Analysis of Lightning-Induced Voltages on Overhead Lines Using a 2-D FDTD Method and Agrawal Coupling Model

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***Abstract*—In this paper, the lightning-generated electromagnetic fields over lossy ground produced by lightning strikes either to flat ground or to a tall tower are calculated using the 2-D finite-difference time-domain (FDTD) method. The resultant horizontal and vertical electric fields are used as forcing functions in the discretized Agrawal electromagnetic coupling equations for the calculation of induced voltages on overhead horizontal conductors without employing the Cooray–Rubinstein formula. Comparison of the results with those obtained using the 3-D FDTD method and with experimental data found in the literature is used to test the validity of the examined method. The approach employed here generally provides sufficient accuracy while allowing significant reduction in computation time and storage requirements as compared to the 3-D FDTD method. From the analysis carried out in this paper, induced voltages appear to be strongly dependent on ground conductivity, somewhat influenced by return-stroke speed, and essentially independent of return-stroke model [transmission-line (TL), modified transmission line with linear current decay with height (MTLL), or modified transmission line with exponential current decay with height (MTLE)].**

***Index Terms*—Electromagnetic coupling model, finite-difference time-domain (FDTD) method, lightning electromagnetic pulse (LEMP), lightning-induced voltage.**

NOMENCLATURE

H	Length of the lightning return-stroke channel.
h	Height of the strike object.
d	Shortest distance between the overhead line and the lightning return-stroke channel.
$I(0,t)$	Lightning channel base current.
$I(z,t)$	Current in the strike object and lightning return-stroke channel at height z.
v	Return-stroke speed.
c	Speed of light in free space.
$\rho_{\rm gr}$	Current reflection coefficient at the channel base (ground) in the case of strikes to flat ground.
$\rho_{\rm top}$	Current reflection coefficient at the top of the strike object for upward propagating waves.
$\rho_{\rm bot}$	Current reflection coefficient at the bottom of the strike object.
Δz	Spatial discretization interval along the z-axis in the 2-D FDTD integration scheme.
Δr	Spatial discretization interval in the radial direction in the 2-D FDTD integration scheme.
Δx	Spatial discretization interval along the x-axis in the discretization of Agrawal coupling equations.
Δt	Time discretization interval.
E_r	Horizontal component of the lightning-generated electric field.
E_z	Vertical component of the lightning-generated electric field.
H_φ	Horizontal component of the lightning-generated magnetic field.
$[v_p^s(x,t)]$	Matrix of the scattered voltage vector.
$[v_p(x,t)]$	Matrix of the total voltage vector.
$[v_p^e(x,t)]$	Matrix of the exciting (or incident) voltage vector.
$[i_p(x,t)]$	Matrix of the current vector along the overhead line.
h_p	Height of conductor p above ground.
$[E_x^e(x,h_p,t)]$	Matrix of the horizontal component of the exciting (or incident) electric field vector along the x-axis at the pth conductor's height h_p.
$E_z^e(x,0,t)$	Vector of the vertical component of the incident electric field.
$[L'_{pq}]$	Per-unit-length inductance matrix of the line.
$[C'_{pq}]$	Per-unit-length capacitance matrix of the line.
$[\xi'_{pq}]$	Transient ground resistance matrix.
$[R_0], [R_L]$	Matrices of resistances at the line terminations.
σ	Conductivity of the medium.
ε	Permittivity of the medium.
μ_0	Permeability of free space.
ε_0	Permittivity of free space.
σ_g	Conductivity of the earth.
ε_{rg}	Relative permittivity of the earth.

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R_g	Grounding resistance of line's neutral conductor.
λ	Current decay height constant.

I. INTRODUCTION

LIGHTNING is a major natural source of electromagnetic radiation that interferes with modern electric and communication systems. The evaluation of lightning-induced voltages typically involves the calculation of the lightning return-stroke electromagnetic field variation along the considered line and a field-to-transmission line coupling model [1]–[5] that describes the interaction of lightning electromagnetic fields with that line.

The ground conductivity plays a role in the evaluation of both lightning-radiated electromagnetic fields and the line parameters. The line parameters include the longitudinal ground impedance and the transverse ground admittance, which are both frequency-dependent. The latter can generally be neglected for typical overhead lines, due to its small contribution to the overall transverse admittance of the line [6]. Rachidi *et al.* [7] showed that for lines whose length does not exceed a certain "critical" value (typically 2 km) and for the strike point equidistant from the line terminations, the surge propagation along the line is not appreciably affected by the ground finite conductivity, and therefore, the ground impedance can also be neglected. In general, however, the ground impedance should be taken into account. In this study, we will neglect the ground impedance and show that this assumption is apparently justified for all the configurations considered in Section III.

For the calculation of lightning-radiated fields over finitely conducting ground, the inclusion of lossy ground effects is necessary, especially for the calculation of the horizontal electric field. Many authors have resorted to the so-called Cooray–Rubinstein approximate formula [8]–[10]. Limits of validity of this formula relative to the exact solution were examined by Wait [11]. It appears to be inapplicable for distances closer than about 200 m and for very-low-conductivity ground (e.g., 0.1 mS/m). It is worth noting that the Cooray–Rubinstein formula can be derived from a more general equation presented by Shoory *et al*. [12].

Hoidalen *et al.* [13] have used a new analytical formulation to calculate the lightning-induced voltages. Its accuracy is believed to be reasonable when the overhead line is located 100 m to 10 km from the lightning channel, the ground conductivity is higher than 0.001 S/m, the length of the line is shorter than 1 km, and for the first few microseconds, when the maximum induced voltage often occurs.

Baba and Rakov [14] calculated lightning-induced voltages for lightning strikes to flat ground and to a tall grounded object using the TL model extended to include a tall strike object without invoking any electromagnetic coupling model [15], [16]. Their calculations were carried out using the 3-D finite-difference time-domain (FDTD) method, and induced voltages on a horizontal conductor were calculated by directly integrating the vertical electric field from the ground surface to the wire height.

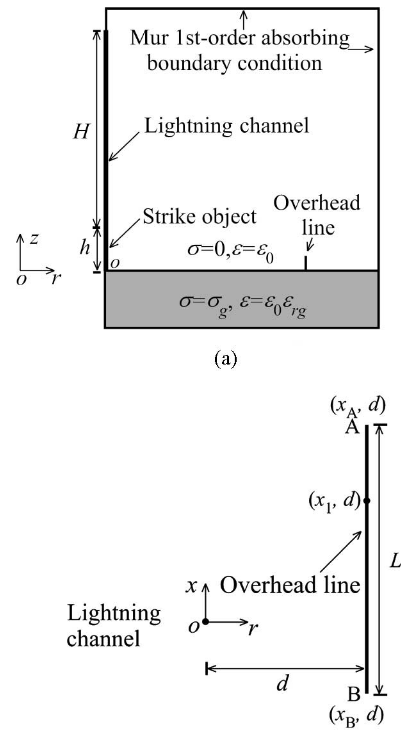


Fig. 1. Configuration to be analyzed using the 2-D FDTD method. (a) Side view. (b) Plan view.

In this paper, we employ a 2-D FDTD method for calculation of lightning-generated electromagnetic fields above lossy ground. Induced voltages are found using the Agrawal electromagnetic coupling model that describes the interaction of these fields with overhead lines. Computed results are compared with those obtained using a more rigorous 3-D FDTD method and with experimental data. We show that our approach provides sufficient accuracy while being more computationally efficient than that based on the 3-D FDTD method.

II. METHODOLOGY

A. Calculation of the Horizontal and Vertical Electric Fields

The configuration of the system is shown in Fig. 1. The length of the lightning return-stroke channel is H. It is assumed to be straight and vertical. The channel base current is $I(0,t)$ and the return-stroke propagation speed is v.

The current distribution $I(z,\, t)$ along the lightning channel for the case of lightning strikes to flat ground for three TL-type models is given by the following

Transmission line model [17]:

$$I(z,t) = I\left(0, t - \frac{z}{v}\right). \quad (1)$$

Modified transmission line model with linear current decay with height (MTLL model) [18]:

$$I(z,t) = \left(1 - \frac{z}{H}\right) I\left(0, t - \frac{z}{v}\right). \quad (2)$$

Modified TL model with exponential current decay with height (MTLE model) [19]:

$$I(z,t) = e^{-z/\lambda} I\left(0, t - \frac{z}{v}\right). \quad (3)$$

The current distribution $I(z, t)$ along the lightning channel based on the TL model for the case of lightning strikes to a tall grounded object of height h is given by [15], [16]

$$I(z,t) = \frac{1-\rho_{\rm top}}{2} \times \sum_{k=0}^{\infty} \left[\begin{array}{l} \rho_{\rm bot}^{k}\rho_{\rm top}^{k} I\left(h, t - \frac{h-z}{c} - \frac{2kh}{c}\right) \\ +\rho_{\rm bot}^{k+1}\rho_{\rm top}^{k} I\left(h, t - \frac{h+z}{c} - \frac{2kh}{c}\right) \end{array} \right], \quad 0 \le z \le h \text{ (along the strike object)} \quad (4)$$

$$I(z,t) = \frac{1-\rho_{\rm top}}{2} \times \left[\begin{array}{l} I\left(h, t - \frac{z-h}{v}\right) \\ +\sum_{k=1}^{\infty} \rho_{\rm bot}^{k}\rho_{\rm top}^{k-1}(1+\rho_{\rm top}) I\left(h, t - \frac{z-h}{v} - \frac{2kh}{c}\right) \end{array} \right], \quad h \le z \text{ (along the lightning channel)} \quad (5)$$

where $\rho_{\rm bot}$ and $\rho_{\rm top}$ are the current reflection coefficients at the bottom of the strike object and at the top of the object, respectively, and k is an index representing the successive multiple reflections occurring at the two ends of the strike object.

The 2-D FDTD meshes are illustrated in Fig. 2, and the finite-difference equations for the horizontal electric field E_r, vertical electric field E_z, and horizontal magnetic fiel, H_φ can be written as in (6)–(8), shown at the bottom of the page [20]

In this paper, we employ the first-order Mur absorbing boundary conditions [21] in order to simulate unbounded space.

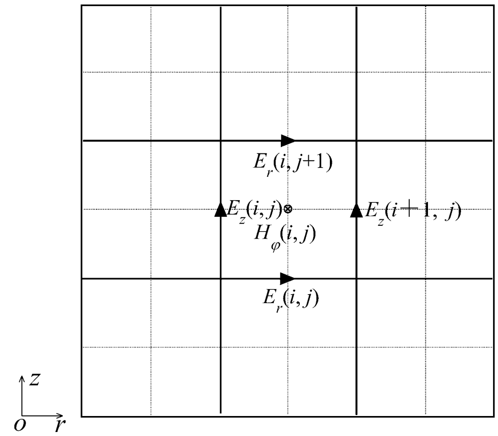


Fig. 2. Two-dimensional FDTD meshes in cylindrical coordinates.

B. Coupling of Electromagnetic Field to Overhead Line

For the case of a multiconductor line, the Agrawal coupling model [4] can be written in the time domain as

$$\frac{\partial}{\partial x}\left[v_p^s(x,t)\right] + [L'_{pq}]\frac{\partial}{\partial t}[i_p(x,t)] + [\xi'_{pq}] \otimes \frac{\partial}{\partial x}[i_p(x,t)] = \left[E_x^e(x,h_p,t)\right] \quad (9)$$

$$\frac{\partial}{\partial x}[i_p(x,t)] + [C'_{pq}]\frac{\partial}{\partial t}\left[v_p^s(x,t)\right] = 0 \quad (10)$$

where $[v_p^s(x,t)]$ is related to the total voltage $[v_p(x,t)]$ by the following expression:

$$\left[v_p^s(x,t)\right] = [v_p(x,t)] - \left[v_p^e(x,t)\right] \quad (11)$$

where $[v_p^e(x,t)] = -\int_0^{h_p} E_z^e(x,z,t)\mathrm{d}z \approx -h_p E_z^e(x,0,t)$ and "$\otimes$" denotes the convolution integral.

The boundary conditions, for the case of resistive terminations, are

$$\left[v_p^s(x_0,t)\right] = -[R_0][i_p(x_0,t)] + [h_p]E_z^e(x_0,0,t) \quad (12)$$

$$\left[v_p^s(x_L,t)\right] = [R_L][i_p(x_L,t)] + [h_p]E_z^e(x_L,0,t) \quad (13)$$

where $[R_0]$ and $[R_L]$ are the matrices of the line termination resistances.

$$E_r^{n+1}\left(i+\frac{1}{2},j\right) = \frac{2\varepsilon-\sigma\Delta t}{2\varepsilon+\sigma\Delta t}E_r^n\left(i+\frac{1}{2},j\right) - \frac{2\Delta t}{(2\varepsilon+\sigma\Delta t)\Delta z}\left[H_\varphi^{n+(1/2)}\left(i+\frac{1}{2},j+\frac{1}{2}\right) - H_\varphi^{n+(1/2)}\left(i-\frac{1}{2},j+\frac{1}{2}\right)\right] \quad (6)$$

$$E_z^{n+1}\left(i,j+\frac{1}{2}\right) = \frac{2\varepsilon-\sigma\Delta t}{2\varepsilon+\sigma\Delta t}E_z^n\left(i,j+\frac{1}{2}\right) + \frac{2\Delta t}{(2\varepsilon+\sigma\Delta t)r_i\Delta r}\left[r_{i+(1/2)}H_\varphi^{n+(1/2)}\left(i+\frac{1}{2},j+\frac{1}{2}\right) - r_{i-(1/2)}H_\varphi^{n+(1/2)}\left(i-\frac{1}{2},j+\frac{1}{2}\right)\right] \quad (7)$$

$$H_\varphi^{n+1/2}\left(i+\frac{1}{2},j+\frac{1}{2}\right) = H_\varphi^{n-1/2}\left(i+\frac{1}{2},j+\frac{1}{2}\right) + \frac{\Delta t}{\mu_0\Delta r}\left[E_z^n\left(i+1,j+\frac{1}{2}\right) - E_z^n\left(i,j+\frac{1}{2}\right)\right] - \frac{\Delta t}{\mu_0\Delta z}\left[E_r^n\left(i+\frac{1}{2},j+1\right) - E_r^n\left(i+\frac{1}{2},j\right)\right]. \quad (8)$$

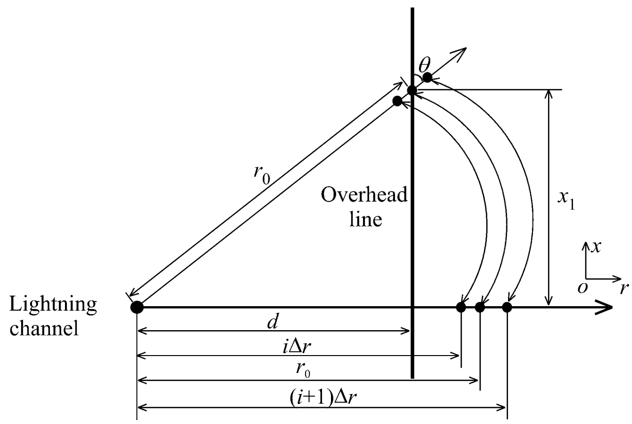


Fig. 3. Relative location of lightning channel and overhead line.

The electric field E_x along the line at distance r_0 from the lightning return stroke channel was calculated using the 2-D FDTD method for configuration shown in Fig. 1. An interpolation technique had to be adopted in case the distance r_0 does not exactly correspond to the FDTD grid point. For the geometry shown in Fig. 3, with $r_0 = \sqrt{d^2 + x_1^2}$, we set $i = \text{int}(r_0/\Delta r)$, so that the horizontal electric field in the radial direction from the lightning channel is

$$E_r(r_0) = \left(1 - \frac{d - i\Delta r}{\Delta r}\right) E_r(i\Delta r) + \frac{d - i\Delta r}{\Delta r} E_r((i+1)\Delta r) \quad (14)$$

and the horizontal electric field along the overhead line is

$$E_x(i) = E_r(r_0)\cos\theta = E_r(r_0)\frac{x_1}{r_0} \quad (15)$$

where $E_x(i)$ is the excitation term in the discretized electromagnetic coupling equations.

Using the point-centered finite-difference technique and neglecting the convolution integral, we can discretize (9), (10), (12), and (13) and solve them directly in the time domain

$$\begin{aligned}\left[v_p^s(i\Delta x, (n+1)\Delta t)\right] &= \left[v_p^s(i\Delta x, n\Delta t)\right] \\ &+ \frac{[C'_{pq}]^{-1}}{\Delta t}\frac{[i_p((i-1)\Delta x, n\Delta t)] - [i_p(i\Delta x, n\Delta t)]}{\Delta x}, \\ & \qquad i = 2, 3, \ldots, n\max - 1 \end{aligned} \quad (16)$$

$$\begin{aligned}[i_p(i\Delta x, (n+1)\Delta t)] &= [i_p(i\Delta x, n\Delta t)] \\ &- \frac{[L'_{pq}]^{-1}}{\Delta t}\left[\frac{\left[v_p^s((i+1)\Delta x, n\Delta t)\right] - \left[v_p^s(i\Delta x, n\Delta t)\right]}{\Delta x}\right. \\ &\left. - \frac{[E_x^e(i\Delta x, h_p, (n+1)\Delta t)] + [E_x^e(i\Delta x, h_p, n\Delta t)]}{2}\right] \\ & \qquad i = 1, 2, \ldots, n\max - 1 \end{aligned} \quad (17)$$

$$\begin{aligned}&\left[v_p^s(1, (n+1)\Delta t)\right] \\ &= -[R_0][i_p(1, (n+1)\Delta t)] + [h_p]E_z^e(1, 0, (n+1)\Delta t) \end{aligned} \quad (18)$$

$$\begin{aligned}&\left[v_p^s(n\max, (n+1)\Delta t)\right] \\ &= [R_L][i_p(n\max, (n+1)\Delta t)] + [h_p]E_z^e(n\max, (n+1)\Delta t). \end{aligned} \quad (19)$$

The horizontal electric field E_x in (17) is computed using the 2-D FDTD method; it can be directly inserted into the finite difference equations to obtain the induced voltages and currents at any position along the line.

The spatial discretization interval Δx in (16) and (17) equals the spatial discretization interval Δr in the calculation of electromagnetic fields and the time discretization interval $\Delta t \leq \Delta x/2c$, which satisfies the Courant stability condition $\Delta t \leq \Delta x/c$.

III. Analysis and Discussion

A. Lightning Strikes to Flat Ground

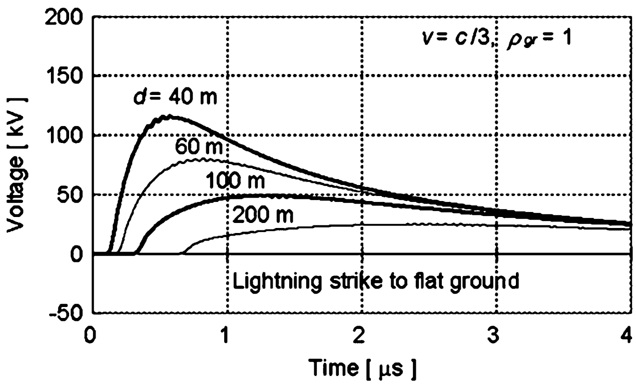
1) Comparison With Voltages Computed Using the 3-D FDTD Method: Baba and Rakov [14] computed induced voltages due to lightning strikes to both flat ground and tall grounded object using the 3-D FDTD method without invoking any electromagnetic coupling model. In their simulation, a 1200-m-long horizontal wire had a radius of 5 mm and was located 10 m above the ground. Each end of the horizontal wire was terminated with a 498-Ω matching resistor. The strike point was equidistant from the line terminations. The conductivity and relative permittivity of the earth for both flat ground case and tall grounded object case were set to $\sigma_g = 0.01$ S/m and $\varepsilon_{rg} = 10$. The return-stroke speed was $v = c/3$. The current waveform used in our simulation was the one proposed by Nucci *et al.* [22] and adopted by Baba and Rakov [14]. Its peak is 11 kA and peak derivative is 105 kA/μs.

In this section, we compare the results obtained using the 2-D FDTD method with those calculated using the 3-D FDTD method for flat ground conditions. The comparison for lightning strikes to tall tower conditions will be presented in Section III-B1.

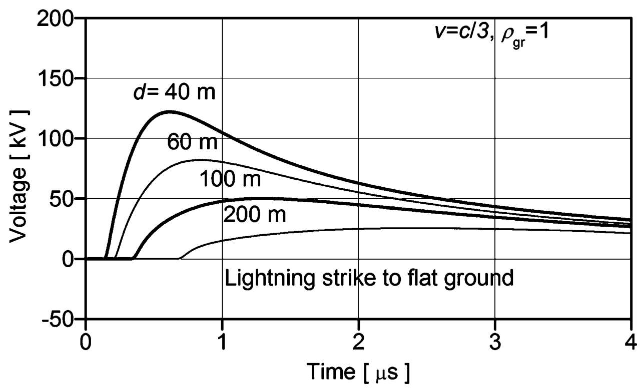
From Fig. 4(a) and (b), one can see that induced voltages calculated using the 2-D FDTD method and Agrawal coupling model agree fairly well with those calculated using the 3-D FDTD method.

2) Comparison With Experimental Data: In this section, we compare lightning-induced voltages calculated using the 2-D FDTD method and Agrawal coupling model with those measured by Barker *et al.* [23]. In Barker *et al.*'s experiment, a rocket-triggered lightning channel was at a distance of 145 m from the center of a two-conductor overhead line, as shown in Fig. 5. The line was 682 m long, and the two conductors were vertically stacked with separation between them being 1.8 m. The line was supported by 15 wooden poles spaced about 49 m apart. The upper conductor was placed above the ground at a height of 7.5 m and simulated the phase conductor. It was connected to the lower conductor by 455-Ω resistors at the termination poles. The lower conductor, which simulated the neutral, was grounded at both ends and at pole 9 (the grounding at pole 9 was treated in our model as a resistive load). The grounding resistance values were between 30 and 75 Ω. Barker *et al.* have measured channel-base currents, corresponding fields, and induced voltages at poles 1, 9, and 15.

We approximated the return-stroke current measured by Barker *et al.* for the only stroke in Flash 93-05 by the sum



(a)



(b)

Fig. 4. (a) Lightning-induced voltages at the center point of the horizontal wire at distances d = 40, 60, 100, and 200 m from the lightning channel, calculated using the 3-D FDTD method. Taken from Baba and Rakov [14]. (b) Same as (a) but calculated using the 2-D FDTD method and Agrawal coupling model, examined in this paper.

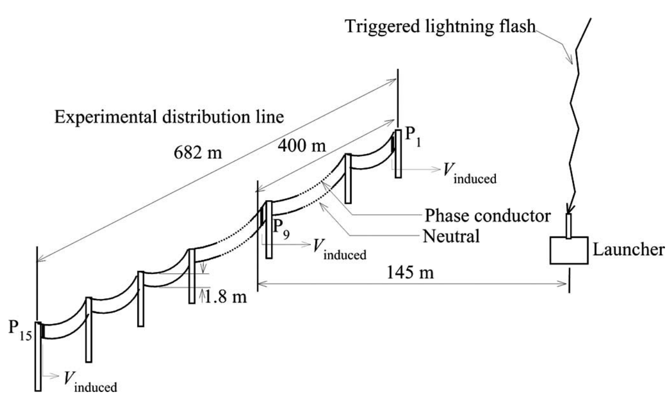


Fig. 5. Experimental configuration. Adapted from Barker *et al.* [23].

of two Heidler functions [24]

$$I(0,t) = \frac{I_0}{\eta}\frac{(t/\tau_1)^m}{(t/\tau_1)^m+1}\exp\left(-\frac{t}{\tau_2}\right) \tag{20}$$

$$\eta = \exp[-(\tau_1/\tau_2)(m\tau_2/\tau_1)^{(1/m)}]. \tag{21}$$

We used the following values of Heidler function parameters: $I_{01} = 13.1$ kA, $\tau_{11} = 0.22\ \mu$s, $\tau_{12} = 88\ \mu$s, $m_1 = 2$, $\eta_1 = 0.93$ for the first function, and $I_{02} = 8.7$ kA, $\tau_{21} = 0.21\ \mu$s, $\tau_{22} = 61\ \mu$s, $m_2 = 2$, $\eta_2 = 0.92$ for the second function. The measured return-stroke current (Flash 93-05) and its approximation by two Heidler functions are shown in Fig. 6.

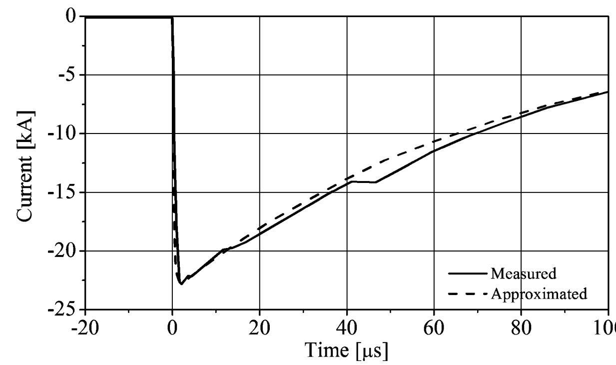


Fig. 6. Comparison of measured return-stroke current for Flash 93-05 and its approximation by two Heidler functions.

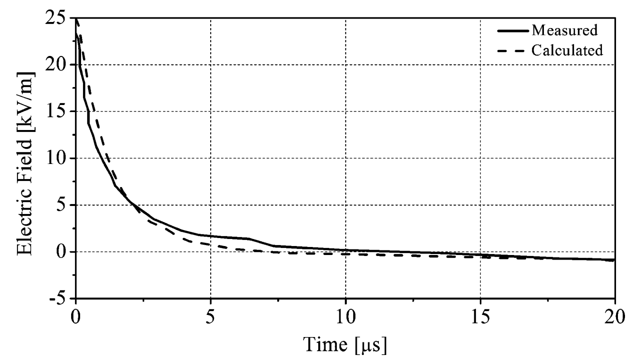


Fig. 7. Comparison of measured and calculated vertical electric field (return-stroke only) at 110 m for Flash 93-05. In the simulation, the MTLL model was employed.

Measured and calculated vertical electric fields (return-stroke only) at a distance of 110 m from the lightning channel are shown in Fig. 7.

In our simulations, we varied the ground conductivity, lightning return-stroke speed, lightning return-stroke model, and grounding resistance value (the same for all three grounds) to examine their influence on the computed induced voltage at pole 9 (at the center of the line).

The simulation results are shown in Fig. 8, where one can see that the ground conductivity plays the most important role in determining the magnitude of induced voltages. The return-stroke speed has also some influence. As to the three return-stroke models (TL, MTLL, and MTLE) and the three grounding resistance values selected for the simulation, they do not seem to have much influence on the calculated results. The match between the simulation results and the experimental data is the best when the ground conductivity $\sigma_g = 3.5 \times 10^{-3}$ S/m and the lightning return-stroke speed $v = 1.3 \times 10^8$ m/s. While our model reproduces measured voltages at pole 9 (at the center of the line) reasonably well, model-predicted voltages at pole 1 differ significantly from measured ones. Differences could be due to model assumptions and uncertainties in the line terminations.

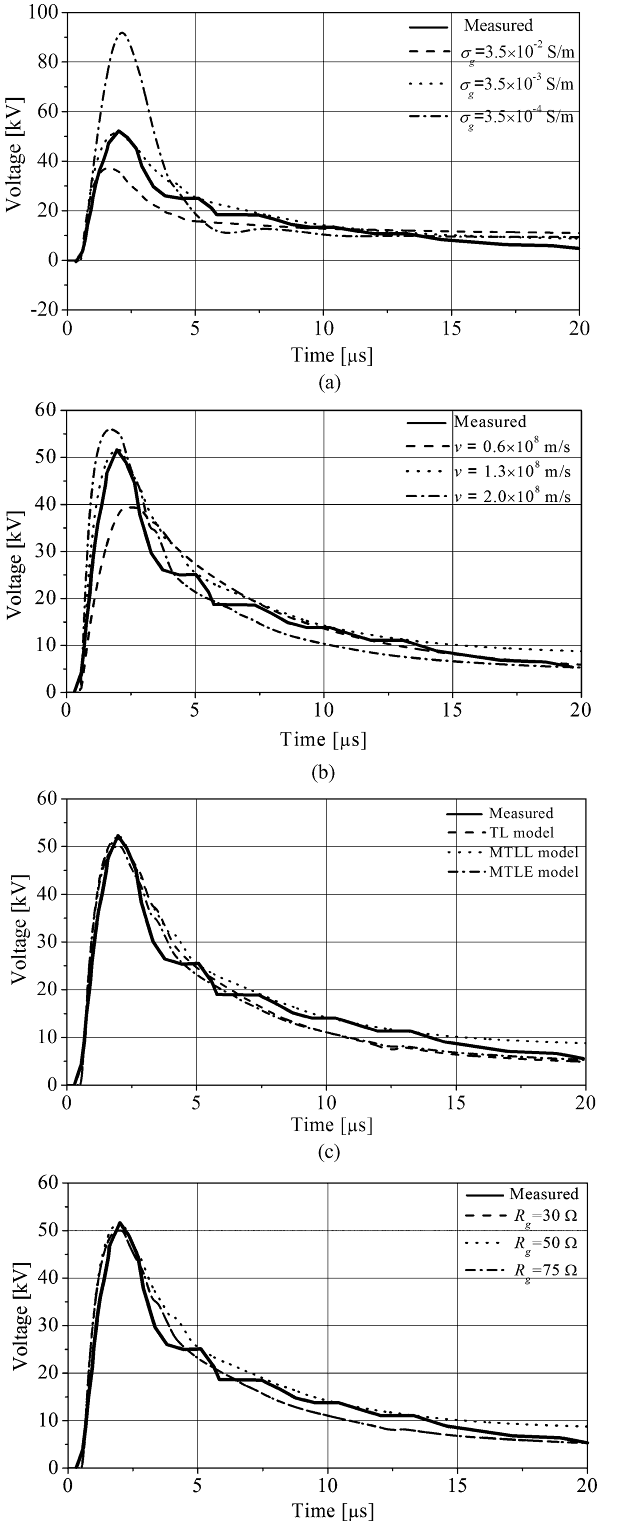


Fig. 8. Measured and calculated voltages at pole 9 for Flash 93-05. (a) Lightning return-stroke speed $v = 1.3 \times 10^8$ m/s, grounding resistance $R_g = 50\ \Omega$, and ground conductivity σ_g is varied. (b) Ground conductivity $\sigma_g = 3.5 \times 10^{-3}$ S/m, grounding resistance $R_g = 50\ \Omega$, and the return-stroke speed is varied. (c) Ground conductivity $\sigma_g = 3.5 \times 10^{-3}$ S/m, lightning return-stroke speed $v = 1.3 \times 10^8$ m/s, grounding resistance $R_g = 50\ \Omega$, and return-stroke model is varied. (d) Ground conductivity $\sigma_g = 3.5 \times 10^{-3}$ S/m, lightning return-stroke speed $v = 1.3 \times 10^8$ m/s, and grounding resistance is varied. In (a), (b), and (d), the TL model was employed.

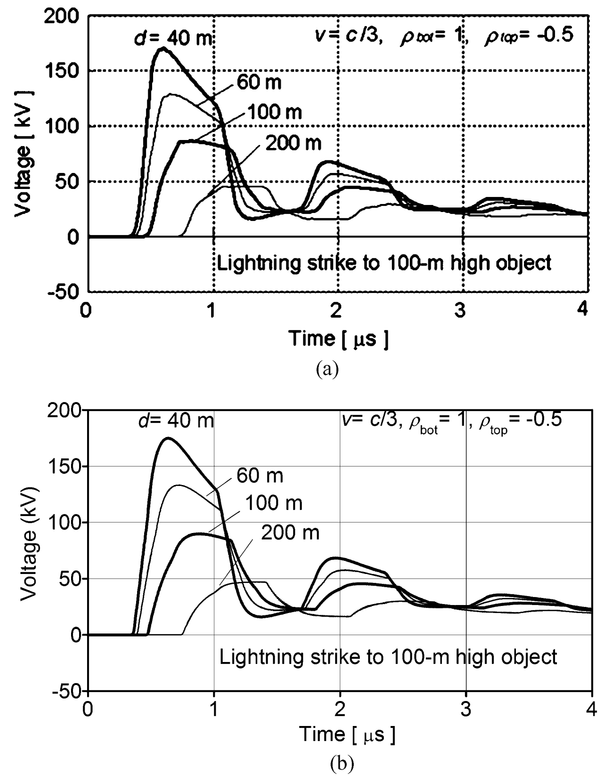


Fig. 9. (a) Lightning-induced voltages at the center point of a horizontal wire at distances $d = 40$, 60, 100, and 200 m from the lightning channel, calculated using the 3-D FDTD method. Taken from Baba and Rakov [14]. (b) Same as (a) but calculated using the 2-D FDTD method and Agrawal coupling model.

B. Lightning Strikes to Tall Grounded Objects

1) Comparison With Voltages Computed Using the 3-D FDTD Method: In this section, we consider lightning strikes to a tall grounded object. The height of the strike object $h =$ 100 m. The current reflection coefficient at the bottom of the object was set to $\rho_{\rm bot} = 1$ and the current reflection coefficient at the top of the object for upward propagating waves to $\rho_{\rm top} = -0.5$. Other than that, the configuration is the same as that introduced in Section III-A1.

We compare our calculated induced voltages with those of Baba and Rakov [14] obtained using the 3-D FDTD method in Fig. 9. It can be seen that the calculated results obtained using these two different approaches agree well.

2) Comparison With Experimental Data: Michishita *et al.* [25] have carried out induced-voltage experiments on the coast of the Sea of Japan from 1993 to 1997. The plan view of the experimental site is shown in Fig. 10. The height of the lightning strike object was 200 m. A horizontal wire 2.5 mm in radius and about 300 m in length was stretched 11 m above the ground. Both ends of this horizontal wire were terminated in 400-Ω resistors. The distance from the close end of the line to the strike object was 373 m. Waveforms of lightning current at the top of the strike object and lightning-induced voltages at both ends of the horizontal wire were measured.

Here, we compare simulation results for Michishita *et al.*'s configuration obtained using the 2-D FDTD method and the

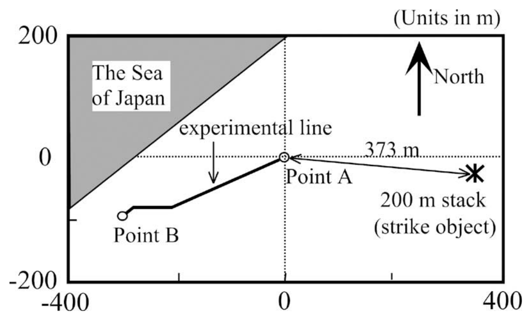


Fig. 10. Plan view of the experimental site. Adapted from Michishita *et al.* [25].

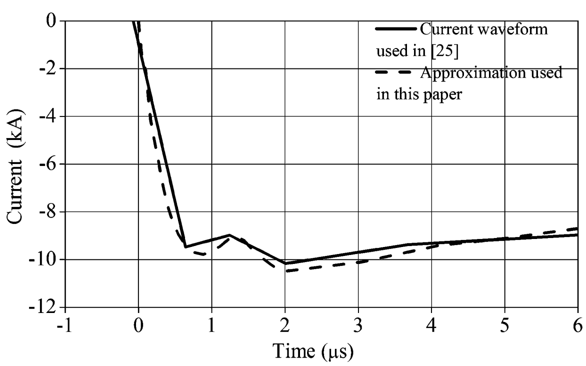


Fig. 11. Current waveform used in [25] and its approximation used in this paper.

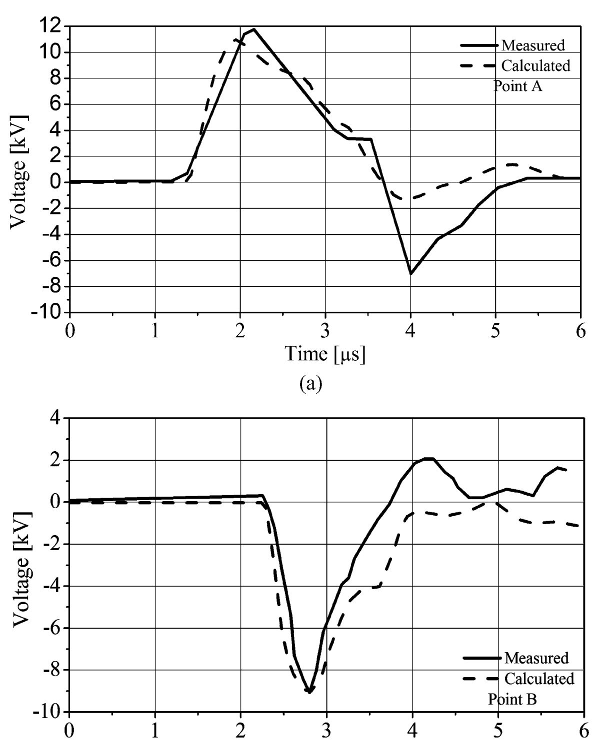


Fig. 12. Comparison of calculated induced-voltage waveforms with experimental data at the termination points. (a) At point A. (b) At point B (see Fig. 10).

Agrawal coupling model with measurements. Fig. 11 shows the current waveform used by Michishita *et al.* and its approximation used in our simulation. We assumed that the lightning return-stroke speed $v = 1.0 \times 10^8$ m/s, and the conductivity and relative permittivity of ground $\sigma_g = 0.01$ S/m and $\varepsilon_{rg} = 10$, respectively. Following Michishita *et al.*, we set $\rho_{\text{top}} = -0.6$, $\rho_{\text{bot}} = 0.42$. Measured and computed induced-voltage waveforms at line terminations (points A and B) are compared in Fig. 12. It is clear from Fig. 12 that induced voltages calculated using the 2-D FDTD method and Agrawal coupling model are in fairly good agreement with the measured ones. Somewhat larger differences at point A might be due to the fact that the grounding resistance is not equal to the characteristic impedance of the overhead line in the experiment, while in the simulation, the grounding resistance is set to be equal to the characteristic impedance of the overhead line in order to avoid reflections at the terminals.

IV. Summary

We examined the 2-D FDTD method combined with the Agrawal electromagnetic coupling model for calculation of lightning-induced voltages on a single or multiconductor overhead line over lossy ground without employing the Cooray–Rubinstein formula. This approach generally provides sufficiently accurate results, while it greatly reduces the memory requirements and computation time as compared to the 3-D FDTD method. Specifically, it can save nearly half of the storage space and needs only a few minutes to obtain the final result. From the analysis carried out in this paper, it can be seen that induced voltages appear to be strongly dependent on ground conductivity, somewhat influenced by return-stroke speed, and essentially independent of return-stroke model (TL, MTLL, or MTLE).

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References

[1] S. Rusck, "Induced lightning overvoltages on power transmission lines with special reference to the over-voltage protection of low voltage networks," *Trans. R. Inst. Technol.*, Stockholm, Sweden, no. 120, 1958, pp. 1–118.

[2] C. D. Taylor, R. S. Satterwhite, and C. W. Harrison, "The response of a terminated two-wire transmission line excited by nonuniform electromagnetic field," *IEEE Trans. Antennas Propag.*, vol. AP-13, no. 6, pp. 987–989, Nov. 1965.

[3] P. Chowdhuri and E. T. B. Gross, "Voltage surges induced on overhead lines by lightning strokes," *Proc. Inst. Electr. Eng.*, vol. 114, no. 12, pp. 1899–1907, Dec. 1967.

[4] A. K. Agrawal, H. J. Price, and S. H. Gurbaxani, "Transient response of multiconductor transmission lines excited by a nonuniform electromagnetic field," *IEEE Trans. Electromagn. Compat.*, vol. EMC-22, no. 3, pp. 119–129, May 1980.

[5] F. Rachidi, "Formulation of the field-to-transmission line coupling equations in terms of magnetic excitation fields," *IEEE Trans. Electromagn. Compat.*, vol. 35, no. 3, pp. 404–407, Aug. 1990.

[6] 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, no. 4, pp. 355–363, Nov. 1998.

[7] F. Rachidi, C. A. Nucci, and M. Ianoz, "Influence of a lossy ground on lightning-induced voltages on overhead lines," *IEEE Trans. Electromagn. Compat.*, vol. 38, no. 3, pp. 250–264, Aug. 1996.

[8] V. Cooray, "Some considerations on the 'Cooray-Rubinstein' approximation used in deriving the horizontal electric field over finitely conducting ground," *IEEE Trans. Electromagn. Compat.*, vol. 44, no. 4, pp. 560–565, Nov. 2002.

[9] V. Cooray, "Horizontal electric fields generated by return strokes," *Radio Sci.*, vol. 27, no. 4, pp. 529–537, Jul./Aug. 1992.

[10] M. Rubinstein, "An approximate formula for the calculation of the horizontal electric field from lightning at close, intermediate, and long range," *IEEE Trans. Electromagn. Compat.*, vol. 38, no. 3, pp. 531–535, Aug. 1996.

[11] J. R. Wait, "Concerning the horizontal electric field of lightning," *IEEE Trans. Electromagn. Compat.*, vol. 39, no. 2, p. 186, May 1997.

[12] A. Shoory, R. Moini, S. H. H. Sadeghi, and V. A. Rakov, "Analysis of lightning-radiated electromagnetic fields in the vicinity of lossy ground," *IEEE Trans. Electromagn. Compat.*, vol. 47, no. 1, pp. 131–144, Feb. 2005.

[13] H. K. Hoidalen, "Analytical formulation of lightning-induced voltages on multiconductor overhead lines above lossy ground," *IEEE Trans. Electromagn. Compat.*, vol. 45, no. 1, pp. 92–100, Feb. 2003.

[14] 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, Feb. 2006.

[15] Y. Baba and V. A. Rakov, "Lightning electromagnetic environment in the presence of a tall grounded strike object," *J. Geophys. Res.*, vol. 110, no. D9, D09108, May 2005.

[16] Y. Baba and V. A. Rakov, "On the use of lumped sources in lightning return stroke models," *J. Geophys. Res.*, vol. 110, no. D3, D03101, Feb. 2005.

[17] M. A. Uman and D. K. Mclain, "Magnetic field of the lightning return stroke," *J. Geophys. Res.*, vol. 74, pp. 6899–6910, 1969.

[18] V. A. Rakov and A. A. Dulzon, "Calculated electromagnetic fields of lightning return stroke," *Tekh. Elektrodinam.*, no. 1, pp. 87–89, 1987.

[19] C. A. Nucci, C. Mazzetti, F. Rachidi, and M. Ianoz, "On lightning return stroke models for LEMP calculations," presented at the 19th Int. Conf. Lightning Protection, Graz, Austria, Apr. 1988.

[20] C. Yang and B. Zhou, "Calculation method of electromagnetic field very close to lightning," *IEEE Trans. Electromagn. Compat.*, vol. 49, no. 1, pp. 133–141, Jan. 2004.

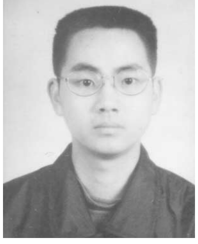
[21] G. Mur, "Absorbing boundary conditions for the finite-difference approximation of the time-domain electromagnetic field equations," *IEEE Trans. Electromagn. Compat.*, vol. EMC-23, no. 4, pp. 377–382, Nov. 1981.

[22] 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. 20 395–20 408, 1990.

[23] P. P. Barker, T. A. Short, A. R. Eybert-Berard, and J. P. Berlandis, "Induced voltage measurements on an experimental distribution line during nearby rocket triggered lightning flashes," *IEEE Trans. Power Del.*, vol. 11, no. 2, pp. 980–995, Apr. 1996.

[24] F. Heidler, "Traveling current source model for LEMP calculation," in *Proc. 6th Int. Symp. Tech. Exhib. Electromagn. Compat.*, Zurich, Switzerland, Mar. 1985, pp. 157–162.

[25] K. Michishita, M. Ishii, A. Asakawa, S. Yokoyama, and K. Kami, "Voltage induced on a test distribution line by negative winter lightning strokes to a tall structure," *IEEE Trans. Electromagn. Compat.*, vol. 45, no. 1, pp. 135–140, Jan. 2003.



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