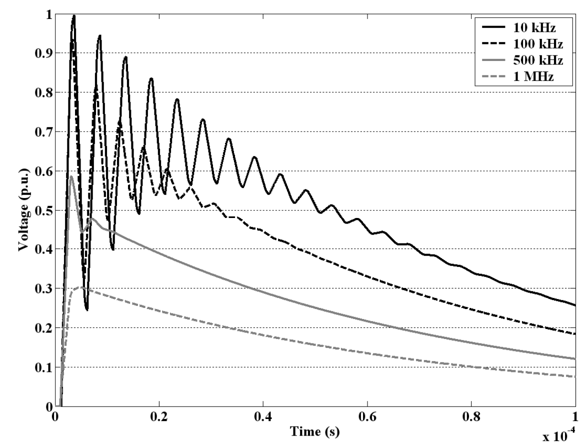

Fig. 15: Voltage recorded at a distance 50 m from the sending end *S* for different frequencies.

In Fig. 16, the transient voltages are recorded at different points across the transmission line. Earth resistivity is 500 Ω·m and the pul parameters have been calculated at 100 kHz. As the distance from the sending point increases the voltage rippling is gradually reduced, due to the reduced influence of the travelling waves along the line.

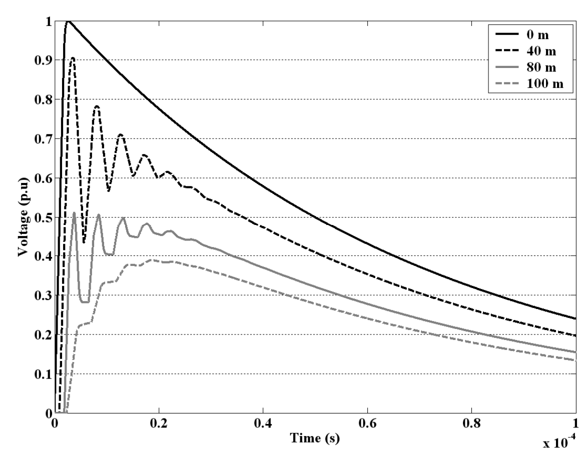

Fig. 16: Voltage recorded at different distances from the sending end *S* at 100 kHz.

Finally, in order to demonstrate the effect of ignoring earth admittance correction term, in Fig. 17 the transient voltages recorded at a point 50 m away from the sending end *S* are presented. The propagation characteristics have been calculated at 500 kHz using the proposed and Sunde's model. As shown, the influence of the earth resistivity is almost negligible for Sunde's model, while the proposed model presents a significant sensitivity, as mentioned previously for the propagation characteristics.

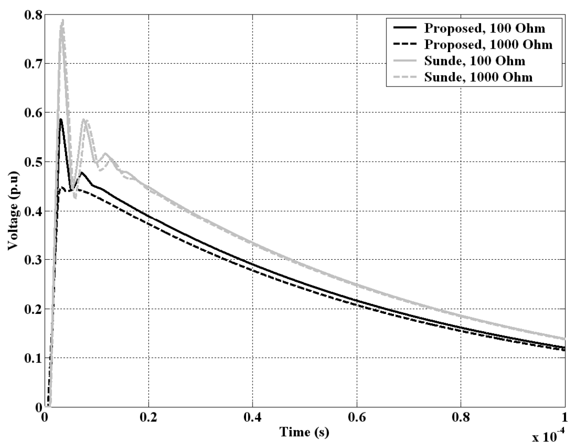

Fig. 17: Voltage recorded at a distance 50 m from the sending end *S* for different models and earth resistivities.

The differences between the results of the two models are amplified as earth resistivity increases, due to the frequency dependent behavior of earth related to the dominant influence at the HF of displacement currents. This type of behavior can only be predicted, by taking into account the earth admittance correction term, as in the proposed model.

VII. Conclusion

A proper formulation for the calculation of the impedances and admittances of underground bare and insulated conductors is presented in this paper. Although, the proposed expressions can be applied to any multiconductor arrangement, the analysis is focused to single conductor configurations.

The impact of the earth EM properties on the propagation characteristics of buried conductors is systematically investigated, considering different earth topologies and cable arrangements. Special emphasis is given on the significance of the earth admittance correction term and the frequency dependent behavior of earth, especially at the high frequency region.

In both bare and insulated conductor cases it is shown that the propagation constant behaves proportionally to the propagation constant of earth, as the EM properties of the earth vary. However, the burial depth does not affect significantly the propagation constant but the characteristic impedance.

More specifically, the introduction of the earth admittance correction terms enables the calculation of the propagation characteristics of bare conductor arrangements, in contrary to most of the earth models presented in the literature. The influence of the EM properties is very significant and the validity of the proposed model is verified comparing results with the corresponding ones obtained by the model of Petrache *et al.*

For the insulated cable case, the same remarks as in the bare conductor case can be concluded, regarding the influence of the EM properties. However, in some cases the direct interpretation of the results is not easy, due to the complex influence of the earth and the insulator. Differences between the proposed and the model of Sunde are recorded, due to the omission of the frequency dependent behavior of the earth through the earth admittance correction terms.

Finally, the calculated propagation characteristics are used in the simulation of fast transients in order to check the significance of the proposed model on the actual transient responses simulation.

The proposed model allows the direct calculation of the earth correction terms of physical conductors in arbitrary underground arrangements. Therefore, it can be used for actual multiconductor power cable systems in various earth structures. In combination with the numerical integration scheme it offers a complete package for the calculation of the transient model parameters of underground cables.

VIII. Appendix

Functions $A'(u)$ and $B'(u)$ are given by:

$$A'(u) = \gamma_1^2 \left(\frac{Cu}{a_1'} e^{-a_1'|h_2 - h_1|} + g_1 \cdot e^{-a_1'(h_1 + h_2)} \right), \tag{A.1a}$$

$$B'(u) = \left(\frac{Cu}{a_1'} e^{-a_1'|h_2 - h_1|} + g_1 \cdot e^{-a_1'(h_1 + h_2)} + \frac{a_1'}{u} p_1 \cdot e^{-a_1' h_2} \right), \tag{A.1b}$$

where

$$g_1 = \frac{Cu}{a_1'} \cdot \frac{a_1'\mu_0 - a_0'\mu_1}{a_1'\mu_0 + a_0'\mu_1}, \tag{A.2a}$$

$$p_1 = \frac{2Cu^2 \mu_0 \mu_1 \left(\gamma_1^2 - \gamma_0^2\right)}{(a_1'\mu_0 + a_0'\mu_1) \cdot (a_1'\gamma_0^2 \mu_1 + a_0'\gamma_1^2 \mu_0)} e^{-a_1' h_1}, \tag{A.2b}$$

$$C = \frac{I \cdot dS \cdot j\omega\mu_1}{4\pi\gamma_1^2}, \tag{A.2c}$$

IX. References

[1] F. Pollaczek, "Uber das Feld einer unendlich langen wechselstromdurchflossenen Einfachleitung," *Elektrische Nachrichtentechnik*, vol. 3, Nr. 4, pp. 339-359, 1926.

[2] E. D. Sunde, *Earth Conduction effects in transmission systems*, 2nd ed., Dover Publications, 1968, pp. 99-139.

[3] N. Theethayi, R. Thottappillil, M. Paolone, C.A. Nucci, F. Rachidi, "External impedance and admittance of buried horizontal wires for transient studies using transmission line analysis," *IEEE Trans. Dielectrics and Electrical Insulation*, vol. 14, Nr. 3, pp. 751 - 761, 2007.

[4] J. R. Wait, "Electromagnetic wave propagation along a buried insulated wire," *Can J. Phys.*, vol. 50, pp. 2402-2409, 1972.

[5] G. E. Bridges, "Transient plane wave coupling to bare and insulated cables buried in a lossy half-space," *IEEE Trans. Electromag. Compat.*, vol. 37, Nr. 1, pp. 62-70, 1995.

[6] E. F. Vance, *Coupling to shielded cables*, John Wiley and Sons, 1978.

[7] E. Petrache, F. Rachidi, M. Paolone, C. A. Nucci, V.A. Rakov, M.A. Uman, "Lightning Induced Disturbances in Buried Cables-Part I: Theory," *IEEE Trans. Electromag. Compat.*, vol. 47, Nr. 3, pp. 498-508, 2005.

[8] A. Sommerfeld, Partial Differential Equations in Physics, Academic Press, Inc, New York, N.Y., 1949.

[9] W. H. Wise, "Propagation of High Frequency Currents in Ground Return Circuits," *Proc. Inst. Radio Engrs.*, Nr. 22, pp. 522-527, 1934.
[10] W. H. Wise, "Potential Coefficients for Ground Return Circuits," Bell Syst. Tech. J., vol. 27, pp. 365-371, 1948.
[11] H. Kikuchi, "Wave Propagation along an Infinite Wire above Ground at High Frequencies," *Electrotech. J., Japan*, vol. 2, pp. 73-78, 1956.
[12] G. K. Papagiannis, D. A. Tsiamitros, D. P. Labridis, P. S. Dokopoulos, "Direct Numerical Evaluation of the Earth Return Path Impedances of Underground Cables," *IET Proceedings on Generation, Transmission and Distribution*, vol. 152, Nr. 3, pp. 321-328, 2005.
[13] A. Ametani, "A general formulation of impedance and admittance of cables," *IEEE Trans.*
[14] N. Theethayi, Y. Baba, F. Rachidi, R. Thottappillil, "On the Choice Between Transmission Line Equations and Full-Wave Maxwell's Equations for Transient Analysis of Buried Wires," *IEEE Trans. On EMC*, vol. 50, Nr. 2, pp. 347-357, 2008.
[15] C. Paul, *Analysis of Multiconductor transmission lines*, 2nd ed., John Wiley and Sons, 2007.
[16] H. W. Dommel, "Electromagnetic Transients Program Reference Manual," Bonneville Power Administration, Portland, OR, 1986.

X. Biographies

Theofilos A. Papadopoulos (S'01) was born in Thessaloniki, Greece, on March 10, 1980. He received his Dipl.-Eng. degree and the Ph.D. degree from the Department of Electrical and Computer Engineering at the Aristotle University of Thessaloniki, in 2003 and 2008 respectively.

His special interests are power systems modeling, powerline communications and computation of electromagnetic transients.

Mr. Papadopoulos has received the Basil Papadias Award for the best student paper, presented at the IEEE PowerTech 07 Conference in Lausanne,

Dimitrios A. Tsiamitros (M'2005) was born in Kozani, Greece, in 1979. He received his Dipl.-Eng. degree and the Ph.D. degree from the Department of Electrical and Computer Engineering at the Aristotle University of Thessaloniki, in 2001 and 2005 respectively.

His special interests are power system modeling and computation of electromagnetic transients.

Grigoris K. Papagiannis (S'79-M'88) was born in Thessaloniki, Greece, on September 23, 1956. He received his Dipl. Eng. Degree and his Ph.D. degree from the Department of Electrical and Computer Engineering at the Aristotle University of Thessaloniki, in 1979 and 1998 respectively.

He is currently As. Professor at the Power Systems Laboratory of the Department of Electrical and Computer Engineering of the Aristotle University of Thessaloniki, Greece. His special interests are power systems modeling, computation of electromagnetic transients, distributed generation and powerline communications.