TRANSIENT BEHAVIOUR OF A HORIZONTAL GROUNDING GRID UNDER IMPULSE CURRENT

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Abstract: In this paper the authors attempt to study the behaviour of grounding grids under impulse lightning current. For the simulation of their transient behaviour, the program PSCAD/EMTDC (Power Systems Computer Aided Design / ElectroMagnetic Transients for DC) has been used. The mathematical model elaborated for the PSCAD/EMTDC is characterised by a circuital approach, which is based on the π nominal circuit. The inductance and the capacity of the equivalent circuit have been programmed in Pascal code. The resistance and the conductance have been estimated using formulas given in the relevant literature. Different simulations have been carried out altering the shape of the impulse current. Numerical results are presented for two extreme cases: in the first case the current is injected in the centre of the grid and in the second one it is injected in one corner of the grid. The aim of this work is to verify the applicability of this approach in the behaviour analysis of grounding systems injected by high impulse currents and compare to each other the numerical results obtained using different simulations.

Keywords: Simulation, circuital approach, grounding systems, grids.

I. INTRODUCTION

Grounding systems constitute one of the most important parts of building constructions. The grounding systems resistance has an essential influence on the protection of the grounded system. As it is stated in the ANSI/IEEE [1] a safe grounding design has two objectives:

1. To provide means to carry electric currents into the earth under normal and fault conditions without exceeding any operating and equipment limits or adversely affecting continuity of service.
2. To assure that a person in the vicinity of grounded facilities is not exposed to the danger of critical electric shock.

Grounding systems can consist of a) one or more verticals [2, 3] or horizontal ground rods [4, 5], b) three or more vertical ground rods connected to each other [2, 3] and to all equipment frames, neutrals and structures that are to be grounded. Such a system that combines a horizontal grid and a number of vertical ground rods penetrating lower soil layers has several advantages in comparison to a grid alone. Sufficiently long ground rods stabilize the performance of such a combined system making it less dependent on seasonal and weather variations of soil resistivity. Rods are more efficient in dissipating fault currents because the upper soil layer usually has a higher resistivity than the lower layers. The current in the ground rods is flown mainly in the lower portion of the rods. Therefore, the touch and step voltages are reduced significantly compared to that of the grid alone [1].

The grounding resistance and other characteristics of the grounding system steady state response can be computed directly in the time domain. The analysis of the transient behavior of a grounding system is simulated usually by a circuital approach [4-12]. Some circuital simulation models are presented below:

1. Using π nominal circuits. In this case, the electrode is divided in parts, each of which is replaced by a π nominal circuit with concentrated parameters [4, 6].
2. Using a transmission line model with distributed parameters. In this case, the parts in which the electrode is divided are replaced by distributed elements dependent on frequency [7-10].
3. Using altered π nominal circuits. The altered π nominal circuits consist of concentrated elements (ohmic resistance and transverse conductance) placed at the ends, while the middle part is replaced by a transmission line part without losses [11, 12].

II. FUNDAMENTALS

The work reported in this paper refers to the problem of transient analysis of a grounding grid buried in depth h under injection of a lightning impulse 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 model is developed through the circuital approach, which models an earth conductor as equivalent π-circuits involving R-L-C-G elements. The coupling of earth conductors can be taken into account by mutually coupled inductances.

The grid consists of horizontal and vertical elementary conductors, each of which can be represented by one or more π nominal circuits. These circuits are made up of elements connected in series or parallel, as shown in Fig. 1.

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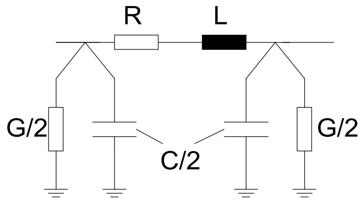

Fig. 1: The π - nominal circuit.

The resistance R and the self inductance L, connected in series, determine the current, while the transverse conductance G and the capacity C, connected in parallel, represent the losses to earth. The most meaningful of the series elements is the inductance, while the resistance, representing the losses in the conductor, is usually negligible. The conductance is the most meaningful of the elements in shunt position, while the capacitance is usually neglected, as it is small in comparison to the conductance.
The current distribution in a cylindrical conductor, through which direct current flows, is uniform, and the conductor resistance R is given by [13]

$$R = \rho \cdot \frac{l}{\pi \cdot r^2} \tag{1}$$

where ρ the resistivity of the conductor
l the length of the conductor
r the radius of the conductor
The transverse conductance of the conductor is given by the following equation [5]:

$$G = \frac{\pi \cdot l}{\rho_s \cdot \ln\left(\frac{2 \cdot l}{r}\right)} \tag{2}$$

where ρ_s the soil resistivity

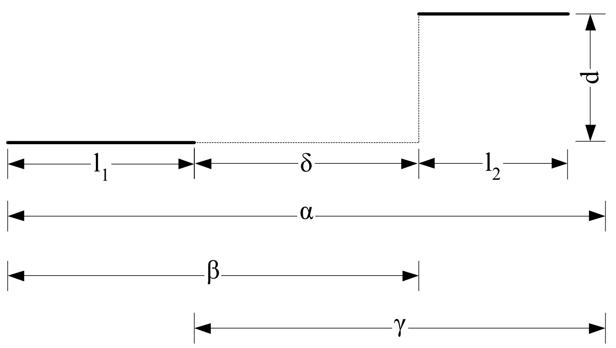

Fig. 2: The arrangement of two parallel conductors.

When current flows through a conductor, a magnetic field, surrounding the conductor, is induced. Variation of the current value causes variation of the magnetic flow and generation of voltage. This phenomenon is represented by the self-inductance. The self-inductance L of a straight cylindrical conductor of length l is given by [14]

$$L = 2 \cdot 10^{-7} \cdot l \times \left(\ln\frac{2 \cdot l}{r} - 1\right) \tag{3}$$

The magnetic coupling between two conductors of length l_1 and l_2 is represented by the mutual inductance, which is computed using equation (4). In the case of vertical and horizontal conductors, equation (4) can be solved in an analytical way to give numerical results [10].

$$L_{ij} = \frac{\mu}{4 \cdot \pi} \cdot \int_{l_i}\int_{l_j} \frac{dl_i \cdot dl_j}{d_{ij}} \tag{4}$$

where d_{ij} the distance between the conductors i and j
μ the magnetic permittivity of the medium
Approximate solving of equation (4) in general case of two parallel conductors, with dimensions as shown in Fig. 2, results in equation (5) [14], which is presented below.

$$\begin{aligned} L_{ij} = 10^{-7} \cdot \Bigg\{ & \alpha \cdot \ln\left[\frac{\alpha}{d} + \sqrt{\left(\frac{\alpha}{d}\right)^2 + 1}\right] - \beta \cdot \ln\left[\frac{\beta}{d} + \sqrt{\left(\frac{\beta}{d}\right)^2 + 1}\right] \\ & - \gamma \cdot \ln\left[\frac{\gamma}{d} + \sqrt{\left(\frac{\gamma}{d}\right)^2 + 1}\right] + \delta \cdot \ln\left[\frac{\delta}{d} + \sqrt{\left(\frac{\delta}{d}\right)^2 + 1}\right] \\ & - \sqrt{\alpha^2 + d^2} + \sqrt{\beta^2 + d^2} + \sqrt{\gamma^2 + d^2} - \sqrt{\delta^2 + d^2} \Bigg\} \end{aligned} \tag{5}$$

In a system of two or more interconnected conductors, in which current flows, the existence of capacity is indispensable. The inverted capacity of conductor k depends on the conductor dimensions and is given by [15]

$$P_k = \frac{1}{2 \cdot \pi \cdot \varepsilon \cdot l} \cdot \ln\frac{1}{r_k} \tag{6}$$

where r_k the radius of the conductor
l the length of the conductor
ε the permittivity of the material
The inverted capacity between to the conductors k and p interacting depends on the conductors distance and is given by [15]

$$P_{kp} = \frac{1}{2 \cdot \pi \cdot \varepsilon \cdot l} \cdot \ln\frac{1}{D_{kp}} \tag{7}$$

where D_{kp} the distance between the conductors
Using equations (6) and (7) the inverted capacities array P is defined. The diagonal elements P_{ii} of P represent the inverted capacity due to the conductor itself, while the non-diagonal elements P_{ij} represent the inverted capacity due to the interacting between the conductors i and j. The capacity of conductors is computed by inverting array P. The derived array C has the following form:

$$C = P^{-1} = \begin{bmatrix} C_1 & C_{12} & C_{13} & C_{1j} & C_{1n} \\ C_{21} & C_2 & C_{23} & C_{2j} & C_{2n} \\ C_{31} & C_{32} & C_3 & C_{3j} & C_{3n} \\ C_{i1} & C_{i2} & C_{i3} & C_i & C_{in} \\ C_{n1} & C_{n2} & C_{n3} & C_{nj} & C_n \end{bmatrix} \tag{8}$$

The capacitance to earth of each one grid conductor is obtained by adding the capacity of the particular conductor and the capacities due to its interacting with the rest of the conductors. Hence, a vector C′ is created, including the capacities $\sum_{k=1}^{n} C_{ik}$ of the n horizontal and m vertical grid conductors.
The π nominal circuit parameters are computed by especially developed Pascal programs giving sufficiently precise results. The programs results form the input of the

circuit simulation program PSCAD/ EMTDC.

III. RESULTS

The investigated grids are shown in Fig. 3. The conductor is made of copper and its radius is 7mm. An equivalent circuit, as that shown in Fig. 1, replaces each branch of the square formed by the horizontal and vertical conductors. For conducting the simulations the grids were supposed to be buried in depth of 0.5m, in soil with resistivity of 100 Ωm or 1000 Ωm.

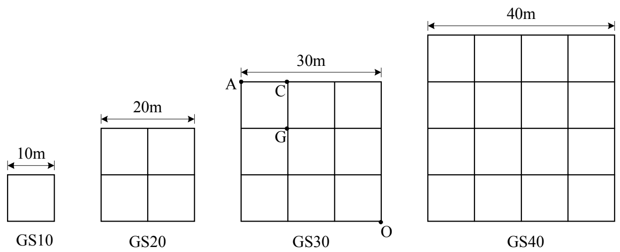

Fig. 3: Investigated grids.

The waveforms of the injected impulse current is given by the following equation:

$$i(t) = I_o \cdot \left(e^{-a \cdot t} - e^{-b \cdot t}\right) \qquad (9)$$

The values of the parameters *a* and *b* of the equation (9) are presented in Table 1. These values have been selected for the simulation of usual lightning currents, which were measured at the NASA Kennedy Space Center, Florida and at Fort McClellan, Alabama by Thottappillil et all [16]. The value of the coefficient I_o is selected as the peak current is equal with 1.0A. Altering the grid dimensions, the soil conductivity and the current injection point, the change of voltage and grounding impedance in the time domain is examined.

Case	*a* [s^{-1}]	*b* [s^{-1}]	T_{crest} [μs]	T_{half} [μs]
1	16667	100000000	0.1	43
2	16667	25000000	0.3	43
3	16667	10000000	0.6	43
4	16667	2857143	1.8	43
5	16667	2127660	2.4	43
6	16667	1538462	3.0	43

Table 1: Parameters of injected currents

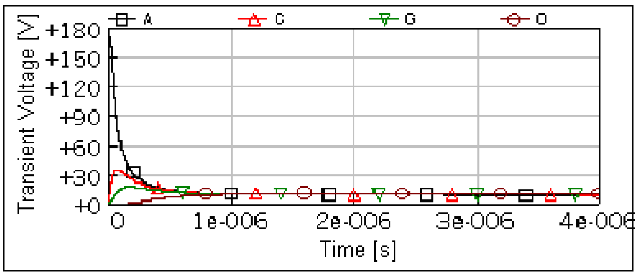

Fig. 4:Transient voltage versus time for injection point the corner A of grid GS30 for soil resistivity 1000 Ωm, The injected current is the case 1 of table 1.

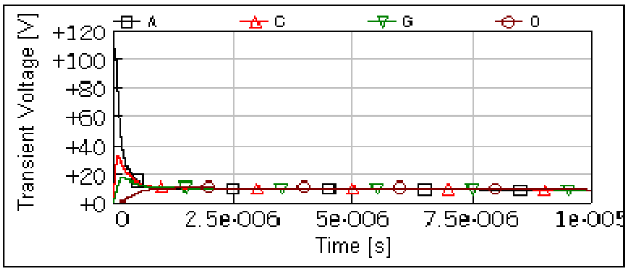

Fig. 5: Transient voltage versus time for injection at the corner A of grid GS30 for soil resistivity 1000 Ωm. The injected current is the case 2 of table 1.

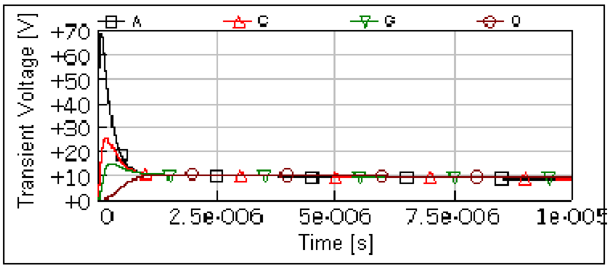

Fig. 6: Transient voltage versus time for injection at the corner A of grid GS30 for soil resistivity 1000 Ωm. The injected current is the case 3 of table 1.

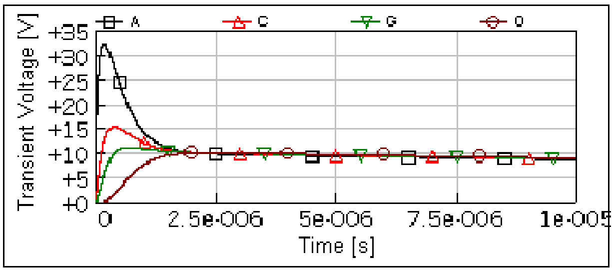

Fig. 7: Transient voltage versus time for injection at the corner A of grid GS30 for soil resistivity 1000 Ωm. The injected current is the case 4 of table 1.

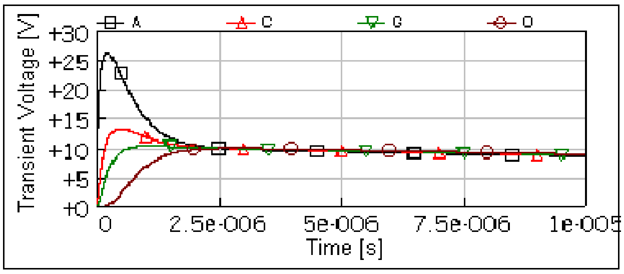

Fig. 8: Transient voltage versus time for injection at the corner A of grid GS30 for soil resistivity 1000 Ωm. The injected current is the case 5 of table 1.

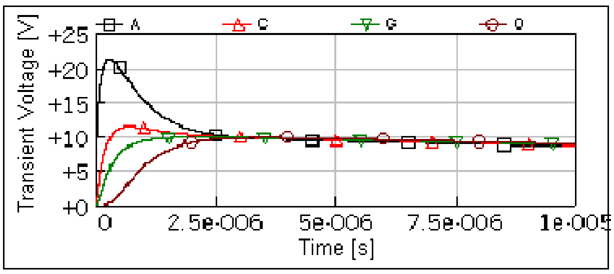

Fig. 9: Transient voltage versus time for injection at the corner A of grid GS30 for soil resistivity 1000 Ωm. The injected current is the case 6 of table 1.

The waveform of transient voltage of the grid GS30 of Fig. 3 when it is buried in soil with resistivity is 1000 Ωm is shown in Figs 4…9 under injection of the impulse current at the corner A. Furthermore, the voltage variation of the grid GS30 not only for the injected point A but also for the other points of the grid (C, G and O) is shown in Figs 4…9. It is obvious that as faster the injected current reaches its peak value (for given time to half value), the higher is the voltage value deployed at all grid points. It is also obvious that as higher the distance between the point considered and the impulse current injection point, the lower the deployed voltage at the considered point. After a 3μs time period the voltage tends to obtain the same value at all grid points. The time, in which that happens, is highly dependent on the time, in which the injected current reaches its peak value. As less the time needed for the current to obtain its peak value, as faster the voltage obtains the same value at all grid points and the transient impedance reaches its steady state value.

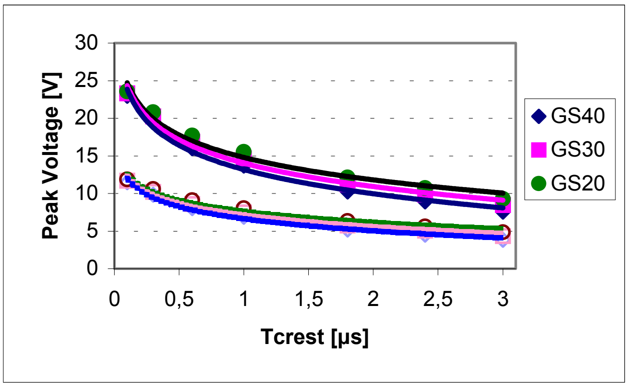

Fig. 10: Variation of the peak of transient voltage versus the time to crest of the injected current of grid GS30 for soil resistivity 100 Ωm

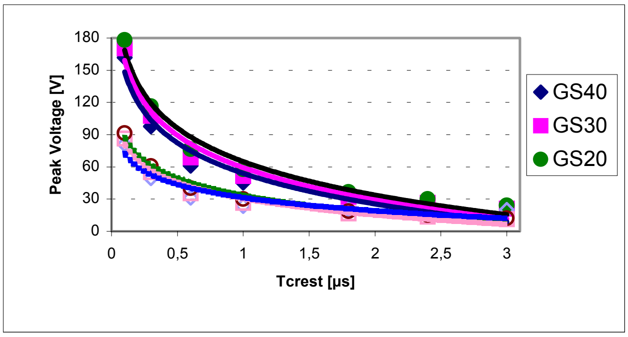

Fig. 11: Variation of the peak of transient voltage versus the time to crest of the injected current of grid GS30 for soil resistivity 1000 Ωm

The variation of the peak value of the transient voltage versus the time to crest of the injection current for soil resistivity equal with 100 Ωm and 1000 Ωm are shown in Figs 10 and 11 respectively. The continues line in the above figures means that the injection is in the corner of the grid and the dot lines means that the injection is in the centre of the grid. The increase of time to crest of the injected current decreases the peak value of the transient voltage.

In Fig. 10 the soil resistivity is ten times less than the one of Fig. 11, so the peak of transient voltage of Fig. 10 is less than the ones of Fig. 11. The influence of the dimensions of the grid and the soil resistivity on the peak value of the transient voltage is also shown in the same figures.

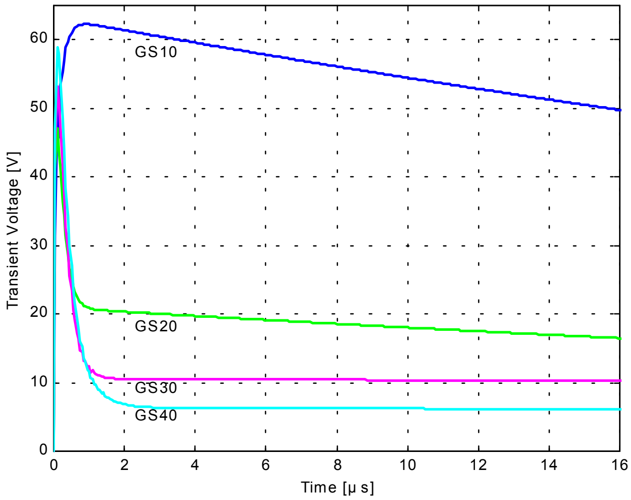

Fig. 12: Transient voltage versus time for injection at the corner of the grids for soil resistivity 100 Ωm.
The injected current is the case 2 of table 1.

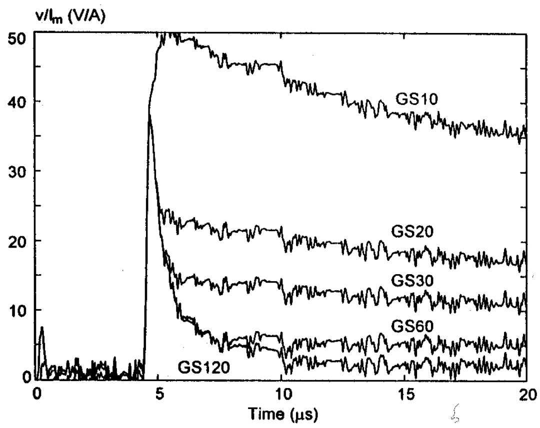

Fig. 13: Transient voltage versus time for injection at the corner of the grids for soil resistivity 100 Ωm,
The injected current is the case 2 of table 1. [8]

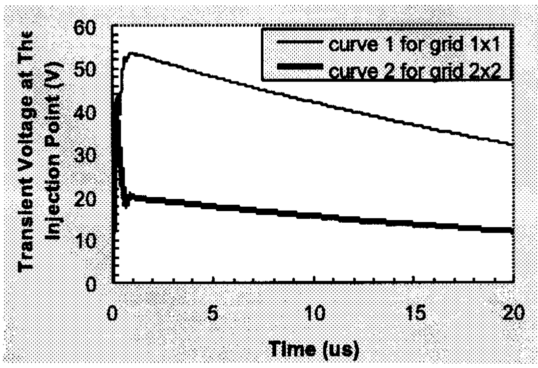

Fig. 14: Transient voltage versus time for injection at the corner of the grids for soil resistivity 100 Ωm,
The injected current is the case 2 of table 1. [9]

For the grids, which are presented in Fig. 3, the simulation results (Fig. 12) are compared with those obtained in the paper of Grcev and Heimbach [8] (Fig. 13) and in the paper of Liu, Zitnik and Thottappillil [9] (Fig.14). It is obvious that the results of the simulations are in a very good agreement, while, moreover, the methodology used for the PSCAD/EMTDC simulation is clearly simpler than that suggested in the other papers [8, 9].

IV. CONCLUSIONS

The contribution of this paper is the suggestion of a new methodology for calculation of the parameters of the π nominal circuit using circuital approach with concentrated parameters. A very good agreement ascertained comparing the results of the suggested method with corresponding results of other researchers. Through the results obtained from the simulations, the influence of the grid dimensions, the kind of the ground and the current injection point on the grid voltage and impedance are presented. The value of the grid voltage and impedance is much higher during the transient response compared to that of the steady state. The waveforms derived for current injection both in the center and at the corner have the same form. During the transient response, the voltage and impedance values are higher for current injection at the corner compared to those obtained for current injection in the center of the grid. On the contrary, during the steady state the corresponding waveforms tend to obtain the same value. Soil with low resistivity, gives rise to transient response of high duration and low maximal value.

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VII. BIOGRAPHIES

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