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A multiconductor transmission line model for grounding grids

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ABSTRACT

In this paper, a new approach for modeling grounding grids excited by lightning currents is proposed. The model is based on considering each set of parallel conductors in the grounding grid as a multiconductor transmission line. Electrical parameters are calculated and modal analysis is used in order to obtain a two port network representation for each set of parallel conductors in the grid. The different two port networks are interconnected following the pattern of connections in the grid; then, the system equations are reduced in order to obtain currents and voltages in the different grid junctions. This approach facilitates calculating the transient leakage currents into the soil and therefore the induced voltage on the soil surface. Finally, the transient step and touch voltages are calculated. The computer model was validated by means of an extensive comparison between obtained results with the proposed model, measurements and calculated results published in the literature. The validation process was extended successfully to grounding grids and vertical and horizontal electrodes.

1. Introduction

Grounding grids provide a low impedance path to high currents during lightning and power system faults. During these events, the grounding grid must also provide a voltage distribution on the soil surface as even as possible, improving in this way the safety of personnel. An additional feature of grounding grids is to serve as a common reference to all electrical and electronic equipment in the system during steady state and transient conditions [1,2].

The performance of grounding grids during power system faults (50–60 Hz) is well known and design procedures have been developed [3,4]. However, the analysis of grounding grids during lightning strikes or steep fronted waves is far more complicated. This is because both phenomena produce a temporal and spatial distribution of currents and voltages in the grid conductors. These phenomena also lead to an uneven voltage distribution in the grid conductors and on the soil surface.

The uneven voltage distribution can be explained in terms of current and voltage waves traveling along the grid conductors. When these surges reach sensitive electronic equipment the transient induced voltage on terminals can be significant, leading to equipment malfunctioning or even insulation failure. On the other hand, transient currents dissipated by the grounding grid produce an uneven voltage distribution on the soil surface which may lead to hazardous conditions to human beings [1].

In this sense, computer models for analyzing the surge distribution in grounding grids and associated equipment are needed in order to carry out electromagnetic compatibility (EMC) studies. These computer models must be accurate, easy to use, computationally efficient and also capable of simulating a great number of conditions appearing in grounding grids and their surroundings. This has long been recognized by the industry and several models to describe these transient events and related topics have been proposed in the literature. A brief description of these models is presented.

Experimental and modeling studies on grounding circuits counterpoise and driven rods were pioneered by Rudenberg, Bewley, Sunde and Bellashi [5–8]. Later on, Gupta extended the analysis to grounding grids where initially empirical formulations were used [9]. A circuit approach with lumped parameters for representing the different components in the grid was proposed by Verma, Ramamoorty et al. in [10,11]. Further developments used a single phase transmission line in the time domain for modeling the grounding grid [12,13]. A drawback in this approach is that mutual coupling between conductors in the grid was not considered in the analysis. Later, Heimbach and Grcev demonstrated that neglecting coupling can lead to significant errors in the solution [14].

An electromagnetic field model for grounding grids based on Maxwell equations was proposed in [15]. This model can be considered as the most accurate for surge propagation studies in grounding grids during lightning strikes, since minimal simplifications are made. However, the large simulation times represent a

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computational disadvantage, being complicated to be used [2] in the analysis of large grounding grids [15].

This sophisticated model was improved latter by Grcev, who proposed a model based on electromagnetic field theory and the modified method of images [1,16]. The range of validity of this model is estimated in a few MHz, which is suitable for simulating lightning currents applied to grounding grids. This model was validated by means of comparisons between measured and computer results.

In 2001, Liu et al. proposed a computer model based on transmission line theory with mutual coupling between parallel components in the grounding grid [17]. The model divides a grid section in small subsections (stubs) and their electrical parameters are calculated by using external software based on the finite element method. A drawback of this approach is the fact that a great number of elements are required for representing a given grid section during a lightning strike. The model was validated through a comparison with results published in the literature for small size grounding grids. The finite element method combined with measurements has also been used for modeling electrode arrangements [18] and grounding grids, especially for calculating the induced voltages on the soil surface due to high currents dissipated into the ground [19]. Recently, there has been a trend to analyze and assess the performance of earthing systems considering the linear and non-linear soil characteristics (soil ionization) [20,21].

The aim of this paper is to develop a computer model for calculating the time and spatial distribution of currents and voltages in the grounding grid and on the soil surface during lightning currents and steep fronted waves. The model is based on considering each set of parallel conductors in the grounding grid as a multiconductor transmission line. A two port network representation for each set of "n" conductors in parallel in the grid is obtained. Then, the different two port networks are interconnected following the pattern of connections in the grid and its representative equations reduced, in order to obtain voltages and currents at any junction in the grid. This approach facilitates calculating the transient leakage current into the soil and then the induced voltage on the soil surface. Finally, the transient step and touch voltage can also be calculated.

The paper is organized as follows: in the second section a Multiconductor Transmission Line (MTL) model for calculating the surge propagation in grounding grids and the induced voltages in the soil surface is proposed. In the third section, the approach used for calculating the electrical parameters for the MTL model is presented. In the fourth section, the computer model is validated by means of a comparison with published results in the literature. Finally, the paper conclusions are presented.

2. Modeling grounding grids

Grounding grids are normally buildup of copper conductors with certain conductivity and permeability. The soil can be considered like a linear and homogeneous half spaced medium with its own resistivity and permeability. The conductors in the grid follow an orthogonal arrangement and they are embedded in a lossy medium. Along the conductors there exist additional longitudinal and transverse field components due to series and parallel losses. For modeling purposes, it is assumed that the field surrounding the conductors is the quasi-transverse electromagnetic field (quasi-TEM), neglecting the fringing influence at the end points [16].

2.1. Simplified model for the grounding grid

Let us consider a grounding grid of size 1 × 1 whose representation is shown in Fig. 1. For modeling purposes each pair of parallel conductors in Fig. 1 can be considered as a MTL with mutual coupling and distributed parameters. For this particular case there are two MTLs each one with two parallel conductors (1–3 and 2–4).

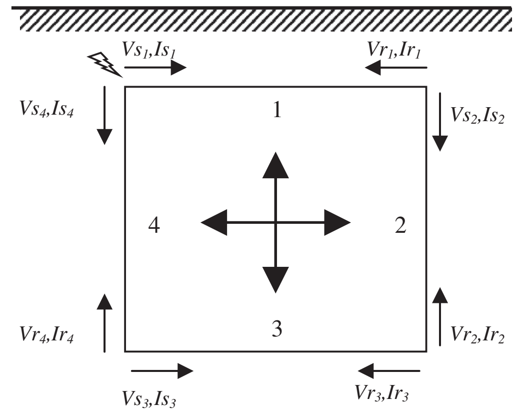

Fig. 1. Grounding grid of size 1 × 1.

The propagation characteristics for each MTL in Fig. 1 can be analyzed in the frequency [19] and time domains [20]. In the frequency domain, voltages and currents at any point "x" along the MTLs can be calculated by solving the following set of equations describing the propagation phenomenon:

$$-\frac{d^2}{dx^2}V = ZYV = PV, \tag{1}$$

$$-\frac{d^2}{dx^2}I = YZI = P_tI, \tag{2}$$

where Z and Y are the series impedance and parallel admittance matrices per unit length respectively. I, V are the current and voltage vectors respectively, $P = ZY$, $P_t = YZ$ and "x" is the variable of length in the MTL.

The solution to Eqs. (1) and (2) using modal analysis is a topic addressed by previous authors [22,23]. Nevertheless, the salient steps for the analysis of MTLs are presented here for completeness and clarity of presentation. The basic idea of modal analysis is to apply a linear transformation in order to diagonalize P and P_t. Let us consider that M and Λ are the matrices of eigenvectors and eigenvalues of P respectively. Then, the solution to (1) and (2) is [22,23]:

$$V(x) = e^{(-\Psi x)}V_a + e^{(\Psi x)}V_b, \tag{3}$$

$$I(x) = Y_o(e^{(-\Psi x)}V_a - e^{(\Psi x)}V_b), \tag{4}$$

where $\Psi = M^{-1}\ \Lambda^{1/2}\ M = P^{½} = (ZY)^{1/2}$, $Y_o = Z^{-1}\ \Psi = (Y/Z)^{1/2}$ is the characteristic admittance matrix and, V_a, V_b are the vectors of integration constants depending on the boundary conditions.

The terminal conditions at the beginning and at the end of the MTL determine the magnitudes for vectors V_a and V_b. For modeling purposes it is convenient to use hyperbolic formulations for Eqs. (3) and (4). Also, a nodal formulation in a two port network representation is desired [22,23]. Then:

$$\begin{bmatrix} I_s \\ I_r \end{bmatrix} = \begin{bmatrix} Y_o\coth(\Psi l) & -Y_o\csc h(\Psi l) \\ -Y_o\csc h(\Psi l) & Y_o\coth(\Psi l) \end{bmatrix}\begin{bmatrix} V_s \\ V_r \end{bmatrix}, \tag{5}$$

in simplified form:

$$\begin{bmatrix} I_s \\ I_r \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}\begin{bmatrix} V_s \\ V_r \end{bmatrix}, \tag{6}$$

where $A = D = Y_o\coth(\Psi l)$, $B = C = -Y_o\,\mathrm{csch}(\Psi l)$, V_s, I_s – voltage and current vectors at the beginning of the line, V_r, I_r – voltages and