Analysis of voltages induced on power outlets due to atmospheric discharges on Radio Base Stations

Ricardo H.T. Chamié Filho *, Lorena F.P. Carvalho, Péricles L. Machado, Rodrigo M.S. de Oliveira

Federal University of Pará (UFPA), Electrical Engineering Post-Graduation Course (PPGEE), Universidade Federal do Pará (UFPA), Rua Augusto Correa, No. 1, CEP 66075-900 Belém, Pará, Brazil

A B S T R A C T

For the first time, full-wave simulations regarding voltages induced on power outlets installed inside buildings, due to lightning strokes on a Radio Base Station located nearby, are performed. The scenario consists of nine buildings with outlets connected to low-voltage distribution lines, conductive ground, a Radio Base Station and grounding systems. Loads connected to the power outlets are also considered. This scenario was modeled with a computer software developed in this work that can numerically represent/model real-world complex structures with realistic parameters. In order to obtain realistic results, Maxwell’s equations are solved numerically by using the FDTD method, which generates full-wave solutions of the problems. Here, electrical conductors are represented with the aid of a thin-wire technique. The analyzed domain is truncated by using the UPML formulation. In order to deal with large tridimensional numerical models, a Beowulf cluster with 16 CPUs is used to accelerate the calculation process. The induced voltages at the energy sockets inside the buildings have been calculated initially without an electric grounding mesh connected to them. In a second moment, the calculation of these induced voltages has been performed for the same structure with a grounding mesh connected to it. In a third simulation, electric loads with resistive–inductive characteristics have been added to the scenario (connected to the energy sockets), simulating residential equipment.

1. Introduction

Brazil is the country with the highest incidence of atmospheric discharges in the world [1]. High-profile structures are frequent targets of such discharges, as is the case of Radio Base Stations (RBS), which are becoming increasingly numerous, especially in urban environments. This way, undesirable effects may occur, such as elevation of electrical voltages on the soil surface due to flowing of discharge currents, as well as the interruption of power transmission and distribution systems.

During the time, surges propagate along a low-voltage distribution system, the final consuming unity tends to be affected, damaging especially electronic devices connected to the power system. However, the study of lightning strokes tends to be very complex as it is a phenomenon of unforeseen circumstances, with regard not only to the places and moments of occurrence, but especially to transient currents and voltages, which are highly dependent on the surrounding elements positioned nearby the lightning stroke point and on their electromagnetic parameters. This way, statistical data have been continuously obtained around the globe [2] in order to improve human understanding of the phenomena and its consequences. Such statistical data were obtained from measurements of lightning currents taken at instrumented towers [3–5] and with rocket...
triggered lightning experiments [6,7]. Accurate numerical representations of lightning channels were recently proposed in [8,9].

In this work, numerical solutions of Maxwell’s equations are obtained by using the Finite-Difference Time-Domain (FDTD) method [10–13], where lossy isotropic media are considered for analysis. The method provides full-wave solutions of Maxwell’s equations in such a way that reflections, refractions and diffractions of scattered waves are taken into account automatically as the simulation is performed. The problem treated in this work consists of nine buildings with outlets connected to external low-voltage distribution lines, conductive ground (electrical permeability and conductivity are considered) a RBS and grounding systems. The lightning discharge strikes the RBS tower, which is present in the vicinity of the buildings. The numerical lightning channel modeling technique follows [9], in which the FDTD method is validated with experimental data from rocket-triggered lightning. Loads connected to the power outlets are also considered. Transient induced voltages are calculated for the outlets and analysis of the obtained data is performed. Critical floors of buildings are identified, as well as the less affected ones.

2. The case studies

In this topic, three different situations are presented. The main objective is to understand, in all these three cases, the behavior of electrical transitory effects produced by an atmospheric current discharge (Fig. 1, that strikes a RBS located nearby), which induces voltages at energy outlets that are represented by two conductors positioned side by side separated by $\Delta$ (edge’s length of the used Yee’s cell) [10,13], located inside the buildings, as shown in Fig. 2a. Case A refers to transitory voltages induced at energy outlets located inside the buildings (no loads are coupled). Case B refers to transitory voltages induced at the same energy outlets, but with a grounding mesh connecting all the buildings presented in the scenario (an equipotentialization schema was defined among the building and the RBS tower). Case C refers to the configuration of Case B, but with the addition of resistive-inductive loads connected to the outlets, which simulate electrical impedances of equipments. The obtained results are compared and then analyzed.

For performing the simulations, a 1/50 $\mu$s-triangular wave form was used for exciting the lightning current [14], which is illustrated by Fig. 1. The lightning current strikes the RCS tower 58 m from ground surface (Fig. 2a), and the lightning channel was modeled as proposed in [9].

2.1. Case A: Metallic tower modeled with real-world parameters, shielded equipment container, six grounding points connected to the neutral conductor and energy outlets inside buildings

A metallic RBS tower with realistic non-prismatic geometry, with an associated equipment container, is considered in Case A (Figs. 2–5). Six equally spaced grounding points connected along the neutral conductor of the power line (Fig. 5) are considered. Nine buildings are located nearby this metallic tower (Fig. 2a) and, in addition, electric circuits that compose the buildings, including cables and energy outlets, have been modeled to the various floors of these edifications (Figs. 2 and 3). These electrical elements (Fig. 4) are connected to the distribution lines, such as it is illustrated by Fig. 5. The calculation of induced voltages is performed at the end point of these circuits (outlets) by evaluating $\int E \cdot dl$ between their terminals.

The RBS tower and the equipment container are usually connected to a small grounding mesh located around these two structures. These meshes are used as voltage reference for the communication equipments and for protecting them from
electrical discharges during the occurrence of short circuits inside the container or from lightning events on the RBS. This protection schema is illustrated by Fig. 2b. The tower is modeled with 15 mm radius metallic conductors and the dimensions of the shielded container are $6 \times 4 \times 3$ m ($x$, $y$, and $z$, respectively). The ground system of the RBS elements follows [14]. The radii of the 3 m-long grounding rods connected to the neutral line are 12 mm, which results in an 80 $\Omega$ ground resistance [14] for a 4 mS/m soil conductivity by using Sundae’s equation. It is important to mention that the line’s and the tower’s parameters are based on [14], which performed several computational lightning strokes studies on RBS towers.

Six grounding points have been connected to the neutral conductor of the power lines likewise [14]. The neutral terminals of the outlets are connected to the neutral conductors of the distribution lines, which are connected to grounding points. The considered power lines are located 10 and 20 m away from the geometric center of the RBS tower, as shown in Fig. 3. The electrical circuits located inside the modeled buildings and connected to the power lines are shown in Fig. 4 and they are identical for each of the buildings of the scenario. The electrical system employed in this work is a three-phase system, with four conductors where the fourth conductor is the grounded neutral one. These three phases are called F1, F2 and F3, as it is indicated by Figs. 3 and 4. The F1 conductor is located next to the neutral cable N, and the F3 phase is located closer to the ground surface (Fig. 3).
The nine buildings, numbered from B1 to B9 (Fig. 6), located around the RBS tower, have dimensions of $24 \times 12.8 \times 24$ m ($x$, $y$ and $z$ dimensions respectively). The distance between two neighbor buildings is 8.6 m and the distance between the two building blocks is 14 m (Fig. 6). The only exception is the building B3, which is separated by 18.6 m from the geometric center of the tower and by 4 m from its neighbor buildings, as shown in Fig. 6. The walls and the floors of the nine buildings are electromagnetically characterized by $\sigma = 0$, $\varepsilon_r = 7.5$ and $\mu_r = 1$, as specified in [15]. Perfect conductivity blocks have been employed in order to model the sustenance structures of the buildings, as it is shown by Figs. 5 and 2b. The road present in this scenario has been modeled by a $168 \times 10 \times 0.8$ m dielectric block, by using the parameters [15] $\sigma = 0$, $\varepsilon_r = 7.5$ and $\mu_r = 1$. The power outlets installed inside the buildings are located 1.6 m from each floor surface (Fig. 4b).

For this case and the following ones, close to reality electromagnetic characteristics have been considered in order to model the soil and the other structures. The parameters $\sigma = 4$ mS/m, $\varepsilon_r = 10$ and $\mu_r = 1$ have been used to model the soil. The analysis domain is compounded by $840 \times 310 \times 320$ cubic Yee, with edges measuring $\Delta = 0.2$ m. In order to deal with this huge numerical volume, a 16-node-Beowulf cluster was employed (with Intel Xeon™ processors), in such a way that the processes are automatically defined by the developed software, in such a manner the numerical volume is distributed between the cluster nodes (divided into subdomains). Message Passing Interface (MPI) is used for exchanging the necessary electromagnetic field components at the interfaces between neighbor subdomains.

Fig. 4. (a) Electrical circuits of the building and its associated sockets (exterior part was removed for illustration proposes) and (b) building dimensions.

Fig. 5. Detailed view of the power lines’ connections to the buildings’ circuits.
The Uniaxial Perfectly Matched Layers has been employed in this work in order to truncate (limiting) the analysis region [11]. The metallic conductors that represent the power lines and the electrical cables have been modeled by using the thin-wire technique developed by Baba et al. [12]. The waveform adopted to model the lightning stroke inside the computational environment follows [14] (peak of 1 kA). This waveform models the current generated by the lightning stroke that ignites the electromagnetic process.

It is worth to mention that the low-voltage distribution lines are considered of infinite length by penetrating them into the UPML absorbing region. This is achieved by performing impedance matching between the thin wires and the absorber’s media [9,16] (the parameters \( r, e, l \), which are used to numerically represent wires’ radii [12], are used in UPML equations for the field components adjacent to the penetrating wires).

2.2. Case B: Grounding mesh added to the analyzed domain, which is connected to the metallic structures of the buildings, to the tower and to the neutral conductors inside the edifications

In this case, the configuration presented in Case A is maintained and the buildings’ foundations and the RBS tower structure with the metallic container and the neutral conductors are now electrically connected to a grounding mesh, which measures 150 × 47 m (Fig. 7). The goal is to evaluate the equipotentialization effect provided by the grounding mesh which connects the elements presented in the scenario. The radii of the conductors of the grounding mesh are 12.7 mm (the thin-wire technique introduced in [12] was also used for modeling the grounding rods and cables). This situation is shown by Fig. 7, which defines the grounding geometry and also indicates the points of the buildings and of the RBS grounding system connected to the added grounding mesh.

2.3. Case C. The addition of residential loads connected to the power outlets inside the buildings

In this last case, residential loads connected to the outlets are considered. Here, the situation presented in Case B is preserved and the loads are included. In [14], an evaluation of this behavior is performed for a single load connected directly to a low-voltage distribution line. In this work, the behavior of transient induced voltages has been computed while an equivalent residential load are connected directly to a power outlets inside the buildings. As far as one of the most common inductive loads found in residences is the domestic refrigerator, this appliance has been adopted to perform the numerical tests. This appliance has average energy consumption of 26.6 kWh, active power of 108.5 W, reactive power of 131 Var and apparent power of 170 VA [17], resulting in a power factor of 0.64.

This equipment’s composition involves different elements with different functions, such as filters, evaporators, a compressor and fragile electronic parts, among others. This equivalent load presented in this work is a simplified model (Fig. 8), which is an approximation of the actual operation of this appliance. The impedance parameters can be obtained by using the frequency of 60 Hz [17]. This way,

\[ Z = R + jX, \]  
(1)

and thus

\[ Z = (61 + j73) \Omega, \]  
(2)

is obtained.
From (2), the values related to the resistive \( R \) and to the inductive \( L \) parts of the equivalent system were 61 Ω and 0.194 H respectively. The mathematical formulation employed to represent the inductive and resistive elements in the FDTD method (Fig. 8b) is described in [18]. The metallic portion of the refrigerator has been modeled by using a metallic block dimensioned to match the appliance’s realistic sizes (Fig. 8a). As the system’s neutral conductor is grounded, the grounding system has been built so that the appliance’s chassis has been connected to the grounded conductor (Fig. 8b). This way, in normal (balanced) operation conditions, there would be reduced risk of electrical shocks to the user. This single phase load is connected to the power outlets on each of the floors (Fig. 8b). There is one of these appliances on each of the building’s floor as shown by Fig. 9.

3. Results

In order to facilitate the understanding of results, buildings have been labeled from B1 to B9, as shown by Fig. 6. Figs. 10–12 show induced voltages on the first, fifth and eighth floors of the building B7. The induced peak voltage on the power outlet located at first floor, which is about 1.6 kV between the neutral and phase conductors, for the simulation time of about \( t \approx 2.5 \mu s \) (Fig. 10), is higher than the induced voltage calculated on the power outlet located on the fifth floor (Fig. 11), which is about 1.5 kV for \( t \approx 7.9 \mu s \). This fact is due to elevation of the soil’s potential, caused by the induced current that circulates on the ground’s surface during the evolution of the lightning stroke at the RBS (conductive coupling). As the \( z \) coordinate increases, the currents flowing from the soil to the top of the building (by electric conduction) tend to be divided while propagating on the metallic parts of the building, especially from the first to the intermediary floors (currents tend to be recombined in higher floors). In addition, electric fields that propagate from the RBS tend to be more intense in higher floors when
Fig. 9. (a) Overview of the last case and (b) detail of a refrigerator installed inside the first floor.

Fig. 10. Induced voltages per kA for the first floor of building B7 (Case A).

Fig. 11. Induced voltages per kA for the fifth floor of building B7 (Case A).
direct incidence is considered. These observations justify increments on the induced voltages observed in the eighth floor of B7 (Fig. 12), where 1.7 kV of peak is reached for $t = 8.5 \mu s$ (Case A). Various oscillations on induced voltages calculated on power outlets can be noticed in Figs. 10–12, which are caused by reflections, diffractions and refractions of the propagating electromagnetic field and to the various discontinues that the conduction currents face all over their course. This is very enlightened when Fig. 13 is observed.

For all the cases considered, it can be observed that induced voltages between the Neutral and phase 3 conductors tend to be more evident, followed by Neutral-Phase 2 and Neutral-Phase 1 induced voltages amplitudes. This way, it can be said that the more the neutral conductor is positioned far from the analyzed phase conductor, the greater will be the induced voltage obtained, as expected. Figs. 14 and 15 show the electric field distribution for $t = 10 \mu s$ at the plane where the outlets of the first floor were installed for Cases B and C. It is possible to see that the field configuration is affected by the loads connected to the outlets, mainly due the modification of the currents which flows through the circuits, which are closed for Case C. It also should be noticed that the presence of the chassis of the refrigerators (that are visible in Fig. 15) also modifies the field configuration due to field reflections and diffractions.

Due to the complexity of the transient waveforms generated on each of the power outlets, the peak and RMS values have been computed and organized on Tables 1–5. RMS values have been calculated in order to study the voltage levels over time. As the obtained induced voltages are discrete and non-sinusoidal functions of time, expression (3) has been employed to obtain RMS values of the voltages $V(t)$ (which have $n$ samples).

$$V_{RMS} = \sqrt{\frac{\sum_{i=1}^{n} V^2[i]}{n}}$$

For all cases, the maximum simulated time is 10 \(\mu\)s, that is represented by $n = 43271$ time steps.
In general, it can be said that in the buildings’ first floor, peak and RMS values of induced voltages tend to be higher than the other floors. As the \( z \) coordinate increases, the tendency is that induced voltages decreases its intensity until at least the fourth floor (at about the half of the buildings’ height). In a similar way, the induced voltages in the higher floors (i.e. seventh and eighth floors) tends to be higher, for both peak and RMS values, when compared to those obtained on the intermediate floors.

![Fig. 14. Electric field distribution for \( z = 1.6 \) m (first floor outlet level) – Case B, \( t = 10 \) μs.](image)

![Fig. 15. Electric field distribution for \( z = 1.6 \) m (first floor outlet level) – Case C, \( t = 10 \) μs.](image)

### Table 1
Peak and RMS induced voltages, for each kA and for 40 kA, obtained for Case A.

<table>
<thead>
<tr>
<th>Case A</th>
<th>1st Floor</th>
<th>2nd Floor</th>
<th>3rd Floor</th>
<th>4th Floor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Peak (for 1kA)</td>
<td>RMS</td>
<td>Peak (for 40kA)</td>
<td>RMS</td>
</tr>
<tr>
<td>BUILDINGS</td>
<td>B1</td>
<td>984.46</td>
<td>572.80</td>
<td>39,378.40</td>
</tr>
<tr>
<td></td>
<td>B2</td>
<td>832.33</td>
<td>568.13</td>
<td>33,293.20</td>
</tr>
<tr>
<td></td>
<td>B3</td>
<td>980.70</td>
<td>577.21</td>
<td>35,328.00</td>
</tr>
<tr>
<td></td>
<td>B4</td>
<td>731.72</td>
<td>559.95</td>
<td>29,268.80</td>
</tr>
<tr>
<td></td>
<td>B5</td>
<td>816.44</td>
<td>587.55</td>
<td>32,657.60</td>
</tr>
<tr>
<td></td>
<td>B6</td>
<td>1,347.66</td>
<td>782.23</td>
<td>53,906.40</td>
</tr>
<tr>
<td></td>
<td>B7</td>
<td>1,594.18</td>
<td>741.49</td>
<td>63,767.20</td>
</tr>
<tr>
<td></td>
<td>B8</td>
<td>1,269.73</td>
<td>761.33</td>
<td>50,789.20</td>
</tr>
<tr>
<td></td>
<td>B9</td>
<td>1,463.34</td>
<td>778.56</td>
<td>58,533.60</td>
</tr>
</tbody>
</table>

In general, it can be said that in the buildings’ first floor, peak and RMS values of induced voltages tend to be higher than the other floors. As the \( z \) coordinate increases, the tendency is that induced voltages decreases its intensity until at least the fourth floor (at about the half of the buildings’ height). In a similar way, the induced voltages in the higher floors (i.e. seventh and eighth floors) tends to be higher, for both peak and RMS values, when compared to those obtained on the intermediate floors.
floors. In addition, as the value of the \( z \) coordinate decreases (starting from the eighth floor) the incident electromagnetic field intensity that comes from the RBS tower is reduced. This fact can be observed in Tables 1–3 or in Tables 4 and 5.

Buildings B6–B9 are located in the same side of the street where the tower is positioned, and all of them have higher induced voltages when compared to the other buildings. The buildings B6–B9 and the constructions B1 and B2 can be considered the most affected.

More specifically, for Case A (Table 1), in which there is no grounding mesh or connected loads, it can be seen that B6–B9 buildings have both higher peak and RMS induced voltages. On the first floor of these buildings, induced voltages around 1.2 kV/kA can be observed, in such a way that B7 is the most affected structure, with induced voltages values over 1 kV calculated on each floor, except for the fourth floor, due to greater proximity to the RBS structure (Fig. 6). A similar behavior was presented by B9. RMS values have a smaller percentage increase than the peak values when comparing results obtained for buildings B1–B5 to values obtained for buildings B6–B9. Intermediate floors are the least affected, as stated previously.

### Table 2
Peak and RMS induced voltages, for each kA and for 40 kA, obtained for Case B.

<table>
<thead>
<tr>
<th>Case B</th>
<th>1st Floor</th>
<th>2nd Floor</th>
<th>3rd Floor</th>
<th>4th Floor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak (for 1kA)</td>
<td>RMS</td>
<td>Peak (for 40kA)</td>
<td>Peak (for 1kA)</td>
<td>RMS</td>
</tr>
<tr>
<td>B1</td>
<td>869.51</td>
<td>475.24</td>
<td>34,780.40</td>
<td>844.57</td>
</tr>
<tr>
<td>B2</td>
<td>822.49</td>
<td>490.50</td>
<td>32,912.40</td>
<td>795.01</td>
</tr>
<tr>
<td>B3</td>
<td>744.18</td>
<td>543.06</td>
<td>29,767.20</td>
<td>730.64</td>
</tr>
<tr>
<td>B4</td>
<td>714.19</td>
<td>436.71</td>
<td>28,567.60</td>
<td>704.57</td>
</tr>
<tr>
<td>B5</td>
<td>809.99</td>
<td>414.21</td>
<td>32,399.60</td>
<td>802.11</td>
</tr>
<tr>
<td>B6</td>
<td>1,316.70</td>
<td>650.61</td>
<td>53,668.00</td>
<td>1,220.50</td>
</tr>
<tr>
<td>B7</td>
<td>1,493.64</td>
<td>774.68</td>
<td>59,745.90</td>
<td>1,416.53</td>
</tr>
<tr>
<td>B8</td>
<td>1,142.69</td>
<td>729.21</td>
<td>45,707.60</td>
<td>1,129.88</td>
</tr>
<tr>
<td>B9</td>
<td>1,335.93</td>
<td>694.40</td>
<td>53,437.20</td>
<td>1,314.42</td>
</tr>
</tbody>
</table>

### Table 3
Peak and RMS induced voltages, for each kA and for 40 kA, obtained for Case C.

<table>
<thead>
<tr>
<th>Case C</th>
<th>1st Floor</th>
<th>2nd Floor</th>
<th>3rd Floor</th>
<th>4th Floor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak (for 1kA)</td>
<td>RMS</td>
<td>Peak (for 40kA)</td>
<td>Peak (for 1kA)</td>
<td>RMS</td>
</tr>
<tr>
<td>B1</td>
<td>859.00</td>
<td>493.77</td>
<td>34,360.00</td>
<td>857.18</td>
</tr>
<tr>
<td>B2</td>
<td>822.65</td>
<td>494.07</td>
<td>32,906.00</td>
<td>822.81</td>
</tr>
<tr>
<td>B3</td>
<td>725.53</td>
<td>457.31</td>
<td>29,021.20</td>
<td>720.54</td>
</tr>
<tr>
<td>B4</td>
<td>726.72</td>
<td>469.33</td>
<td>29,068.80</td>
<td>722.92</td>
</tr>
<tr>
<td>B5</td>
<td>804.84</td>
<td>490.66</td>
<td>32,193.60</td>
<td>796.19</td>
</tr>
<tr>
<td>B6</td>
<td>1,330.53</td>
<td>638.38</td>
<td>53,211.20</td>
<td>1,310.55</td>
</tr>
<tr>
<td>B7</td>
<td>1,496.48</td>
<td>729.51</td>
<td>59,859.20</td>
<td>1,552.19</td>
</tr>
<tr>
<td>B8</td>
<td>1,338.00</td>
<td>623.63</td>
<td>45,528.00</td>
<td>1,328.58</td>
</tr>
<tr>
<td>B9</td>
<td>1,308.17</td>
<td>724.37</td>
<td>52,326.80</td>
<td>1,312.93</td>
</tr>
</tbody>
</table>

Analyzing Case B (Table 2), in which a grounding mesh is present and no loads are connected to outlets, B7 building is the most affected by induced voltages with peak and RMS values around 1.1 kV/kA. For this critical case, there was considerable reduction in all peak voltages when comparing to Case A (Table 4). The larger percentage reductions in peak voltages occurred in the eighth floor (10.34%) and from fourth to sixth floors, ranging from 6.58% to 8.55%. An increase on the RMS values calculated on B7 has also been noticed. These most considerable increases were 11.15% (fourth floor), 7.20% (third floor) and 7.13% (seventh floor). However, in general, the grounding mesh has brought benefits to almost all buildings. B6 presented reductions of 10% or more on peak voltage for the fourth to seventh floor and increases in peak voltages for the fourth to the eighth floors (from 0.79% to 16.67%). B4 presented a significant reduction in RMS voltages on all floors (from 8% to 21%).

When charges have been connected to the power outlets (considering the grounding system), induced voltages had a significant reduction in peak and RMS values when compared to Case A on the B7 building (building positioned nearest to the RBS tower). In this case, two aspects have to be considered: (1) the induced voltage on a resistor is a function of the current.
which flows through it, and the induced voltage in an inductor is a function of the time variation of induced current which flows through it (lightning strokes higher frequencies are in kHz); (2) the equipments’ chassis (Fig. 8b) partially protect the power outlets from the incident electromagnetic field, as these chassis have been modeled employing perfect conductors \( \sigma = \infty \), resulting in reflection of these fields. This could be observed in most cases. It is worth to mention that the voltages shown in Table 3 are indicative of the buildings and floors more susceptible to dielectric strength breakdown between outlet terminals, what would promote short-circuits and the consequent damages for connected equipments. Once more, this case shows that the intermediate floors (3–5) tend to be naturally less susceptible to higher induced voltages on outlets than the other floors when lightning discharges occur in RBS systems installed nearby.

4. Final remarks

In this work, the behavior of induced voltages (due to lightning discharges) inside modeled structures with realistic parameters has been computationally analyzed. The FDTD method employed here was validated in [19] and it provides efficient and precise solutions, in which phenomena like reflections, refractions and diffractions of electromagnetic waves are taking into account naturally, as the FDTD is a full-wave method. It should be emphasized that as far as FDTD is a full-wave numerical method for solving Maxwell’s equations, conductive coupling is also automatically considered along with field coupling [9,13,16,18,19].

Induced voltages were calculated on power outlets due to a lightning stroke at the top of a RBS tower located near these structures. The calculation of such induced voltages on power outlets was performed between phases and between phase and neutral conductors. The distance of buildings to the lightning stroke point is an important parameter when analyzing the effects of induced voltages on these structures. While comparing peak voltages induced by taking buildings as reference, as closer the building is to the tower, the greater is the induced voltage, as expected. Specifically, for B7 and B8, which are located at the same side of the street where the tower is installed, induced voltage peaks in their power outlets reach 1.4 kV/kA or more, while the other buildings show maximum voltages of about 800 V/kA.

The analysis performed by floor on the buildings shows that the first, second, seventh and eighth floors of all analyzed buildings tend to have the highest peak induced voltages on their power outlets. It is important to observe that, in general, intermediate buildings (third, fourth and fifth floors) are less affected by the lightning stroke, which seem to be naturally protected, as previously discussed.

According to [20], there are two main situations that can cause the damaging of equipment when it is connected to electrical network due to overvoltage associated to lightning: air dielectric breakdown (promoting temporary short circuit between electrical phases) and/or when the absolute value of voltage between residence’s phases is over 600 V. Air’s dielectric strength is about 3 MV/m [20,21]. This way, for the present problem, air dielectric breakdown would occur for voltages over 60 kV (because distance between the phases is 0.02 m). Thus, refrigerators damages would probably occur in building 7, in floors 1, 2 and 8, if current peaks reach 40 kA. It is worth mentioning that, although rarely, currents can reach peaks greater than 40 kA and dielectric insulation can be weaker (depending on temperature, humidity, etc.), and equipment damage could take place in other buildings and floors.

In future works, it is suggested to include in the scenario transformer models, clampers, circuit-breakers and non-linear behavior of final consuming loads, as well as to consider soil ionization in order to turn the computational model closer to reality. Studies related to direct lightning discharges on buildings and irregularities of the ground’s media (vegetation, stones, discontinuities, etc.) and frequency dependency of parameters can be also considered in future works.

References


