Transient Analysis of Parameters Governing Grounding Systems by the FDTD Method

Eduardo T. Tuma, Ronaldo O. dos Santos and Carlos Leonidas da S.S. Sobrinho

Abstract — The main purpose of this work is the development of a parallel-environment computational code to numerically analyze transient behavior of grounding systems parameters by employing the Finite Difference Time Domain Method (FDTD-3D). The results obtained for potential, current and Transitory Grounding Resistance (TGR), considering an electrode, strongly agree with those of literature. Additional results have been obtained through the analysis of several grounding configurations. Such results can be used to project systems able to provide higher levels of protection from lightning discharges or failures of the electrical power system.

Keywords – Discharge Protection, FDTD Method, Grounding Resistance, Parallel Processing, Transitory Analysis.

I. INTRODUCTION

The structure of high voltage substations is usually threatened by dangerous potentials due to atmospheric and operational surges. In both cases, the voltage increase in the grounding system can be extremely critical and able to cause many classes of problems related to electromagnetic interference, besides risks and damages to instruments and people. Several works has been published describing new TGR and voltage measurements methods on grounding meshes [1][2]. It is observed that grounding systems are usually represented by pure resistances in surges analysis by EMTP [1], while such parameter should be treated as a time function. The objective of this article is to present numerical solutions based on the FDTD Method, which has been used to calculate Transitory Grounding Resistances (TGRs) for many grounding meshes through collected values of transitory currents and voltages. The obtained results for one grounding rod agree with experimental data collected by [3].

The results presented here can be useful for projecting new grounding systems with improved protection capabilities during occurrences of lightning strokes or failures of the local electrical power system for the several proposed situations.

II. THEORY

The updating expressions for the components of the electric and magnetic fields, considering a conductive media, have been obtained through the Yee algorithm within the FDTD method [4][5]. Before the implementation of these finite difference equations, the cells dimensions and the time step have been defined in such way to avoid numerical instability. When the time-domain equations are employed to solve the Maxwell's electromagnetic equations for a certain scenario with no limits, the numerical domain in which the fields are computed must be delimited. This is possible through truncating the grid with absorbing regions in the desired limits of the numerical domain, simulating the propagation to the infinity and avoiding the addition of unreal reflections into the simulating environment [6].

In order to solve such problems, it is convenient the application of the Uniaxial Perfectly Matched Layer (UPML) absorbing boundary condition, which have reached widespread use due to its efficiency [7]. Aiming at improved precision and avoiding higher levels of discretization, the Thin Wire Technique [5] has been used to model some metallic structures which radius are much smaller than the cells dimensions used in the present research.

Considering the large electrical dimensions involved, the code has been processed under a parallel processing environment [8]. The grounding mesh has been solved using a Beowulf cluster composed by ten PCs, named Amazonia (LANE 02). The hardware is based on the Athlon XP 1800+ processor, with 1.5GB of DDR RAM in each node and a conventional 100Mbits/s switched network. The master node is a dual Athlon XP 1800+ with 2GB of DDR RAM and 1GBit/s network interface.

II. THE SIMULATING METHOD AND RESULTS

A. Single grounding electrode results

The simulation of a transitory current pulse effects in a single grounding electrode, aimed at the evaluation of the voltage, current and TGR during the transient period. Thus, such system has been modeled by a grounding electrode (GE) connected to a current injection circuit. The measurement of the potential is made through a conductor, which is grounded at 50m from GE and follows 1.5m over the ground surface to one cell far the GE, where the potential measurement is performed (Fig. 4). Figure 1 shows the partitioning of the analyzed computational domain into ten sub-domains by...
applying the parallel processing technique. The analyzed domain has the following dimensions:

- **X-direction**: 70 m (280 cells)
- **Y-direction**: 40 m (160 cells)
- **Z-direction**: 35 m (140 cells).

The abbreviations of Fig. 1 are:

- **GE**: Grounding Electrode
- **RCE**: Remote Current Electrode
- **RVE**: Reference remote Voltage Electrode
- **PEC**: Perfect Electrical Conductor.

The implementation data of the grounding system under analysis are the following:

**Current circuit**: composed by a 3m long electrode of 0.5x0.5 m$^2$ of transversal section area, a 20m long horizontal current wire toward y-direction with diameter of 0.135m, an 2.5m long remote current electrode which diameter is 0.135m buried 1.5m deep. The pulse generator, which can be treated as a voltage source, is located on top of the grounding electrode. The wave front time is 0.063 µs and the wave tail time is 500 µs. The peak voltage has been set to 515 Volts, which waveform is shown in Fig.2. A 435 ohms resistor has been properly modeled and adapted between the voltage source and serial-circuit, characterizing the current source. Figures 3, 4 and 5 show the schema of the system under analysis.

The ground’s relative permittivity has been set to 50. The ground’s relative magnetic permeability has been considered unitary and its electrical conductivity set to 2.28 mS/m [3].

The voltage impulse wave is represented by the following formulation:

For $ndt \leq 1.5T_f$

$$V_s(ndt) = V_{\max} \left(e^{-\alpha_1 ndt} - e^{-\alpha_2 ndt}\right) \sin^2(\alpha_3 ndt) / A_0$$

For $ndt > 1.5T_f$

$$V_s(ndt) = V_{\max} \left(e^{-\alpha_1 ndt} - e^{-\alpha_2 ndt}\right) / A_0$$

where,

- $V_s$ = instantaneous voltage
- $V_{\max}$ = peak voltage
- $T_f$ = wave front time
- $T_t$ = wave tail time

**Voltage Circuit**: constituted by 3m long remote potential electrode which diameter is 0.25m and 1.5m buried, a 50m long reference potential line with transversal section of 2mm$^2$. The simulation was performed by sampling the region of interest with cubic Yee's cells. The spatial sampling interval has been set to 0.25m and the Courant [6] condition was satisfied by the time increment of dt=481.452 picoseconds.

The grounding electrode has been modeled as a high conductivity metal. The conductors and rods used to obtain the feeding current were modeled by the thin wire technique because their diameters are very small when compared to the dimension of the used Yee's cell. As long as the voltage circuit's current is very low, this circuit has not been modeled with the thin wire formulation.

The ground’s relative permittivity has been set to 50. The ground’s relative magnetic permeability has been considered unitary and its electrical conductivity set to 2.28 mS/m [3].
The transitory electrical potential has been measured at the higher edge of the voltage electrode at the cell indexed by (111,110,80), shown by (3).

\[ V(n) = -E_z(111,110,80)dz \]  
where \( n \) is the number of interactions.

The transitory current injected in the grounding electrode has been calculated using the Ampère’s law, resulting:

\[ I(n) = \left[ H_x(110,109,80) - H_x(110,110,80) \right]dx + \left[ -H_y(109,110,80) + H_y(110,110,80) \right]dy \]  

The evaluation of TGR is performed from the values obtained in (3) and (4)

\[ TGR(n) = \frac{V(n)}{I(n)}. \]  

The simulation results for the current, voltage and transitory grounding resistance is illustrated by Fig.6.

Observe that using this distinct methodology with respect to the way data are processed and boundary conditions, the obtained results are identical to that obtained experimentally by the reference [3], what validates the results of the experiment, qualifying the implemented system, within the FDTD techniques, to new prospections aiming at the solutions of critical problems of grounding systems.

Fig.6. Results for one electrode obtained through the simulation

B. Long vertical electrode results (height from 3 to 12m)

The transitory behavior has been analyzed for a long vertical electrode by employing the same previously used excitation circuit and calculating the transitory voltage, current and TGR. The chosen criteria was the increase of the electrode length by three meters each new simulation up to 12m, as illustrated by Fig.7. There exist practical situations in which longer rods are used depending on the magnitude of the resistivity at the different layers of the extractified ground, in a sense to reach grounding resistance specified by the project with reduced cost [9].

Fig.8 shows the obtained results for the TGR, voltage and current for the four different rod lengths.

It is important to emphasize that up to 0.16 \( \mu \)s, the TGR, voltage and current curves are nearly coincident for the different rod lengths. Fig.9 shows the TGR steady-state behavior as a function of the rod length. It shows that the
TGR decreases with the rod enlargement, tending to saturation.

Fig. 8. Voltage, Current and TGR transitory responses for various rod lengths

Fig. 9. TGR steady-state behavior as function of the rod length

C. RESULTS FOR A GROUNDING SYSTEM COMPOSED BY TWO PARALLEL ELECTRODES

Employing two identical rods spaced by 3m, as shown by Fig. 10, the TGR and the voltage were reduced by about 20 Ω and 8 Volts when compared with the single rod system, as expected. The current was increased by 0.04 Ampères.

The result of the simulation shown by Fig. 11 presents values compatible to the following expression:

\[ R_{haste} > R_{hastes} > \frac{R_{haste}}{2} \quad (6) \]

D. FOUR-ELECTRODE GROUNDING SYSTEM RESULTS

Figure 12 and Figure 13 show the rod arrangement and the transitory TGR, voltage and current curves, respectively.

Fig. 10. The couple-rod grounding system

Fig. 11. TGR, Current and Voltage: comparison for one and two rods.

Fig. 12. Four-aligned-electrode grounding system

Considering a homogeneous ground region in which four rods are sequentially set as shown in Fig. 7, the TGR steady-state level (16Ω) is below the steady-state level corresponding to the arrangement shown in Fig. 12, (20Ω). However, for the transient instants, the TGR peaks with large magnitudes (up to 50 ohms) are observed during the interval from 0 to 0.1µs, for the first case, while the second arrangement provides transient TGR levels under 22Ω in the interval between 0.4 and 0.6 µs. The results obtained for both cases suggests improved transient performance for parallel rods and for improved steady-state performance longer rods should be used.
The results presented here shows that the proposed method, based on the FDTD technique, can be effectively applied to analyze transient phenomena related to lightning discharges in grounding systems. The simulations involved systems formed by one, two, four and sixteen parallel rods and one example of a long vertical rod. The obtained results for voltage, current and transient resistance for one rod strongly agree with the experimental data presented by [3]. The other simulations, for parallel disposals, had coherent results in which smoother transient curves are observed as long as the number of rods is increased. The absolute value of the grounding resistance for steady-state instants varied in the range of 55 Ω to 9 Ω and the voltage in the range of 28 Volts to 5 Volts as the number of rods was increased.

Concerning to the case of the long rods, the results for 3, 6, 9 and 12m presented similar waveforms up to 0.16 µs. From this instant on, the waveforms had pronounced variations, reaching steady-state in the range of 55 and 9 Ω (for the lengths of 3 and 12 m, respectively).

Although the TGR calculation has been made based on systems formed by 0.5 x 0.5 m² electrodes, commercial rods with reduced diameters can be used in simulations. In this case, the thin wire technique [5] should be employed. The methodology can be used when it is necessary to analyze a conductive multiple-layers ground. This work shows that FDTD has great potential to analyze such problems, although it can be limited by the huge amount of memory necessary and long processing time. Such problems have been bypassed by the employment of parallel processing techniques.

IV. REFERENCES


