Design of a Reduced Scale Model To Measure Lightning Electric Fields Over An Inclined Terrain

Edison Soto
Department of Electrical,
Electronic and Computer Engineering
Manizales, Colombia
Email: easotor@unal.edu.co

Ernesto Perez
and Javier Herrera
Department of Mechanical
and Electrical Engineering
Medellin, Colombia
Email: eperezg@unal.edu.co, jherreram@unal.edu.co

***Abstract*—Lightning electromagnetic fields have been calculated traditionally considering that terrain is flat. It is important to consider the influence of the orography in the lightning electric fields, specially in countries that are surrounded by mountains. Although, a first approximation to the phenomenal can be obtained by means of the use of numerical methods, a reliable measurement of those fields can be obtained by means of experimentation. In this paper, we present the design of a reduced scale model to measure electric fields near inclined terrains. Also, simulations done by means of the FDTD method are presented with the aim to show the expected measurements of the reduced scale model.**

***Index Terms*—Electromagnetic fields, lightning induced voltages, non-flat terrains, inclined terrains, Reduced Scale Model, Finite Difference Time Domain Method (FDTD).**

I. Introduction

The electromagnetic field produced by lightning has been studied by several authors aimed to calculate lightning induced voltages in transmission and distribution lines, phone lines and near electrical systems [1–3]. There is an important influence of the electromagnetic field in the amplitude and wave shape of the lightning induced voltages. The lightning electromagnetic fields have been calculated considering that the terrains are flat [1, 3–5]. Nevertheless, it is not the case of many places in the world, as the Andean and the Alpes region, that are surrounded by mountains and where the flat terrain approximation could not be reasonable and it is expected that the electric fields will be different. For this reason, it is important to calculate and to measure the electric fields near non-flat terrains.

Different studies, have been conducted in order to have a reasonably estimation of lightning electromagnetic pulse (LEMP). One of the most classical approach has been done using analytical expressions based on dipole technique [6–8], considering lightning as a straight vertical antenna over a perfectly conducting ground plane. In order to take into account ground conductivity, Cooray-Rubinstein [9–11] introduced a formula for calculating the horizontal electric field over non-perfect soil. Some other approaches use more complicated schemes [12] solving the so-called Sommerfeld integrals[13]. However, these approaches, in general use a flat terrain. In order to include more complex configurations, and non-homogeneous propagation media, it is possible to use numerical methods for solving Maxwell equations. For example, for LEMP calculations it has been used Finite Element Method (FEM) [14, 15], method of moments [16, 17], and the Finite Difference Time Domain method (FDTD)[18–22], which will be used in this paper. The FDTD for solving Maxwell equations, has been introduced by Yee [23, 24] and has become popular for calculating electromagnetic fields [25]. Several applications of the method has been presented to calculate lightning electromagnetic fields [18–21], in general, considering flat terrain.

Although numerical or analytical approximations can be useful in many cases, a few models have been developed to calculate electromagnetic fields over non-flat terrains. For this reason, some measurements need to be done in order to obtain real behavior of the phenomenal. In this paper, we measure those fields by means of a reduced scale model. A reduced scale model is important to a) the validation of codes that calculate over-voltages induced by the lightning electromagnetic pulse (LEMP) and b) the prediction of the LEMP-induced voltages for those cases which, due to their extreme complexity, cannot be simulated with the existing version of these codes [26]. The scale factors can be derived by applying Maxwell's equations to the real system and the reduced-scale model and, then, by relating the quantities of interest in both systems [26]. The scale factors obtained when the medium is air are shown in Table I, where p is the ratio between the quantities in the model and in the full-scale system and α is the relation between electric and magnetic fields in the model and in the full scale system.

This paper present the design of a reduced scale model, which allows the measurement of lightning electric fields above a flat and non-flat terrain configuration, both over perfect and non perfect soil. The performance of the reduced scale model is simulated by means of the FDTD-3D method. The knowledge generated in this work, allows the improvement of overhead line indirect lightning performance and lightning location systems which is related with the improvement of Power Quality.

II. Reduced Scale Model

The choice of length scale factor depends on the available space and the minimal wave front that can be generated and measured [26][27]. Because the location of the reduced scale

TABLE I
SCALE FACTORS: RATIOS BETWEEN THE VALUES OF THE QUANTITIES IN THE MODEL AND IN THE FULL-SCALE SYSTEM. ADAPTED FROM [26][27]

Quantity	Relation
Length (l)	p
Time (t)	p
Electric Field (E)	α
Magnetic Field (**B**)	α
Resistance (R)	1
Capacitance (C)	p
Inductance (L)	p
Impedance (Z)	1
Propagation Velocity (v)	1
Frequency (f)	1/p
Conductivity(σ)	1/p
Voltage (V)	α.p
Current (I)	α.p
Resistivity (ρ)	p
Dielectric Constant (ϵ)	1
Magnetic Permeability (μ)	1
Wave Length (λ)	p

model will be the soccer field of the Faculty of Minas of National University of Colombia in Medelln, a scale factor p =α= 1:200 is allowed. The reduced scale model is composed by the following components [26][27]:

A. Ground Plane

A rectangular plane 3x10 m^2 will be constructed, by means of interconnected aluminum plates (corresponding to 600x2000 m^2 in the full-scale system). Due to scale factor of conductivity shown in Table I, the aluminum plates can be considered as perfect electric conductors in the full scale model. The aluminum plates will be placed over a metallic table 0.8 m in height. The metallic structure will be inclined a suitable angle to verify the influence of the inclined terrain in the electromagnetic fields.

B. Return Stroke Channel

The return stroke channel consists of the union of two copper conductors wounded on an insulating rod of PVC. The height of each rod is 3 m. The injection of a step voltage at rod base has a current response as the shown in Fig. 1. According to this figure the travel time of the wave from the bottom of the channel and go back is approximately 200 ns. The return stroke velocity is equal to:

$$v = \frac{l}{\tau} = \frac{6m}{200ns} = 3x10^7 m/s \qquad (1)$$

The velocity measured along the channel is approximately 10 % of that of light in free space. The surge impedance can be obtained of the division between voltage and current in the first 200 ns, it is equal to 4 kΩ approximately.

C. Stroke Current Generation System

The current is generated by means of a voltage source injected into the base of the lightning channel. The source is a voltage multiplier circuit as the shown in Fig. 2. The circuit consists of 4 steps and generates a voltage of 680 V D.C.

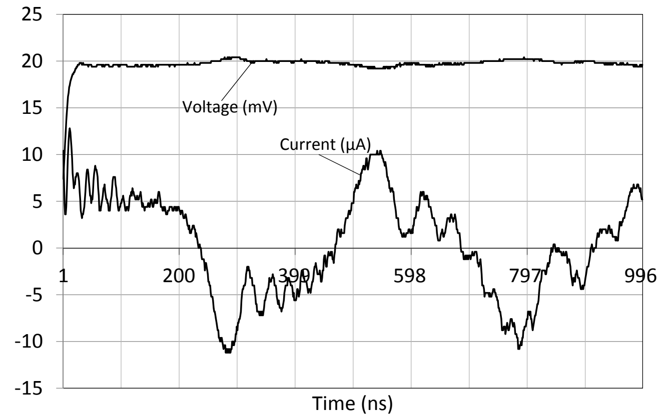

Fig. 1. Voltage injected and measured at channel base

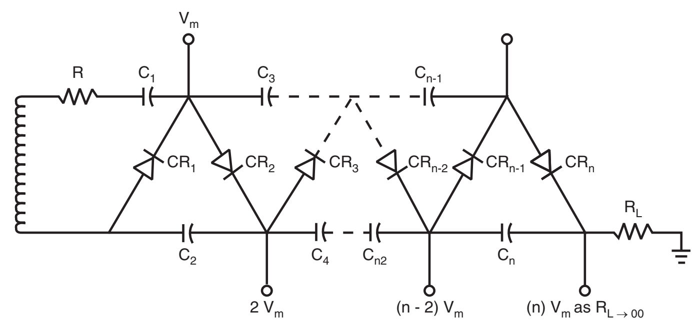

Fig. 2. Cascade multiplier circuit of n steps. Taken from (—-)

In order to obtain a voltage drop less than 10 % in a time of 0.7 ms, taking into account a load of the channel of 4 kΩ, capacitors of 6.8 μF were chosen. The simulated load current is shown in Fig. 3. The peak value of the current is 170 mA and a decrement of 6.7 % in the first 1ms is seen.

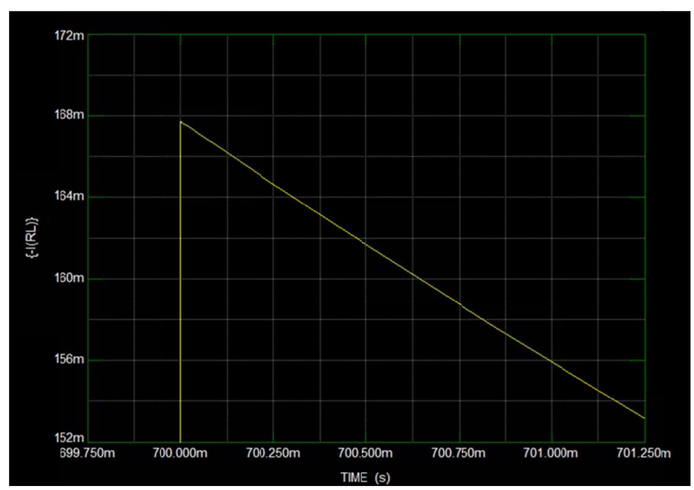

Fig. 3. Current measured at load end of the stroke current generation system

The voltage produced is injected into the lightning channel by means of a very fast switching dispositive MOSFET, which can produce a front time of approximately 20 ns.

D. Overhead distribution line

The line is a copper conductor, 5m long, 5 cm height and a radius of 0.4 mm. The line at full-scale will be equivalent to a 1km line, 10 m height and 80 mm radius.

E. Measuring System

The electric field is measured by means of a ring, concentric with return stroke channel. The measured voltage at this ring is proportional to electric field [26]. The induced voltage is measured at beginning and at end of line by means of an oscilloscope with a bandwidth of 100 MHz, 1GS/s and 1 mV/div.

III. Methodology for calculating lightning electromagnetic fields

In order to simulate the reduced scale model, the finite difference time domain method (FDTD) was employed in the 3-D Cartesian coordinates system [24]. It was simulated a metallic plate $3 \times 10\ m^2$ with a very high conductivity (σ=1e8), surrounded by a concrete space (corresponding to the soccer field where the model will be placed). The concrete conductivity was assumed to be σ=7,14 mS/m.

The grid dimensions were 15 (in x)$\times$10 (in y) $\times$6 (in z) m^3 (see Fig. 4) and the space step was set as $\triangle x = \triangle y = \triangle z = 0.05m$, due to the available computational capability. The inclined terrains was represented by staircases in 3D [24].

It has been simulated a lightning channel with a base current characterized by a peak value of 170 mA and a front time of 20 ns. (The obtained channel base current at reduced scale model). It can be represented by a Heidler function [20] given by the following parameters: $I_{01} = 160mA, \tau_{11} = 4.47ns, \tau_{12} = 200ns$. The lightning channel was placed at the middle of the working space. For simplicity, it was used a TL model to represent the return stroke current along the channel [28][29]. It has been simulated the height of the constructed channel (6 m) and the return stroke velocity measured (30 m/μs) at this channel (See Section II-B).

In order to validate the electromagnetic field obtained by FDTD code [23], it was compared the electric field calculated by the 3D-FDTD methodology with the integral equations developed by Uman [8] for LEMP calculation. The vertical electric field calculated at a distance of 1 m from the lightning channel described above, at ground level over a perfectly conducting flat terrain is shown in Fig. 5. It is possible to see a good agreement between the two methods.

IV. Results

Two configurations are simulated according to the arrangements to be implemented in the reduced scale model, as is shown below:

A. Flat ground

The first is the configuration described in Fig. 4, where a ground plane is placed in the middle of a working volume with a soil of concrete. The vertical electric field E_z measured at point P1 is seen in Fig. 6.

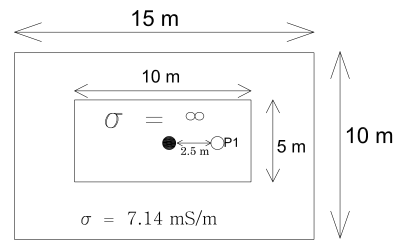

Fig. 4. Simulated space. The ground plane and lightning channel is at the middle of the working space

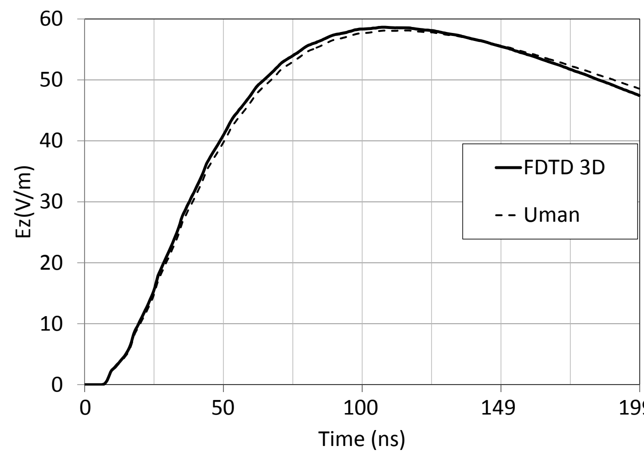

Fig. 5. Vertical Electric field E_z calculated at a distance of 1 m from the channel of the reduced scale model over a perfect conducting flat ground

B. Inclined terrain

The second configuration is the result of inclining the ground plane of the previous configuration, an angle α of 30°. It is presented in Fig. 7. With the aim of comparison, the perpendicular electric field E_p to the ground was calculated in each simulation (for flat terrain the perpendicular electric field E_p is equal to vertical electric field E_z). In Fig. 8 is presented the perpendicular electric field E_p obtained at points P1 and P2 compared with the vertical electrical field for flat terrain. The electric field at Point P2 is enhanced in magnitude compared with the case of flat terrain. It is explained by the closeness between lightning channel and measurement point *P2* . The perpendicular electric field E_p at point *P1* is decreased in magnitude compared with the case of flat terrain, this could be explained due to the lightning channel is farther from the measurement point *P1*. The tendency of the results presented previously in Fig. 8, coincides with inclined lightning channel studies published before [16][30]. It is explained because according to the method of images, an inclined lightning channel is equivalent to a vertical lightning that strikes an inclined terrain [31].

The tendency presented above is applicable to points located aside lightning channel (according to other simulations done, not presented). It implies that a line placed over an inclined terrain has a vertical electric profile highly variable from that obtained for flat terrain (due symmetry of the fields). For this

SICEL VII Simposio Internacional sobre Calidad de la Energía Eléctrica 2013

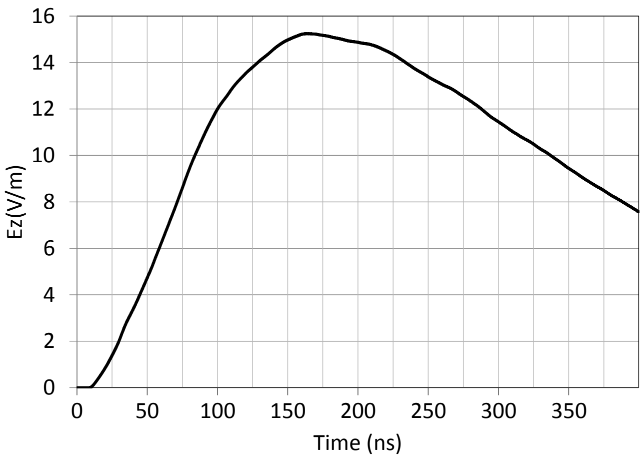

Fig. 6. Vertical Electric Field E_z measured at Point P1 in configuration presented in Fig. 4

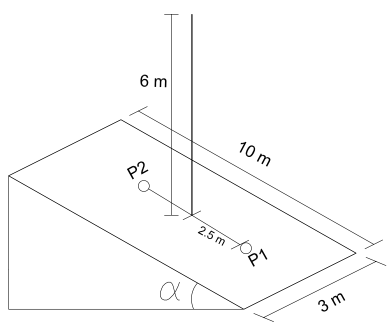

Fig. 7. Configuration of Inclined terrain. The electric fields are calculated at points P1 and P2.

reason it is expected a different magnitude and wave-shape of lightning induced voltages was found.

V. Conclusions

The design of a reduced scale model to measure the electric field over an inclined terrain has been presented. The results of this experiment serves as validation of numerical codes developed previously to determine the influence of the orography on lightning electromagnetic fields. This knowledge is useful to the improvement of lightning location systems and lightning induced voltages calculation.

A modeling of the reduced scale model has been presented. A ground plane that can be inclined an angle α surrounded by a space of concrete that represents the soccer field in that is placed the model is striked by the lighting channel constructed. The lightning current is generated by means of a voltage multiplier system. The overall space is simulated by means of the 3D FDTD method.

The results found of the electric field above an inclined terrain shows a significant difference respect the flat terrain case. The electric field calculated at point P1 decreases its value respect the flat terrain case, because the farness of the point to the lightning channel, while at point P2 the electric

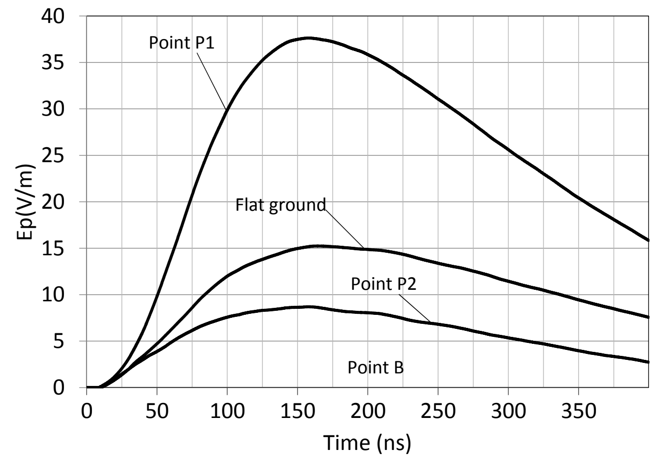

Fig. 8. Perpendicular electric field E_p calculated at Point P1 in configuration presented in Fig. 7

field increase its magnitude as a result of the closeness with the lightning channel.

It is expected that the results obtained by Finite Difference time domain method in 3-D Cartesian coordinates system, could be validated by the constructed reduced scale model. So that reliable and real data could be used to improve the performance of distribution networks placed over non-flat terrains.

Acknowledgment

The first author would like to thank COLCIENCIAS for academic support given for this research.

References

[1] C. A. Nucci, F. Rachidi, and M. V. Ianoz, "Lightning Induced Voltages on Overhead Lines," *IEEE Trans. Electromagn. Compat.*, vol. 35, no. 1, pp. 75–86, 1993.

[2] Y. Baba and V. A. Rakov, "Voltages Induced on an Overhead Wire by Lightning Strikes to a Nearby Tall Grounded Object," *IEEE Trans. Electromagn. Compat.*, vol. 48, no. 1, pp. 212–224, 2006.

[3] V. Cooray and V. Scuka, "Lightning-Induced Overvoltages in Power Lines : Validity of Various Approximations Made in Overvoltage Calculations," *IEEE Trans. Electromagn. Compat.*, vol. 40, pp. 355–363, 1998.

[4] A. Borghetti, C. Nucci, and M. Paolone, "An Improved Procedure for the Assessment of Overhead Line Indirect Lightning Performance and Its Comparison with the IEEE Std . 1410 Method," vol. 22, no. 1, pp. 684–692, 2007.

[5] P. Yutthagowith, A. Ametani, N. Nagaoka, and B. Yoshihiro, "Lightning-Induced Voltage Over Lossy Ground by a Hybrid Electromagnetic Circuit Model Method With Cooray Rubinstein Formula," vol. 51, pp. 975–985., 2009.

[6] M. J. Master and M. A. Uman, "Transient electric and magnetic elds associated with establishing a nite electrostatic dipole," *American Journal of Physics*, vol. 51, no. 118126., 1983.

[7] M. Rubinstein, "Methods for Calculating Electromagnetic Fields from a Known Source Distribution: Application to Lightning," *IEEE Transactions on Electromagnetic Compatibility*, vol. 31, no. 2, 1989.

[8] M. Uman and E. Krider, "The Electromagnetic Radiation from a finite antenna," *AJP*, vol. 43, 1975.

[9] V. Cooray, "Horizontal Field generated by Return Strokes," *Radio Science*, vol. 27, no. 5, pp. 529–537, 1992.

[10] M. Rubinstein, “An Approximate Formula for the Calculation of the Horizontal Electric Field from Lightning at Close, Intermediate, and Long Range.” *IEEE Transactions on Electromagnetic Compatibility*, vol. 38, pp. 12–16, 1996.
[11] V. Cooray, “Some considerations on the CoorayRubinstein approximation used in deriving the horizontal electric eld over nitely conducting ground,” *IEEE Transactions on Electromagnetic Compatibility*, vol. 44, no. 4, pp. 560–566, 2002.
[12] M. R. F. Delno, R. Procopio, “Lightning return stroke current radiation in presence of a conducting ground: 1. Theory and numerical evaluation of the electromagnetic elds (2008) .” *Journal of Geophysical Research*, vol. 113, no. D05110, pp. 1–10, 2008.
[13] A. Sommerfeld, “Uber die ausbreitung der wellen in der drahtlosen telegraphie,” *Annals of Physics*, vol. 28, p. 665, 1909.
[14] D. J. R. J.-M. Jin, *Finite Element Analysis of Antenna and Arrays , 2009.* John Wiley & Sons In, Hoboken, 2009.
[15] F. Napolitano, A. Borghetti, C. Nucci, F. Rachidi, and M. Paolone., “Use of the full-wave Finite Element Method for the numerical electromagnetic analysis of LEMP and its coupling to overhead lines.” *Electric Power Systems Research*, no. ISSN: 03787796, 2012.
[16] R. Moini, S. Sadeghi, B. Kordi, and F. Rachidi, “An antenna-theory approach for modeling inclined lightning return stroke channels,” *Electric Power Systems Research*, vol. 76, no. 11, pp. 945–952, Jul. 2006.
[17] Y. Baba, M. Ishii, and S. Member, “Numerical Electromagnetic Field Analysis of Lightning Current in Tall Structures,” vol. 16, no. 2, pp. 324–328, 2001.
[18] J. Cardoso and C. Sartori, “An analytical-FDTD method for near LEMP calculation,” *IEEE Transactions on Magnetics*, vol. 36, no. 4, pp. 1631–1634, Jul. 2000.
[19] C. Yang and B. Zhou, “Calculation Methods of Electromagnetic Fields Very Close to Lightning,” *IEEE Transactions on Electromagnetic Compatibility*, vol. 46, no. 1, pp. 133–141, 2004.
[20] F. Heidler, J. Cvetic, and B. V. Stanic, “Calculation of Lightning Current Parameters,” *IEEE Transactions on Electromagnetic Compatibility*, vol. 14, no. 2, 1999.
[21] A. Mimouni, F. Rachidi, and Z.-e. Azzouz, “Electromagnetic Environment in the Immediate Vicinity of a Lightning Return Stroke,” *Journal of Lightning Research*, vol. 2, pp. 64–75, 2007.
[22] Y. Baba and V. Rakov, “Influence of strike object grounding on close lightning electric fields, vol. 113,” *Journal of Geophysical Research*, vol. 113, no. D12109, doi:10.1029/2008JD009811, 2008.
[23] K. Yee, “Numerical Solution of Initial Boundary Value Problems Involving Maxwell’s Equations in Isotropic Media,” *IEEE Transactions on Antennas and Propagation*, vol. Ap-14, 1966.
[24] A. Taflove and S. C. Hagness, *Computation Electrodynamics: The finite-Difference Time Domain Method*, 2000.
[25] A. Z. Elsherbeni and V. Demir, *The Finite-Difference Time-Domain Method for Electromagnetics with MATLAB Simulations.*, Scitech, Ed. Scitech, 2008.
[26] A. Piantini, S. Member, J. M. Janiszewski, A. Borghetti, C. A. Nucci, and M. Paolone, “A Scale Model for the Study of the LEMP Response of Complex Power Distribution Networks,” *IEEE Trans. on Power Delivery*, vol. 22, no. 1, pp. 710–720, 2007.
[27] W. d. C. Boaventura, “Estudo da tensão induzida ém lihnas aéreas por descargas atmosféricas utilizando técnicas de modelo reduzido,” Ph.D. dissertation, 1990.
[28] M. Uman and D. Mclain, “Magnetic Field of Lightning Return stroke,” *Journal of Geophysical Research*, vol. 74, 1973.
[29] ——, “Calculations of Lightning Return Stroke Models,” *Journal of Geophysical Research*, vol. 85, 1985.
[30] M. Izadi M. Z. A. A. Kadir and C. G., “Evaluation Of Electromagnetic Fields Associated With Inclined Lightning Channel Using Second Order Fdtd-Hybrid Methods.” *Progress In Electromagnetics Research*, vol. 117, no. (May), pp. 209–236, 2011.
[31] E. Soto, “Electromagnetic field calculation produced by lightning in non flat terrain and the effect in the lightning induced voltages on distribution networks,” Ph.D. dissertation, 2010.