Effects of Lightning Electromagnetic Pulse on a Nearby Overhead Horizontal Conductor

Md. Osman Goni Non-member (Khulna University of Engineering & Technology, Bangladesh, osman@ieee.org)
Akihiro Ametani Member (Doshisha University, Kyoto, Japan, aametani@mail.doshisha.ac.jp)
Eiji Kaneko Senior Member (University of the Ryukyus, Okinawa, Japan, kaneko@eee.u-ryukyu.ac.jp)

Keywords: FDTD method, horizontal conductor, ground conductivity, induced voltage, nearby lightning strike

A nearby lightning strike can induce significant currents in long horizontal and tall down 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 is 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 a nearby lightning strikes. In this paper, homogeneous non-perfect ground is also examined to investigate the influence of soil conditions on induced effects.

Figure 1 describes the full-scaled model of a horizontal conductor of 2 km in length and radius of 1.15 m. The rectangular analysis space of 100 m, 2100 m, and 100 m in the x, y and z directions respectively, with space length $\Delta s = 5$ m has been simulated. The radius of the wire and space length of the simulated area are chosen according to the guidelines of Noda et al. and also to save memory requirements and computation time in a personal computer. The ground thickness was 10 m and it was modeled with different ground conductivities. The step-like current pulse having a magnitude of 60 kA and a maximum time derivative of $600$ kA/$\mu$s has been considered to simulate the indirect lightning stroke current.

The source is injected at 45 m from the horizontal conductor and at 10 m above the ground surface. The magnitude of the first peak of all the cases of observation is given in the Table 1 for simplicity. The succeeding peaks as observed in some cases are ignored because of overdamped oscillation due to computational instability for larger scale model. Those oscillations may be optimized by considering distributed loading on horizontal transmission line. In such a horizontal conductor and striking point arrangement, where the striking point is on the extension of the line, the induced-voltage increases with increasing ground conductivity which is different from the result obtained in Ishii et al. This is due to the arrangement of the lightning source in this present research which is simulated above the ground surface rather than at the ground surface.

The lightning-induced voltage on an overhead horizontal wire, with lossy and lossless ground are studied based on FDTD simulations. This work reports that (1) By comparing the current waveforms calculated at the excitation point, the induced voltage or current increases with increasing ground conductivity corresponding to different soil conditions. (2) In a nearby lightning strike, the induced voltages on the horizontal overhead wire are greatly affected by the distance from the striking point. The lightning-induced voltage at the near-end is higher than at the far-end. (3) It is also shown that the ground conductivity influences the induced voltage. The lightning-induced voltage becomes larger with the increase of the ground conductivity. This is valid when the injection is above the ground surface rather than at the ground.
Effects of Lightning Electromagnetic Pulse on a Nearby Overhead Horizontal Conductor

Md. Osman Goni* Non-member
Akihiro Ametani** Member
Eiji Kaneko*** Senior Member

A nearby lightning strike can induce appreciable currents in long horizontal and tall down 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 is 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 a nearby lightning strikes. In this paper, homogeneous non-perfect ground is also examined to investigate the influence of soil conditions on induced effects.

Keywords: FDTD method, horizontal conductor, ground conductivity, induced voltage, nearby lightning strike

1. Introduction

A nearby 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/interferences caused by the induced currents on the electrical and electronic systems in the vicinity and for systems mounted on the conductors (towers). For a rough estimation 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.

There is a large amount of literature on the problem of induced currents on conductors of electrical distribution lines and telecommunication lines(3,4). Detailed studies on the lightning-induced disturbances in buried electrical cables have also been carried out(5,6). Similarly, the induction effect in the protection systems as well as the electrical network of a building has also been considered(6,9). A Vertical conductor model has also been investigated(5-8). However, the characteristics of the induced voltages on horizontal and vertical conductors due to lightning strikes in the vicinity and with different ground conductivities seems to be less studied.

The present paper evaluates the basic characteristics of the induced currents in horizontal overhead lines due to a lightning hit in the vicinity under different values of ground conductivities.

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 EMTP(11). 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(12).

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 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(13). 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 is employed to represent absorbing planes.

So far in most of FDTD analyses of transient and steady-state voltages, large solid electrodes, 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. 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. The validity is already tested by comparing grounding-resistance values obtained through FDTD simulations on simple buried structures with theoretical values.

1.1 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.

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

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. The near end A is connected to a pulse generator which is placed at the bottom of the ground plane. The length of the vertical current lead wire is 45 cm. The remote end B is either terminated or left open.

The conductor system is excited by a current pulse generator (PG) placed at the bottom of terminated end A via a current lead wire which has an internal impedance of 50 Ω in series. The arbitrary voltage source produces a steep-front voltage wave having a risetime of 4 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. The PG 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. As the time taken for the reflection from the open end to the measuring position is observed to be 450 cm * 2/(30 cm/ns) = 30 ns.

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 Δx = 5 cm. An earth is placed at the bottom of the analysis space with a thickness of 10 cm and a resistivity $\rho = 1.69 \times 10^{8}$ Ω·m. The gap length is 30 cm. The gap length is maintained as the space length Δz 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 (14) of Ref. (16) with $\alpha = 0.001$ which is a small positive value specified by the user in order to prevent instability of the numerical integration due to round-off error. 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 0.23Δx = 1.15 cm of radius was chosen accordingly.

The FDTD method is normally a time-consuming method. However, the progress of computers in terms of speed and memory is 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 x 6 m x 2 m) and up to 9 μs for the actual model (100 m x 2100 m x 100 m model in Fig. 8) with a time increment of 0.096 ns and 9 ns respectively. Therefore, the computation time for the above two different scale models are about 1 min and 3 min respectively, regardless of ground parameters.

1.2 Analyzed Results

Computed voltage and current are shown in Fig. 2 as are computed at the injected point of PG for the horizontal conductor model of Fig. 1. Fig. 3 shows the results for the horizontal conductor model in which the far end B is also terminated to the ground. In both cases, the reflection of voltage and current waveforms are observed to be exactly at 30 ns because the model is characterized by a lossless and uniform line where the traveling wave propagates through the conductor at the velocity of light.

To this point, we have presented the analysis of current and voltage waveforms of Figs. 2 and 3 with ground having high conductivity ($\sigma = 5.8 \times 10^{7}$ S/m). The effect of finite ground on the resultant overvoltage also needs to be analyzed. Fig. 4
Lightning Electromagnetic Pulse on a Nearby Overhead Horizontal Conductor

shows the resultant current recorded at the injection point influenced by the finite ground conductivities showing different soil conditions and with a relative permittivity of 10.

From Fig. 4, the current waveforms show that as conductivity increases, current increases. Time-to-crest is the same in every case and the current drops at the lower soil conductivity (namely, 1 mS/m or less) and continues decreasing but increasing gradually at higher conductivity (above 5 mS/m) until reflection from the short-circuited end reaches the measuring point. Hence, the low conductivity of the soil blocks the current flowing into the soil and forces the current to move toward the terminal end of the electrode.

2. Induced Voltage Due To Nearby Lightning Strike

In this section, reduced scale model of a horizontal conductor system, as shown in Fig. 5, is presented to analyze the induced effects due to a nearby lightning strike.\(^\text{(25)}\)

The same step-like \(z\)-directional voltage source considered for the model of Fig. 1 is also applied here at 50 cm above the ground surface instead of placing to the ground (i.e., at the same height as the horizontal conductor) and 0.8 m from the left end of the horizontal conductor and simulates as indirect lightning hit. Unlike the experimental setup by Pokharel et al.\(^\text{(24)}\), we did not consider an elevated structure with lightning channel as we only considered a lightning pulse of 40 ns width initiated at a point near to the overhead line and therefore, the return stroke is not considered in this analysis. The same analysis space size is considered with different ground parameters to examine the distance dependent induced-voltages.

The induced-voltages are computed at the ground level along with the horizontal conductor and at 0.8 m and 4.8 m from the injection point. In this paper, these voltages are treated as near-end and far-end voltages respectively. The two voltage waveforms of Fig. 6 are in the same \(z\)-directional parameter as the injected voltage and computed at the line terminations. Figure 7 shows the voltages induced on the horizontal conductor which are computed in between the horizontal conductor and auxiliary voltage measuring wire in three different locations. Geometric configuration is already reported in Tsumura et al.\(^\text{(18)}\) which is perpendicular to he horizontal conductor. Both Figs. 6 and 7 also demonstrate that the peaks of these induced-voltages decrease as we move far away from the stroke location.

Table 1 shows the effect of the ground conductivities on
Table 1. Effect of the ground conductivities on the induced voltage on the horizontal conductor at different distances from the strike point (Reduced-scale model)

<table>
<thead>
<tr>
<th>Distance (meter)</th>
<th>$\sigma = 5 \times 10^8$ mS/m</th>
<th>$\sigma = 5$ mS/m</th>
<th>$\sigma = 1$ mS/m</th>
<th>$\sigma = 0.2$ mS/m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(mV)</td>
<td>(mV)</td>
<td>(mV)</td>
<td>(mV)</td>
</tr>
<tr>
<td>0.8</td>
<td>53</td>
<td>53</td>
<td>53</td>
<td>53</td>
</tr>
<tr>
<td>1.8</td>
<td>30.5</td>
<td>28.2</td>
<td>28.2</td>
<td>28.2</td>
</tr>
<tr>
<td>4.8</td>
<td>26.9</td>
<td>9.35</td>
<td>7.53</td>
<td>4.2</td>
</tr>
</tbody>
</table>

Fig. 8. Large-scale horizontal conductor arrangement (stroke location is at the 45 m from the left end simulating nearby lightning strike)

the induced voltage $v$ at different horizontal distances from the strike location. The waveforms of those induced voltages are observed to be similar to Fig. 7 for the model of Fig. 5 with varying soil conditions. Near the strike point, the magnitude of induced voltage does not have significant dependence on the ground conductivity. But the magnitude of the induced voltage obviously depends on the horizontal distance from the strike point regardless of the ground conductivity. Pokharel et al.\cite{24} shows that the induced voltage will be lower for a perfect conductor than for a finite ground. This is because of the location of simulated strike is at the ground and thus the ground conductivity affects not only the shape of induced voltage but also its magnitude. In this paper, we consider a strike location parallel to the horizontal conductor and at a height of 50 cm from the ground surface. This type of lightning may be attributed to a downward leader and strikes in an open field where personnel or other small objects (e.g., umbrella, golf club, fishing rod, etc.) can be exposed to a direct hit. At the same time, the induced voltage or current in the vicinity of the lightning path cannot be ignored and should be considered as serious issues like a direct hit.

Due to the computation time and large memory storage, a small-scale model has been chosen for the analysis of induced effects due to indirect hits. It is also necessary to investigate those effects with a full-sized analysis space in order to show the length dependent parameters. Non-linear effects such as soil ionization have not been included in this investigation. Fig. 8 describes the full-scaled model of a horizontal conductor of 2 km in length and radius of 1.15 m. The rectangular analysis space of 100 m, 2100 m, and 100 m in the $x$, $y$ and $z$ directions respectively, with space length $\Delta s = 5$ m has been simulated. The radius of the wire and space length of the simulated area are chosen according to the guidelines of Ref. (16) and also to save memory requirements and computation time in a personal computer. The ground thickness was 10 m and it was modeled with different ground conductivities. The step-like current pulse having a magnitude of 60 kA and a maximum time derivative of 600 kA/$\mu$s has been considered to simulate the indirect lightning stroke current. The source is injected at 45 m from the horizontal conductor and at 10 m above the ground surface.

Figure 9 shows the induced voltages at different distances in between the near-end to far-end of the horizontal conductor. The simulation has been carried out by the FDTD method, postulating mainly homogeneous ground with conductivities of 1 mS/m and 5 mS/m and relative permittivity of 12 corresponding to different soil conditions\cite{17}. The effect of high conductivity ground (namely, Cu-ground) to that induced voltage is also included for comparison with finite conductivities. The responses can be calculated up to 9 $\mu$s with a time increment of 9.62 ns because of temporary storage limitations. At the closer-end, the voltage waveforms started with positive peaks but at the distant-end the waveforms are negative because the polarity of the horizontal electric field is dependent on the distance from the striking point\cite{25}. In
Table 2. Effect of the ground conductivities on the induced voltage on the horizontal conductor at different distances from the strike point (large-scale model)

<table>
<thead>
<tr>
<th>Distance (meter)</th>
<th>$\sigma = 5.8E-7$ S/m</th>
<th>$\sigma = 5$ mS/m</th>
<th>$\sigma = 1$ mS/m</th>
<th>$\sigma = 0.2$ mS/m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(kV)</td>
<td>(kV)</td>
<td>(kV)</td>
<td>(kV)</td>
</tr>
<tr>
<td>10</td>
<td>8.04</td>
<td>6.4</td>
<td>5.25</td>
<td>4.3</td>
</tr>
<tr>
<td>500</td>
<td>$-15.8$</td>
<td>$-11$</td>
<td>$-8.36$</td>
<td>$-6.86$</td>
</tr>
<tr>
<td>1500</td>
<td>$-12.3$</td>
<td>$-4.05$</td>
<td>$-2.08$</td>
<td>$-1.07$</td>
</tr>
</tbody>
</table>

Fig. 9(c), the waveform for $\sigma = 1$ mS/m is not shown because the positive peak is so high that it could not be drawn in the same scale. The magnitude of the first peak of all the cases for Fig. 9 is given in the Table 2 for simplicity. The succeeding peaks as observed in some cases are ignored because of overdamped oscillation due to computational instability for larger scale model. Those oscillations may be optimized by considering distributed loading on horizontal transmission line.

In such a horizontal conductor and striking point arrangement, where the striking point is on the extension of the line, the induced-voltage increases with increasing ground conductivity which is different from the result obtained in Ref. (25). This is due to the arrangement of the lightning source in this present research which is simulated above the ground surface rather than at the ground surface. Table 2 summarizes the above results.

3. Conclusions

The lightning-induced voltage on an overhead horizontal wire, with lossy and lossless ground, associated with a first stroke above the earth surface and at a distance of about 2 km from the injection point, is studied based on FDTD simulations. The following conclusions are made.

1. By comparing the current waveforms calculated at the excitation point, the induced voltage or current increases with increasing ground conductivity corresponding to different soil conditions.

2. In a nearby lightning strike, the induced voltages on the horizontal overhead wire are greatly affected by the distance from the striking point. The lightning-induced voltage at the near-end is higher than at the far-end.

3. It is also shown that the ground conductivity influences the induced voltage. The lightning-induced voltage becomes larger with the increase of the ground conductivity. This is valid when the injection is above the ground surface rather than at the ground.

Acknowledgment

The authors are indebted to T. Noda and M. Ishii for their technical support and providing useful information.

(Manuscript received March 3, 2008, revised Oct. 14, 2008)

References


Md. Osman Goni (Non-member) 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. Dr. Goni is the Director of the Lightning Research Group of Khulna University of Engineering and Technology, Bangladesh. He is a member of IEEE, ACES, IEB and AGU.

Akihiro Ametani (Member) 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 1978 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.

Eiji Kaneko (Senior Member) 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 senior member of IEEE and IEE of Japan.