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An efficient transient analysis of realistic grounding systems: Transmission line versus antenna theory approach

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ABSTRACT

An efficient transmission line (TL) model for the analysis of the transient behavior of realistic grounding system is presented. The model is based on the general solution of the TL equations in the frequency domain expressed in terms of the Φ-matrix, or the direct time domain solution based on the Finite Difference Time Domain (FDTD) method. The presented TL approach provides relatively simple numerical implementation, accurate results and requires rather low computational time. The accuracy of the results obtained via TL approach is in a good agreement with the numerical results computed via the rigorous antenna theory approach based on the integral equation formulation and corresponding boundary element solution.

1. Introduction

Modeling of simple grounding systems (single conductor buried horizontally or verticaly in a lossy medium) using the transmission line (TL) theory has been already reported in many papers, e.g. [1–4]. Also, some rather simplified mathematical models addressing the transient behavior of a grounding grid using TL approach and adopting lumped equivalent circuits are encountered in the literature [5,6]. ED Sunde [1] has shown how to consider a single conductor buried horizontally or vertically in a lossy medium as a transmission line. Nowadays, there are many commercial codes (e.g. EMTP) for the analysis of a grounding system using an equivalent circuit derived from the TL theory [7,8]. Representing a set of bars (conductors) by lumped circuits, it is also possible to develop use so called Transmission Line Modeling method (TLM method) to analyze the transient behavior of a grounding grid [9].

A number of numerical approaches to the analysis of a grounding grid has been proposed by several authors [10–17]. An efficient approach to solve Maxwell's equations directly in the time domain is related to the use of Finite Difference Time Domain (FDTD) considering open borders and the soil–air interface [11]. In the last two decades a rigorous transient analysis of complex grounding systems (e.g. grounding grids) is usually carried out by means of the wire antenna theory and various Pocklington integro-differential equation formulations in the frequency domain. These Pocklington equation types are commonly solved by means of some variant of (Moment Method (MoM)) [12,13] or Boundary Element Method (BEM) [14,15]. Some formulations are based on the systems of partial differential equations and related solutions via the Finite Element Method (FEM) [16,17]. On the other hand, the implementation of these methods always requires high computational cost. Furthermore, bearing in mind that the soil is an inhomogeneous medium whose physical properties depend on a number of parameters, it is in some scenarios appropriate to use a simplified mathematical model to account for the transient behavior of grounding grid. In particular, such an approach makes sense when the transient response is strongly associated with the actual input data.

Therefore, an objective of this work is to propose an original model for the transient analysis of the grounding grid, thus providing engineers to rapidly perform parametric studies without great loss of accuracy.

The approach proposed in this work is based on the use of the general solutions of the transmissions line (TL) equations in the frequency domain using Chain matrix (Φ-matrix), or in the time domain by means of the FDTD method, and Kirchhoff's laws of

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continuity. To model the transient behavior of grounding system under lightning strike, the ground is considered as a radial or meshed network consisting of thin conductors. From the considered network topology which is represented by a set of branches interconnected by electrical nodes a system of equations is assembled. This system of equations reflects all differential equations representing the propagation phenomena throughout the network and taking into account the continuity conditions on the interconnected nodes and initial conditions at injection node. The proposed approach enables one to overcome the difficulty of taking into account the open boundaries of two semi-infinite media (air and ground). In addition, the benefit of the frequency domain analysis is to account for the frequency variation of the soil resistivity. Also, the advantage of the time domain modeling accounts for the non-linearity phenomena, such as the ionization of the soil under very high intensities of the current.

The paper is organized as follows; First, the overview of the models for grounding systems based on the TL theory of the lines is given, followed by a proposed improvement based on Transmission Lines and Antenna Theory. Finally, some illustrative computational results, obtained via both approaches are presented.

2. An overview of grounding models using the theory of lines

The theory of the lines is generally derived from Maxwell's equations [18]. The soultions are posed in the form of waves propagating parallel to the line and with corresponding boundary conditions, then an equivalent circuit is found. The single mode of propagation along the line is considered. The propagation constant along the structure of the single mode corresponds to the propagation constant of the lines.

The modeling approach based on the theory of lines has been promoted by ED Sunde [1] who has shown how to deduce the per unit lines parameters of a buried conductor.

Based on the theory of transmission lines, some authors propose analytical expressions for the assessment of the transient voltage or current when the ground is a simple linear conductor. An alternative is related to the use of FDTD or the nodal matrix equation. An overview of both approaches is given below

2.1. FDTD solution of the telegrapher's equations

In this case one simply needs to solve the telegrapher's equations

$$\begin{cases} \frac{\partial}{\partial x}[v(x,t)]+[R][i(x,t)]+[L]\frac{\partial}{\partial t}[i(x,t)]=0 \quad (1) \\ \frac{\partial}{\partial x}[i(x,t)]+[G][v(x,t)]+[C]\frac{\partial}{\partial t}[v(x,t)]=0 \quad (2) \end{cases} \tag{1,2}$$

by implementing the finite difference discretisation in space and time and taking into account the conditions at the conductor ends (generator and load) [18], where $[L]$ and $[R]$ are per-unit length matrix of inductance and resistance $[C]$ and $[G]$ are per-unit length matrix of capacitance and conductance.

x is the space variable that indicates the direction of propagation, and t is time.

Finally, $v(x,t)$, $i(x,t)$is the unknown distributed voltage and current along the conductor, respectively.

2.2. FDTD solution of voltage differential equation

For a single conductor transmission line, if the wave propagation occurs along the x axis only, then (1) and (2) could be combined to obtain the following voltage equation:

$$\frac{\partial^2 v}{\partial x^2}-RGv-(RC+LG)\frac{\partial v}{\partial t}-LC\frac{\partial^2 v}{\partial t^2}=0 \tag{3}$$

Implementing the finite difference discretization, the resulting matrix system can be written as follows [19]:

$$[\mathrm{F}][\mathrm{v}]=[\mathrm{E}] \tag{4}$$

where $[F]$ is the coefficient matrix, $[v]$ is the vector of unkown nodal voltages and $[E]$ is the excitation vector (which includes generators current or voltage).

Solving the matrix Eq. (4), the current distribution is obtained by integrating (2) numerically.

2.3. Nodal matrix equation modeling

The model is based on the representation of (1) and (2) by lumped constant circuit. Furthermore, use of Kirchhoff's laws the following expression for the equivalent network yields [8]

$$[\mathrm{Y}][v(t)]=[\mathrm{k}] \tag{5}$$

where [v(t)] is the vector of unknown voltage in each time steps, $[Y]$ is real matrix, [k] is known vector determined from source functions at time t and from the state of the system at previous steps.

Note that M. Ramamoorty [6] considers a grid as a meshed network of bar (conductor). Furthermore, each bar of grid is considered to be a line represented by a very simplified equivalent circuit (each element is modeled only with its inductance and ground conductance). In this case, a differential equation, derived from Kirchoff's current law at each node, is posed. The nodal equation, thus obtained, is solved numerically by the method of Runge Kutta [6]. Also most of the models proposed in the literature based on the theory of lines use simplified equations usually neglecting the capacitive effect in the soil.

3. An improved transmission line approach

In the case of a conducting wire buried vertically or horizontally in a homogeneous soil, as shown by Sunde [1], it is possible to express the relationship between current and voltage by the time domain transmissions line equations [18]

$$\frac{\partial v(x,t)}{\partial x}+Ri(x,t)+L\frac{\partial i(x,t)}{\partial t}=0 \tag{6}$$

$$\frac{\partial i(x,t)}{\partial x}+Gv(x,t)+C\frac{\partial v(x,t)}{\partial t}=0 \tag{7}$$

where R is the per-unit length series resistance. L, G and C are the effective per-unit length inductance, conductance and capacitance of the conductor, respectively. The per unit line parameters of buried vertical and horizontal electrodes, respectively, can be calculated via the expressions developed by E.D. Sunde [1].

Different configurations of grounding systems, composed entirely of wire conductors are shown in the Fig. 1.

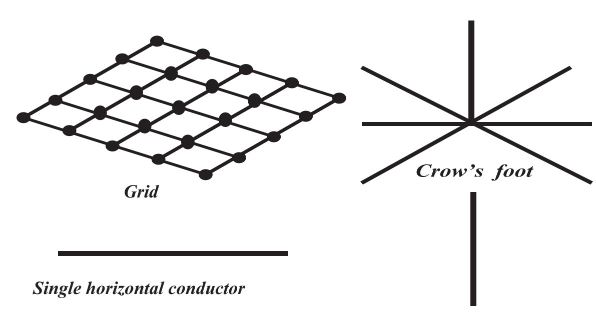

Fig. 1. Representation of a grounding system by single conductor, or by interconnected conductors.