Novel Formulation to Determine the Potential on the Soil Surface Generated by a Lightning Surge

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This paper presents the development of an analytical formulation for estimating the potential in the soil surface, caused by electric current calculated on a grounding conductor through the Transmission Line Modeling Method (TLM). The formulation has great significance in its use in conjunction with one-dimensional numerical methods in general manner, which are not able to determine such potentials directly. The proposed study is focused on lightning surges and it takes into account the frequency dependence of the soil properties.

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

I. INTRODUCTION

SEVERAL numerical methods can be used for the representation and analysis of grounding systems [1]. Many of such methodologies can be implemented in one (1D), two (2D) or three (3D) dimensions, as the case of TLM [2]. An approach in one-dimension enables the analysis on a single coordinate space, either x, y or z. An implementation in two-dimensional leads the calculations in a plane and finally, three-dimensional methods allow a spatial analysis.

The choice of a numerical method, as well as its dimension to the solution of an electromagnetic problems in general manner, should be made based on the requirements of the system representation to be analyzed, taking into account its accuracy, procedure of implementation and computational performance.

3D methodologies are more versatile and suitable for the representation of more elaborate structures, materials with different properties, non-homogeneous medium and irregular geometries. However, the degree of implementation complexity and the high computational processing make this approach less attractive in comparison with a method in one-dimension, for representation and analysis of simple structures, such as horizontal or vertical grounding electrodes in homogeneous soil.

On the other hand, a 3D method is able to determine the quantities of interest at any point P of a study domain S, as illustrated in Fig. 1. Thus, the potential generated at one point on the soil surface can be determined directly. To solve this problem base on a 1D method, which has its computation restricted to a single coordinate, and in the case study on the grounding electrode, it becomes necessary to estimate the voltages in the space S indirectly.

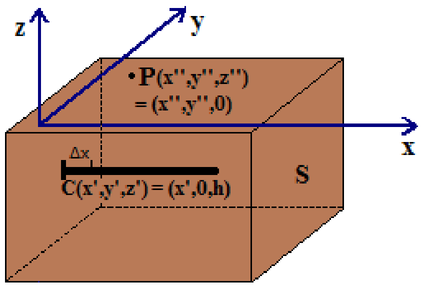

Fig. 1. Representation of a point P and a conductor C buried in a depth h in a tree-dimensional space S.

II. ANALYTICAL FORMULATION

Starting from a current *I* (A) dissipated along a grounding electrode with length *l* (m), buried in homogeneous soil with resistivity ρ_s (Ωm) and considering a correction factor f_c, the potential in the soil surface *V* (V) for an stationary analysis in low frequency (60 Hz) can be determined based on (1) [3].

$$V = \frac{I \cdot \rho_s}{2 \cdot \pi \cdot l} \cdot f_c \qquad (1)$$

However, in the case of fast phenomena, such a lightning, the stationary approach is considered incorrect, being important in this case to consider the behavior of the medium as a function of frequency. Consequently, a medium should be described by the behavior of its conductivity σ and permittivity ε in a complex representation with frequency dependence ω.

In the formulation, it is assumed that the electrical current *I* at a time *t* injected into a grounding conductor can also be represented in a complex form and that it is uniformly distributed along the symmetry axis of the conductor. Adopting the correction factor f_c and the propagation constant γ associated with the factor $e^{j\gamma r}$, it is possible estimate the potential *V(x'',y'',z'')* in a point *P* on the soil surface, now considering the dependence of soil parameters with the frequency. Starting from (1) and based on a mathematical development, it is obtained (2),

$$V(x'',y'',z'') = \frac{I \cdot e^{-j\omega t}}{2 \cdot \pi \cdot l \cdot (\sigma_s + j\omega \cdot \varepsilon_0 \cdot \varepsilon_r)} \cdot e^{j\gamma \cdot r} \cdot ln\left(\frac{\sqrt{x^2 + y^2 + z^2} + x}{\sqrt{(x-l)^2 + y^2 + z^2} + x - l} \right) \quad (2)$$

where: $V(x'',y'',z'')$ is the voltage (V) in point of coordinates $P(x'',y'',z'')$ (m); t is the time (s); ω is the angular frequency (rad/s); $Ie^{-j\omega t}$ is the complex current (A); l is the electrode length (m); ε_r is the soil relative permittivity; ε_0 is the vacuum permittivity (F/m); σ_s is the soil conductivity ([Ωm]-1); γ is the propagation constant; r is the distance between the middle point of conductor C and point P on the soil surface (m) and x, y and z are the relative coordinates.

With this equation, the current I determined on a grounding electrode by a method in one-dimension can be used to estimate the potential generated in the soil by means of a numerical implementation.

III. Computation and Results

In order to illustrate the elevation of potential on the soil surface, a horizontal electrode buried in homogeneous soil parallel to x axis, with length l = 10 m, radius a = 6.5 mm and divided in 10 segments (Δx = 1 m) is considered. In this study the soil is characterized by its resistivity ρ_s = 100 Ωm and relative permittivity ε_r = 10. Also a current surge with 10 kA (8 x 20) μs applied in the origin of the electrode in a point $C(x',y',z')$ = (0,0,-h) with a representative frequency f = 500 kHz is assumed. Based on (2) it is possible to draw equipotential curves in the time, as shown in Fig. 2.

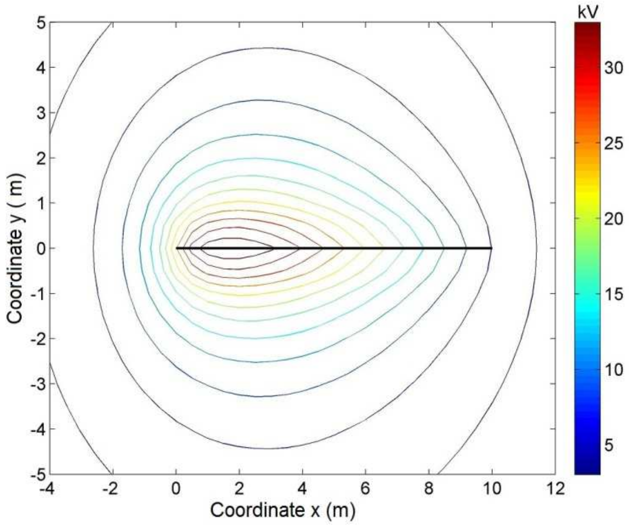

Fig. 2. Equipotential curve produced on the soil surface in t = 4.1 μs.

IV. Validation

In order to validate the proposed formulation, comparisons is made with results from simulations performed in a computational tool, which presents a solution based on Electromagnetic Model [4]. It is used a conductor horizontally buried in the soil with length l = 10 m and depth h = 0.5 m and radius a = 6.5 mm.

Fig. 3 illustrates the application of a current surge characterized as a fast wave, represented by the double exponential function $I(t)$ = 11043.33 · ($e^{-79238.91t}$ - $e^{-4001095t}$). In this simulation, it is used an electrode with the same characteristics previously presented considering a soil with resistivity ρ_s = 500 Ωm and relative permittivity ε_r = 10.

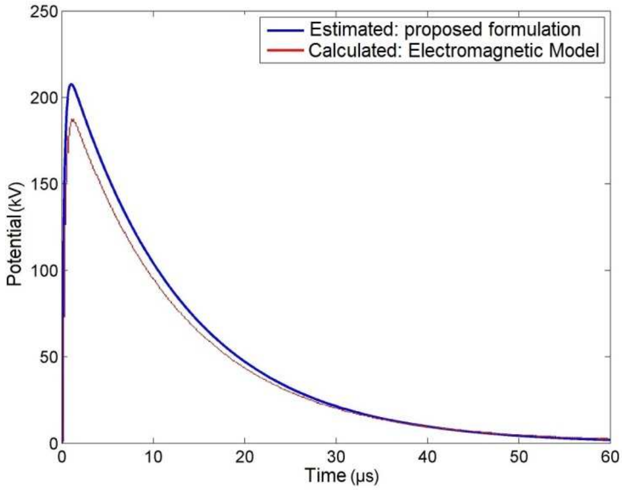

Fig. 6. Generated potential on the soil surface. Comparison between Electromagnetic Model and proposed formulation for a fast current surge.

V. Conclusions

In this study is presented an equating to estimate potentials generated on the soil surface due to the electrical current dissipation in a grounding conductor. Starting from studies of low frequencies and based on a quasi-stationary approximation and plain waves modeling, the potential on the soil surface can be analytically estimated for fast surge transients.

Such equating, which was conceived for horizontally buried electrodes in one layer homogeneous soil, has shown great relevance to the establishment of the referred potentials as base in electrical quantities determined in one-dimensional numerical methods. The proposed formulation is not restricted for use only with the TLM-1D method, having generalist applicability to other methodologies that are able to estimate the electric current on the electrode.

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VI. References

[1] M. N. O. Sadiku *Numerical Techniques in Electromagnetics with MatLab*. New York: CRC Press, 2009.

[2] C Christopoulos, *The Transmission-Line Modeling Method – TLM*. 1st ed. New York: IEEE PRESS, 1995.

[3] R. J. Heppe, "Computation of Potential at Surface Above an Energized Grid or Other Electrode," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-98, no. 6, pp. 1978–1989, Nov. 1979.

[4] CDEGS, SES Safe Engineering Services & Technologies Ltd., 2006.