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# FDTD Analysis of Lightning-Induced Voltages on Shielded Telecommunication Cable with Multipoint Grounding

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## Abstract

In this paper, the lightning-induced voltages on shielded twisted-pair wires with multipoint grounding on cable sheath are calculated by using finite-difference time domain (FDTD) method. The equivalent single-wire line that represents a bundle of twisted-pair wires is adopted for computational efficiency. A finitely conducting ground is also taken into account in both lightning electromagnetic field calculations and surge propagation along the shielded cable for a practical simulation. It is found that multipoint additional grounding on cable sheath provides more shielding effectiveness especially in the early time response of the lightning-induced voltages. From this study, the requirements for lightning surge protection devices in a telecommunication subscriber cable can be established.

***Key words*** : lightning EM field, coupling, shielded cable, induced voltage, grounding

## Ⅰ. INTRODUCTION

Induced voltages caused by lightning on a telecommunication subscriber cable can cause damages to telecommunication electronic control and management systems. Several studies using transmission line theory have been performed to estimate the incident electromagnetic (EM) field coupling to the transmission line[1]~[3]. The EM fields due to a nearby lightning return stroke over a perfect ground plane was calculated in [4]~[6]. In the case of a lossy ground plane, the formula for the adequate numerical calculation of lightning EM fields was proposed in [7]. The effects of a lossy ground in solving transmission line equations was presented by using ground impedance[3]. For multiconductor transmission lines, the ground transient resistance, i.e., inverse Fourier Transform of the ground impedance, was recently developed in[8],[9] for the time domain calculation of induced voltages on overhead transmission lines. For a shielded cable, induced currents on the cable sheath due to lightning EM fields induce voltages on the inner wires. This physical behavior of shielded cable can be described by the transfer impedance of shield material[3],[10].

The telecommunication subscriber cable is usually the shielded twisted-pair wires. The cable sheath is also usually grounded at every several hundred meters to reduce the induced voltages on the cable. For shielded twisted-pair wires with additional grounding on the cable sheath, however, the time-domain analysis of lightning-induced voltages is rarely found in the literature. In this paper, the induced voltages on shielded twisted-pair wires due to a typical nearby lightning return stroke are calculated by the FDTD method. The effect of the multipoint grounding on cable sheath is also examined. For a bundle of twisted-pair wires in the calculation of induced voltages, an equivalent single-wire line representation was proposed in [11]. The equivalent single-wire line representation is adopted for computational efficiency. A finitely conducting ground is taken into account in both electromagnetic field calculations and surge propagation along the wires for a practical simulation.

## Ⅱ. EM FIELDS DUE TO LIGHTNING RETURN STROKE

The geometry of a lightning channel and a telecommunication subscriber cable is shown in Fig. 1. The EM field due to a nearby lightning stroke over a perfectly conducting ground plane can be calculated by assuming the lightning channel as a vertical unidimensional antenna and modeling the channel current[6]. In this study, the lightning channel current waveform used in [5] is adopted and the lightning EM fields are calculated by using the modified transmission line (MTL) model[4],[5]. The vertical component of lightning electric fields $E_z$ is calculated with reasonable approximation assuming perfectly conducting ground in case the observation point does not exceed a few kilometers from the lightning channel. The horizontal component of electric fields $E_\rho$, however, is more affected by a finite conductivity of

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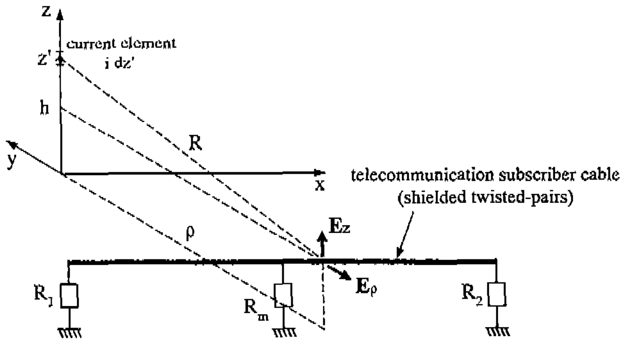
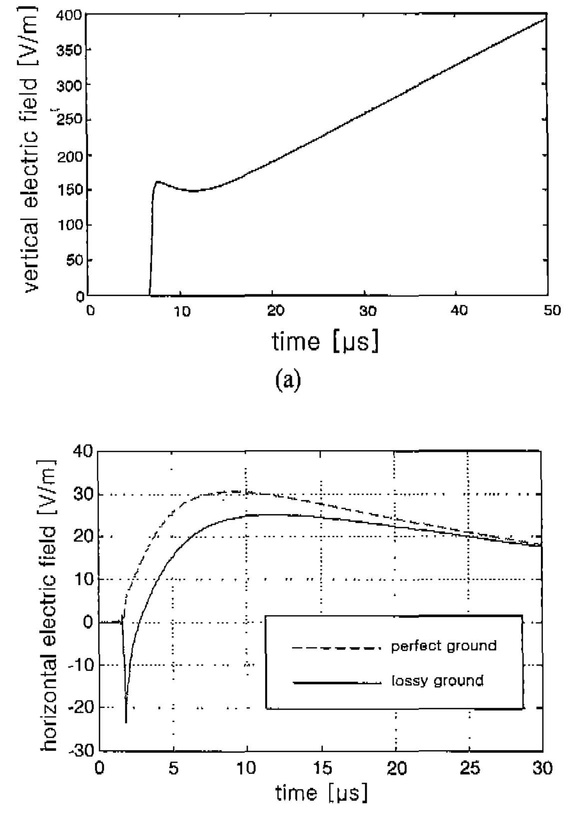


Fig. 1. Geometry of a lightning channel and a telecommunication subscriber cable.

a ground plane. It is also known that the contribution of $E_\rho$ to induced voltages on a overhead transmission line is greater than that of $E_z$. Therefore, the calculation of $E_\rho$ is great concern for the simulation of lightning-induced voltages.



(a)

(b)

Fig. 2. Calculated electric fields.
(a) vertical component ( $\rho$ = 2 km and $h$ = 10 m)
(b) horizontal component ( $\rho$ = 500 m and $h$ = 6 m)

Considering a finitely conducting ground, $E_\rho$ can be calculated by the simple formula assuming the low frequency approximation, $\sigma_g \gg \omega\varepsilon_0\varepsilon_{rg}$, as follows[7]:

$$E_\rho(\rho,z,j\omega) = -H_{\phi p}(\rho,0,j\omega)\frac{\sqrt{\mu_0}}{\sqrt{\varepsilon_0\varepsilon_{rg}+\sigma_g/j\omega}} + E_{\rho p}(\rho,z,j\omega) \qquad (1)$$

where the subindex $p$ implies the field calculation in the hypothesis of a perfectly conducting ground. $\mu_0$ and $\varepsilon_0$ are permeability and permittivity of free space, respectively. $\varepsilon_{rg}$ and $\sigma_g$ are relative permittivity and conductivity of a ground plane, respectively.

Fig. 2 shows the calculated vertical and horizontal components of electric fields. The calculated waveforms show good agreement with the results shown in [5],[7]. The waveform of a measured typical vertical electric field at 2 km from the lightning channel for a natural subsequent return stroke was compared with the calculated one assuming a perfectly conducting ground plane as shown in Fig. 2(a)[5]. It was verified that the measured and calculated waveforms are similar. Regarding the horizontal electric field, the waveform is affected by the finite conductivity and permittivity of the ground as shown in Fig. 2(b). Note that the horizontal component of electric field is due to the different distances and different retardation times of the fields produced by the current in each channel segment and its image. The farther distance from the lightning channel, therefore, the more affected waveform by a lossy ground.

## Ⅲ. TRANSMISSION LINE EQUATIONS

The transmission line equations involving a lossy ground are expressed as follows[9]:

$$\frac{\partial}{\partial x}v^s(x,t) + L'\frac{\partial}{\partial t}i(x,t) + \xi'_g * \frac{\partial}{\partial t}i(x,t) = E_x^{inc}(x,h,t) \qquad (2)$$

$$\frac{\partial}{\partial x}i(x,t) + G'v^s(x,t) + C'\frac{\partial}{\partial t}v^s(x,t) = 0 \qquad (3)$$

where $v^s(x,t)$ is the scattered voltage and $i(x,t)$ is the line current. $E_x^{inc}(x,h,t)$ is the horizontal component of incident electric field along the line at the line height $h$. $L'$, $G'$, and $C'$ represent inductance, conductance, and capacitance of per-unit-length, respectively. $\xi'_g$ is called the transient ground resistance, i.e., the inverse Fourier Transform of a ground impedance $Z_g$[3],[8],[9], and expressed as

$$\xi_g = F^{-1}\frac{Z_g}{j\omega} \qquad (4)$$

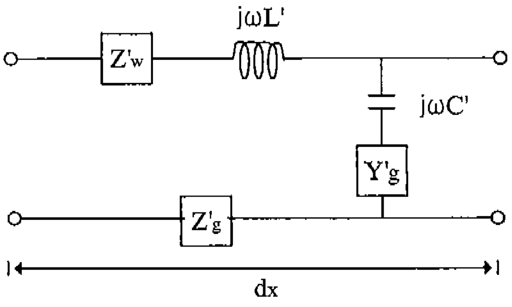


Fig. 3. Differential section of a line over a lossy earth.

Fig. 3 illustrates the equivalent circuit for a differential section of line involving a lossy ground. The ground impedance $Z'_g$ is much greater than wire impedance $Z'_w$ for a typical overhead telecommunication line. Thus, $Z'_w$ is neglected in this studied. The shunt admittance $Y'_g$ representing the ground is expressed as

$$Y'_g = \frac{\gamma_g^2}{Z'_g} \tag{5}$$

where $\gamma_g$ is the propagation constant in the ground. The per-unit-length parameters in (2) and (3) are discussed in more details in[2],[3],[5].

The total voltage is the sum of the scattered and incident voltage and is expressed as

$$v(x,t) = v^s(x,t) + v^{inc}(x,t) = v^s(x,t) - \int_0^h E_z^{inc}(x,t)\,dz \tag{6}$$

where $v^{inc}(x,t)$ is the incident voltage and $E_z^{inc}(x,t)$ is the vertical component of the incident electric field.

The boundary conditions for the scattered voltage are given by

$$v^s(x_0,t) = -R_1 i(x_0,t) + hE_z^{inc}(x_0,0,t) \tag{7}$$

$$v^s(x_0+L,t) = R_2 i(x_0+L,t) + hE_z^{inc}(x_0+L,0,t) \tag{8}$$

where $R_1$ and $R_2$ are the resistances of line terminations.

At the additional grounding position of the cable sheath, the FDTD solutions should satisfy the boundary conditions in (7) and (8), simultaneously. The point-centered finite-difference expression at the grounded position is expanded as [12]:

$$\begin{aligned}(v_m^{n+1})^s = {} & \left(\frac{\triangle x}{\triangle t}R_m C' + 1\right)^{-1}\left\{\left(\frac{\triangle x}{\triangle t}R_m C' - 1\right)(v_m^n)^s\right. \\ & \left. + R_m\left(i_{m-1/2}^{n+1/2} - i_{m+1/2}^{n+1/2}\right) + \left(\int_0^h E_z^{inc}dz\right)_m^{n+1} + \left(\int_0^h E_z^{inc}dz\right)_m^n\right\}\end{aligned} \tag{9}$$

where subindex $m$ and $n$ imply space lattice point at grounded position and time step, respectively. $\triangle z$ and $\triangle t$ are space and time increment in the finite-difference notation, respectively. $R_m$ is the resistance of the grounded position.

## Ⅳ. EM COUPLING THROUGH A SHIELDED CABLE

Fig. 4 shows a simple shielded transmission line system with additional grounding at the middle of the cable sheath. Lightning EM fields induce voltage $v_s$ and current $i_s$ on the cable sheath and can penetrate through imperfections in the cable sheath. Thus, the diffusion of the EM fields through the sheath material occurs.

Assuming the external circuit (exterior of cable sheath and ground plane) is independent of the behavior of the internal circuit (twisted-pair wires and interior of cable sheath), the induced voltages and currents on the internal circuit can be calculated by the following equations

$$\frac{\partial}{\partial x}[v_i(x,t)] + [L'_i]\frac{\partial}{\partial t}[i_i(x,t)] = [v'_{si}] \tag{10}$$

$$\frac{\partial}{\partial x}[i_i(x,t)] + [C'_i]\frac{\partial}{\partial t}[v_i(x,t)] = [i'_{si}] \tag{11}$$

where $[v_i(x,t)]$ and $[i_i(x,t)]$ are induced internal circuit voltage and current matrices due to $[v'_{si}]$ and $[i'_{si}]$. The sources $[v'_{si}]$ and $[i'_{si}]$ are related to the external line responses by

$$v'_{si}(x,t) = z'_t(t) * i_s(x,t) \tag{12}$$

$$i'_{si}(x,t) = -y'_t(t) * v_s(x,t) \tag{13}$$

where $z'_t(t)$ and $y'_t(t)$ are inverse Fourier Transform of the transfer impedance and transfer admittance of the shield, respectively.

An aluminum foil shield is usually used in a telecommunication subscriber cable. The transfer impedance of the foil shield imitates that of a corresponding solid tubular shield of identical radius and thickness. For a solid tubular shield, electric field shielding is much greater than magnetic field shielding, i.e., the transfer impedance term dominates much more than the

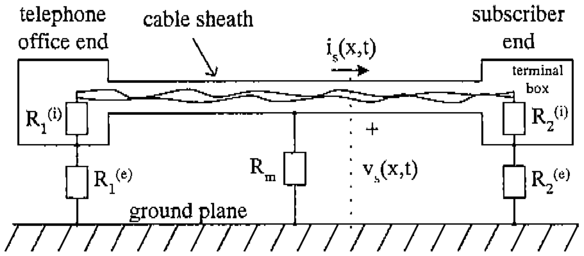


Fig. 4. Geometry of internal twisted-pair wires and cable sheath with additional grounding.

transfer admittance term. As a result, transfer admittance term is neglected in this paper. The transfer impedance for a tubular shield is expressed as [3],[10]:

$$Z_t = R'_0 \frac{(1+j)\triangle\delta}{\sinh[(1+j)\triangle/\delta]} \qquad [\Omega/\mathrm{m}] \qquad (14)$$

where $\triangle$ is the shield thickness and $\delta$ is the skin depth in the shield material. $R'_0$ is the dc per-unit-length resistance of the shield. Fig. 5 shows the cross-sectional view of test cable. The thickness of the shield is 0.2 mm. The transfer impedance of the test cable is shown in Fig. 6.

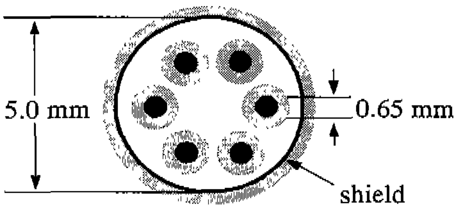


Fig. 5. Cross-sectional view of test cable.

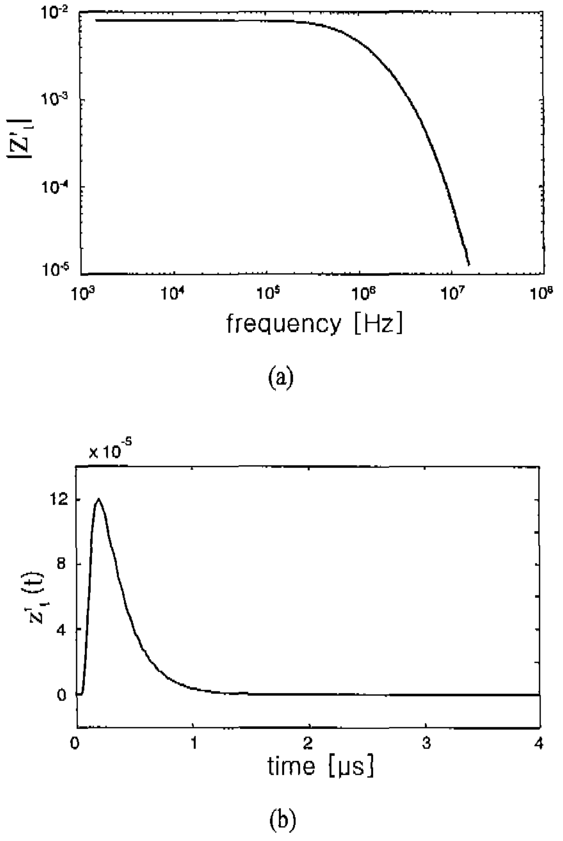


Fig. 6. Transfer impedance of the test cable.

(a) Magnitude of the transfer impedance

(b) Inverse Fourier Transform of the transfer impedance

A telecommunication subscriber cable is composed of several tens to hundreds of twisted-pair wires. It becomes complex and time consuming to compute the induced voltages on such a cable since the line parameters in the multiconductor transmission line equations become large in size and the functions of the line axis $x$. An equivalent single-wire line representation provides compact transmission line equations and great computational efficiency.

For twisted pairs of wires, it is a common practice that incident electromagnetic fields distributes the same voltage and current sources on the wires. It is also reasonable to assume that the wires are identical and carry the same voltage and current. Under these assumptions, the unknown quantities, $[v_i(x,t)]$ and $[i_i(x,t)]$, in (10) and (11) become the column matrices whose elements are identical. For an equivalent single-wire line, therefore, the per-unit-length parameters can be approximately expressed as

$$L'_{i,eq} \cong \frac{1}{N}\sum_{p=1}^{N}\sum_{q=1}^{N}[L'_{i,pq}] \qquad (15)$$

$$C'_{i,eq} \cong \frac{1}{N}\sum_{p=1}^{N}\sum_{q=1}^{N}[C'_{i,pq}] \qquad (16)$$

where N is the number of twisted-pair wires within the shield.

## V. SIMULATION RESULTS

The lightning electromagnetic fields are calculated by the method used in [5]. The return stroke velocity of $1.3\times10^8$ m/s and decay constant of 1.7 km are used. The conductivity and relative permittivity of the ground are assumed 0.01 S/m and 10, respectively. The telecommunication subscriber cable is assumed 1000 m long and 5 m above the lossy ground plane.

The termination resistances of external circuit, $R_1^{(e)}$ (telephone office end) and $R_2^{(e)}$ (subscriber end) as shown in Fig. 4, are selected 10 and 100 $\Omega$, respectively. The internal resistances $R_1^{(i)}$ and $R_2^{(i)}$ are assumed to be matched to the internal characteristic impedance. The resistances at the additional grounding point $R_m$ are assumed 100 $\Omega$. The lightning stroke location is at the same distance away from the line terminations and at the distance of 50 m from the line center.

The induced currents on the cable sheath $i_s(x,t)$ with no additional grounding are shown in Fig. 7. Before the reflected waves reach the termination, the amplitudes of induced currents are symmetrical around the striking point, but the sign reverses at the mid-point of the cable sheath. This is because the lightning stroke position is at the middle of the cable. So, the horizontal component of electric field in the direction of the cable is changed. At the point closest to the striking point, the

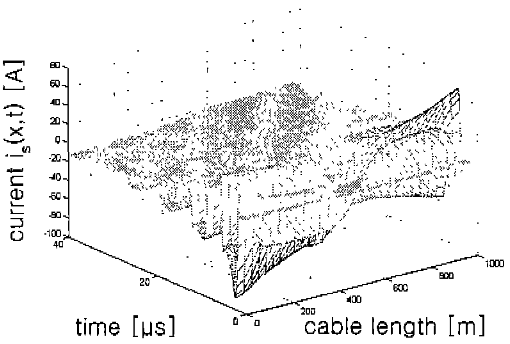
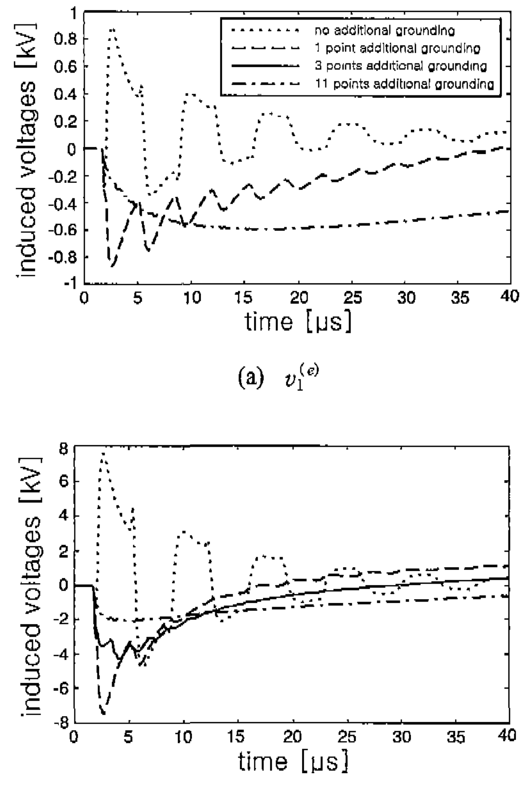


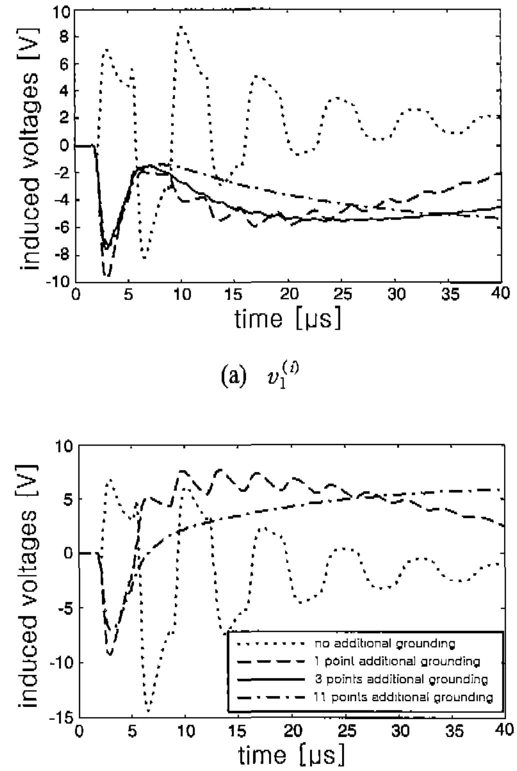
Fig. 7. Induced current on cable sheath.

horizontal field is perpendicular to the cable, and there is no field component in the cable direction. The induced voltages on the cable sheath at the terminations are shown in Fig. 8. Note that the waveforms show periodical component due to the wave reflections at both terminations and additional grounding position except for the case of 11 points additional grounding. The induced voltage in the case of 11 points additional grounding shows the smallest time derivative and the best shielding effectiveness in early time responses among the test cases. The time derivative in the early time response is very important to determine the requirement of surge protection devices.



(b) $v_2^{(e)}$

Fig. 8. Induced voltages on cable sheath.
1 point additional grounding: grounding at the middle of the cable sheath.
3 points additional grounding: grounding at every 250 m
11 points additional grounding: grounding at every 83.3 m



(b) $v_2^{(i)}$

Fig. 9. Internal voltage responses.

The internal voltage responses are shown in Fig. 9. Even though the terminations of the internal circuit are matched, there are oscillations on the wires due to the resonances on the cable sheath, especially, in the case of no additional grounding. 11 points additional grounding case do not improve the reduction of the induced voltages when compared with 3 points additional grounding case. For the geometry of the cable we have chosen for the simulation, additional grounding at every 250 m can efficiently reduce the induced voltages on the twisted-pair wires in the cable sheath.

## Ⅵ. CONCLUSION

The lightning-induced voltages on a shielded telecommunication subscriber cable with multipoint grounding on a cable sheath are calculated by FDTD method under a practical configuration. The effects of lossy ground in both the electromagnetic field calculation and the surge propagation along the wires have been taken into account. Besides, the single-wire line representation for twisted-pair wires is adopted for computational efficiency. In the test case, the cable sheath grounding at every 250 m can reduce the induced voltages on the twisted-pair wires in the sheath almost as much as grounding at every 83 m.

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