A Circuit Human Body Model for an Indirect Lightning Strike Analyzed by means of an FDTD Method

V. A. Alrim, S. A. Amanatiadis, A. X. Lalas, and C. S. Antonopoulos

Department of Electrical and Computer Engineering
Aristotle University of Thessaloniki, Thessaloniki, GR-54124, Greece
chanto@auth.gr

Abstract **─** In the present paper, a simplified lumped element human body, stroked by a lightning touch volage, is designed and analyzed using the finite-difference time-domain (FDTD) method. The extracted results are compared with an electronic circuit simultor validating our numerical method. Moreover, other touch voltage scenarios are investigated, measuring and comparing the current that flows through different body parts. Additionally, the induced current to a human body, being in the vicinity of a lightning stroked object, is accurately calculated through the FDTD algorithm. The inability of the circuit modeler to simulate non-contact configurations proves the necessity of our numerical algorithm, while the possibility of the electric discharge effect is introduced.

Index Terms **─** Circuit model, FDTD, high voltage, human body, lightning.

I. INTRODUCTION

Lightning is a natural phenomenon that may have a serious impact on human beings, because of its impressive appearance and mainly its severe threats imposed on life and structures [1-3]. Several mechanisms have been so far reported to explain its interaction with humans, like the direct strike that occurs when the lightning channel terminates on the body, exposing it at the full lightning current [4-6]. However, only a small percentage of the incidents are due to this case; consequently the more realistic touch voltage and side flash cases are examined in this work. The first one occurs if the person holds a lightning stroked object, while the latter when the human stands close to it and a discharge path is created between the object and the human.

The proposed method uses a simplified human model, realized with lumped elements [7]. The current flow through the human body is extracted by means of a home-made FDTD algorithm [8], while it is compared with an electronic circuit simulator for the simple case of a telephone-mediated strike. The results are almost identical proving the FDTD efficiency even under the condition of low frequencies. Likewise, utilizing our numerical algorithm, the current flow through various parts of the human body is measured for diverse cases of touch voltage strikes. Several scenarios have been studied such as the contact of the head and hand with a grounded or ungrounded stroked object, e.g., the aforementioned telephone device. Furthermore, a popular arrangement that involves the contact of the human hand with a grounded or an ungrounded stroked object is also thoroughly examined. For the above cases, the current which flows through different human body parts is measured via the FDTD method.

Moreover, the implemented algorithm is employed at problems of more complicated geometries and conditions, without making additional approximations, unlike its electronic simulation counterpart. Finally, a non-contact scenario is investigated revealing a further impact of a lightning strike. In particular, the induced current because of a side flash is computed, at several body parts, whereas the possibility of an electric discharge should not be ignored, due to its devastating effect on humans.

II. THEORETICAL ASPECTS

The circuit model of the human body related to a lightning strike, approximating the body parts via lumped elements, as in Fig. 1, has been proposed in [6], [7]. It consists of commonly accepted lines including an internal resistance split of approximately 1 kΩ between arms, torso, and legs as internal components. The skin resistivity parts are significantly larger than their internal counterparts, exhibiting a parallel resistance and capacitance of 10 kΩ and 0.25 μF, respectively, except for head's capacitance, which is increased.

Our test scenario involves a grounded telephone that mediates the lightning current to the human body, since the lightning may strike the telephone wire directly and as a result, its power passes in the telephone set. In normal operation the person holds the telephone with one hand (point 2 in Fig. 1 (b)), and presses the handset to the ear (point 1), creating a capacitive coupling of approximately 88 μF, in the case of the lightning strike.

Submitted On: February 26, 2015
Accepted On: January 9, 2016

This touch voltage application has a return path via the feet (point 3) or any other body part that touches an earthed structure. Another scenario examines a corresponding application, where the telephone device is not grounded or the floor insulation is adequately efficient, and the circuit only involves points 1 and 2. On the third one, the input voltage is connected directly at point 2, simulating the contact of the human with any ungrounded stroked object, while on the latter case the object is assumed grounded, so the return path is completed via the feet (point 3).

The second application does not involve the coupling capacitance, since the human is now not touching the stroked device or alternatively the stroked wire, but is standing in its vicinity at distance d, as illustrated in Fig. 1 (a).

The main extracted result from the numerical algorithm is the current that flows through several body parts for the examined situations. It is measured via the current density that flows through a circular loop, as

$$I = \iint \vec{J} \cdot d\vec{S} \,. \tag{1}$$

The strike is modelled as a double exponential function defined by its two time parameters t_1, t_2 and its peak value A. Although, in the literature the lightning is implemented as a current source, in our work a voltage source is selected, because the strike is mediated via the telephone or an alternative device. The double exponential voltage has the form [9] of:

$$v(t) = A(e^{-t/t_1} - e^{-t/t_2}) \,. \tag{2}$$

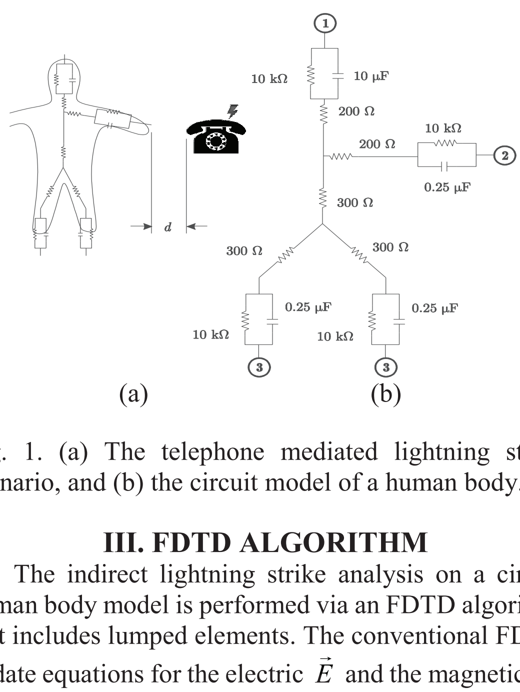


Fig. 1. (a) The telephone mediated lightning strike scenario, and (b) the circuit model of a human body.

III. FDTD ALGORITHM

The indirect lightning strike analysis on a circuit human body model is performed via an FDTD algorithm that includes lumped elements. The conventional FDTD update equations for the electric $\vec{E}$ and the magnetic $\vec{H}$ field are derived starting from the Maxwell equations:

$$\nabla \times \vec{E} = -\mu \frac{\partial \vec{H}}{\partial t}, \tag{2a}$$

$$\nabla \times \vec{H} = \varepsilon \frac{\partial \vec{E}}{\partial t} + \vec{J}, \tag{2b}$$

where ε and μ are the dielectric permittivity and the magnetic permeability of the medium respectively, while $\vec{J} = \sigma \vec{E}$ is conduction current, for conductivity σ.

Utilizing 1st order finite differences to approximate the original equations and the conventional Yee lattice [9] for the electric and the magnetic field components, their update equations are extracted straightforwardly as [8]:

$$E_x\Big|_{i,j,k}^{n+1} = \frac{2\varepsilon - \sigma\Delta t}{2\varepsilon + \sigma\Delta t} E_x\Big|_{i,j,k}^{n} + \frac{2\Delta t}{2\varepsilon + \sigma\Delta t}\frac{1}{\Delta h} \cdot \left(H_z\Big|_{i,j+1/2,k}^{n+1/2} - H_z\Big|_{i,j-1/2,k}^{n+1/2} - H_y\Big|_{i,j,k+1/2}^{n+1/2} - H_y\Big|_{i,j,k-1/2}^{n+1/2}\right), \tag{3}$$

for the E_x electric field component, while similar update equations are derived for the rest components. The lumped elements are imported in the equations as conduction currents $\vec{J}$ located at the desired electric field component locations, Fig. 2. Thus, assuming a lumped element positioned at an E_x component, the final update equation for this specific location is evaluated as:

$$E_x\Big|_{i,j,k}^{n+1} = E_x\Big|_{i,j,k}^{n+1} - I_x^{n+1}\left(E_x\Big|_{i,j,k}^{n+1}, E_x\Big|_{i,j,k}^{n}, \cdots, E_x\Big|_{i,j,k}^{1}\right), \tag{4}$$

where the function $I_x^{n+1}(\cdots)$ depends on the relation that connects the current and the voltage, namely

$$I_x^{n+1} = \frac{2\Delta t}{2\varepsilon + \sigma\Delta t} \frac{E_x\Big|_{i,j,k}^{n+1} + E_x\Big|_{i,j,k}^{n}}{2R}, \tag{5a}$$

$$I_x^{n+1} = \frac{C}{2\varepsilon + \sigma\Delta t}\left(E_x\Big|_{i,j,k}^{n+1} - E_x\Big|_{i,j,k}^{n-1}\right), \tag{5b}$$

for a resistor R and a capacitor C, respectively [10].

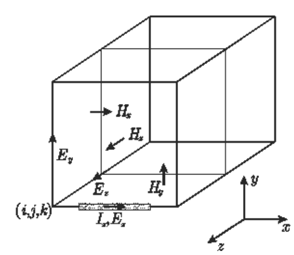


Fig. 2. The utilized Yee lattice.

IV. TOUCH VOLTAGE ANALYSIS

A. Numerical verification

Firstly, the initial touch voltage case is explored where the head and the arm are connected to the input voltage via 88 pF capacitances. The human body is realized as parallel lumped elements in the FDTD algorithm connected through lossless wires, while the dimension from head to feet is about 1.8 m to realistically model the average human height. The feet and input voltage touch the ground, modeled as a perfect electric conductor (PEC) boundary condition. The remaining boundaries are terminated with a 4-cell perfect matched layer (PML) to approximate the free space. Although, other terminating techniques can be utilized, such as MUR-I for dielectric materials [11, 12], PML is advantageous for domains involving lumped elements in free-space. The domain is divided in 60×52×37 cubic cells of 8 cm edge dimensions, while the time-step is set to Δt = 177.4 ps, a setup that is maintained throughout our analysis. The minimum wavelength of the analysis is extracted through a Fourier transformation of the input signal and the resulting wavelengths per unit cell are approximately 200. This value is expected due to the problem's relatively low frequencies, typically about 20 MHz for a double exponentially modeled lightning. On the other hand, the PSPICE electronic circuit simulator is utilized to compare the extracted FDTD results. The electronic simulator is selected for comparison due to its advantageous performance for closed loop lumped element scenarios. The input voltage is calculated via (2) setting $A = 9.5$ kV, $t_1 = 66.7$ μs and $t_2 = 0.54$ μs, leading to the typical double exponential waveform of Fig. 3, where the rise time is 0.25 μs and the pulse time is 50 μs [13].

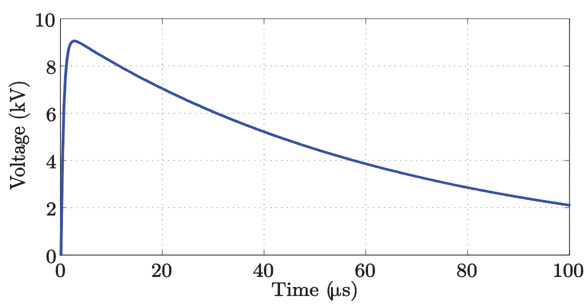


Fig. 3. Input voltage of the stroked telephone.

The comparison of the current flow in the human's arm between the two individual numerical methods, sketched in Fig. 4. As observed, the implemented FDTD method is effectively accurate at low frequency problems which use lumped element networks, revealing that a touch voltage strike is lethal for a human since the current outreaches 1 A.

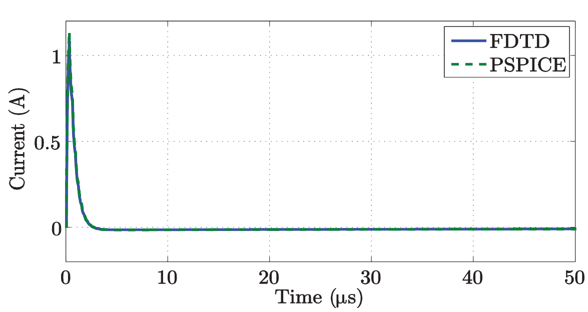


Fig. 4. Comparison of the current flow at the human hand in the touch voltage scenario between the implemented FDTD algorithm and the PSPICE simulator.

B. Touch voltage scenarios

After verifying the accuracy of the numerical algorithm, several different setups are examined to extend the applicability of the FDTD method. Initially, the previous setup is retained and the current flow through several different body parts is extracted via (1) and depicted in Fig. 5. One can easily discern that the current which flows through the torso is double the value of other body parts. This outcome is straightforward since the current from the head and arm is added, flows though torso, and then it is divided at the legs.

The next scenario involves the same telephone mediated strike except that the device is now ungrounded. The location of the source is assumed between the head and the hand and the current that flows through them, represented in Fig. 6, is significantly bigger than the one through the legs and torso since there is no return path via the ground. Although, this current is not larger than 25 mA, it should not be ignored and this is a major advantage of the FDTD algorithm compared to the electronic simulator. The latter is not capable of calculating the current outside closed loops, which is necessary on several complicated situations.

Additionally, the situation where the human simply touches a grounded lightning stroked object is investigated and the outcomes are sketched in Fig. 7. The human head is not included in the closed loop circuit, because of the return path through the feet, and the fact that its current is negligible. However, the current that flows across the hand and the torso exceeds 1 A and is obviously lethal for the human, while at feet the current is divided by half.

As a last touch voltage case, we study the impact of an ungrounded lightning stroked object when the human comes in contact with it. The results are corresponding to our previous scenario except that the current is now about 15 times decreased due to the ungrounded object, depicted in Fig. 8. The current flows again from the hand through the torso and it is divided at feet, with a maximum value of approximately 85 mA, which is adequate to disturb the human. As already mentioned, the FDTD algorithm is capable of calculating this considerable current, unlike the electronic simulator counterpart.

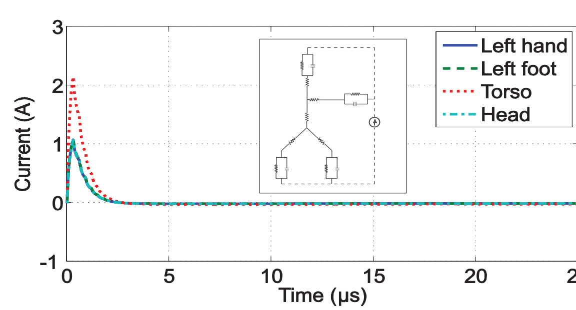


Fig. 5. Current flow through several body parts in the case of a grounded telephone mediated strike.

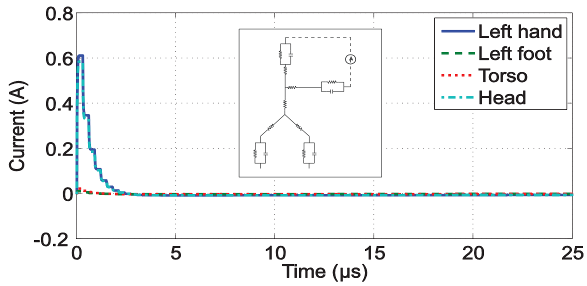


Fig. 6. Current flow through several body parts for ungrounded telephone mediated strike.

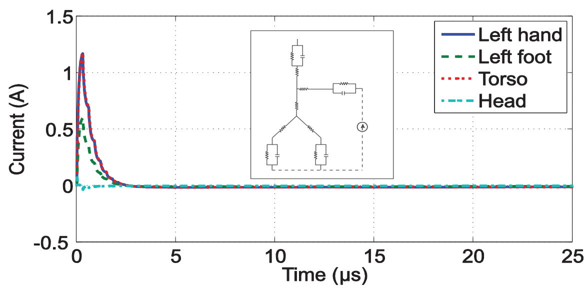


Fig. 7. Current flow through several body parts of a human touching a lightning stroked grounded device.

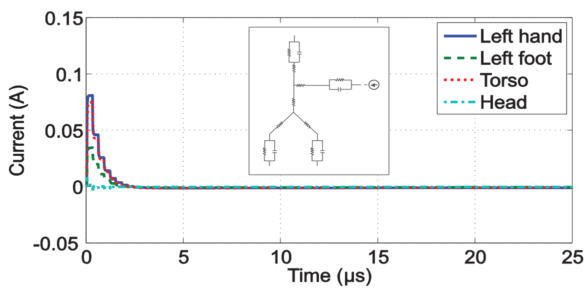


Fig. 8. Current flow through several body parts of a human touching a lightning stroked ungrounded device.

V. SIDE FLASH INVESTIGATION AND DISCHARGE POSSIBILITY

In the previous section, our numerical algorithm calculated the current that flows through body parts that are outside closed loops, revealing a first advantage compared to the electronic circuit simulator. Although, the simulation time of the latter is significantly reduced compared to the FDTD method, it is not capable of solving more complicated implementations, unless some approximations are applied, which can easily lead to degraded results. In this section, the side flash scenario is examined, where the lightning stroked object is not in direct contact with the human and the induced current to several body parts is extracted through (1), and depicted in Figs. 9 to 12. In this case, it is obvious that the current at each body part is increased drastically as the human approaches the stroked device, but is not lethal because of the effect's short duration and the current's low values. Specifically, the current through the arm is slightly exceeding 100 mA, even at distance $d = 10$ cm. Furthermore, at torso it is fairly increased for any distance, but it remains at low levels, while at legs it is divided by half with respect to the touch voltage scenarios. Finally, the current through the head remains at negligible levels, less than 10 mA.

It is critical to mention that the electric field between the arm and the device receives extremely high values, increasing the possibility of a hazardous electric discharge. Therefore and owing to its significance, the disruptive effect technique is briefly introduced in the present work [14]. In this manner, we are able to estimate the possibility of an electric discharge versus the temporal variation of the potential between two points $V(t)$, calculated through the electric field data of the numerical algorithm. According to this approach, the time integral DE of the difference between the evaluated potential $V(t)$ and a predefined voltage V_0 is:

$$DE = \int_{t_{on}}^{t_{off}} (V(t) - V_0)^k \, dt \, , \tag{6}$$

where k is another predefined parameter. If the integral in (3) exceeds a specific DE threshold, a hazardous electrostatic discharge is very likely to occur. The values of V_0, k, and DE are acquired through measurements, rather than analytically, and their accuracy depends on the problem under study [15, 16]. However, the relevant literature lacks data for the examined distances, and further measurements are necessary to estimate accurately the electric discharge possibility, which is outside the scope of the present work.

The distribution of the electric field at $t = 4$ μs, is illustrated in Fig. 13 (a) for the lightning stroked object at distance $d = 20$ cm. Here, the extremely high value of the potential difference between the hand and the source is revealed, confirming the increased possibility of an electric discharge. Moreover, in Fig. 13 (b), where the electric field distribution of a touch voltage scenario is depicted, one can observe the concentration of the field at the capacitors. At both cases, the zero electric field corresponds to the location of the conductors, as expected from the theory.

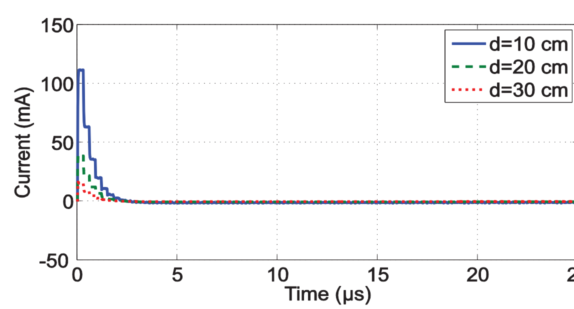


Fig. 9. Current flow through human's hand for induced by a stroked object at distance d.

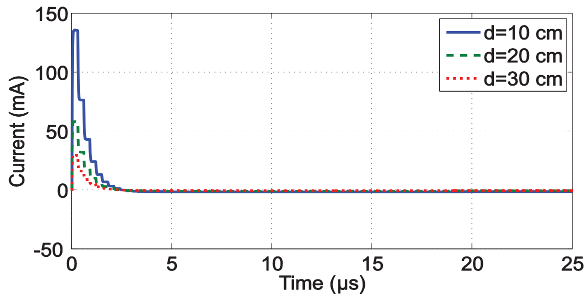


Fig. 10. Current flow through human's torso for induced by a stroked object at distance *d*.

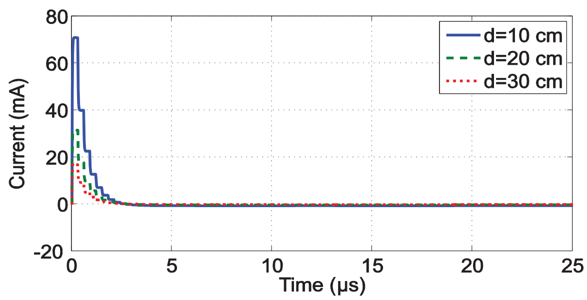


Fig. 11. Current flow through human's leg for induced by a stroked object at distance *d*.

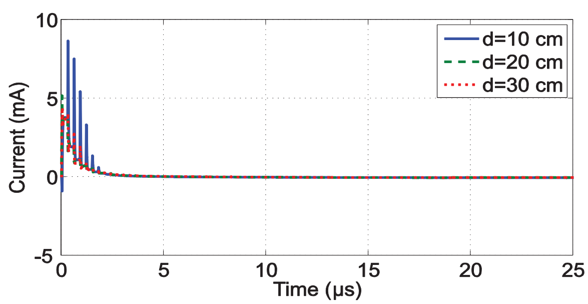
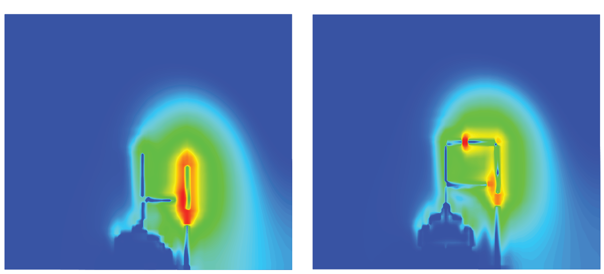


Fig. 12. Current flow through human's head for induced by a stroked object at distance *d*.



(a) (b)

Fig. 13. Distribution of electric field at: (a) side flash and (b) touch voltage scenarios.

VI. CONCLUSION

The circuit model of the human body, stroked by touch voltage of a lightning, has been modeled in the present paper. The results, extracted by the FDTD algorithm and the electronic circuit simulator, have been compared successfully, while the current flow through several body parts of various scenarios has been investigated. In the non-contact case of a side flash, the FDTD method has proven that applies effectively unlike the electronic circuit solver that is unable to solve it without inaccurate approximations. Moreover, a brief introduction to the disruptive effect technique has been involved in order to estimate the possibility of a hazardous electric discharge effect. Overall, the FDTD algorithm is more effective to solve complicated problems, even at low frequencies.

ACKNOWLEDGMENT

This research has been co-financed by the EU (European Social Fund - ESF) and Greek national funds through the Operational Program "Education and Lifelong Learning" of the National Strategic Reference Framework (NSRF) – Research Funding Program: ARISTEIA. Investing in knowledge society through the European Social Fund.

REFERENCES

[1] M. Szczerbiński, "Lightning hazards and risks to humans: Some case studies," *J. Electrostat.*, vol. 59, no. 1, pp. 15-23, 2003.

[2] C. Gomes and M. Ab Kadir, "A theoretical approach to estimate the annual lightning hazards on human beings," *Atmos. Res.*, vol. 101, no. 3, pp. 719-725, 2011.

[3] I. Pop, V. Topa, C. Munteanu, A. Racasan, and E. Merdan, "Human exposure to power frequency electric field inside very high voltage substations," *IEE Environ. Eng. Manag. J.*, vol. 10, no. 4, pp. 499-504, 2011.

[4] M. O. Goni, E. Kaneko, and A. Ametani, "Simulation of lightning return stroke currents and its effect to nearby overhead conductor," *ACES J.*, vol. 24, no. 5, pp. 302-307, 2009.

[5] S. Cristina and A. Orlandi, "Calculation of the induced effects due to a lightning stroke," *IEE Proc. B Electr. Power App.*, vol. 139, no. 4, pp. 374-380, 1992.

[6] V. Cooray, *The Lightning Flash*, IET Power Engineering Series, vol. 34, London, 2003.

[7] A. D. Dias, M. Tello, D. S. Gazzana, and G. C. Potier, "Revisiting lightning body model," in *Proc. X international Symposium on Lightning Protection*, Curitiba, Brazil, 2009.

[8] A. Taflove and S. C. Hagness, *Computional Electrodynamics: The Finite-Difference Time-Domain Method*, Artech House, Norwood, 1995.

[9] Kane S. Yee, "Numerical solution of initial boundary value problems involving Maxwell's equations in isotropic media," *IEEE Trans.*

Antennas Propag., vol. 14, no. 3, pp. 302-307, 1966.

[10] W. Sui, D. A. Christensen, and C. H. Durney, "Extending the two-dimensional FDTD method to hybrid electromagnetic systems with active and passive lumped elements," *IEEE Transactions on Microwave Theory and Techniques*, vol. 40, no. 4, pp. 724-730, 1992.

[11] B. Mukherjee and D. K. Vishwakarma, "Application of finite difference time domain to calculate the transmission coefficient of an electromagnetic wave impinging perpendicularly on a dielectric interface with modified MUR-I ABC," *Defence Science Journal*, vol. 62, no. 4, pp. 228-235, 2012.

[12] B. Mukherjee, "Numerical solution in FDTD for absorbing boundary condition over dielectric surfaces," *Journal of Advance Research in Scientific Computing*, vol. 4, pp. 13-23, 2012.

[13] W. Jia and Z. Xiaoqing, "Double-expression of lightning current waveforms," in *Proc. Conference on Environ-mental Electromagnetics (CEEM)*, Dalian, P. R. China, 2006.

[14] A. Jones, "Evaluation of the integration method for analysis of non-standard surge voltages," *AIEE Trans. Power App. Syst.*, vol. 73, pp. 980-990, 1954.

[15] R. Caldwell and M. Darveniza, "Experimental and analytical studies of the effect of non-standard waveshapes on the impulse strength of external insulation," *IEEE Trans. Power App. Syst.*, vol. PAS-92, no. 4, pp. 281-284, 1973.

[16] Z. Datsios, P. Mikropoulos, and T. Tsovilis, "Estimation of the minimum shielding failure flashover current for first and subsequent lightning strokes to overhead transmission lines," *Electr. Pow. Syst. Res.*, vol. 113, pp. 141-150, 2014.