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NOVEL LIGHTNING INCIDENCE MODEL BASED ON THE ELECTRIC FIELD GRADIENT: 2D ELECTROSTATIC ANALYSES

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Abstract - The lightning trajectory was, for a long time period, considered as a random and unpredictable phenomenon, making the estimated approaches with low precision. Therefore, to assist the design of the lightning protection system (LPS), several empirical models were developed to predict the lightning trajectory. This paper proposes a novel lightning incidence model based on the electric field gradient. Moreover, the proposed method is evaluated and compared with the classical methods.

1 - INTRODUCTION

Lightning strikes can injure humans and damage the electrical system. One lightning striking a power line may damage the equipments and shut down the power line. If lightning strikes a house or a building directly, it will cause its destruction by mechanical and thermal stresses, generating dangerous induced voltages.

It is estimated that in Brazil around 70% of disconnections in transmission power lines and 40% in distribution power linear are caused by lightning strikes. Moreover, it causes the damage of 40% of the transformers. Such numbers have a considerable impact on the power quality, which can be observed by the high correlation between the frequency of lightning and the DEC and FEC indices of most companies within the electricity sector [1].

The protection systems against lightning have been developed, and further studies are being conducted to improve their reliability, because there isn't a perfect lightning protection system (LPS). Therefore, studies which try to understand the lightning trajectory and formation can improve even more the current LPS.

The lightning trajectory was, for a long time period, considered as a random and unpredictable phenomenon, making the estimated approaches with low precision. Therefore, to assist the design of the LPS, several empirical models were developed to predict the lightning trajectory. Such models are called lighting incidence models.

The main purpose of this paper is to propose a novel lightning incidence model based on the electric field gradient. Then, we intend to evaluate different air terminal arrangements and choose the one which will result in an optimized LPS design. Furthermore, the proposed method will be evaluated and compared with traditional methods.

2 – INCIDENCE MODELS

The LPS have been reviewed by several researchers [2-4] and standards and there are three basic recommended methods for determining the position of the air termination system, and they are described as follows.

2.1 – THE PROTECTION ANGLE METHOD

The protection angle method was the first method to determining the protection zone [5,6]. The protection angle (cone angle) is the angle created between the tip of the vertical rod and the line projected down to the surface on which the air rod sits. It is assumed that the lightning should hit the air rod and the area below the apex of the cone is protected.

The protection angle varies changing the height of the air rod and the class of LPS (between 23° and 80°). Moreover, it is suitable for simple shaped buildings (<60m of height) and it is not recommended for transmission lines (TL) [7]. In this case, it is used earth wires, with its position determined by the electrogeometric model which is suitable to define protection zones for all types of structure.

2.2 – ELECTROGEOMETRIC MODEL

Gilman and Whitehead [8] published the electrogeometric model (EGM) in 1973 applied to high voltage transmission power lines. The EGM was first accepted for power lines and it was adapted for general buildings. The EGM is based in the striking distance concept which consists to estimate the distance between the downward leader and the reference plane, if one building is beyond this estimated distance (R_a), the downward leader may strikes the building [9,10]. Several literatures [10,11] use the empirical expression given by (1) to estimate the value of R_a (m).

$$R_a = A.I_p{}^B, \qquad (1)$$

Where I_P is the peak current of the lightning in kA, A and B are empirical constant parameters [10,11].

2.3 – ROLLING SPHERE METHOD

The RSM is a simple way to identify areas of a structure that need protection including the possibility of side strikes to the structure. The RSM is a simplification of the EGM applied to massive buildings with complex geometry. It uses the striking distance as the EGM, but the protection geometry is represented by imaginary spheres of radius *S* over the surface of a structure, where a piece of equipment is said to be protected from a direct stroke if it remains below the curved surface of the sphere [9,10].

The class and radii of LPS for the RSM are I(20m), II(30m), III(45m), IV(60m), these radii are determined by (I).

2.4 – LEADER PROGRESSION MODEL

The Leader Progression Model (LPM) was presented by Dellera and Garbanati [12,13].This model is used for specific cases where the EGM simplifications can induce significant errors, i.e. transmission lines along hills and mountains. The basic idea behind this model consists to represent the evolution of the downward lightning channel by consecutives steps to obtain the possible lightning trajectory lines. Such steps have around 50m distance. The downward leader direction is determined checking the highest average value of the electric field module [11-13].

The LPM analyses the lightning strike over two variables: the shielding failure width (SFW) and the lateral distance (LD). O SFW is the longitudinal interval which contains the paths that reach the structure. LD is the longitudinal boundary which contains the furthest path [12]. The disadvantage of the LPM is the simulation time required to calculate each step.

3 – PROPOSED METHOD

A novel incident model based on the electric filed gradient, then the model is based on the property of the lightning follow the path with lower dielectric strength for a given electric potential difference (EPD).

Considering a positive downward leader generated by a thundercloud with V_N of potential is flowing in direction of a grounded structure, as shown in Figure 1. At time t, the tip of the leader is located at position $\vec{r}_t$ where the potential is $V_L(\vec{r}_t)$and the electrical field is $\vec{E}_L(\vec{r}_t)$.

After a time interval Δt, the electric field $\vec{E}_L(\vec{r}_t)$ causes a step with of length $\lambda_t$to the new position $\vec{r}_{t+\Delta t}$, where the potential is now $V_L(\vec{r}_{t+\Delta t})$, due to the impedance Z_t.
Using the Ohm's law for the position $\vec{r}_t$ and $\vec{r}_{t+\Delta t}$,, the electric potential difference produces a electric current $i_L(\vec{r}_t)$ limited by the impedance Z_t.

The transition of the downward leader occurs due to the disruptive discharge through the air, thus the capacitance between the intervals is neglected. Furthermore, we will ignore the inductance effect. Therefore, the impedance is a pure resistance, i.e. $Z_t \approx R_t$.

Regarding the first Ohm's Law, the potential is given by:

$$V_L(\vec{r}_t) - V_L(\vec{r}_{t+\Delta t}) = R_t i_L(\vec{r}_t). \quad (2)$$

Multiplying the equation (2) by -1 and applying the vector operator gradient, it is obtained the direction of the greatest rate of increase of the magnitude of the electric field.

At the position $\vec{r}_{t+\Delta t}$, where the medium is homogeneous and isotropic, the all over direction resistance have the same value and the lightning flows where the current is higher, that is:

$$\vec{E}_L(\vec{r}_{t+\Delta t}) - \vec{E}_L(\vec{r}_t) = R_t \nabla i_L. \quad (3)$$

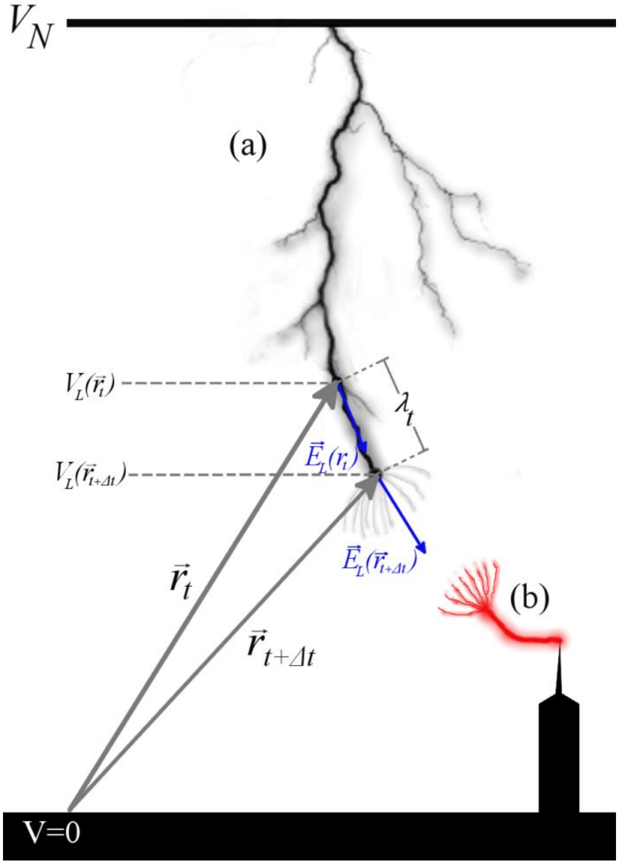

Figure 1 – Proposed Incidence model (a) downward leader (b) upward leader

Taking the second Ohm's Law, the resistance (R_t) in function of the step length (λ_t), the lightning ionized channel conductivity (σ_L) and the channel's transversal area (A_t), is given by,

$$R_t = \frac{\lambda_t}{\sigma_L A_t} \quad (4)$$

Then, by substituting (4) in (3), we obtain

$$\vec{E}_L(\vec{r}_{t+\Delta t}) - \vec{E}_L(\vec{r}_t) = \frac{\lambda_t}{\sigma_L A_t} \nabla i_L. \quad (5)$$

Rearranging again (5), we have

$$\vec{E}_L(\vec{r}_{t+\Delta t}) - \vec{E}_L(\vec{r}_t) = \lambda_t \nabla \frac{i_L(\vec{r}_t)}{\sigma_L A_t}. \quad (6)$$

The current density $J_L(\vec{r}_t)$ of the ionized channel is

$$\vec{J}_L(\vec{r}_t) = \frac{i_L(\vec{r}_t)}{A_t} \hat{A}_t \Rightarrow J_L(\vec{r}_t) = \frac{i_L(\vec{r}_t)}{A_t}. \quad (7)$$

From continuum form of the Ohm's Law, we can express the electric field in function of the current density, and the lightning ionized channel conductivity, that means,

$$\vec{J}_L(\vec{r}_t) = \sigma_L \vec{E}_L(\vec{r}_t) \Rightarrow \frac{J_L(\vec{r}_t)}{\sigma_L} = E_L(\vec{r}_t). \quad (8)$$

Substituting (7) in (8) and then in (6), we achieve the following equation

$$\vec{E}_L(\vec{r}_{t+\Delta t}) = \vec{E}_L(\vec{r}_t) + \lambda_t \nabla E_L(\vec{r}_t). \quad (9)$$

Equation (9) shows the electric field which is responsible to push the downward leader of a lightning. The term $\lambda_t \nabla E_L(\vec{r}_t)$ is named as deviation component and it shows that the lightning has a direction component pointing to the greatest rate of increase of the magnitude of the electric field.

The advantage of (9) above (6) is the reduced number of variables in the deviation component. Since the gradient in (6) acts on three variables (assuming σ_L and A_t as constant), the gradient in (9) handles only the magnitude of the electric field.

3.2 - AN ELETROSTATIC ANALYSES

When a downward positive lightning is leaving the cloud, there is no conduction pathway of ionized air. Thus, the electric field between the cloud and the ground is affected by the structures on the ground. This electrostatic field will be called as background electric field $\vec{E}_b(\vec{r}_t)$. If the influence of the generated electric field is neglected in the next steps, time-domain simulations for the lightning trajectory are not necessary. Therefore, it is possible to describe the lightning trajectory through an electrostatic model given by,

$$\vec{E}_L(\vec{r}_{t+\Delta t}) \approx \vec{E}_b(\vec{r}_t) + \lambda_t \nabla E_b(\vec{r}_t). \qquad (10)$$

The electric field of a lightning was approached in function the background electric field $\vec{E}_b(\vec{r}_t)$, which is only function of the position $\vec{r}_t$. Neglecting the inertial forces, the expression (9) can be simplified to an electrostatic model, as described in (10), even so, describing the lightning behavior as close as the reality. Hence, the estimation of the striking point in a structure is carried out by an electrostatic model. This assumption distinguishes the proposed method from the LPM.

The advantage of the electrostatic model described in (10) in comparison with (9) is the lower simulation time.

4–SIMULATION AND RESULTS

To evaluate the proposed model, the software COMSOL *Multiphysics®* is used. 2D finite element models of building and transmission lines were modeled by using the electrostatic problem. All simulations were carried out within a square domain of 250mx250m. The upper level of each domain is defined with 12,5MV, on the other hand, the lower level is the ground. In a thunder storm, the ground and the clouds can act like as a parallel plate capacitor. Unlike the regions around one structure, the potential inside the ground-earth capacitor changes linearly with the height,

$$V_{top} = \frac{V_{cloud}}{H_{cloud}} \cdot H_{grade}, \qquad (11)$$

where V_{cloud} the potential at the base cloud (-100MV) and the H_{cloud} is the typical altitude of a cloud about 2km [11] and H_{grade} is the height of the square domain.

The first simulation was carried out for a rectangular building with 20m height, 10m width and a house with 4m height, 8m width spaced by 7m from each other. The materials are: the air with relative permittivity equal to 1 and the structures are made of concrete with relative permittivity equal 6 [15].

The proposed model will be evaluated analyzing the space between the two structures.

In addition, the evaluation of the proposed model was carried out for transmission lines. For the 2D simulation, the TLs are composed by three conductors (phases), equally spaced by 11.5m and 40.5m above the reference plane. The TLs are protected by two earth wires with 14.50mm of diameter, spaced by 11.5m and 54.47m over the reference plane. This is a typical geometry of transmission lines of 500kV. The line materials have relative permittivity equal to 1.

In this paper, the simulations are carried out by using a personal computer (Intel four cores 3.33 GHz processor, 8 GB RAM and 4GB memory video).

4.1 – LIGHTNING INCIDENCE FOR MASSIVE BUILDINGS

In Fig. 2a, we have a structure without the LPS. The black lines are the background electric field lines $\vec{E}_b(\vec{r}_t)$. As depicted, these lines are smoothly curved near to the structure. Considering that the lightning is restrained only by the background electric field, the striking distance would be 9m, as shown in Fig 2a. However, applying the electric field gradient like in (10), we obtain the cyan lines. As shown in Fig 2a, there are many lines striking the building's corner. The higher diverted line has a distance of 27m.

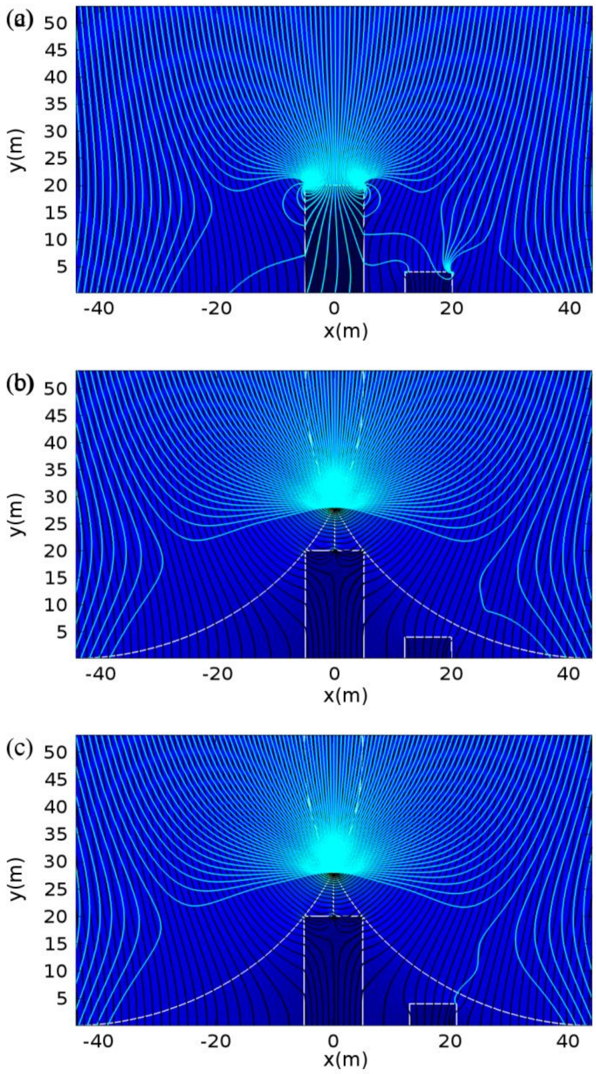

Figure 2 - Lightning trajectory estimation on massive strutures: (a) without LPS, (b) with LPS projected by RSM. (c) Possible failure case of the RS.

In Fig. 2b, the structure is protected by LPS system (rod with 8m height) installed at the top of the highest building and it is solid grounded. The white lines represent the path of the curved surface of the RSM with radius of 50m. This value is the typical step length [14]. With a LPS system, both structures are protected, since the air rod captures the lightning strike. However, if the space distance between the structures is increased to 8m, the RSM (white lines) shows that the house is still safe. On the other hand, the proposed model shown that the house had a side strike, as shown in Fig. 2c.

It was also evaluated, the influence of the absolute permittivity of the air through a probabilistic model with a standard deviation of 0.01. The result of this disturbance is a lightning trajectory similar to the real case, as shown in Fig. 3a. This result was not observed in the literature. Considering the probabilistic permittivity of the air, Fig. 3a shows that the RSM is valid for the proposed model. Nevertheless, if the standard deviation is higher than 0.01, we obtain patchy lightning trajectories, which did not hit the ground and the structures.

In Fig. 3b, the house is place at the edge of the RSM protection zone. Therefore, house's corner can be hit by the lines. The simulations presented in the Fig. 3a and Fig 3b shown the consistence between the RSM and the proposed model. Moreover, another aspect of such simulation is the fast simulation time around 5 s.

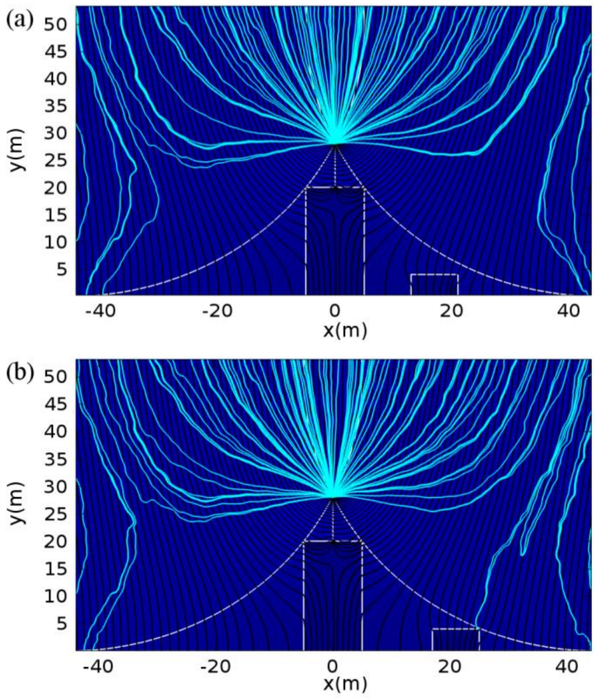

Figure 3 - Lightning trajectory estimation on massive strutures with a air relative permititvity standart deviation of 0.01. (a) Protected house, (b) Edge of protection.

4.2 – LIGHTNING INCIDENCE FOR TRANSMISSION LINES

This is a 2D simulation of the transversal cross-section of a 500V voltage TL. Nevertheless, we have considered zero the electric potentials of all lines. The grade base was grounded and the top potential was obtained by (11).

Figure 4 shows the proposed model in comparison with the LPM and the EGM. The evaluation of the proposed model was carried out for TLs in three different orographic locations presented in the literature (flat territory, on the ridge of hills, and mountain side) and comparing the proposed method with the EGM [13].

(i) Flat territory where the TL is over a flat ground at the sea level (Fig. 4a);
(ii) Along mountain sides where the TL is over a hill characterized by 30º of slope and 200 m of altitude (Fig. 4b);
(iii) Along the ridge where the TL is at the top of the hill characterized by a hill with 400m of altitude (Fig. 4c).

For the flat territory, the lightning trajectory (cyan lines) starts at level 250m, while Fig. 4a shows only the level below 110m. The phase conductors are marked as A, B, C and the earth wires as E and D. The white arc lines (striking distance) whose centers are at phase A and C are PQ and ST, and the arc lines QR and RT have their center in the earth conductors.

Above the flat territory, the TLs are protected by a shield of 1m, since no lightning stroke the phase lines. Since, the striking distances of PQ and ST are too small (around 3m) the probability of a lightning strike is small. In addition, such result is similar to the LPM model described in [12].

Figure 3b depicts the situation of TLs installed at positive ground obliquities (slope>0°), in this case with a slope of 30°. From Fig. 3b, the arc line ST is cut off and the arc line PQ increases to 29m.

For the proposed model, six cyan lines have touched the phase conductor A in different trajectories. In this case, the phase conductor C is completely protected. In fig. 4c the TL is at the top of the hill, the arc lines PQ and ST are larger than the first case, now the phase conductors A and C are very vulnerable to lightning strikes.

All simulations results illustrated in fig. 4 didn't take into account the general shape of the TL tower to estimate de lightning trajectory. For this purpose, a new numerical simulation was carried out. The cable geometry was kept as the same as the latter simulation.

It can be observed that even with the metal structure of the TL tower, the conductors are protected with a shielding failure less than 1m. Therefore, no cyan line hit the phase conductors.

Another important aspect of the developed lightning incidence model based on the electric field gradient is its fast simulation time. The simulation time for each result shown in Figures 4 and 5, was around 27s. This short time was achieved due to electrostatic analyses utilized to determine the lightning trajectory. In case of a time-domain simulation to show the evolution of the downward or upward leader, the simulation time would be higher, since it is necessary to calculate each step of a downward moving leader. Similar results have been published for the LPM [12,13], thus the proposed model based on the electric field gradient is valid, for electrostatic analyses.

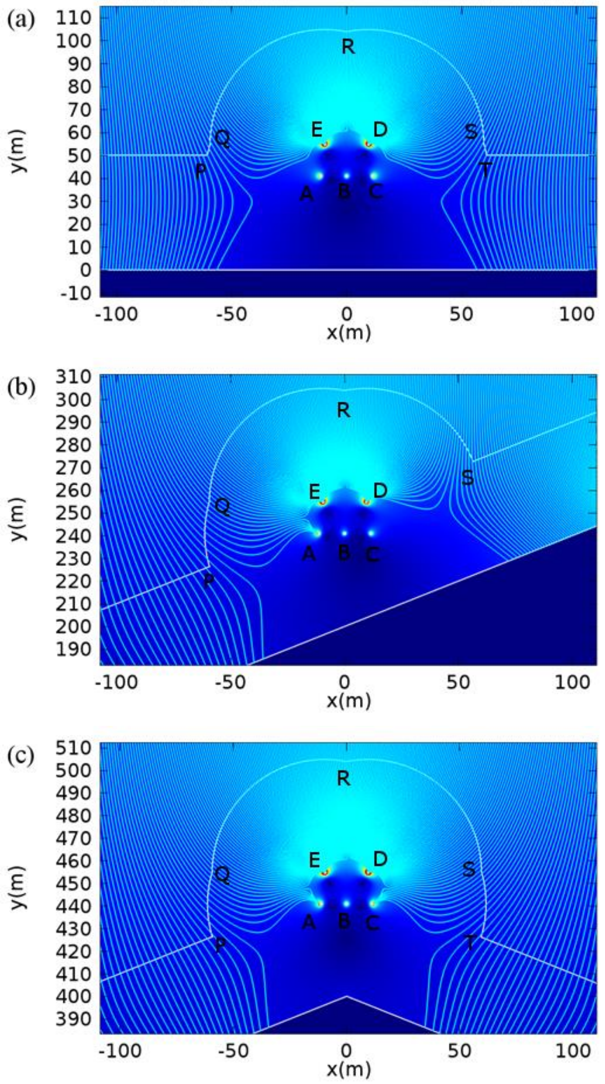

Figure 4 – Lightning trajectory estimation on 500V transmission lines.

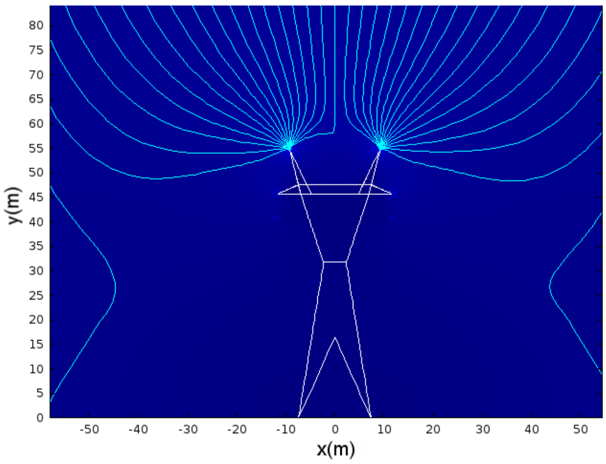

Figure 5 - Lightning trajectory estimation for the tower of transmission lines.

5 - CONCLUSIONS

The novel lightning incidence model based on the electric field gradient and the electrostatic analyses described in this manuscript had similar results, whether using traditional LPM or classical methods to determine the lightning trajectory.

The model electrostatic analysis has a faster simulation time and is easier to implement in the finite element method. For the 2D simulations the most simulation time was around 27s, using a basic PC hardware configuration.

Due to the good simulation performances, the proposed lightning incidence model will be applied to 3D model for structures like: tower of transmission lines, hangars, oil distillation tower, etc. Finally, the position, the protection zone and the design of LPS can be evaluated by the proposed model.

7 – ACKNOWLEDGMENT

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8 - REFERENCES

[1] ELAT. *Sistema Elétrico*. 2014. Disponível em:< www.inpe.br/webelat/homepage>, Acess in April the 14th 2016

[2] GOLDE, R.H.,“Lightning Protection”, London, U.K.: *Edward Arnold*, 1973

[3] UMAN, M.A. “The Art and Sciense of Lightning Protection”. Cambridge, U.K.: *Cambrige University Press*, 2008.

[4] COORAY, V.“Lightning protection”,*The Institution of Engineering and Technology*. 2009.

[5] CAVENDISH,H., WATSON, W., FRANKLIN, B.,and ROBERTSON, J.,“Report of the committee apponited by the Royal Society to consider a method of securing the power magazine at Purfleet”,*Phil. Trans. Roy. Soc.* 63, 1773

[6] GOLDE,R.H.,“The lightning protection of tall structures:In Review of Lightning Protection Tecnology for Tall Structures”,ed. J. Hughes, Publ. no. AD.-A075 449, *Office of Naval Reseach*, Arlington, Virginia. pp. 242-9, 1977b

[7] NBR 5419-3, “Lightning Protection Part 3: Physcal damage to structures and life hazard”, *ANBT*, 2015

[8] GILMAN, D.W.,and WHITEHEAD, R.E.,“The mechanism of lightning flashover on high-voltage and extra-high-voltage transmission lines”,*Electra* 27.3,pp. 65-96, 1973

[9] LEE, R.H.,“Lightning Protection of Buildings”,*IEEE Transactions on Industry Application,* Vol. IA-15, NO. 3. 1979

[10] VISACRO, S.,“Descargas atmosféricas: Uma Abordagem de Engenharia”,*Artliber,* 2005

[11] POTIER, G.C., GAZZANA, D.S.,DIAS, G.A.D., and SILVA, L.C.F,“Física dos Raios & Engenharia de Proteção”,*ediPURS*, 2010

[12] DELLERA,L., and GARBAGNATI,E.,“Lightning stroke simulation by means of the leader progression model. I. Description of the model and evaluation of exposure of free-standing structures”,*Power Delivery, IEEE Transactions on* 5.4, 1990, pp. 2009-2022

[13] DELLERA,L.,and GARBAGNATI, E.,“Lightning stroke simulation by means of the leader progression model. II. Exposure and shielding failure evaluation of overhead lines with assessment of application graphs”,*Power Delivery, IEEE Transactions on* 5.4, 1990, pp. 2023-2029

[14] RAKOV, V.A., and UMAN, M. A. “Lightning: physics and effects”. *Cambridge University Press*. 2007

[15] DAVES, J.L.,and ANNAN,A. P.,“Ground-Penetrating Radar for High-resolution mapping of soil and rock stratigraphy”,*Geophysical Prospecting*. Vol 37, Issue 5, 1989, pp. 531-551

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