The Transmission Line Modeling Method to Represent the Soil Ionization Phenomenon in Grounding Systems

Daniel S. Gazzana [1], Arturo S. Bretas [1], Guilherme A. D. Dias [1], Marcos Telló [2]

[1] Department of Electrical Engineering, UFRGS University.
[2] State Company of Electrical Energy CEEE-D.
[1] Av. Osvaldo Aranha, 103, CEP: 90030-190, Porto Alegre - RS, Brazil.
[2] Av. Joaquin Porto Vilanova, 201, CEP: 91410-400, Porto Alegre - RS, Brazil.
dgazzana@ece.ufrgs.br, abretas@ece.ufrgs.br, gaddias@terra.com.br, marcost@ceee.com.br

Abstract— **This paper presents an extended methodology based on the transmission line modeling method (TLM) aiming at a soil ionization representation for the simulation of grounding systems. This natural phenomenon can be better represented by taking into account the variation of the resistive and conductive components present in the TLM circuit. The proposed analytical formulation is introduced with a focus on the computational implementation of the transmission line modeling method in one dimension (TLM-1D).**

Index Terms— **Computational electromagnetics, Grounding, Ionization, Lightning protection.**

I. INTRODUCTION

In recent years, numerical methodologies have been developed and optimized for grounding systems transient analysis. The finite element method (FEM), the moments method (MoM), the finite difference time domain method (FDTD) and the transmission line modeling method (TLM) [1] are some of the state of the art techniques. The TLM is one of the most studied and developed methods in recent years, being used for the solution of Maxwell's equations in electromagnetic waves propagation.

TLM, sometimes called transmission line matrix method, is a differential numerical technique which can be implemented both in the time and in the frequency domains. In this method, Maxwell's equations are solved by analogy with the transmission line theory.

Grounding systems are one of the main resources responsible for dissipating the current originating from a lightning to the earth, functioning as an important component for protection and safety. As well as the frequency dependence of the soil parameters [2]-[3] and the inductive behavior of the electrode during the early time of the lightning surge [4], the soil ionization is an important phenomenon that must be taken into account in the modeling and analysis of grounding systems.
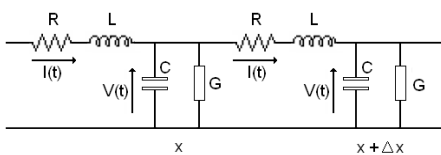

Fig. 1. Transmission line in one dimension.

In this context, this paper aims at presenting a general procedure to be incorporated into the one dimensional transmission line modeling method in order to confer to the classic algorithm an improved representation of the grounding electrodes and its interaction with the surrounding medium.

II. SOIL IONIZATION

During the process of current dissipation through the grounding system, if the voltage in the electrodes is high enough with consequent generation of an electric field exceeding a given threshold – critical electric field – the rupture of the soil dielectric around the electrodes up to a certain radial distance may occur. This region, referred to as ionized, can be interpreted as a type of irregular wrap conductivity around the grounding conductors [5]. This process culminates in a reduction of electrical resistivity in the ionized region. This phenomenon can be interpreted as if the electrode assumed a larger diameter than its original value.

The implementation of a mathematical model representing the soil disruption can be idealized considering the variation of soil resistivity and/or the increase of the electrode diameter. Studies have shown that in fact the only soil property that is affected in the ionization process is the resistivity. The electric permittivity and magnetic permeability are not significantly changed and the practical effect of the soil disruption consideration is the reduction of the generated earth potential [5].

If the critical electric field is exceeded, an increase in the radius of the conductor around the ionized region is established. Based on the transmission line representation, this increase in the diameter implies the need for a change in the line parameters per unit length with consequent alteration of the circuit elements present in the model [6]-[7]. In this approach, the model is composed of a set of small sections (segments), with lumped components as shown in Fig. 1.

III. ANALYTICAL FORMULATION

In [8] a formulation is presented to determine the tower footing resistance, according to (1) and (2)

$$R_T = \frac{R_0}{\sqrt{1 + \frac{I}{I_g}}} \qquad (1)$$

$$I_g = \frac{E_{cr} \cdot \rho_s}{2 \cdot \pi \cdot R_0^2} \qquad (2)$$

where R_T is the nonlinear tower footing resistance (Ω), R_0 is the static grounding resistance (Ω), I is the lightning current (A) and I_g is the lightning current from which the soil ionization initiates (A).

In order to take into account the change in the resistive component of the segments present in the transmission line model shown in Fig. 1, the reduction in its resistance must be made considering the R component and not the static grounding resistance R_0. Thus, the R component is given by (3) [7]

$$R = \frac{\rho_c \cdot \Delta x}{\pi \cdot a^2} \tag{3}$$

where R is the resistive component in the TLM model (Ω), a is the radius (m) and ρ_c is the conductor resistivity (Ωm).

Substituting (3) in (1), the nonlinear grounding resistance varying in time can be rewritten as in (4).

$$R(t) = \frac{\rho_c \cdot \Delta x}{\pi \cdot a^2} \cdot \frac{1}{\sqrt{1 + \frac{I(t)}{I_g}}} \tag{4}$$

In a similar manner, it can be stated that the soil disruption can be better represented, if besides the reduction in the resistive component $R(t)$, the increase in the conductance G is considered in the model. Therefore, based on (1), the nonlinear conductance in time $G(t)$ can be estimated by using (5) for a horizontal electrode and (6) for a vertical rod.

$$G(t) = \frac{2 \cdot \pi \cdot \Delta x}{\rho_s \cdot \left[ln\left(\frac{2 \cdot l}{\sqrt{2 \cdot h \cdot a}} \right) - 1 \right]} \cdot \sqrt{1 + \frac{I(t)}{I_g}} \tag{5}$$

$$G(t) = \frac{2 \cdot \pi \cdot \Delta x}{\rho_s \cdot ln\left(\frac{2 \cdot l}{a} \right)} \cdot \sqrt{1 + \frac{I(t)}{I_g}} \tag{6}$$

In the proposed study, the inductive and capacitive elements present in the TLM model do not change during the ionization, because this phenomenon does not produce significant alterations in the soil permeability and only a slightly change in the soil permittivity [9].

IV. SIMULATION RESULTS

In the developed simulations, a horizontal electrode was used. This type of electrode with $l = 12$ m length and cross section of 13 mm ($a = 0.0065$ m) is commonly used as grounding in transmission lines of the electric power system. The electrode was buried at $h = 0.5$ m depth in one layer homogeneous soil with different properties The lightning was represented by a current source, a double exponential wave of 50 kA (8 x 20) μs injected in one of the conductor extremities (origin). Fig. 2 illustrates the behavior of the voltage at the origin of the electrode using the classical TLM-1D method without considering the soil ionization (dashed lines) in comparison to the proposed model, which takes into account this phenomenon (solid lines).

A reduction of 17.54% can be determined based on the maximum potential generated at the origin of the electrode with a mean value of 6.09 % from a comparison of the simulations given in Fig. 2.
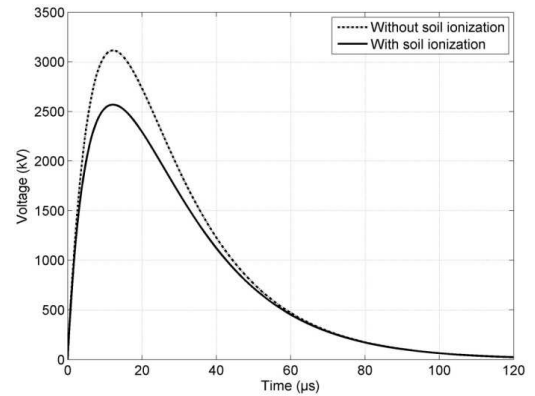

Fig. 2. Voltage at the origin of the electrode buried in urban areas ($\rho_s = 1000$ Ωm, $\varepsilon_r = 6$).

V. CONCLUSIONS

In this work a methodology for the numerical representation of soil ionization was introduced based on the transmission line modeling method. Taking as reference the main models developed so far, a novel solution to the problem was sought in order to confer a general procedure to be incorporated in the TLM-1D algorithm.

Considering the simulation results, the fact that the soil ionization is an important phenomenon is reinforced and should be considered in the numerical representation of grounding systems. The reduction of the potential on the electrode can assume significant values, especially in case of soil with high resistivity. It can be concluded that the developed TLM-1D based model is a reliable alternative to represent this natural mechanism, sometimes neglected in the development of computational models.

REFERENCES

[1] C Christopoulos, *The Transmission-Line Modeling Method in Electromagnetics*. Morgan & Claypool Publishers, 2006. p. 123.
[2] 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, Jan. 2007.
[3] S. Visacro, and R. Alipio, "Frequency dependence of soil parameters: experimental results, Predicting formula and influence on the lightning response of grounding electrodes," *IEEE Transactions on Power Delivery*, vol. 27, no. 2, pp. 927-935, Apr. 2012.
[4] L. Grcev, "Lightning surge efficiency of grounding grids," *IEEE Transactions on Power Delivery*, vol. 26, no. 3, pp. 1692-1699, Jul. 2011.
[5] A. M. Mousa, "The soil ionization gradient associated with discharge of high currents into concentrated electrodes," *IEEE Transactions on Power Delivery*, vol. 9, no. 3, pp. 1669-1677, Jul. 1994.
[6] D. S. Gazzana, A. S. Bretas, G. A. D. Dias, and M. Telló, "Transient response of grounding electrode with emphasis on the transmission line modeling method (TLM)," presented at 30th International Conference on Lightning Protection, Cagliari, Italy, 2010.
[7] R. Velasquez, and D. Mukhedkar, "Analytical modeling of grounding electrodes transient behavior," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-103, no. 6, pp. 1314–1322, Jun. 1984.
[8] A. F. Imece, D. W. Durbak, H. Elahi, S. Kolluri, A. Lux, D. Mader, T. E. McDemott, A. Morched, A. M. Mousa, R. Natarajan, L. Rugeles, and E. Tarasiewicz, "Modeling guidelines for fast front transients*,"* *IEEE Transactions on Power Delivery*, vol. 11, no. 1, pp. 493-506, Jan. 1996.
[9] Y. Liu, "Transient response of grounding systems caused by lightning: modelling and experiments," Ph.D. dissertation, Faculty of Science and Technology, Univ. Uppsala, 2004.