Potential on the Soil Surface Generated by a Lightning Based on Transmission Line Modeling Method

Daniel S. Gazzana, Alex B. Tronchoni, Arturo S. Bretas, Guilherme A. D. Dias, Roberto C. Leborgne, Marcos Telló

Abstract-- **This paper presents a practical application of a formulation for estimating the potential on the soil surface, originated by an electric current calculated in a grounding conductor through the Transmission Line Modeling Method (TLM). This study discusses the use of such formulation, which can increase the applicability of one-dimensional numerical methods that are not able to determine such potentials directly and it is focused on the evaluation of the transient generated by a lightning surge taking into account the frequency dependence of the soil properties.**

Keywords: **Computational electromagnetics, Grounding, Lightning, Transmission Line Modeling Method.**

I. INTRODUCTION

THE first step in the study and analysis of grounding systems behavior concerning the dissipation of currents resulting from lightning surges or short-circuit in the electrical power system is the correct selection of the electrical quantities of interest. Consequently, these quantities like voltages, currents, fields and impedances will serve as a point of reference for distinct approaches and needs in different areas of technical knowledge.

Electrical grounding is one of the focuses of study within electromagnetic compatibility (EMC), together with transient analysis, quality of energy and system reliability. Within the context of EMC, grounding is a component which must ensure that interference signals do not disturb the normal operating characteristics of a given electrical system. For instance, in the area of electrical power systems, grounding is linked to the requirement of a low impedance path to the soil. In telecommunications, electrical grounding is associated with obtaining low impedance values between devices and between such devices and the soil. With respect to the area of radio frequency, once more grounding systems can be seen as a low impedance path for high frequencies [1].

Taking that into account, it can be seen that the determination of the electrical quantities on the conductor with consequent identification of the grounding impedance is satisfactory, partially meeting EMC requirements. However, grounding systems must guarantee not only the correct operation of the electrical system, but also promote safety to the people. In this case, a more comprehensive study needs to be carried out. Therefore, it is necessary to analyze the electrical quantities produced on the soil surface, among them the generated potential.

Thus, in order to contribute to the study of impulsive grounding associated to supportability evaluation and personal safety, [2]-[6] can be used as reference works. In such studies the mathematical formulation development and computational implementation for the estimation of potentials produced on the soil surface from the dissipation of electric current in a horizontal grounding electrode are presented. The present study has its contribution together with the use of one-dimensional numerical methods, in this case the Transmission Line Modeling Method in one dimension (TLM-1D), for determining electrical quantities under and on the soil surface. The originality can be attributed to the increase of the potential of methods in one dimension to solve problems involving three-dimensional space.

II. PROPOSED STUDY

Several numerical methods can be used for the representation and analysis of grounding systems. Many of such methodologies can be implemented in one, two or three-dimensions, as is the case of the TLM [7].

One-dimensional approach allows the analysis of the system of interest on a single coordinate space, either x, y or z. In turn, a two-dimensional implementation can estimate the quantities of interest on a plain and finally, three-dimensional methods allow a spatial analysis.

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

Tri-dimensional methodologies are more versatile and suitable for the representation of more elaborate structures, materials with different properties, non-homogeneous media and irregular geometries. However, the degree of complexity

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for the implementation 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 electrodes in a homogeneous soil.

Additionally, it is known that the error in a model is intrinsic to its representation process, which is directly related to its distance from the real world, and also related to the representation of a continuous behavior in a discrete manner. When dealing with a dynamic process, which is the case of electrical current dissipation in time in a grounding system, this error tends to propagate and accumulate. The appearing of a quantitative error is directly associated with the number of iterations in the present computational step, linked also to a qualitative error. This depends on the dimensions of the modeling space and the discretization. Consequently, the accumulation of such errors leads to a decrease of the accuracy given to the model compared to the real world [7]. Thus, these arguments reinforce the use of methods in one dimension for representation of simple systems, which can provide more accuracy to the model.

On the other hand, a tri-dimensional method can determine the amount of interest at any point *P* of a study domain *S*, as shown in Fig. 1. Therefore, the potential generated at one point on the soil surface can be directly determined.

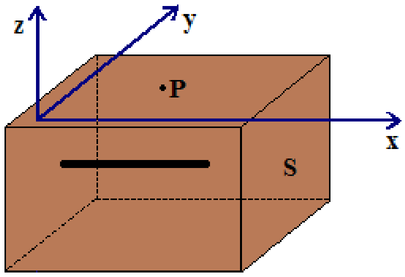

Fig. 1. Study domain in a tri-dimensional space.

To solve this problem based on a method in one dimension, which has its computation restricted to a single coordinate and in the present case study on the grounding electrode, it is necessary to estimate the voltages in the space *S* indirectly.

The study developed by Robert J. Heppe [2]-[3] presents a methodology to calculate the potentials produced on the soil surface considering the electric current dissipated to the earth from the short-circuit of the electric power system. This approach focuses on low frequency and steady state, taking into consideration only the soil resistivity ρ_s for the medium representation in its formulation. However, for high frequencies, besides resistivity, electric permittivity ε and magnetic permeability μ of the soil must be taken into consideration [8]. Also, in the case of very fast phenomena such as a lightning surge, the conductivity σ and relative permittivity ε_r of the soil are dependent on the frequency [9]-[10].

In this context, the following analytical formulation allows for the estimation of the potentials on the soil surface considering a specific frequency, named characteristic frequency, within the surge of current spectrum applied to the electrode.

III. 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 a stationary analysis in low frequency (60 Hz) can be determined based on (1).

$$V = \frac{I\cdot\rho_s}{2\cdot\pi\cdot l}\cdot f_c \tag{1}$$

However, in the case of fast phenomena, such as lightning, the stationary approach is considered not appropriate. In this case it is important 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 to 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, (2) is obtained,

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

where: *V(x'',y'',z'')* is the voltage (V) in a 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); *x*, *y* and *z* are the relative coordinates.

With this equation, the current *I* determined on a grounding electrode by a one-dimensional method can be used to estimate the potential generated on the soil by means of a numerical implementation. The complete formulation and deductions are presented in [11].

IV. Computation and Results

In order to illustrate the potential on the soil surface a horizontal electrode buried in a homogeneous soil parallel to axis *x*, with length l = 10 m, radius a = 6.5 mm and divided into 10 segments (Δx = 1 m), was considered. In this study the soil is characterized by 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 point *C(x',y',z')* = (0,0,-*h*) with a representative frequency *f* = 500 kHz was assumed. It is noteworthy that all the estimated results based on (2) presented here consider the absolute value of the potential on the soil surface. Fig. 2 to 5 show the calculated potential at point *P(x'',y'',z'')* = (0,0,0) located on the soil surface at the surge insertion point in the electrode considering different burial depths *h* of the grounding conductor.

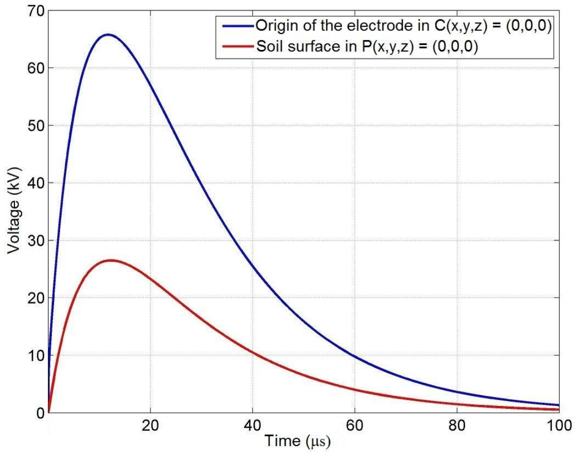

Fig. 2. Potential calculated at a point *P* on the soil surface considering depth of the grounding electrode *h* = 1 m.

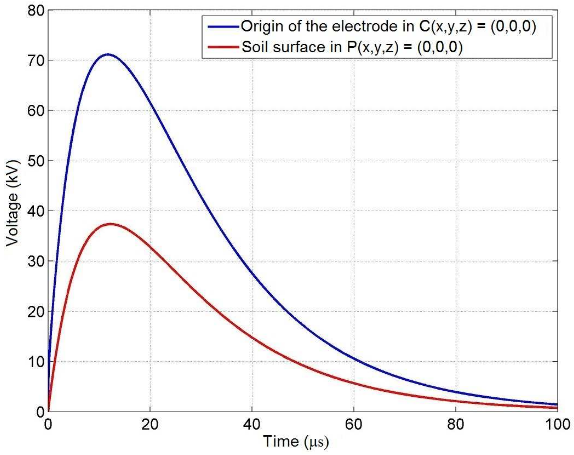

Fig. 3. Potential calculated at a point *P* on the soil surface considering depth of the grounding electrode *h* = 0.5 m.

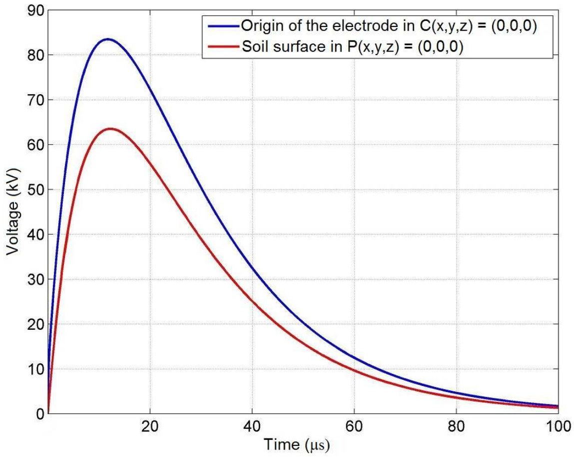

Fig. 4. Potential calculated at a point *P* on the soil surface considering depth of the grounding electrode *h* = 0.1 m.

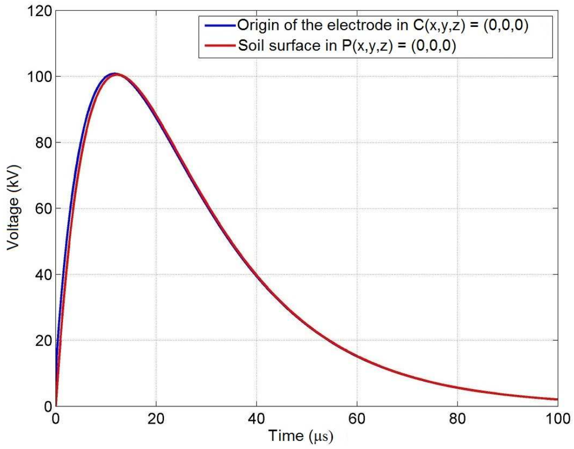

Fig. 5. Potential calculated at a point *P* on the soil surface considering depth of the grounding electrode *h* = 0.01 m.

Analyzing Fig. 2 to 5, it can be seen that as the burial depth of the electrode decreases, the voltage generated at the point of analysis on the soil surface increases. The same behavior can be observed in the voltage produced in the electrode. However, the difference of potential between the voltage produced in the conductor and the voltage generated on the soil decreases with depth. In other words, as the physical layout of a horizontal conductor placed on the soil approaches the surface, the voltage difference between the electrode and the surface layer of the soil tends to be null. Fig. 5, which considers an electrode with 1 cm burial depth, illustrates such scenario. Table I quantifies the maximum potential produced in the electrode and generated on the soil surface illustrated in Fig. 2 to 5, reinforcing the aforementioned arguments.

TABLE I
MAXIMUM POTENTIALS GENERATED

Burial Depth of the electrode (m)	Max. voltage in the electrode (kV)	Max. voltage on the soil surface (kV)	Max. voltage difference (kV)
1	65.77	26.5	39.27
0.5	71.12	37.36	33.76
0.1	83.45	63.49	19.97
0.01	100.81	100.52	0.29

Given a plain *s(x,y)* located on the soil surface, illustrated in Fig. 6, one can estimate the evolution of the potential on a line segment present in this plain for a given time *t*. Considering the same surge characteristics, medium and electrode presented in the previous example, to a depth *h* = 0.5 m, the potential on the profiles *p1* and *p2* for the time *t* = 12.3 µs can be seen in Fig. 7 and Fig. 8 respectively. In this example the discretization used (step *x* to the profile *p1* and step *y* to the profile *p2*) is of 0.5 m.

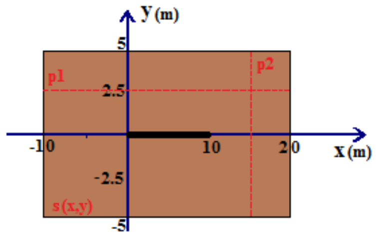

Fig. 6. Study domain on the soil surface.

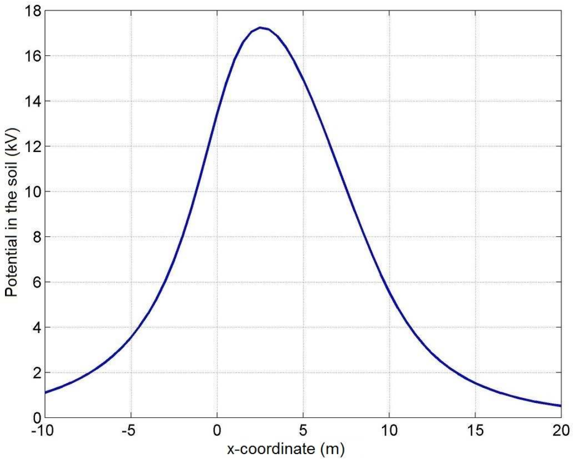

Fig. 7. Calculated potential in a profile *p1* on the soil surface.

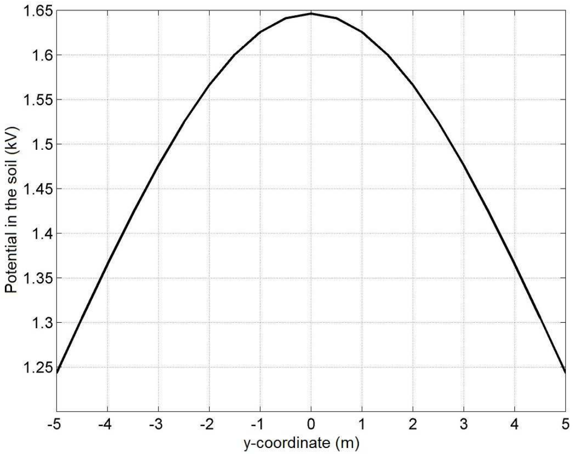

Fig. 8. Calculated potential in a profile *p2* on the soil surface.

Finally, based on the determination of potential surfaces, it is possible to draw equipotential curves over time, as shown in Fig. 9.

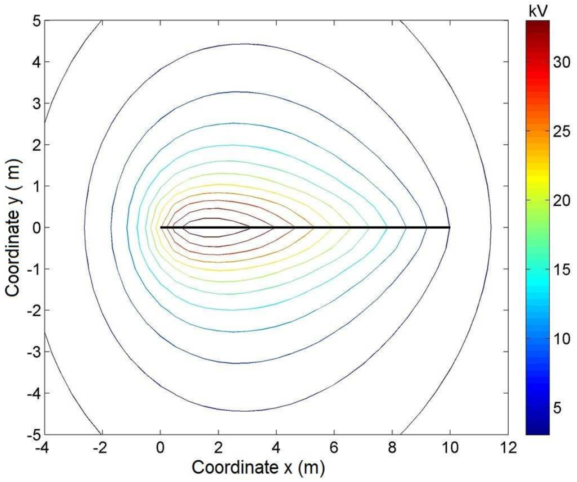

Fig. 9. Equipotential curves produced on the soil surface in $t = 4.1$ µs.

V. VALIDATION

In order to validate the proposed formulation, comparisons were made with results from simulations performed in a computational tool which presents a solution based on the Electromagnetic Model [12]. A horizontal conductor buried in the soil with length $l = 10$ m and depth $h = 0.5$ m and radius $a = 6.5$ mm was used.

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

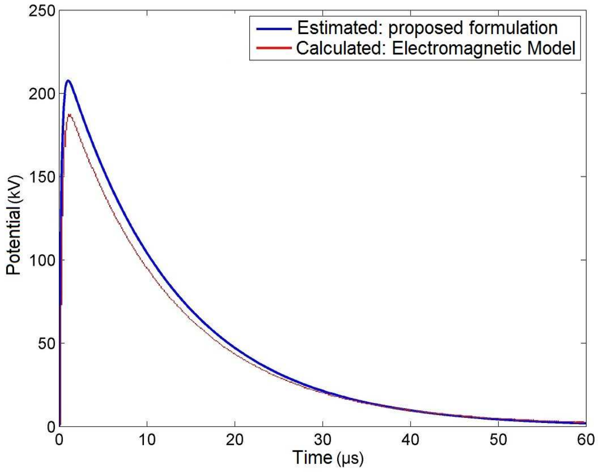

Fig. 10. Generated potential on the soil surface. Comparison between Electromagnetic Model and proposed formulation for a fast current surge.

As well as for fast waves, in the case of slow waves the developed formulation presents good results. Additionally, soil resistivity varying from 80 Ωm to 1000 Ωm and permittivity within a scale from 15 to 6 were considered presenting a satisfactory convergence.

VI. CONCLUSIONS

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

In the presented formulation, in addition to the electric resistivity, the electric permittivity and magnetic permeability of the soil were also taken into account with frequency dependence.

In the case studies, practical applications of the use of analytical formulation were made to evaluate the potential generated on the soil surface in different scenarios. From the electrical current dissipated in the grounding conductor utilized in Lightning Protection System (LPS), the reduction of voltages on the soil with the increase in the distance of the surge insertion point as well as the variation of the magnitude for the different kinds of soils was observed.

Such formulation, which was conceived for horizontally buried electrodes in one-layer homogeneous soil, has shown great relevance to the establishment of the referred potentials based on the electrical quantities determined in one-dimensional numerical methods. This approach allows for the calculation of the variables related only to the ground conductor, requiring an indirect estimation to determine the increase of potential on the soil surface. The proposed formulation is not restricted for use only with the TLM-1D method, having a general applicability to other methodologies that can estimate the electric current in the electrode.

Based on the proposed formulation, comparisons were made with results from simulations using the Electromagnetic Model, which is considered the most accurate technique for the solution of Maxwell's equations due to its minimal approximations. In the case of atmospheric surge represented by slow waves, as well as for the fast waves, the developed formulation presented a satisfactory convergence considering soil with different properties.

Finally, the proposed model can offer better applicability to one-dimensional methods, especially the TLM-1D, in the representation of transients and high frequencies. The proposed formulation has proved to be a suitable solution for the estimation of potentials on the soil, providing evaluation of several contact mechanisms with a lightning surge contributing to the development of further studies related to the supportability and human safety.

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