TRANSIENT BEHAVIOUR OF A HORIZONTAL GROUNDING ROD UNDER IMPULSE CURRENT

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Abstract: In this paper the authors present an application of the Electromagnetic Transient Analysis Program (EMTP) to study the transient behaviour of a horizontal grounding rod, under impulse lightning current. The model put out for the EMTP is characterised by a circuital approach. The aim of this work is to verify the applicability of this approach in the behaviour analysis of the ground systems excited by high impulsive currents. Numerical results are laid out for typical configurations of ground linear electrodes, although the model could be applied to every element of a complex grounding system.

Keywords: Grounding system, Impulse lightning current, EMTP circuital model.

INTRODUCTION

Grounding requirements arose from the need to provide protection from lightning strokes and industrially-generated static electricity. Structures and electrical equipment are connected to earth, i.e., grounded, to provide necessary conduction paths for lightning and static discharges. The resistance of grounding systems has an essential influence on the protection. Grounding systems can consist of one or more vertical or horizontal ground rod(s), three or more vertical ground rods connected to each other, two or three-dimensional grids from metal rods and foundation grounding systems. Some grounding systems are: hemispherical electrode, driven rod and grounding grids [1, 2]. The behaviour of the grounding system under lightning determines the degree of protection provided by it. All of the above make obvious the purpose of analysis procedures predicting the transient response of grounding systems and they can be implemented in a digital simulation model only if a circuital approach is adopted. This approach has the major advance of being simple to implement in a digital model able to adapt easily itself to each configuration of grounding system also in presence of non-linear ionization phenomena, but, on the other hand, it implicitly assumes that one knows how to derive the elements of the equivalent electrical network. For this reason, the authors will preliminarily study a criterion to evaluate the lumped parameters of the equivalent electrical network [3].

FUNDAMENTALS

The work reported in this paper refers to the problem of transient analysis of a horizontal grounding rod under impulse lightning current.

In order to validate the behaviour of grounding systems the knowledge of their performance over a wide range of frequencies is required. The basic models developed so far are the following:

- The Network Approach, which models an earth conductor as equivalent π-circuits involving R-L-C elements. The coupling of earth conductors can be taken into account by mutually coupled inductances.
- The Transmission Line Approach, where the interconnected linear ground conductor is treated by the travelling wave technique.
- The Electromagnetic Field Approach, which is strictly based on the theorems of electromagnetism and with the least neglects possible. The problems are defined in terms of retarded potentials and are solved by the method of moments.

All three developed models produce equations for the grounding system's impulse impedance depending on time, thus depending on the contents of the frequency spectrum[2].

When a grounding system is excited by an impulsive current, there are an electromagnetic force self induced by the variable magnetic field and a displacement current in the earth due to the variable electric field.

The conductors that make up this system are represented in analogy with a transmission line characterised by losses and wave distortion [4, 5, 6]. Without the model of the lines that consists of the four distributed parameters, it is indispensable to split the conductor into a finite number of sections with the right length in order to consider lumped line parameters (partitioning process).

Each electrode can be considered as an equivalent circuit formed by a cascade of cells (Fig. 1). Each cell is made up by elements connected in series and parallel: the resistance (R) in series with the self inductance (L), and the parallel of the capacity (C) and the conductance (G) in shunt position.

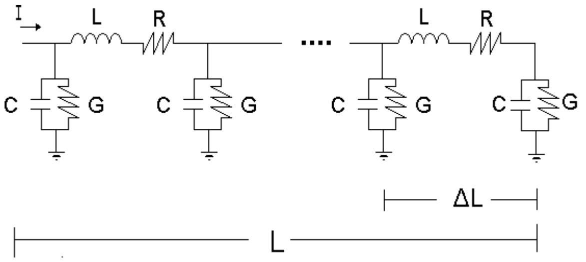

Fig. 1: Equivalent electrical network of horizontal grounding electrode.

The more meaningful parameters are the self inductance L and the transverse conductance G, that represents the losses to earth, the losses in the conductor are usually negligible while, for soil with good conductivity, the effect of the capacity is small in comparison with the conductance. For these reasons some authors have considered the problem as either a propagation problem [7], or a diffusion problem [8].

The kind of cell which has to be used to represent the circuit equivalent to every section of the conductor is very important: in particular, the main problem is the choice of the shunt parameters (G, C) position. The simulation of the behaviour of the buried wires has been led using for each section of the conductor a π cell with lumped parameters [5, 6, 9].

The choice of the expressions to use in the evaluation of the electrical parameters of each double bipole is a relevant problem when a circuital approach is adopted to analyse the transient behaviour of grounding systems.

$$R = \rho_e \cdot \frac{4 \cdot \Delta L}{\pi \cdot D^2} \tag{1}$$

$$G = \frac{2 \cdot \pi}{\rho_g} \cdot \frac{\Delta L}{\ln\left(\frac{2 \cdot L}{D}\right) + \ln\left(\frac{L}{2 \cdot H}\right)} \tag{2}$$

$$L = \frac{\mu \cdot \Delta L}{2 \cdot \pi} \cdot \left[\ln\left(\frac{2 \cdot L}{D}\right) + \ln\left(\frac{L}{2 \cdot H}\right)\right] \tag{3}$$

$$C = 2 \cdot \pi \cdot \varepsilon \cdot \frac{\Delta L}{\ln\left(\frac{2 \cdot L}{D}\right) + \ln\left(\frac{L}{2 \cdot H}\right)} \tag{4}$$

The expression of the electrical parameters used in this paper is determined assimilating the conductor, immersed in a homogeneous medium, to a linear source consisting of an infinite number of closely aligned elementary sources. The scalar electrical potential of a generic point in the space is obtained by integrating the infinitesimal potentials generated by the elementary sources linear distribution. The non-homogeneity of the medium due to the separation plane between air and ground can be brought into account using the “principle of images”. The above mentioned method is applied to determine the G parameter under the hypotheses, verified in this case, of D«4L and of 4H«L, and then, using the fields analogy [10, 11], the expressions of the parameters R, G, L, C are derived as the above formulas (1-4) show.

THE EMTP APPLICATION

The electric network sources implemented in the EMTP allow a choice between very different functions of time. The most common source in the lightning study is the surge function or double exponential. The value of the parameters I_0, a and b are defined by the peak value, time of the peak and the time of one half of the peak value. The principal shortcomings of this type of source is that its derivative is not continuous in the origin. This fact creates some difficulties when the source is directly applied to the inductor element.

Since a buried wire interested by an impulsive current is assimilated by a single-phase transmission line, there are at least three ways to describe it into the EMTP:

- As a cascade of π circuits with lumped elements (single-phase or multiphase nominal π circuits).
- As a series of lossless transmission lines connected to the earth by means of conductance to describe the current flowing in the earth (single or multiphase lossless lines).
- In the frequency domain as transmission line with frequency dependent parameters.

The most common way is the first. It is the simplest and works well both with a simple geometry of the grounding system (like a single buried wire). The model consists of a series of lumped resistance and inductance connected to the earth at each side by means of a parallel of capacitance and conductance (Fig. 1). Every π circuit represents a short section in which the buried conductor has been divided. The criteria of the division are very important, because if the section is too long the solution will be less accurate, and if too short, it will consume too much memory. The great number of simulations performed for a buried horizontal wire have proved that of about 1 meter long elements is a good choice.

The principal difficulties in the simulations are derived from the fact that a current source is connected directly to an inductor. Which forces the trapeziodal rule of integration to be adapted by the EMTP to work as a differentiator creating numerical oscillations around the current value, whenever the derivative of the current changed abruptly. This effect is amplified when the step of the integration chosen for the simulation is too high. The step of integration of 0.01 µs is a good choice on the simulations made on a long buried wire, both in accuracy and speed of the calculation, for almost all earth conductivities and common waveshapes of injected currents. The use of nonlinear component described by a piecewise characteristic, guarantees the convergence of the solution efficiently.

NUMERIC RESULTS

Table 1 summarises the numerical values of the electrical and physical parameters relative to the computed tests.

The authors have execute a lot of simulations using EMTP, with the aim to verify the reliability of each numerical test varying the analysis conditions by changing ΔL, ΔT, ρ and ε as indicated in Table 1.

In this and in the next sections, referring to the analysis conditions it is defined as main conditions the following: ΔL=1 m, ΔT=0.01 µs.

Description	Application A	Application B
Current	$i(t)=I_0\cdot(e^{-at}-e^{-bt})$ $I_0=1.55227$ A $a=0.00364\ \mu s^{-1}$ $b=0.65221\ \mu s^{-1}$ or $I_{max}=1.4993065$ A $T_1=4.2111146\ \mu s$ $T_2=203.9671\ \mu s$	$i(t)=I_0\cdot(e^{-at}-e^{-bt})$ $I_0=52.2689$ kA $a=0.00184\ \mu s^{-1}$ $b=2.46650\ \mu s^{-1}$ or $I_{max}=51.9499$ kA $T_1=1.1135336\ \mu s$ $T_2=381.08503\ \mu s$
Rod	L=100 m D=5 mm H=60 cm $\rho_e=0.25\cdot10^{-6}\ \Omega m$	L=100 m D=5 mm H=60 cm $\rho_e=0.25\cdot10^{-6}\ \Omega m$
Ground A	$\rho_g=10\ \Omega m$ $\varepsilon_r=80$	$\rho_g=10\ \Omega m$ $\varepsilon_r=80$
Ground B	$\rho_g=10^4\ \Omega m$ $\varepsilon_r=5$	$\rho_g=10^4\ \Omega m$ $\varepsilon_r=5$
Analysis	T=15 µs ΔL=1/2/5/10 m ΔT=.1/.01/.001 µs	T=15 µs ΔL=1/2/5/10 m ΔT=.1/.01/.001 µs

Table 1: Numeric values of electrical and natural characteristics of applications.

Application A

This test refers to the impulse response of a horizontally buried linear electrode excited by a lightning current (Fig. 2) that does not generate ionization phenomena. The current has been simulated by means of a double exponential function. The EMTP potential results are summarised in Figs. 3, 4 for both cases of ground resistivity. On varying the time step (ΔT) the solution is stable, while on varying the subdivision step (ΔL) the solution becomes unreliable for ΔL=10 m, because of the comparable dimension of the elementary unit with respect to the wavelength of the highest harmonic component of the impulsive current.

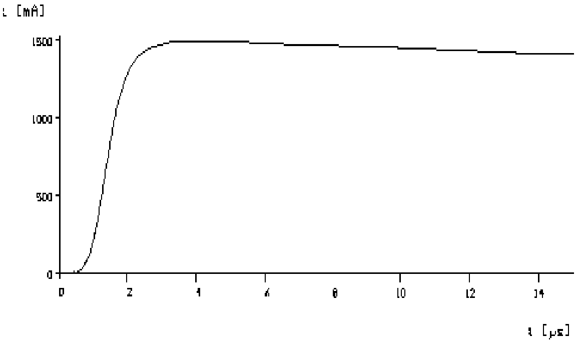

Fig. 2: Current vs. time (Application A).

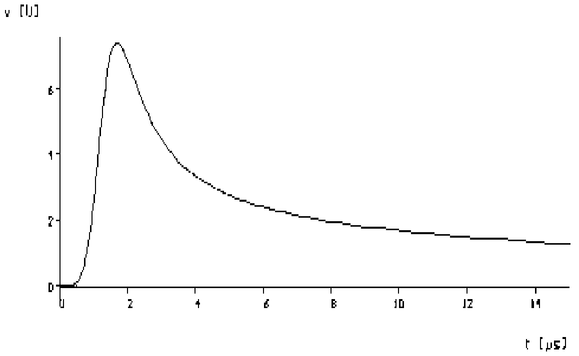

Fig. 3: Potential vs. time (Application A, Ground A).

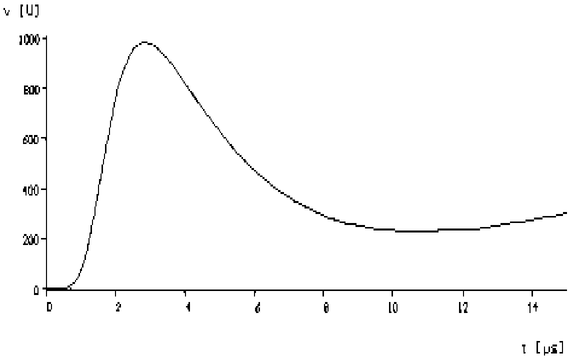

Fig. 4: Potential vs. time (Application A, Ground B).

Application B

This test refers to the impulse response of a horizontally buried linear electrode excited by a lightning current (Fig. 5) that generates intense ionization phenomena. The current has been simulated by means of a double exponential function that represents a strong lightning stroke. The EMTP potential results are summarised in Figs. 6, 7 for both cases of ground resistivity.

Analysing the first simulation (ρ_g=10 Ωm), the solution is stable for ΔT≤0.01 is and ΔL≤1 m. ΔT values greater than the previous one introduce numerical instability while ΔL values greater than 1 m make the solution unreliable (the wavelength of the highest harmonic component of the impulsive current is comparable with the step of subdivision).

Analysing the second simulation (ρ_g=10000 Ωm), the solution is stable for $\Delta T \leq 0.001$ μs and $\Delta L \leq 1$ m. As the previous simulation, ΔT values greater than 0.001 μs introduce numerical instability while ΔL values greater than 1 m make the solution unreliable.

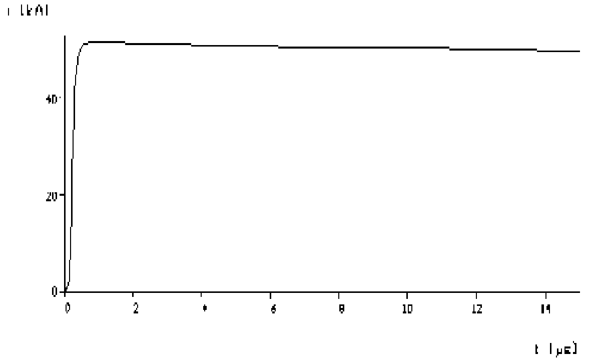

Fig. 5: Current vs. time (Application B).

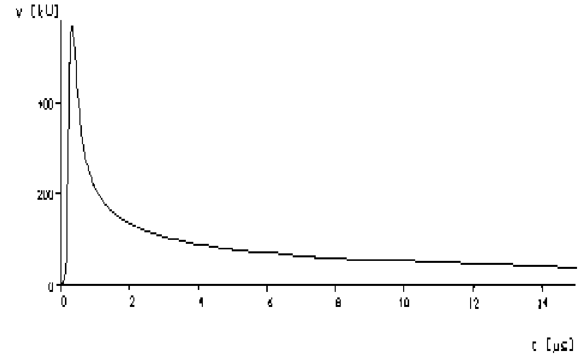

Fig. 6: Potential vs. time (Application B, Ground A).

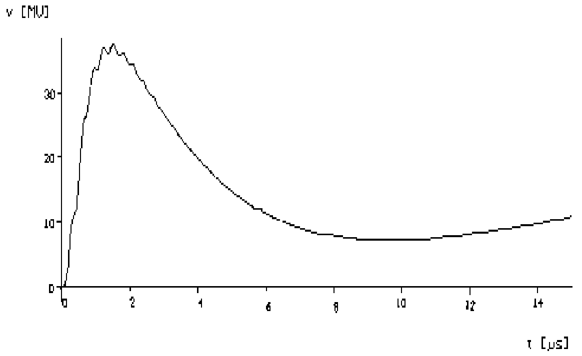

Fig. 7: Potential vs. time (Application B, Ground B).

CONCLUSIONS

For both cases of ground resistivity if the time step and the length step is low enough ($\Delta T \leq 0.001$ μs, $\Delta L \leq 1$ m) the solution remains stable. For values of ΔL in the vicinity of 10 m the solution is out of the ordinary due to comparable values of the wavelength of the highest harmonic of the impulse current and the elementary length ΔL. The computer aided optimisation of any planned grounding system is very useful, since its improvement after the installation is a difficult and not always successful or even possible work. The purpose of this work has been to execute an extensive analysis to verify the possibility and reliability of using the EMTP in the simulation of the transient behaviour of grounding system also when the non-linear ionization phenomena are present and also to describe a reliable circuital model.

REFERENCES

1. *Gonos I. F., Antoniou M. K., Topalis F. V., Stathopulos I. A.: "Behaviour of a grounding system under impulse lightning current", Proceedings of the 6th International Conference and Exhibition on Optimization of Electrical and Electronic Equipments (OPTIM '98), May 14-15, 1998, pp. 171-174.*
2. *Menter E. Frank, Grcev Leonid: "EMTP-Based Model for Grounding System Analysis", IEEE Transactions on Power Delivery, Vol. 9, No. 4, October 1994, pp. 1838-1849.*
3. *Verma R., Mukhedkar D.: "Impulse impedance of buried ground wire", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-99, No. 5 Sept/Oct 1980, pp.2003-2007.*
4. *A. Geri and G. M. Veca: "Representation and analysis of the equivalent lightning protection system network for non-linear problems in the electromagnetic interference control", International Telecommunications Energy Conference, Orlando, U.S.A., October 21-25, 1990, Conference Proceedings, pp. 323-329.*
5. *A. Geri: "PROTEZIONE DELLE STRUTTURE CONTRO I FULMINI. Analisi del comportamento dell' impianto di protezione soggetto a scarica impulsiva mediante modello matematico alle differenze finite", Tesi di Laurea, Università di Roma "La Sapienza", Facoltà di Ingegneria, Luglio 1987.*
6. *S. Cattaneo, B. L. Colombo, F. Mocci: "Impiego di programmi di simulazione di uso generale nello studio del comportamento ad impulso degli impianti di terra", Conference Proceedings, Simposio sugli impianti di terra, Palermo, 6-7 Dicembre 1990, Atti della riunione, pp. 277-293.*
7. *Velasquez, D. Mukhedkar: "Analytical modelling of grounded electrodes transient behaviour", I.E.E.E. Trans. on Power Apparatus and Systems, Vol. PAS-103 No. 6, June 1984.*
8. *C. Mazzetti, G. M. Veca: "Impulse behaviour of ground electrode", I.E.E.E. Trans. on Power Apparatus and Systems, Vol. PAS-102 No 9, Sept. 1983.*
9. *E. Garbagnati, A. Geri and G. M. Veca: "Comportamento ad impulso degli impianti di terra", Conference Proceedings, Simposio sugli impianti di terra, Palermo, 6-7 Dicembre 1990, Atti della riunione, pp. 157-173.*
10. *E. Astuni: "Elettrotecnica", Vol. 1, 2 e 3, Zanichelli Bologna, 1983.*
11. *A. Asta: "Impianti di terra, elettrodi marini, fini, costituzione, caratteristiche, problemi", Simposio sugli impianti di terra, Palermo, 1975.*