Transient Response of the Grounding Grid of a Power Line Tower Subject to a Lightning Discharge

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***Abstract*—This paper discusses basic concepts of the lightning phenomena and lightning protection systems (LPS) commonly employed in power lines. It is proposed a FDTD implementation to compute the transient parameters of arbitrary geometries exposed to lightning strikes. The implementation is first validated by comparison to results reported in the literature. Afterwards, a lightning discharge on a complex system composed of power line conductors, shield wires, tower structure, grounding conductors (counterpoises), concrete foundations and steel-frames is modeled, for which the transient response is investigated.**

***Index Terms*—Finite-difference time-domain (FDTD) method, grounding grid, lightning protection.**

I. Introduction

LIGHTNING strikes have fascinated mankind for millennia and even with all the recent technological advances it still remains a relevant and up-to-date research topic. A typical cloud-to-ground lightning flash culminates in the formation of an electrically conducting plasma channel through the air in excess of 5 km tall, from the cloud to the ground surface. Lightning discharges may reach up to 30 million volts at 100 thousand amperes, during a period of time of the order of microseconds [1].

Consequences of lightning range from radio noise to catastrophic damage, when the lightning directly strikes a specific zone, facility or person. A direct discharge on a power line or induced voltages caused by a lightning strike on its vicinities may cause line flashover or insulation failure of transformers, arresters or other equipment, which may ultimately lead to system failure.

Lightning protection systems are designed to protect structures from damage due to lightning strikes by intercepting such strikes and safely conducting discharge currents to ground, from which follows that the grounding grid is the critical component of an LPS. Overhead power lines are commonly equipped with a shield or earth wire which is a bare conductor grounded at the top of each tower structure and parallel to the line conductors, in order to reduce the probability of direct lightning strikes to the phase conductors.

This work develops an investigation on the transient response of the grounding system of a power line by using Yee FDTD algorithm [2]. It is developed a specific implementation to simulate lightning surges, which is justified by the fact that most commercial FDTD software is designed to work within the high frequency spectrum, typical of scattering problems, and also by the fact that they are often limited to standard waveforms, such as sinusoidal, Gaussian pulse etc.

In order to validate the code, a simple geometry consisting of one air terminal and a square grounding mesh with vertical rods is simulated and results are compared to the literature. Then a system comprised of power line conductors, shield wires, tower structure, counterpoises, concrete foundations and steel-bars buried in a finite-conductivity soil is simulated. Transient grounding resistance, currents injected into the soil, step voltages, tower touch voltage are computed, of which a qualitative analysis is performed.

II. Mathematical Model

A. Review of the FDTD method

The FDTD method provides a direct approximation of Maxwell equations by means of central finite differences, which are evaluated for electrically small discrete subdomains [2]. Referring to the geometry shown in Fig. 1, the time-domain solution to Maxwell equations is obtained using the modified Yee algorithm, expressed in (1)-(7) [2], [4].

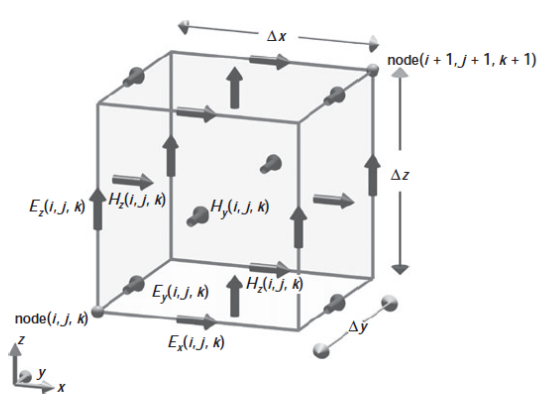

Figure 1. Representation of Yee lattice with modified node numbering, reproduced from [5].

$$H_x^n(i{,}j{,}k) = H_x^{n-1}(i{,}j{,}k) + \tilde{E}_y^{n-1}(i{,}j{,}k+1) - \tilde{E}_y^{n-1}(i{,}j{,}k) - \tilde{E}_z^{n-1}(i{,}j+1{,}k) + \tilde{E}_z^{n-1}(i{,}j{,}k), \tag{1}$$

$$H_y^n(i{,}j{,}k) = H_y^{n-1}(i{,}j{,}k) + \tilde{E}_z^{n-1}(i+1{,}j{,}k) - \tilde{E}_z^{n-1}(i{,}j{,}k) - \tilde{E}_x^{n-1}(i{,}j{,}k+1) + \tilde{E}_x^{n-1}(i{,}j{,}k), \tag{2}$$

$$H_y^n(i{,}j{,}k) = H_z^{n-1}(i{,}j{,}k) + \tilde{E}_x^{n-1}(i{,}j+1{,}k) - \tilde{E}_x^{n-1}(i{,}j{,}k) - \tilde{E}_y^{n-1}(i+1{,}j{,}k) + \tilde{E}_y^{n-1}(i{,}j{,}k), \tag{3}$$

$$\tilde{E}_x^n(i{,}j{,}k) = C_a(m)\tilde{E}_x^{n-1}(i{,}j{,}k) + C_b(m)[H_z^{n-1}(i{,}j{,}k) - H_z^{n-1}(i{,}j-1{,}k) - H_y^{n-1}(i{,}j{,}k) + H_y^{n-1}(i{,}j{,}k-1)], \tag{4}$$

$$\tilde{E}_x^n(i{,}j{,}k) = C_a(m)\tilde{E}_y^{n-1}(i{,}j{,}k) + C_b(m)[H_x^{n-1}(i{,}j{,}k) - H_x^{n-1}(i{,}j{,}k-1) - H_z^{n-1}(i{,}j{,}k) + H_z^{n-1}(i-1{,}j{,}k)], \tag{5}$$

$$\tilde{E}_z^n(i{,}j{,}k) = C_a(m)\tilde{E}_z^{n-1}(i{,}j{,}k) + C_b(m)[H_y^{n-1}(i{,}j{,}k) - H_y^{n-1}(i-1{,}j{,}k) - H_x^{n-1}(i{,}j{,}k) + H_x^{n-1}(i{,}j-1{,}k)], \tag{6}$$

$$R = \frac{\Delta t}{2\varepsilon_0}, R_a = \left(\frac{c\Delta t}{\Delta}\right)^2, R_b = \frac{\Delta t}{\mu_0 \Delta}, \tilde{E} = R_b \vec{E} \tag{7}$$

$$C_a = \frac{1 - R\sigma(i{,}j{,}k)/\epsilon_r(i{,}j{,}k)}{1 + R\sigma(i{,}j{,}k)/\epsilon_r(i{,}j{,}k)}, C_b = \frac{R_a}{\epsilon_r(i{,}j{,}k)R\sigma(i{,}j{,}k)}, \tag{8}$$

where subscripts x, y and z denote the respective components of the magnetic field $\vec{H}$, in A/m, and electric field $\vec{E}$, in V/m; ε is the electric permittivity, in F/m; μ is the magnetic permeability, in H/m; Δt is the time-step, in s; c is the speed of light, in m/s; Δ is the space discretization unit, in m; and σ is the electric conductivity, in S.

The time-increment Δt in equations above must satisfy the following stability condition:

$$c_{max}\Delta t = \frac{1}{\sqrt{\frac{1}{\Delta x^2} + \frac{1}{\Delta y^2} + \frac{1}{\Delta z^2}}}, \tag{9}$$

where c_{max} is the maximum wave propagation velocity within the domain and Δx, Δy and Δz are the domain space discretization units, along axis x, y and z [4].

With the modified algorithm, the scattered fields are determined by setting all components in the domain equal to 0 for $t \leqslant 0$ and iterating equations above over the desired period of time.

FDTD calculations require the solution domain to be bounded, since no computer can process an unlimited amount of data. Modeling an open scattering problem requires special techniques in order to accurately represent the system under study, namely absorbing boundary conditions (ABCs). There is a wide range of methods available for this purpose, however, the perfectly matched layer (PML) introduced by Berenger has been proven to be one of the most robust ABCs in comparison with other techniques adopted in the past [5]. The PML technique consists of surrounding the computational domain with a finite-thickness material based on fictitious constitutive parameters to create a wave-impedance matching condition, which is independent of the angles and frequencies of the wave incident on each boundary.

B. Lightning discharge model

Under normal circumstances, the atmosphere air is an insulating medium. However, during a thunderstorm, once a strong electric field is formed and the breakdown threshold is reached, a conductive lightning channel composed of ionized plasma is established, through which the discharge current flows [6].

The lightning current is modeled as pulse characterized by a peak value, rise time and half-value time. According to IEC 61312-1, the discharge current is a function of time, expressed in ampères by (10) [3]:

$$I_s(t) = \frac{I_0}{\eta} \frac{(t/\tau_1)^n}{1 + (t/\tau_1)^n} e^{(-t/\tau_2)}, \tag{10}$$

where I_0 is the current amplitude at the base of the lightning channel, in A; τ_1 is the rise time constant, in s; τ_2 is the half-value time constant, in s; n is an integer (2,...,10); and η is the current amplitude correction factor, given by:

$$\eta = e^{[(\tau 1/\tau_2)(n\tau 1/\tau_2)]^{-1/n}}. \tag{11}$$

In order to introduce $I_s(t)$ into the FDTD model, a current source and a loop electrode with ground return path are employed [7]. The loop electrode is positioned at a remote location from the system under study (e.g. distance > 100 m) to simulate the discharge current in a practical situation, as illustrated in Fig. 2.

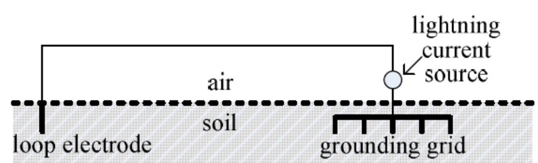

Figure 2. Lightning equivalent current source, reproduced from [7].

III. Simulations

A. Simple test case

Fig. 3 shows a system studied by Chen et al., composed of 1 air terminal and a grounding grid with 12 peripheral rods and a mesh with size 5 m, made of reinforced steel with conductivity $\sigma_{steel} = 7.96 \times 10^6$ S/m and diameter 10 mm [7]. The grounding grid is buried 1 m below the surface of the soil, which is assumed to be an uniform medium with conductivity $\sigma_{soil} = 0.002$ S/m and permitivitty $\varepsilon_r = 10$. The lightning current is a pulse with peak value 10 kA, $\tau_1 = 2.6$ μs, $\tau_2 = 40$ μs, $n = 1$. Fig. 4 shows the current distribution along vertical rods numbered from 1 to 7 obtained by Chen [7]. Fig. 5 contains the response of the proposed FDTD program.

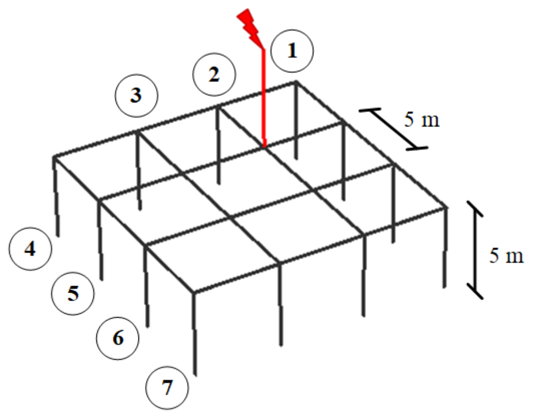

Figure 3. A simple grounding grid with horizontal and vertical conductors.

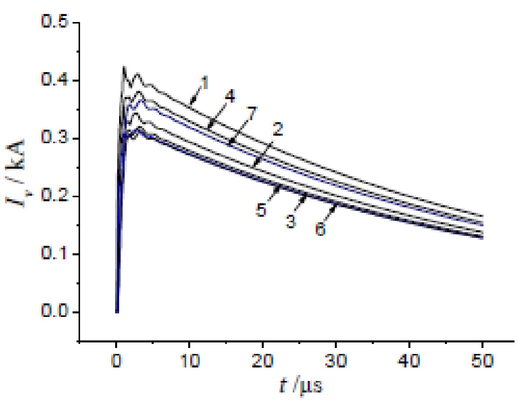

Figure 4. Current distribution along vertical rods in Fig. 3, reproduced from [7] (reference values).

As results agree with the reference values, the implemented code is considered validated. The next section follows with the simulation of a lightning strike on a power line tower.

B. Grounding grid of a power line tower

The system under study, shown in Fig. 6, is composed of the tower structure, phase conductors, shield wires, grounding conductors, also known as counterpoises, and the concrete foundations with steel-frames. Tables I and II summarize the constitutive properties and dimensions of the materials used. For conductors, the thin-wire approximation is used [5]. The concrete foundations are modeled as solid cylinders with diameter 70 cm, length 10 m, extending to deep below the soil surface, which is assumed to be at z =0. The counterpoises are 25 m long, buried at 50 cm depth. The tower height is 30 m.

The lightning model, whose waveform is shown in Fig. 7, is a pulse with peak value 30 kA, $\tau_1 = 1$ μs, $\tau_2 = 50$ μs, $n = 1$, which is reported to be typical of lightning strokes [12]. The lightning strike is assumed to hit the top of the tower.

Fig. 8 shows the transient grounding resistance, defined as the ratio of the electrode potential rise and the discharge current. It can be seen that although the transient grounding

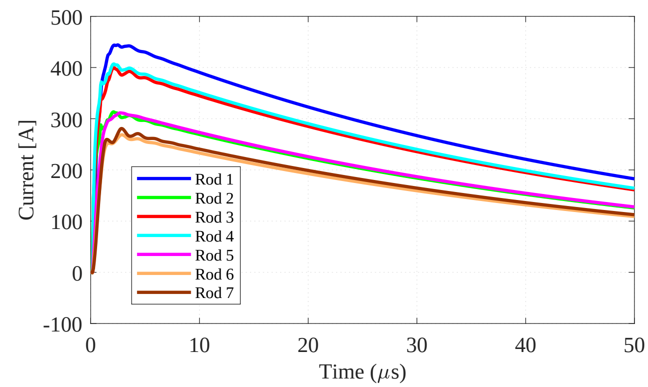

Figure 5. Current distribution along vertical rods in Fig. 3, for the proposed implementation. Results agree with the reference values of Fig. 4 .

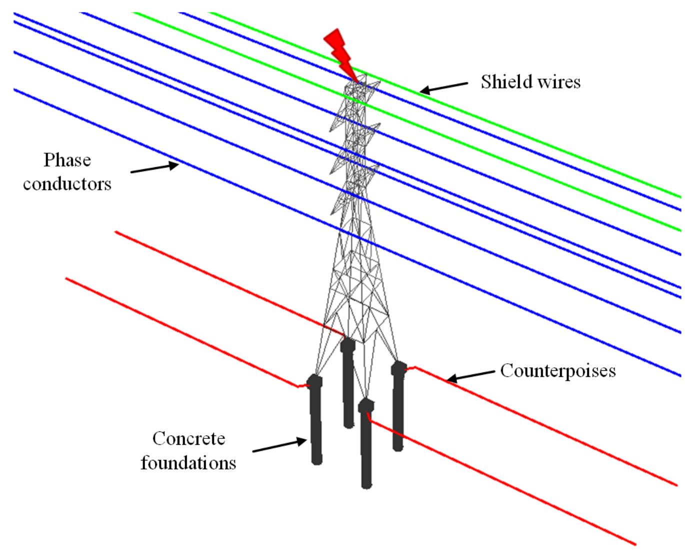

Figure 6. Transmission line tower, conductors, counterpoises and foundations.

resistance has the unit of ohms, it is not simply a pure resistance, as it shows a transient behavior before it stabilizes at a value of the order of 8 Ω.

Figs. 9 and 10 present, respectively, the currents injected into the soil by the counterpoises and the tower foundations. Figures are zoomed into the first 20 μs, which Fig. 8 demon-

Table I
PROPERTIES OF MATERIALS, COMPILED FROM [7]–[11]

Description	Material	σ (S/m)	ε_r	μ_r
Phase conductors	Aluminium	2.54×10^7	1	1.06
Shield wires	EHS Steel	4.09×10^6	1	63.29
Tower structure/steel-frames	EHS Steel	4.09×10^6	1	63.29
Counterpoises	Copper	5.80×10^7	1	1
Soil	Dry clay	2×10^{-3}	10	1
Foundations	Dry concrete	1×10^{-6}	4.5	1

Table II
DIMENSIONS OF CONDUCTORS

Description	**Radius (m)**
Phase conductors	1.2570×10^{-2}
Shield wires	0.4572×10^{-2}
Tower structure/steel-frames	0.05
Counterpoises	0.4572×10^{-2}

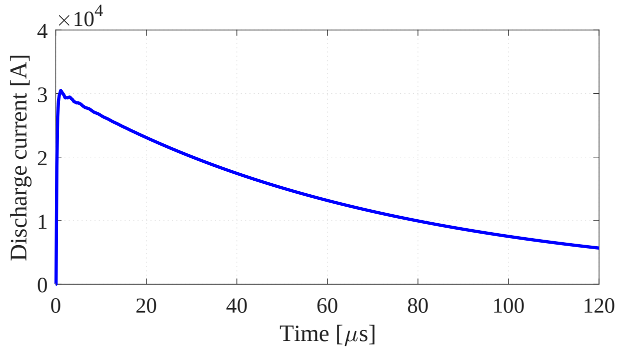

Figure 7. Lightning discharge waveform, with rise time 1 μs and half-value time 50 μs.

strates to be the period where the transients reach the most considerable magnitudes. They indicate that the counterpoises play the most significant role in discharging the lightning current to the ground, as expected, since it is the controlled grounding device. However, the contribution of the tower foundations, of the order of 32% of the current flowing through the counterpoises, is not to be neglected, even though the concrete in dry conditions is a poor conductor.

As a consequence of the current injection into the ground, touch and step voltages arise at the tower vicinity. Fig. 11 shows the touch voltage at 1 m apart from the tower. Fig. 12 presents the electric field intensity at the soil surface (z =0) at time $t = 1$ μs, corresponding to the instant when the discharge current reaches its peak value. Since the electric field is the gradient of the scalar potential, the figure also happens to describe the step voltage distribution around the tower.

Finally, Fig. 13 contains a side view of the electric field distribution around the tower. It can be seen that the energy flows throughout the external surface of the metallic tower, which works as a Faraday cage, as expected. Also, the shielding effect of the earth wires is evident, as the electric field intensities close to the phase conductors are considerably low.

Electromagnetic field magnitudes are maximum at the top of the tower and symmetrically distributed throughout the geometry. As time progresses, values fade away. With enough simulation time, values are expected to vanish completely.

IV. CONCLUSIONS

This work provided a review of basic lightning discharge mechanisms, with a FDTD implementation to simulate arbi-

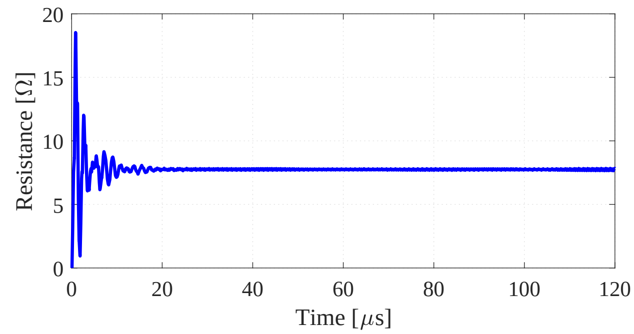

Figure 8. Transient grounding resistance of the earthing grid. Values oscillate over time until a stable value of 8 Ω is reached.

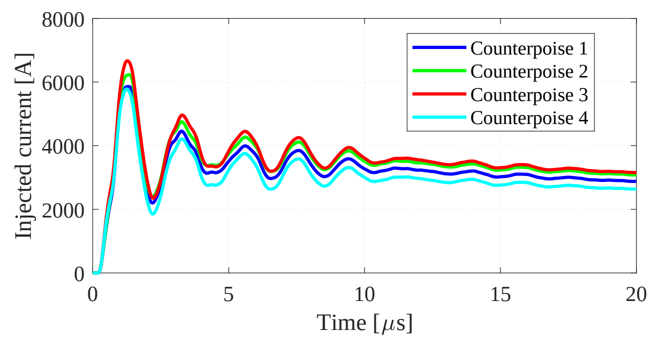

Figure 9. Currents injected into the soil by the counterpoises. Curves follow the trend of the lightning discharge, with a maximum value of 6.6 kA being injected by counterpoise 3.

trary geometries subject to lightning strikes. The code was validated by comparison with results reported in the literature, then a complex system was simulated. The system consisted of an LPS commonly employed in transmission lines, which is the shield wires above and parallel to the phase conductors,

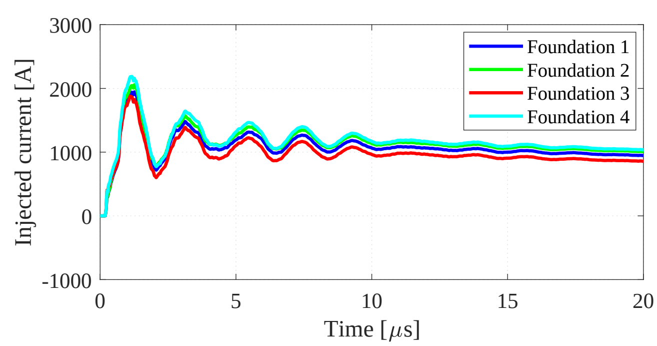

Figure 10. Currents injected into the soil by the tower foundations. Values are of the order of 32% of the ammount discharged by the counterpoises, even though the dry concrete is a poor conductor. Maximum value is 2.1 kA.

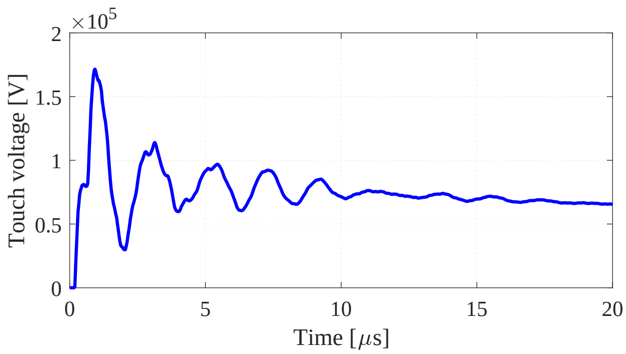

Figure 11. Touch voltage at the tower vicinity. Maximum value of 171.4 kV exceeds the tolerable limit (≈ 18.5 kV) for an exposure time of 110 μs.

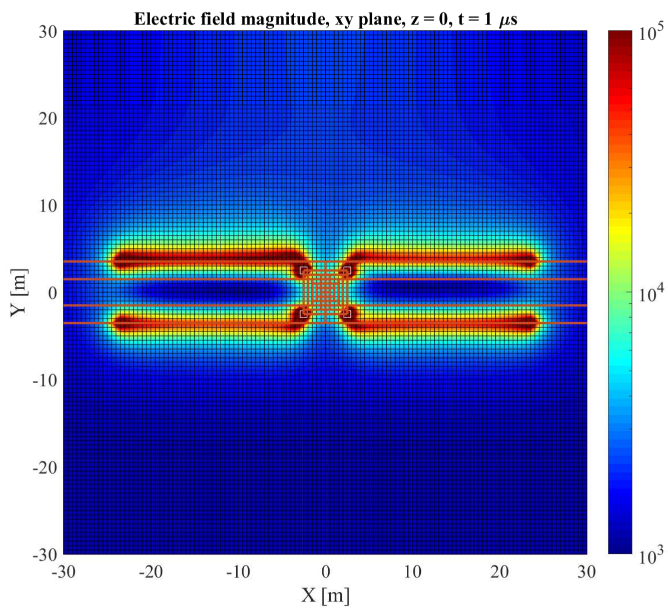

Figure 12. Top view of the electric field magnitude at the soil surface (step voltage), logarithmic color scale. The maximum value is 94 kV, exceeding the maximum step voltage limit. Highest magnitudes occur at the extremities of the conductors.

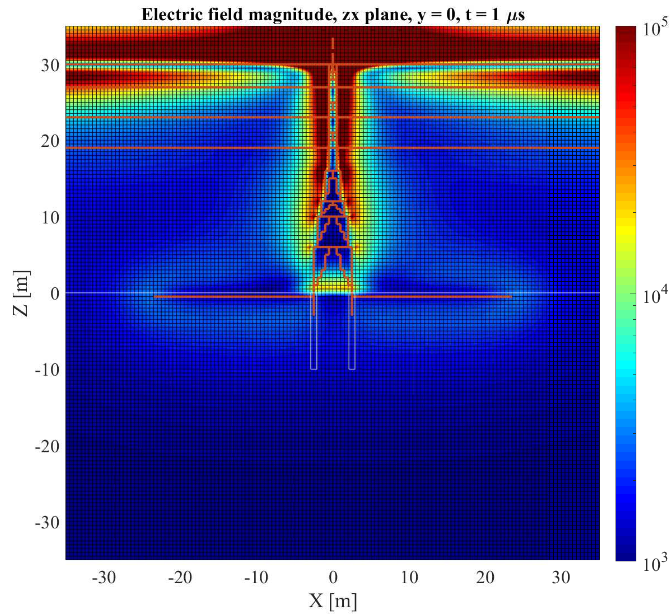

Figure 13. Side view of the electric field magnitude around the tower, logarithmic color scale. The shielding effect is visible close to the phase conductors and inside the tower structure (Faraday cage).

grounded at every tower by means of earthing conductors named counterpoises. Transient grounding resistance, currents injected into the soil, touch and step voltages and electric field distribution around the tower were analyzed, considering a typical lightning current. Results were coherent to the expected physical behavior and showed the hazards to which people are exposed when close to the system under study. The shielding effect of the transmission line earth wires was observed, as well as of the tower metallic structure.

The FDTD method proved to be a computationally expensive, yet powerful tool for determining the transient response of grounding grids subject to lightning strikes. One strength of this method that is worth to highlight is the ability to handle heterogeneities, such as layered structures and finite volumes of solids with different constitutive parameters. This became evident with the current distribution along the concrete foundations of the tower.

Further research and development of this work will include the transient interferences caused by the transmission line on nearby structures, such as pipelines and metallic fences.

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