Simulations of Lightning Strokes near Transmission Lines in Urban Environments by Using the Finite-Difference Time-Domain Method

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Abstract - Numerical full-wave solutions of induced voltages on low-voltage energy lines due to atmospheric discharges on cell phone radio base stations (RBS), installed at the proximities of such lines, are presented for the first time in this work. Structures, such as towers and buildings, which present high structural complexity, have been modeled in order to obtain realistic results. In particular, this paper shows the importance of considering the effects related to real electrical conductivity and permittivity of the soil (in technical literature, PECs have been used to represent the soil in similar problems). For this purpose, a software has been developed in which Maxwell’s equations are numerically solved by using a parallel implementation of the Finite-Difference Time-Domain Method (FDTD), producing full wave solutions for the problem. The thin wire formulation has been implemented for representing thin cylindrical electric conductors and transmission lines.

Index Terms — atmospheric discharges, induced voltages, low voltage energy lines, parallel FDTD method, radio base stations.

I. INTRODUCTION

Quite recently, due to world-wide expansion of cell phone systems in urban areas, towers and similar structures have continuously being built and are ordinarily found in cities, operating as Radio-Base Stations (RBSs). Considerably high, around 50 meters up, these structures are preferential points for atmospheric discharge strokes. The occurrences of these discharges on telephony towers cause a series of undesirable effects, either in the ground (such as increase of potentials and return currents in grounding systems) or in energy transmission lines (causing outbreaks due to electromagnetic induction). Such outbreaks are characterized by high speed voltage transients induced on low voltage lines, which affect the consumer units by causing serious damages to electric and electronic devices.

This way, the proposition of this work is to study the behavior of the induced voltages and fields on transmission lines, due to atmospheric discharges on high metallic structures (such as RBSs), considering a set of complex structures with different materials around the regions of interest. In this work, the dielectric parts of buildings (and metal frameworks) are considered. Previous works such as [1-2] have employed different methods for numerical simulation of similar problems, modeling simpler structures, though.
In this work, the Finite-Difference Time-Domain method (FDTD) [3] is used to solve Maxwell’s equations, considering lossy isotropic media. This technique produces full-wave solutions for the analyzed problems, in which phenomena such as reflections, refractions and diffractions are implicitly considered, implying in realistic solutions. The methodology employs a virtual wave absorber [4] for mesh truncation and the thin-wire formulation to represent the cylindrical conductors [5], promoting substantial economy of the necessary processing time and RAM memory, due to the high density of the computational grid that is required to model these conductors with traditional FDTD method. The function used as current source is a triangular pulse (1 µs / 50 µs), as defined in [1]. The soil model adopted has real conductivity, and the ground electrical permittivity was also taken into account.

II. METHODOLOGY

A. The FDTD method

Due to the fact that real electromagnetic problems are not usually analytically treatable, numerical solutions are required. For this reason, in 1966, the FDTD method was proposed by Kane Yee to numerically solve Maxwell’s equations.

For isotropic and lossy media, Faraday’s and Ampère’s equations, in their differential forms, can be easily written in the finite difference form. This way, it is necessary to discretize the analysis domain by using the so called Yee’s Cells, with dimensions ($\Delta x$, $\Delta y$, $\Delta z$). In this case, the time step ($\Delta t$) must satisfy Courant’s [6] stability criterion (1):

$$\Delta t \leq \frac{1}{c \sqrt{(1/\Delta x^2) + (1/\Delta y^2) + (1/\Delta z^2)}}$$

in which $c$ is the speed of light in free space.

The spatial increments $\Delta x, \Delta y, \Delta z$ must satisfy the condition $\Delta x, \Delta y, \Delta z \leq 0.1 \lambda$ [7], in which $\lambda$ is the minimum wavelength in the analyzed problem. This is a practical criterion for minimization of numerical dispersion effects. In this paper, it has been used 60% of the limit defined by (1).

B. UPML for conductive media

The use of numerical methods for solving open problems requires the truncation of the analysis region. This is a necessary procedure due to the fact that computers have limited resources, such as memory, disk space and processing capacity; otherwise, in this case, an infinite number of cells and time steps would be required for performing a FDTD simulation.

In order to address this problem, specific truncation techniques must be employed to limit the numerical domain by absorbing incident waves, simulating propagation to infinity and avoiding unwanted reflections from the limits of the domain into the analysis region. This way, the environment obtained acts as anechoic chambers.

For this purpose, one of the most efficient formulations is the Uniaxial Perfect Matched Layer (UPML) [4], in which waves impinging on these regions are absorbed regardless of incidence angle, polarization or frequency. This medium is represented by a set of parallel layers with gradual increase
of their attenuation functions, as it departs from the analysis region. This technique has been employed in this paper, considering the conductive media.

C. Thin Wires

For simulations in which metallic cylindrical elements with electrically small radius must be considered, the thin wire technique must be employed. In this work, the method presented in [5] is employed for modeling transmission lines. This way, modifications of the parameters $\varepsilon$, $\sigma$ and $\mu$ were introduced to define the electric ($E$) and the magnetic ($H$) field components located around the cylindrical wire conductors. Such modifications are given by:

$$
\sigma^* = \sigma \frac{\ln(1/0.23)}{\ln(\Delta s/r_0)} 
$$

(2)

$$
\varepsilon^* = \varepsilon \frac{\ln(1/0.23)}{\ln(\Delta s/r_0)} 
$$

(3)

$$
\mu^* = \mu \frac{\ln(\Delta s/r_0)}{\ln(1/0.23)} 
$$

(4)

in which $r_0$ is the conductors radius to be implemented, $\sigma$ (conductivity), $\varepsilon$ (permittivity) and $\mu$ (permeability) are the original medium parameters and $\Delta s=\Delta x=\Delta y=\Delta z$ represents the cell’s edge dimension in the analysis domain.

D. Parallel Computing and LANE SAGS Software

The Beowulf cluster architecture has been employed and configured in this work. The built cluster is composed by a master computer and three nodes. This system uses the following services: Network File System (NFS) for disk sharing; Network Information Service (NIS) and Remote Shell (rsh) are used for managing user authentication and job execution permissions among the cluster’s computers. Message exchange for this distributed memory system is accomplished through the use of the LAM/MPI library. Each machine has four 64 bits Intel Xeon processors.

Human errors are usual while complex structures are being modeled, especially when someone works manually with parallel processing (at programming code level). For avoiding such a problem, the parallel FDTD solver, called LANE SAGS (Synthesis and Analysis of Grounding Systems), developed in [8], automatically distributes tasks (boundary conditions and specific calculations) among the cluster processors. The processing time required for concluding each simulation presented in this work is approximately one day, using the sixteen Intel Xeon™ cores.

III. CASE STUDIES AND THE OBTAINED RESULTS

Case I: For software validation purposes, the problem simulated in [1] was reproduced here (Fig. 1). It consists on a metallic block used for representing the RBS tower and power transmission lines with grounding points from the neutral cable. As in [1], the ground is modeled as a perfect conductor. The distance between the two neighbor grounding points is 150 m. As it can be seen in Fig. 1.a and
1.b, the neutral cable is connected to the ground through a perfect conducting wire and by an 80 Ω resistance [1]. The wire (from neutral to the ground) radius is 12.7 mm and the metallic tower, which the atmospheric discharge strikes, is 50 meters high. The tower is placed 20 meters away from the low voltage line. The transmission lines (15 mm radius) penetrate the UPML (impedance is matched), acting this way as infinite long lines. The current source profile, employed in [1] and adapted from [9], is used in this work. Mathematically, the source is defined by (5) and (6).

\[ I_S(t) = \frac{I_{max}}{T_f} t \quad \text{for } t \leq T_f \]  \hspace{1cm} (5)

\[ I_S(t) = \left( -\frac{I_{max}}{10^{-4}} t \right) + 1010 \quad \text{for } t > T_f \]  \hspace{1cm} (6)

in which \( T_f = 10^{-6} \) s, \( I_{max} = 1000 \) A, in which a \( 1 / 50 \) µs source is generated.

Figs. 1 and 2 show the computer models for cases I and II, respectively. For both cases, the computational grid has \( 840 \times 150 \times 320 \) cubic Yee Cells of edge lengths \( \Delta = 0.2 \) m. For case II, the electromagnetic characteristics of the soil are: \( \sigma = 0.004 \) S/m, \( \varepsilon_r = 10 \) and \( \mu_r = 1 \). The grounding rods are 3 m long, with a radius of 12.7 mm (Fig. 2.a and 2.b). In this case, the 80 Ω resistance was obtained by calculating rod’s equivalent radius through Sundae’s equation [10]. For both cases, the current source point is positioned two cells above the top of the tower. For this purpose, magnetic field components around the vertical metallic discharge channel were excited. This was defined for the subsequent cases (see Fig. 3).
Figs. 3-4 show the results measured in the plane represented by Figs. 1.a and 2.a, from the ground surface to each cable of the power line (shortest path). These induced voltage values are calculated for each kA injected by the atmospheric discharge in order to check the influence of the two soil models analyzed. It is important to mention that the results obtained for the first case (Fig. 3) agree with those available in [1], and the results shown in Fig. 4 reveal the importance of considering the real parameters of the earth and solving the problem, employing a full-wave methodology. Comparisons between these two figures show important increases in induced voltages for Case II (peak voltage is increased by 2.5 kV).
The tower conductors and grounding rods are metallic cylinders of 15 mm and 12.7 mm radius, respectively. Figs 6-7 show the same structure (Fig. 5) in 3D, using LANE-SAGS software. Fig. 6 shows the complete domain of analysis, and Fig. 7 shows the details of the base of the tower, container and grounding mesh. Another low voltage line with similar parameters to the previous one was also added, located 10 m away from the metallic tower (Figs. 5-7). Fig. 8 shows the results for induced voltages in V/kA (induced voltages on cables per kA of injected current at system excitation point) as a function of time for each conductor (lives and neutral) for both lines. Induced voltage values of 10 kV/kA can be measured for the energy line located 20 m away from the tower and 14 kV/kA for the energy line located 10 meters away from the tower. In this Figure, as expected, induced voltages tend to be more intense in conductors located near the metallic tower. Finally, it can be seen from Figs. 4 and 8 that modifications on the structure of the tower increase the induced voltage peak in approximately 1.5 kV, due to the fact that the atmospheric discharge strikes closer to the energy line if compared to the second case.
IV. CONCLUSIONS

In this work, complex and realistic computational models have been generated with the objective of calculating the induced voltages on low voltage lines, due to the electromagnetic fields originated from lightning strokes on an RBS tower. The analysis of the obtained results shows high levels of overvoltage and potential differences between live to live and live to neutral cable conductors on electrical distribution systems during lightning strokes. The results generated with the FDTD method are full-wave solutions for complex structures, involving: dielectric materials, a complex tower model, transmission lines, grounding systems, and the consequent complex electromagnetic interactions, i.e., surface waves, diffractions, refractions, and reflections. It has been shown that all of those aspects substantially affect the obtained results; in particular, it has been observed that the electromagnetic properties of the soil increase the calculated values of the induced voltages on transmission lines in 2.5 kV, when compared to the first case presented in this work. It is worth mentioning that the geometry of the tower, its grounding mesh, the equipment container and the addition of another power line to the region of analysis also affect the induced voltages on remote transmission lines during the time evolution of the electromagnetic propagation, due to lightning stroke on the RBS, in which peak values of 10 kV and 14 kV have been obtained. All those values calculated here in these simulations (relative to transitory high voltages induced in transmission lines) represent high risk when considering the final consumer unit, causing possibilities of both material and human damages. Such structures are usually located near residences, or in places with constant circulation of people. This problem requires special attention by the cell phone and energy companies and by the government regulators as well, who should promote further research for minimizing the unwanted consequences.
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VI. REFERENCES