Simulation of Lightning Return Stroke Currents and Its Effect to Nearby Overhead Conductor

[1]M. O. Goni, [2]E. Kaneko, and [3]A. Ametani

[1]Faculty of Electrical & Electronic Engineering,
Khulna University of Engineering & Technology, Bangladesh
[2]Faculty of Engineering, University of the Ryukyus, Okinawa, Japan
[3]Department of Electrical Engineering, Doshisha University, Kyoto, Japan
[1]osman@ieee.org, [2]kaneko@eee.u-ryukyu.ac.jp, [3]aametani@mail.doshisha.ac.jp

Abstract – A nearby lightning strike can induce significant currents in long horizontal and vertical conductors. Although the magnitude of the current in this case is much smaller than that encountered during a direct strike, the probability of occurrence and the frequency content are higher. In view of this, appropriate knowledge of the characteristics of such induced currents is relevant for the interpretation of recorded currents. Considering these, the present paper discusses a modeling procedure that permits simulation of lightning-induced voltages or currents on overhead lines due to nearby lightning strikes. The hypothesis of perfect conducting ground, generally adopted in studies on the subject, is discussed in order to better assess the validity of the simulation results. In this paper, a homogeneous non-perfect ground is also investigated for its influence on lightning-induced voltages. The procedure for analyses of the voltages induced on an overhead line by a nearby lightning return stroke with a striking point at unequal distances from the line terminations is presented. The analysis shows that lightning-induced voltages depend on the soil conductivity.

Keywords: Finite difference time domain (FDTD) method, ground conductivity, horizontal conductor, induced voltage, and nearby lightning strike.

I. INTRODUCTION

Sensitive and sophisticated electronic components are increasingly used in data-transmission networks, in power system equipment (circuit breakers, disconnectors, control and protection circuits), and in household appliances. These components, compared to electromechanical ones used in the past, may suffer logic upset or damage at significantly lower levels of induced electromagnetic interference particularly from transients. Transients caused by lightning (direct and/or indirect) can be one of the major causes of malfunction or even destruction of those components. In particular, lightning-induced voltages, which can cause micro-interruptions of the power supply or disruption in telecommunication or data-transmission networks during thunderstorms, have been seriously revisited due to the increasing demand by customers for good quality in the power supply and reliability in the transmission of information. The opening of the telecommunication market, followed now by that of the electrical power market is only accelerating this trend.

As a result, the evaluation of lightning induced disturbances on both overhead and buried conductors has recently been attracted considerable attention [1–4]. Typical examples are power transmission and distribution cables, submarine fiberoptic cables, and telecommunication cables. There is no clear explanation in the power system literature about the relation between the number of outages during thunderstorms and lightning flash density in the proximity of the failure place. However, a case reported in Sweden, in which one high-voltage and several distribution transformers exploded during a heavy thunderstorm, leaving 11000 people without electricity for 24 hours, is symptomatic of the impending danger of lightning, in particular as it occurred in a highly developed country. This case also shows that the interruption of information and electric supply in a modern society can have severe consequences. A lightning stroke in the proximity of a big hotel in Lausanne, Switzerland, induced a voltage in the satellite antenna and destroyed the TV sets in the building. Direct lightning strokes on trees during heavy thunderstorms caused accidents and death to human and animals in rural areas of Bangladesh. A two-year survey of lightning-induced voltages on telecommunication lines has been performed in the 1990s in France [4]. A total number of 16000 short events (lightning pulses on the telecommunication line, lightning and/or switching pulses on the mains) have been recorded at nine sites during the measurement period. From these events, 27 peak values exceeded 1.5 kV, with a maximum value of 3.5 kV, which represents a dangerous value for any kind of telecommunication equipment.

The interaction between lightning and installations can be any one of the following:

1) Direct, if a lightning stroke directly hits a line connected to the installation or the equipment.

1054-4887 ' 2009 ACES

2) Indirect, if the strike is at a distance and the currents are induced by the electromagnetic field generated by the lightning discharge.

To analyze the effects of indirect lightning strikes on transmission lines or various equipment, it is necessary to go through the following steps:

1) The development of lightning return-stroke models, which means the modeling of the spatial-temporal distribution of the current in the lightning channel.

2) Radiated electromagnetic fields by such a current distribution including propagation effects over a soil with finite conductivity.

3) The evaluation of the voltages induced on nearby overhead lines resulting from the coupling between the electromagnetic field and the line conductors.

The aim of this paper is to present the simulation results of currents and voltages showing the lightning induced disturbances on horizontal conductors either terminated or grounded at the ends. Even though extensive experimental investigations have been performed on the effect of nearby lightning on vertical conductors and/or, tower(e.g.,[4,5]), to the best of our knowledge, simulation characterization for horizontal overhead conductors with different conductivities is limited in the scientific literature.

An indirect lightning strike can induce appreciable currents in both horizontal and vertical conductors. The magnitudes of such induced currents are definitely much lower than those experienced during a direct hit. However, their frequency of occurrence is comparatively higher. Accurate knowledge of the characteristics of induced currents would help in the characterization and classification of currents recorded on instrumented conductors. Such knowledge would also be useful for the study of the electromagnetic noise/interference caused by the induced currents on electrical and electronic systems in the vicinity, and for systems mounted on the conductors (towers). For a rough estimate of the number of strikes in the surrounding area, the information on the annual frequency of induction due to a strike in the vicinity can be used in conjunction with the number of direct hits. In view of these facts, investigations on the characteristics of the induced effects seem to be essential.

II. METHOD OF ANALYSIS

Numerical electromagnetic analysis is becoming a powerful approach to analyze a transient which is hard to solve by a conventional circuit-theory based approach such as the Electromagnetic Transient Program (EMTP) [6]. It follows from a solution of Maxwell's equations for boundary conditions of the EM field at the surface of the conductor and the earth. However, it is still based on some idealistic hypotheses, such as homogeneous earth and ideal contact between the conductor and the soil. Additionally, only a few papers consider nonlinear phenomena [7].

Unfortunately, there is no systematically developed and reliable set of experimental data available that would serve as a standard, so we consider here the EM model as the basis for comparison.

Numerical electromagnetic analyses based on the Finite difference time domain (FDTD) method are effective to analyze the transient response of a large solid conductor or electrode. The accuracy of this method, applied to such an analysis, has been fully investigated in comparison with an experiment and shown to be satisfactory [8]. As this method requires long computation time and large memory capacity, the analysis is restricted to rather small spaces.

The FDTD method employs a simple way to discretize a differential form of Maxwell's equations. In the Cartesian coordinate system, it generally requires the entire space of interest to be divided into small rectangular cells and calculates the electric and magnetic fields of the cells using the discretized Maxwell's equations. As the material constant of each cell can be specified arbitrarily, a complex inhomogeneous medium can be easily analyzed. To analyze fields in an open space, an absorbing boundary has to be set on each plane which limits the space to be analyzed, so as to avoid reflection there. In the present analysis, the second-order Mur's method [9] is employed to represent absorbing planes.

So far in most of FDTD analyses of transient and steady-state voltages, large solid electrodes [8,10], which can be decomposed into small cubic cells, have been chosen and thin-wire electrodes have been dealt with. This is because an equivalent radius of a thin wire in a lossy medium has already been developed [11,12]. In the present paper, an equivalent radius for a thin wire in lossy medium is utilized with the help of the concept proposed for an aerial thin wire [11]. The validity is already tested by comparing grounding-resistance values obtained through FDTD simulations on simple buried structures with theoretical values [12,13]. The FDTD method also yields reasonably accurate lightning-induced voltages on a horizontal wire above ground by lightning strikes to a tall grounded object [14].

A. *Models for Analysis*

As an electromagnetic field produced by lightning is basically responsible for the current induction, a model to be employed for study must be based on the electromagnetic model. Thus, the present paper employs the electromagnetic model, which ensures reliable description of the associated field problem and has been successfully employed in the literature for the estimation of currents and fields in the vicinity [15-17].

In measuring a transient response of a horizontal electrode, a horizontal current lead wire and a horizontal voltage reference wire have been used [8,18], although it is desirable to place the horizontal conductors perpendicular to one another in order to reduce undesired inductions. Recently, Tsumura *et al.* [13] recommended that the perpendicular arrangement of the voltage reference wire is an appropriate one. However, the difference in the evaluated voltage peaks due to wire arrangements is only 6%.

A 1/50 reduced-scale model is considered here in order to simulate a lightning stroke initiated at ground level. The upward leader induces voltages on the nearby horizontal overhead line by the electromagnetic field.

Figure 1 shows a representative arrangement of the horizontal conductor system in which AB is considered to be a horizontal copper conductor of 4 m in length. Both ends of the conductor are terminated to the ground. The length of the vertical current lead wire is taken to be 5 m and is placed at a distance of 50 cm from the horizontal overhead line. Pulse current was injected from the bottom of the model channel with an internal impedance of 50 Ω. The vertical lightning channel is considered to be a perfectly conducting cylinder excited by a delta-gap step voltage source. The arbitrary voltage source produces a steep-front wave having a risetime of 4.1 ns to 119 V. The voltage waveform is sustained another 40 ns with a slow rise of the voltage to 180 V. Then it goes to zero [11]. The current pulse generator was modeled as a z-directional voltage source, of which the waveform was given by a piecewise linear approximation of its open voltage as in Fig. 2. The source waveform is assigned in such a way as to allow the propagation time through the entire horizontal and other associated conductor system.

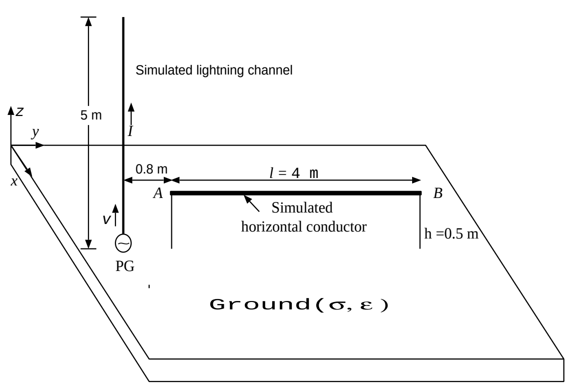
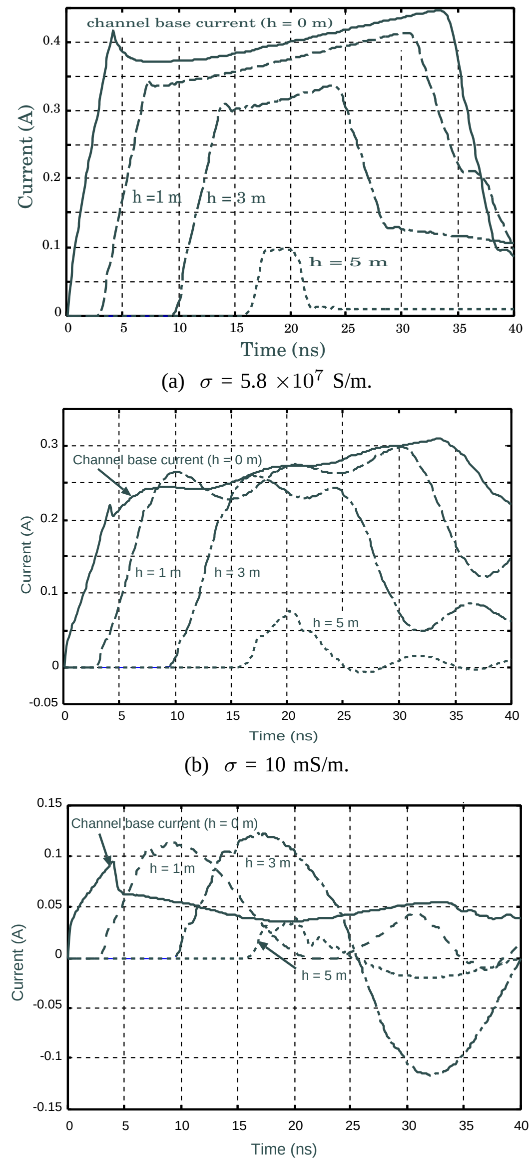


Fig. 1. Arrangement of the simulated lightning return-stroke channel for the calculation of currents and voltages induced on a nearby overhead line of unequal distance from the terminated ends.

For the present FDTD simulation, the conductor system shown in Fig. 1 is surrounded by a large rectangular analysis space of 2 m, 6 m, and 2 m in the x, y and z directions respectively, with space length $\Delta s = 5$ cm. An earth is placed at the bottom of the analysis space with a thickness of 10 cm and a resistivity $\rho = 1.69 \times 10^{-8}\,\Omega - \mathrm{m}$. The gap length is maintained as the space length Δs of the conductor system at which a voltage probe or current probe is placed to record the voltage and current. The time step for the simulation was determined by equation (14) of [11] with $\alpha = 0.001$, and all the six boundaries of the cell were treated as second-order Liao's absorbing boundaries. The radius of the horizontal thin wire was taken into account by the method discussed in the previous paper and $0.23\Delta s = 1.15$ cm of radius was chosen accordingly [11,12].



(a) σ = 5.8 $\times 10^7$ S/m.

(b) σ = 10 mS/m.

(c) σ = 1 mS/m.

Fig. 2. Current waveforms for different heights of the vertical lightning channel with different ground conductivities.

The FDTD method is normally a time-consuming method. However, progress of computers in terms of speed and memory has been considerable, and even a personal computer can be used for the FDTD calculation here. In fact, the simulations presented in this paper were performed by a personal computer with Intel Pentium 4, 2.80 GHz CPU and 512 MB RAM. Responses are calculated up to 40 ns for the reduced-scale model (2 m $\times$ 6 m $\times$ 2 m) with a time increment of 0.096 ns. Therefore, the computation time for the present scaled models are about 4 min respectively, regardless of ground parameters.

The current distribution, $I(z,t)$, along the lightning channel for the case of strike initiated at ground, is given by Baba and Rakov [19],

$$I(z,t) = \frac{1+\rho_{gr}}{2} I_{sc}(0, t - \frac{z}{v}) \quad (1)$$

where v is the return-stroke speed and $I_{sc}(0,t)$ is the lightning short-circuit current injected at $z = 0$ instead of $z = h$, which is also known as the channel-base current, and ρ_{gr} is the current reflection coefficient at the channel base. Typical values of v are one-third to two-thirds of c. Figure 2 shows the computed waveforms of the current distribution using the FDTD method which can also be represented by equation (1). The current distribution for the case of strikes to a tall object and for the case of strikes to flat ground correspond to the same lightning discharge, as required for examining the influence of strike object. In the FDTD calculations, the lightning channel and strike object can also be represented by a vertical array of current sources [20]. The arbitrary waveform of lightning short-circuit current $I_{sc}(h,t)$ or $I_{sc}(0,t)$ is specified by the current waveform proposed by Noda *et al.* [11]. In the case of a lightning strike to flat ground, the current reflection coefficient at the channel base (ground) is set to $\rho_{gr} = 1$ $(Z_{ch} >> Z_{gr})$, where Z_{ch} and Z_{gr} are the equivalent impedance of the lightning channel and grounding impedance of the strike object, respectively. The assumption $\rho_{gr} = 1$ is supported by the results from triggered-lightning experiments that show that lightning is capable of lowering its grounding impedance to a value that is always much lower than the equivalent impedance of the lightning channel [21,22]. It can be seen that in the TL model, the longitudinal current $I(z',t)$ in a straight and vertical lightning channel at an arbitrary height z' and time t is expressed as follows,

$$I(z',t) = I(0, t - \frac{z'}{v}).$$

B. Analyzed Results

Figure 2 shows the channel currents at different heights due to injected lightning return stroke current at ground with different soil conductivities. Channel current waveforms with a copper ground (as shown in Fig. 2(a)) are determined mainly by the characteristics of the injected current waveforms. These currents are treated as the total current waveform I_{tot}, at different heights calculated using the FDTD method for a vertical perfectly conducting cylinder excited at its bottom by a lumped source [23]. The current waveform at $z = 0$ m (bottom) of Fig. 2(a) is also considered as an incident current due to this lumped source. If we consider the vertical phased current source array along the channel, then the peaks of all the current waveforms at different heights would be the same (e.g., Fig. 3 of [23]). In this case, those current waveforms are to be treated as incident current waveforms at different heights. Thus the scattered current can be obtained as $I_{scat} = I_{tot} - I_{inc}$.

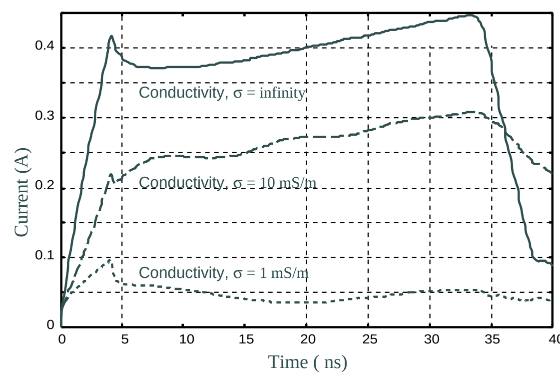


Fig. 3. Channel base currents for different soil conditions.

As seen in Fig. 2(a), the current pulse attenuation is accompanied by the lengthening of its tail while the rise-time of the current pulse is almost constant. These characteristics of the current waveforms are different for different ground conductivities. The magnitude of the channel currents are decreasing with decreasing of ground conductivity. Because of the finite ground conductivities, the curves of the channel currents in Figs. 2(b) and 2(c) exhibit nonlinear characteristics after their first peaks. Figure 3 illustrates the channel base currents computed by the FDTD method with different soil conductivities. It is evident from this result that the channel base current decreases with decreasing ground conductivity.

Figure 4 shows the normalized currents computed at different heights of the lightning channel characterized by a finite ground ($\sigma = 10$ mS/m). Here the normalization is termed by the ratio of the channel current at specific height to the channel base current (e.g., $I_n(z,t) = I(z,t)/I(0,t)$). Figure 5 illustrates the scattered current waveforms, I_{scat}, at different heights with a copper ground.

Figures 6 and 7 show the waveforms of the vertical electric field and azimuthal magnetic field respectively at the near end of the terminated overhead horizontal conductor due to a nearby lightning strike to flat ground. Similarly, Figs. 8 and 9 correspond to the waveform of the electric and magnetic fields at the distant end. Those

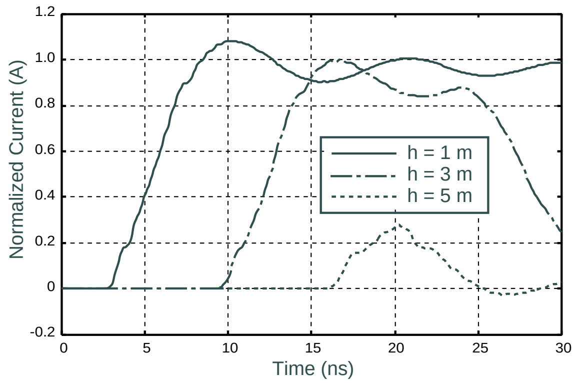


Fig. 4. Normalized currents observed at different heights of the return-stroke elevated channel for a finite ground conductivity ($\sigma = 10$ mS/m).

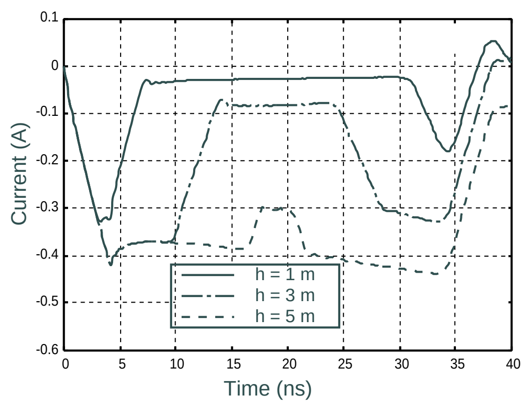


Fig. 5. Scattered current waveforms, I_{scat}, at different heights obtained as the difference between the total current and the incident current for the lumped source with a copper ground.

results are obtained for different ground conditions. The fields nearer to the striking location are larger in magnitude than at the far end. This result agrees satisfactory with other simulation (Numerical Electromagnetic Code (NEC-2)) and experimental results (Figs. 3(a) and 4(a) of Pokharel *et al.* [24]). The validity of the results of vertical electric field E_z and azimuthal magnetic field H_ϕ at the ground surface due to a vertical lightning strike to flat highly conducting ground using the FDTD method has already been examined with corresponding fields calculated using exact analytical expressions derived by Thottappillil *et al.* [25]. The later expressions are valid for the TL model, vertical channel terminating on flat, perfectly conducting ground, and return-stroke velocity equal to the velocity of light ($v = c$). In the FDTD procedure, we used the distribution of current along the lightning channel given by equation (1) with ($v = c$) and $\rho_{gr} = 1$, which was represented by a vertical array of current sources. The lightning short-circuit current $I_{sc}(0, t)$ was the same as that proposed by Nucci *et al.* [26].

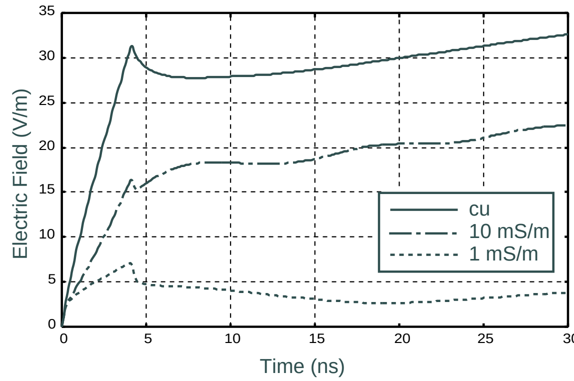


Fig. 6. Waveforms for the vertical electric field at the near end of the terminated overhead conductor due to a lightning strike to a flat ground with different soil conditions.

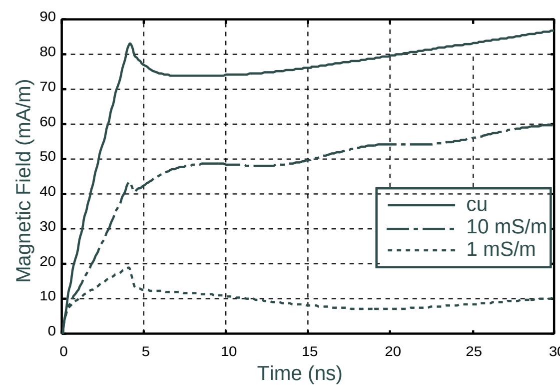


Fig. 7. Waveforms for the azimuthal magnetic field at the near end of the terminated overhead conductor due to a lightning strike to a flat ground with different soil conditions.

Thottappillil *et al.*'s analytical expressions for E_z and H_ϕ on the ground surface at a distance d from the lightning channel are reproduced as follows,

$$E_z(d, t) = \frac{I(0, t - d/c)}{2\pi\epsilon_0 cd}, \tag{2}$$

$$H_\phi(d, t) = \frac{I(0, t - d/c)}{2\pi d}. \tag{3}$$

Note that equation (2) gives the exact total electric field, which is the sum of the electrostatic, induction, and radiation components, and equation (3) gives the exact total magnetic field which is the sum of the induction and radiation components [25]. Hence, Figs. 6 to 9 show the field computation based on the analytical formula [25] using the FDTD results for the currents.

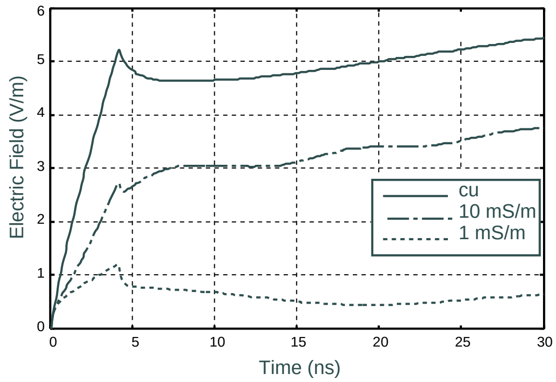


Fig. 8. Waveforms for the vertical electric field at the far end of the terminated overhead conductor due to a lightning strike to a flat ground with different soil conditions.

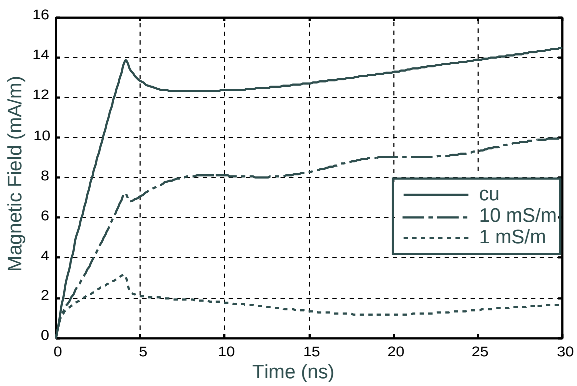


Fig. 9. Waveforms for the azimuthal magnetic field at the far end of the terminated overhead conductor due to a lightning strike to a flat ground with different soil conditions.

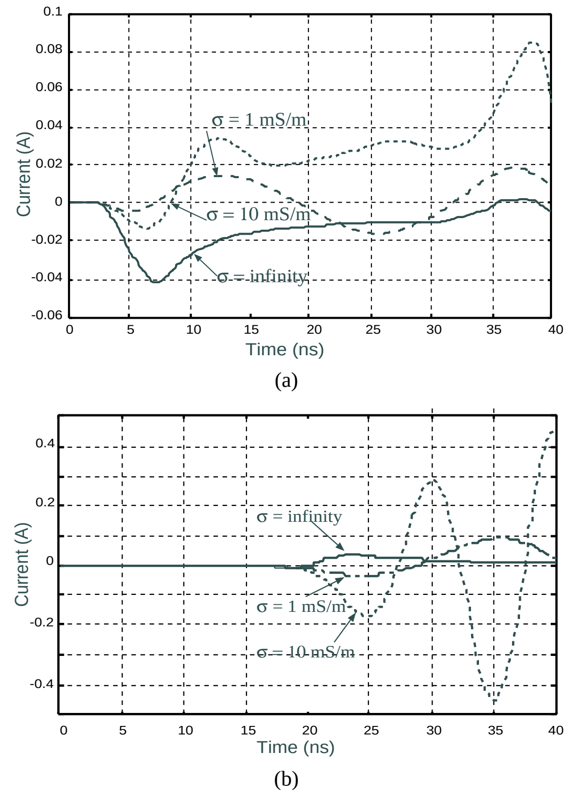


Fig. 10. Induced currents at the terminated ends of the overhead horizontal conductor for varying soil conductivities; a) near end, and b) far end.

Now the induced currents at the terminated ends of the overhead horizontal line computed for grounds having various soil conditions are shown in Figs. 10(a) and 10(b). These induced currents are due to the coupling between the electromagnetic field and the line conductor. The first peak of this induced current in proximity to the lightning source is large in the case with infinite conductivity. The polarity of the induced current with infinite ground conductivity is observed to be different from current waves with finite ground as distance increases from the striking location.

C. Terminations at Equidistance from the Source

Figure 11 illustrates the case with a simulated lightning channel in which the same return stroke current is considered at the bottom of the channel. Now the stroke location is equidistant from the line terminations and at 50 cm from the line center of a 1/50 reduced-scale model. By using the aforementioned approach, it is possible to simulate and analyze the effect of protection elements installed at the entrance of a substation, control building of a communication tower, or even household appliances. The dimension of the analysis space and cell size are taken to be the same as assumed in the earlier section. Figure 12 represents the induced currents at the terminated ends equidistant from the stroke location for varying soil conditions. Similar characteristics for the induced currents has also been observed in Fig. 10(a). Induced voltages due to a nearby lightning strike at the center of the overhead horizontal conductor are represented in Fig. 13. These voltages are computed across the overhead line and a auxiliary potential wire. Results show that decreasing ground conductivity also decreases the induced voltages on the overhead horizontal line. These properties are good agreement with the results obtained by Pokharel *et al.* [Fig. 11 of [24]] using a Sommerfeld integral and a Norton's approximation. Although there are some differences in the wavetails because of the computational method considered in this work. Figure 14 shows the magnetic field distribution a $t = 40$ ns on the $y - z$ plane, when a part of the incoming wave reflects at the earth surface (a snapshot of its animation visualized by MATLAB). Those fields penetrate the nearby conductor and induce currents on it.

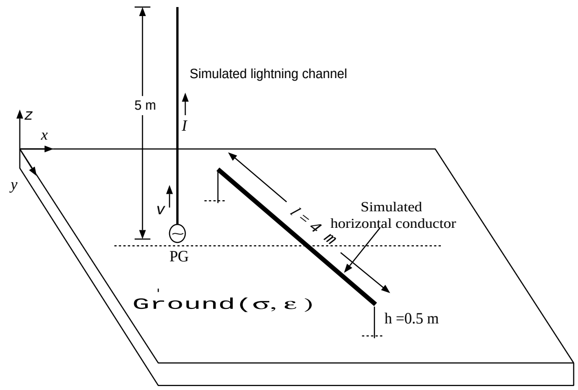


Fig. 11. Arrangement of the simulated lightning channel equidistant from the terminated both ends of the overhead horizontal conductor.

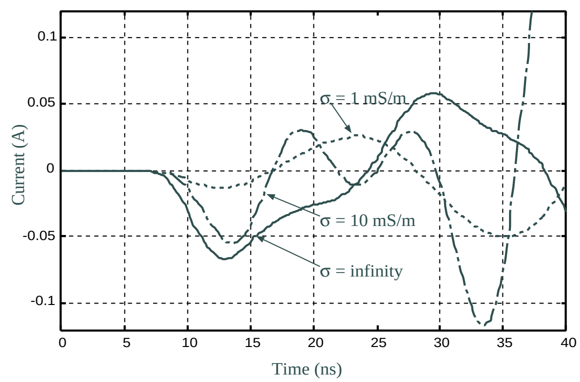


Fig. 12. Induced currents at the terminated ends of the overhead horizontal conductor equidistant from the simulated lightning source for various soil conductivities.

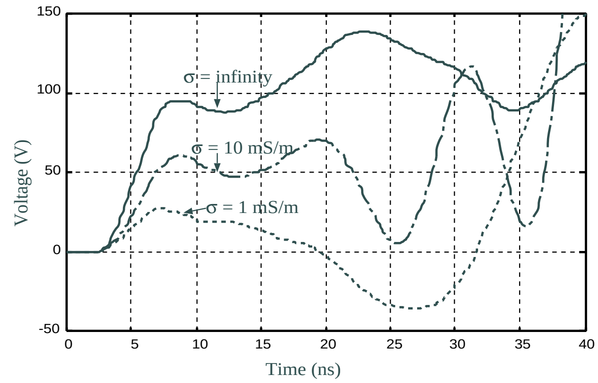


Fig. 13. Induced voltages at the nearest location of the horizontal conductor computed across the conductor and auxiliary potential wire with different soil conductivities.

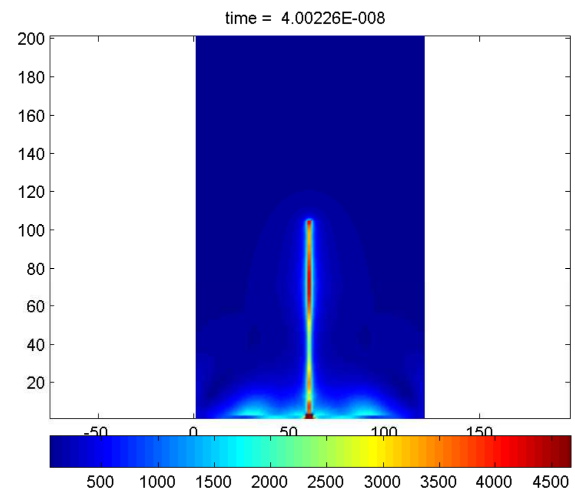


Fig. 14. Magnetic field strength (A/m) at $t = 40$ ns corresponding to gray scale at the bottom; unit of vertical and horizontal axes is in cells ($\Delta s = 5$ cm) .

III. CONCLUSIONS

A time-domain method for numerical electromagnetic analysis, i.e., FDTD, is applied to analyze the proximity effect due to a nearby lightning stroke to flat ground. Induced currents and voltages are investigated at the near and far ends of the terminated horizontal conductor which is at a short distance from the stroke location. The effects of ground conductivity depending on soil conditions are also evaluated and presented in this paper. The validity of the results are examined with the analytical data and also with simulation results using NEC-2. Although it is difficult to analyze the large computational domain including finitely conducting ground, the FDTD method offers more accurate results and advantages over NEC-2.

The electric and magnetic fields are calculated using the well known analytical expression considering the currents calculated here by the FDTD method. A nearby lightning stroke at the center position of the horizontal overhead conductor has been analyzed and induced voltages are measured at the line in order to investigate the performance of surge arrester connected to the line with different ground conductivities. Furthermore, this work examines the behavior of vertical lightning channel current with different ground conditions and gives insightful results for a scaled model which facilitates the analysis with larger scale model including surge protectors.

The above findings regarding the lightning-induced voltages in the absence of a tall strike object have important implications for optimizing lightning protection means for telecommunication and power distribution lines.

REFERENCES

[1] F. M. Tesche, A. W. Kalin, B. Brandly, B. Reusser, M. Isnoz, D. Tabara, and P. Zweiacker, “Estimates of lightning-induced voltage stresses within buried

shielded conduits," *IEEE Trans. Electromagn. Compat.*, vol. 40, pp. 492–504, 1998.

[2] B. Djebari, L. Guerin, and M. Gleonec, "Conducted EM disturbances on the telecommunication terminal equipment ports," *Int. Symp. EMC*, Rome, Italy, Sep. 13–16, 1994.

[3] M. G. Sorwar, H. Ahmed, and M. M. Ali "Analysis of transients in overhead telecommunication subscriber line due to nearby lightning return stroke," *IEEE Int. Symp. Electromagn. Compat.*, vol. 2, pp. 1083–1088, Aug. 1998.

[4] M. Ishii, K. Michishita, and Y. Hongo, "Experimental study of lightning- induced voltage on an overhead wire over lossy ground," *IEEE Trans. Electromagn. Compat.*, vol. 41, no. 1, pp. 39–45, Feb. 1999.

[5] U. Kumar, V. Hegde, and V. Shivanand, "Preliminary studies on the characteristics of the induced currents in simple down conductors due to a nearby lightning strike," *IEEE Trans. Electromagn. Compat.*, vol. 48, no. 4, pp. 805–816, Nov. 2006.

[6] Working Group of IEEJ, "Numerical electromagnetic analysis and its application to power system transients," *IEEJ WG Report*, 2003–2007.

[7] T. Mozumi, Y. Baba, M. Ishii, N. Nagaoka, and A. Amatani "Numerical electromagnetic field analysis of archorn voltages during a back-flashover on a 500 kV twin circuit line," *IEEE Power Delivery*, vol. 18, no. 1, pp. 207–213, 2003.

[8] K. Tanabe, "Novel method for analyzing dynamic behavior of grounding systems based on the FD-TD method," *IEEE Power Eng. Rev.*, vol. 21, no. 9, pp. 55–57, Sep. 2001.

[9] G. Mur, "Absorbing boundary conditions for the finite-difference approximation of the time-domain electromagnetic-field equation," *IEEE Trans. Electromagn. Compat.*, vol. EMC-23, no. 4, pp. 377–382, 1981.

[10] K. S. Yee, "Numerical solution of initial boundary value problems involving Maxwell's equation in isotropic media," *IEEE Trans. Antennas and Propagation*, vol. AP-14, no. 4, pp. 302–307, 1966.

[11] T. Noda and S. Yokoyama, "Thin wire representation in finite difference time domain surge simulation," *IEEE Trans. Power Delivery*, vol. 17, no. 3, pp. 840–847, 2002.

[12] Y. Baba, N. Nagaoka, and A. Ametani, "Numerical analysis of groundng resistance of buried thin wires by the FDTD Method," *Int. Conf. on Power Syst. Trans(IPST)*, New Orleans, USA, 2003.

[13] M. Tsumura, Y. Baba, N. Nagaoka, and A. Ametani, "FDTD simulation of a horizontal grounding electrode and modeling of its equivalent circuit," *IEEE Trans. Electromagn. Compat.*, vol. 48, no. 4, pp. 817–825, Nov. 2006.

[14] Y. Baba and V.A. Rakov, "Voltage 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, Feb. 2006.

[15] Y. Baba and M. Ishii, "Numerical electromagnetic field analysis of lightning current in tall structures," *IEEE Trans. PWRD*, vol. 16, no. 2, pp. 324–328, Apr. 2001.

[16] Y. Baba and M. Ishii, "Characteristics of electromagnetic return-stroke models," *IEEE Trans. Electromagn. Compat.*, vol. 45, no. 1, pp. 129–134, Feb. 2003.

[17] B. Kordi, R. Moini, W. Janischewskyj, A. M. Hussein, V. O. Shostac, and V. A. Rakov, "Application of the antenna theory model to a tall tower struck by ligtning," *J. Geophys. Res.*, vol. 108, pp. ACL 7/1–ACL7/9, no. D17 4542, 2003.

[18] K. Tanabe, A. Asakawa, T. Noda, M. Sakae, M. Wada and H. Sugimoto, "Varifying the novel method for analyzing transient grounding resistance based on the FD-TD method through comparison with experimental results," *CRIEPI Report*, no.99043, 2000. (in Japenese)

[19] Y. Baba and V. A. Rakov, "On the use of lumped sources in the lightning return stroke models," *J. Geophys. Res.*, vol. 110, D03101, doi:10.1029/2004JD005202, Feb. 2005.

[20] Y. Baba and V. A. Rakov, "On the transmission line model for lightning return stroke representation," *Geophys. Res. Lett.*, vol. 30, no. 24, p. 2294, doi:10.1029/2003GL018407, Dec. 2003.

[21] V. A. Rakov, M. A. Uman, K. J. Rambo, M. I. Fernandez, R. J. Fisher, G. H. Schetzer, R. Thottappillil, A. Eybert-Berard, J. P. Berlandis, P. Lalande, A. Bonamy, P. Laroche, and A. Bondiou-Clergerie, "New insights into lightning processes gained from triggered-lightning experiments in Florida and Alabama," *J. Geophys. Res. Lett.*, vol. 103, no. D12, pp. 14117–14139, 1998.

[22] V. A. Rakov, "Transient response of a tall object to lightning," *IEEE Trans. Electromagn. Compat.*, vol. 43, no. 4, pp. 654–661, Nov. 2001.

[23] Y. Baba and V. A. Rakov, "On the mechanism of attenuation of current waves propagating along a vertical perfectly conducting wire above ground: Application to lightning," *IEEE Trans. Electromagn. Compat.*, vol. 47, no. 3, pp. 521–532, Aug. 2005.

[24] R. K. Pokharel, M. Ishii, and Y. Baba, "Numerical electromagnetic analysis of lightning-induced voltage over ground of finite conductivity," *IEEE Trans. Electromagn. Compat.*, vol. 45, no. 4, pp. 651–656, Nov. 2003.

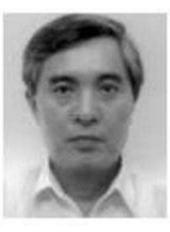
[25] T. Thottappillil, J. Schoene, and M. A. Uman, "Return stroke transmission line model for stroke speed

near or equal to that of light," *Geophys. Res. Lett.*, vol. 28, no. 18, pp. 3593–3596, 2001.

[26] C. A. Nucci, G. Diendorfer, M. A. Uman, F. Rachidi, M. Ianoz, and C. Mazzetti, "Lightning return stroke current models with specified channel-base current: A review and comparison," *J. Geophys. Res.*, vol. 95, no. D12, pp. 20395–20408, 1990.

Md. Osman Goni was born in Bangladesh on February, 1971. He received his B.S. degree in electrical and electronic engineering from Bangladesh Institute of Technology, Khulna in 1993. He joined the Institute in 1994. He received M.S. degree and D. Eng. degree from the University of the Ryukyus, Japan in 2001 and 2004 respectively. He is currently an assistant professor and has been engaged in teaching and research in digital signal and image processing, electric power and energy system, electromagnetic energy engineering, electromagnetic theory, electromagnetic fields computation, transient phenomena, lightning and EMP effects on power and telecommunication networks, FDTD method, MoM, NEC-2, lightning surge analysis, vertical conductor problems, EMTP etc. He is the author or co-author of about 20 scientific papers presented at international conferences and published in reviewed journals.

Eiji Kaneko was born in Japan, on September 16, 1952. He received M.S. degree from Nagoya University in 1977. He joined in Toshiba Corporation in April 1977 and engaged in research and development of vacuum interrupter and discharge. He received D. Eng. degree from Nagoya University in 1989. He is now professor of University of the Ryukyus. He has been engaged in teaching and research on electric power and energy system engineering, electromagnetic energy engineering etc. Dr. Kaneko is a member of IEEE and IEE of Japan.



Akihiro Ametani received the B.S. and M.S. degrees from Doshisha University, Kyoto, Japan, in 1966 and 1968, respectively, and the Ph.D. degree from the University of Manchester Institute of Technology (UMIST), Manchester, U.K., in 1973. He was with Doshisha University from 1968 to 1971, UMIST from 1971 to 1974, and the Bonneville Power Administration, Portland, OR, for the summers of 1976 to 1981. He has been a Professor at Doshisha University since 1985. He was the Director of the Institute of Science and Engineering of Doshisha University from 1997 to 1998 and the Dean of the Library and Computer/Information Center from 1998 to 2001. Dr. Ametani is a Chartered Engineer in the U.K., a Distinguished Member of CIGRE, and a Fellow of the IEE. He has been a Vice President of the IEE of Japan since 2004.