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# Traveling Wave Characteristic of Induced Voltage on Buried Cable by Direct Lightning

By

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## Abstract

This paper describes a numerical method to calculate the traveling wave characteristic of induced voltage on a buried cable generated by direct lightning. The propagation constant of the metallic sheath-earth circuit is calculated by considering the thickness of the protection jacket. The mutual impedance of every coupling circuit is calculated by using the electromagnetic theory. The numerical processing is carried out by the inverse Laplace transform. Finally, some numerical examples are presented.

## 1. Introduction

It is important to investigate the traveling wave characteristic of induced voltage on a buried coaxial cable, because this study gives effective information about the protection of communication cables or intermediate communication instruments from direct lightning, analysis of crosstalk between toll cables and so on.

Various reports have been given on these problems over a long time<sup>1)-5)</sup>. Theoretical studies have been done in the complex frequency domain and fundamental equations considering the physical constants of surrounding media have been given. The solutions of these equations are very complicated functions in the frequency domain, and it is impossible to get their solutions in the time domain. Therefore, an approximate method such as the operational calculus by Heaviside has been used.

The physical model of a buried coaxial cable is composed of several transmission lines and coupling impedances. Recently, Nagono has reported a numerical method for this problem by applying the inverse Fourier transform<sup>6)</sup>. He considered the effects of the physical constants of the surrounding media, but used resistances at direct current as coupling impedances.

In this paper, we use the theoretical solutions given by the electromagnetic theory

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as coupling impedances and investigate a more precise method to calculate the traveling wave characteristic of induced voltage on a buried coaxial cable.

Numerical processing is carried out by the inverse Laplace transform<sup>7)</sup>.

## 2. Analysis in complex frequency domain

### 2. 1 Induced voltage on coaxial cable

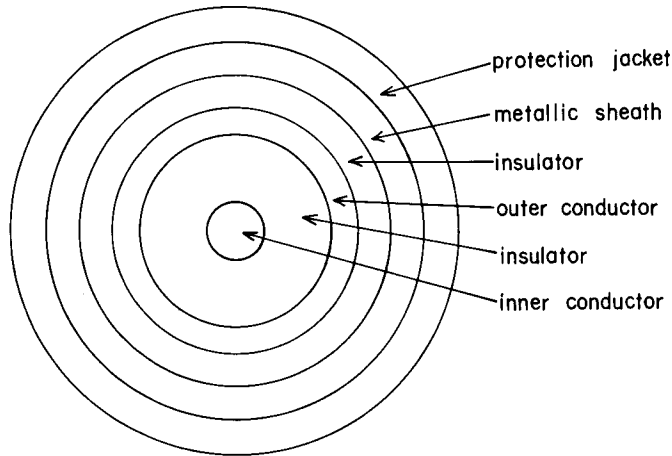


Figure 1 Cross-section of coaxial cable

Here, we consider a buried coaxial cable whose cross-section is shown in Fig. 1. A metallic sheath is insulated from the earth by a protection jacket. The physical model of this cable system is composed of three transmission lines and two coupling impedances as shown below.

The propagation constant, characteristic impedance, line impedance per unit length, line admittance per unit length, line voltage and line current for every circuit are given as follows.

metallic sheath-earth circuit :  $\Gamma, K, Z, Y, V_{se}, I_{se}$

outer conductor-metallic sheath circuit :  $\Gamma_o, K_o, Z_o, Y_o, V_{os}, I_{os}$

inner conductor-outer conductor circuit :  $\Gamma_c, K_c, Z_c, Y_c, V_{io}, I_{io}$

Impedance for every coupling is given as follows.

between metallic sheath-earth circuit and outer conductor-metallic sheath circuit :  $Z_s$

between outer conductor-metallic sheath circuit and inner conductor-outer conductor circuit :  $Z_{s2}$

The metallic sheath-earth circuit and the outer conductor-metallic sheath circuit have an infinite length for the longitudinal direction of the coaxial cable. For the inner conductor-outer conductor circuit, intermediate communication instruments are located at every  $p$  meters.

Let us investigate the following model as shown in Fig. 2. The origin of the longitudinal direction is determined at the point where the impulsive current  $J$  is imposed into the metallic sheath-earth circuit by direct lightning.  $Z_a$  and  $Z_b$  are impedances of intermediate communication instruments at the points  $x=q$  and  $x=q-p$ .

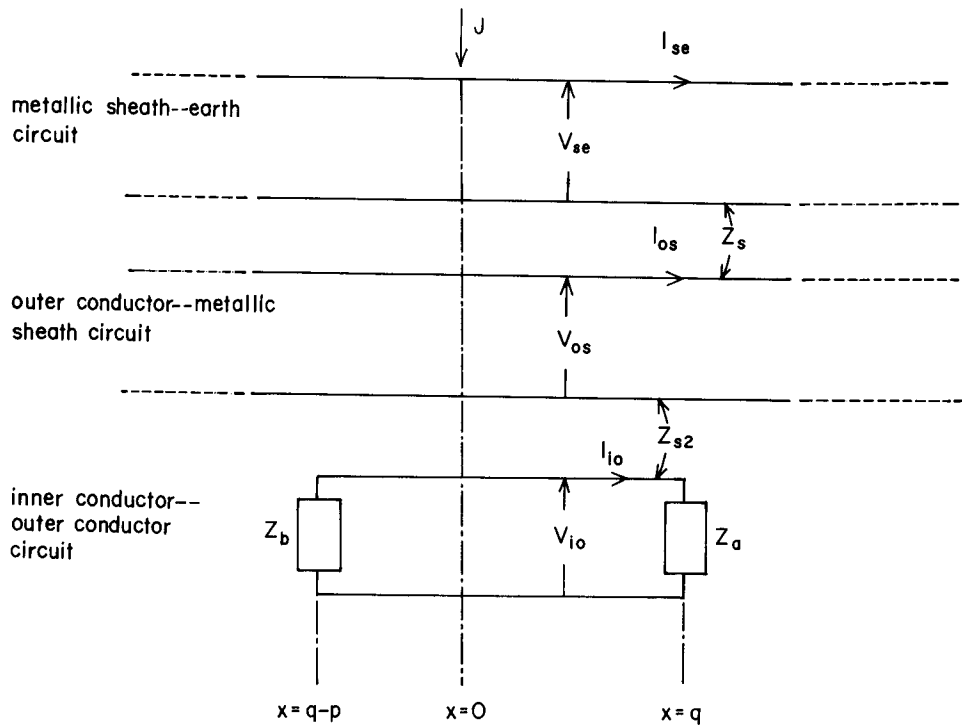


Figure 2 Circuit model of buried coaxial cable system

The voltage and current of the metallic sheath-earth circuit are determined by the following set of equations.

$$\left. \begin{aligned} \frac{dV_{se}(x)}{dx} &= -Y \cdot I_{se}(x) \\ \frac{dI_{se}(x)}{dx} &= -Z \cdot V_{se}(x) \end{aligned} \right\} \quad (1)$$

General solutions of Eq. (1) are given as follows.

$$\left. \begin{aligned} V_{se}(x) &= K[A \cdot \exp(-\Gamma x) + B \cdot \exp(\Gamma x)] \\ I_{se}(x) &= A \cdot \exp(-\Gamma x) - B \cdot \exp(\Gamma x) \end{aligned} \right\} \quad (2)$$

$A$  and  $B$  are arbitrary constants which are determined by the boundary conditions and  $\Gamma = \sqrt{Z \cdot Y}$  and  $K = \sqrt{Z/Y}$ . The detailed explanation about  $\Gamma$  will be given later.

In the above model of Fig. 2, a half of the impulsive current propagates toward  $+x$  direction and the other half propagates toward  $-x$  direction, so we can get the following results

$$\left. \begin{aligned} I_{se}^+(x) &= (J/2) \cdot \exp(-\Gamma x) & x \geq 0 \\ I_{se}^-(x) &= -(J/2) \cdot \exp(\Gamma x) & x < 0 \end{aligned} \right\} \quad (3)$$

where, the upper symbol  $+$  means  $+x$  direction and  $-$  means  $-x$  direction.

From the above results, a current to propagate the  $-x$  direction is obtained to replace the  $x \rightarrow -x$  of current to propagate the  $+x$  direction. Hence, it may be sufficient to consider only the  $+x$  direction for a while, and the upper symbol  $+$  can be abbreviated.

The voltage and current of the outer conductor-metallic sheath circuit are determined by the following set of equations.

$$\left. \begin{aligned} \frac{dV_{os}(x)}{dx} &= -Y_o \cdot I_{os}(x) + E_o(x) \\ \frac{dI_{os}(x)}{dx} &= -Z_o \cdot V_{os}(x) \end{aligned} \right\} \quad (4)$$

$E_o(x)$  means the distributed voltage source given by coupling impedance  $Z_s$  and Eq. (3) as follows.

$$E_o(x) = Z_s \cdot I_{se}(x) = (Z_s J/2) \cdot \exp(-\Gamma x) \quad (5)$$

The general solutions of Eq. (4) are given as follows.

$$\left. \begin{aligned} V_{os}(x) &= K_o \{ [A_o + P_o(x)] \exp(-\Gamma_o x) + [B_o + Q_o(x)] \exp(\Gamma_o x) \} \\ I_{os}(x) &= [A_o + P_o(x)] \exp(-\Gamma_o x) - [B_o + Q_o(x)] \exp(\Gamma_o x) \end{aligned} \right\} \quad (6)$$

$A_o$  and  $B_o$  are arbitrary constants which are determined by the boundary conditions.  $P_o(x)$  and  $Q_o(x)$  are determined as follows.

$$\left. \begin{aligned} P_o(x) &= \frac{1}{2K_o} \int_0^x E_o(x) \exp(\Gamma_o x) dx = \frac{Z_s J}{2K_o(\Gamma - \Gamma_o)} [1 - \exp[-(\Gamma - \Gamma_o)x]] \\ Q_o(x) &= \frac{1}{2K_o} \int_0^x E_o(x) \exp(-\Gamma_o x) dx = \frac{Z_s J}{2K_o(\Gamma + \Gamma_o)} [1 + \exp[-(\Gamma + \Gamma_o)x]] \end{aligned} \right\} \quad (7)$$

Propagation constant  $\Gamma_o$  and characteristic impedance  $K_o$  are given as follows

$$\left. \begin{aligned} \Gamma_o &= \sqrt{Z_o \cdot Y_o} = \sqrt{(R_o + sL_o) sC_o} \\ K_o &= \sqrt{Z_o / Y_o} = \sqrt{(R_o + sL_o) / sC_o} \end{aligned} \right\} \quad (8)$$

where  $R_o$ ,  $L_o$ ,  $C_o$  mean per unit length resistance, inductance, capacitance of the outer conductor-metallic sheath circuit and  $s$  is the Laplace operator.

In the model of Fig. 2,  $B_o$  must be equal to

$$B_o = -Q_o(\infty) = -\frac{Z_s J}{2K_o(\Gamma + \Gamma_o)} \quad (9)$$

and the remaining constant  $A_o$  is determined by the condition at the origin.

When a breakdown of insulation does not occur at the origin,  $I_{os}(0)$  must be equal to 0 and we have  $A_o = B_o$ . The voltage and current are determined as follows in this case.

$$\left. \begin{aligned} V_{os}(x) &= \frac{Z_s J}{2(\Gamma^2 - \Gamma_o^2)} [\Gamma_o \exp(-\Gamma_o x) - \Gamma \exp(-\Gamma x)] \\ I_{os}(x) &= \frac{Z_s J \Gamma_o}{2K_o(\Gamma^2 - \Gamma_o^2)} [\exp(-\Gamma_o x) - \exp(-\Gamma x)] \end{aligned} \right\} \quad (10)$$

When a breakdown of insulation occurs at the origin,  $V_{os}(0)$  must be equal to 0 and we have  $A_o = -B_o$ . The voltage and current are determined in the same way as stated above.

For the inner conductor-outer conductor circuit, as is shown in Fig. 2, we must take into account the voltages and currents of  $+x$  and  $-x$  directions.

The voltage and current of  $+x$  direction are determined by the following set of equations.

$$\left. \begin{aligned} \frac{dV_{io}^+(x)}{dx} &= -Y_c \cdot I_{io}^+(x) + E_c^+(x) \\ \frac{dI_{io}^+(x)}{dx} &= -Z_c \cdot V_{io}^+(x) \end{aligned} \right\} \quad (11)$$

$E_c^+(x)$  means the distributed voltage source given by coupling impedance  $Z_{s2}$  and current  $I_{os}^+(x)$  as follows:

$$E_c^+(x) = Z_{s2} I_{os}^+(x) \quad (12)$$

The general solution of Eq. (11) is given as follows.

$$\left. \begin{aligned} V_{io}^+(x) &= K_c \{ [A_c^+ + P_c^+(x)] \exp(-\Gamma_c x) + [B_c^+ + Q_c^+(x)] \exp(\Gamma_c x) \} \\ I_{io}^+(x) &= [A_c^+ + P_c^+(x)] \exp(-\Gamma_c x) - [B_c^+ + Q_c^+(x)] \exp(\Gamma_c x) \end{aligned} \right\} \quad (13)$$

$A_c$  and  $B_c$  are arbitrary constants which are determined by the boundary conditions.

$P_c^+(x)$  and  $Q_c^+(x)$  are determined as follows.

$$\left. \begin{aligned} P_c^+(x) &= \frac{1}{2K_c} \int_0^x E_c^+(x) \exp(\Gamma_c x) dx \\ Q_c^+(x) &= \frac{1}{2K_c} \int_0^x E_c^+(x) \exp(-\Gamma_c x) dx \end{aligned} \right\} \quad (14)$$

The propagation constant  $\Gamma_c$  and characteristic impedance  $K_c$  are given as follows

$$\left. \begin{aligned} \Gamma_c &= \sqrt{Z_c \cdot Y_c} = \sqrt{(R_c + sL_c) / sC_c} \\ K_c &= \sqrt{Z_c / Y_c} = \sqrt{(R_c + sL_c) / sC_c} \end{aligned} \right\} \quad (15)$$

where  $R_c$ ,  $L_c$ ,  $C_c$  mean per unit length resistance, inductance, capacitance of the inner conductor-outer conductor circuit.

The voltage and current of  $-x$  direction are obtained by replacing the upper symbol  $+$  with  $-$  in Eq. (11) ~ Eq. (14).

In the model of Fig. 2, the inner conductor-outer conductor circuit is terminated by a lumped impedance  $Z_a$  at  $x=q$  and by  $Z_b$  at  $x=q-p$ . Thus we have the following relations.

$$\left. \begin{aligned} V_{io}^+(q) &= Z_a I_{io}^+(q) \\ V_{io}^-(q-p) &= -Z_b I_{io}^-(q-p) \end{aligned} \right\} \quad (16)$$

At the origin, the voltage and current must satisfy the following relations.

$$\left. \begin{aligned} V_{io}^+(0) &= V_{io}^-(0) \\ I_{io}^+(0) + I_{io}^-(0) &= 0 \end{aligned} \right\} \quad (17)$$

From these relations, we have the following simultaneous equation to determine the arbitrary constants  $A_c^\pm$  and  $B_c^\pm$ .

$$\begin{bmatrix} 1 & 1 & -1 & -1 \\ 1 & -1 & 1 & -1 \\ (K_c - Z_a) \exp(-\Gamma_c q) & (K_c + Z_a) \exp(\Gamma_c q) & 0 & 0 \\ 0 & 0 & (K_c + Z_b) \exp[-\Gamma_c (q-p)] & (K_c - Z_b) \exp[\Gamma_c (q-p)] \end{bmatrix} \times \begin{bmatrix} A_c^+ \\ B_c^+ \\ A_c^- \\ B_c^- \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ (Z_a - K_c) P_c^+(q) \exp(-\Gamma_c q) - (Z_a + K_c) Q_c^+(q) \exp(\Gamma_c q) \\ -(Z_b + K_c) P_c^-(q-p) \exp[-\Gamma_c (q-p)] + (Z_b - K_c) Q_c^-(q-p) \exp[\Gamma_c (q-p)] \end{bmatrix} \quad (18)$$

## 2. 2 Propagation constant of metallic sheath--earth circuit

When the influence of the thickness of the protection jacket is negligible, the propagation constant of the metallic sheath--earth circuit is given by the following formula :

$$\Gamma(s) = \frac{1}{\sqrt{2}} \sqrt{\mu s (\epsilon s + g)} \quad (19)$$

where

$\mu$  : permeability of soil [H/m]

$\epsilon$  : permittivity of soil [F/m]

$g$  : conductivity of soil [S/m].

The factor  $1/\sqrt{2}$  is used when the coaxial cable is buried several meters under the surface of the earth.

When the influence of the thickness of the protection jacket is considered, the propagation constant of the metallic sheath--earth circuit is given as

$$\left. \begin{aligned} \Gamma^2(s) &= Z(s) \cdot Y(s) \\ Z(s) &= Z_i(s) + (\mu s / \pi \hat{a} \gamma^2) \{ \Gamma(s) K_1[\Gamma(s) \hat{a}] - \sqrt{\gamma^2 + \Gamma^2(s)} K_1[\hat{a} \sqrt{\gamma^2 + \Gamma^2(s)}] \} \\ \hat{a} &= \sqrt{a_o^2 + 4d^2} \\ \gamma &= \sqrt{\mu s (\epsilon s + g)} \\ Y(s) &= \{ Y_i^{-1}(s) + K_0[\Gamma(s) \hat{a}] \}^{-1} \end{aligned} \right\} \quad (20)$$

where

$\hat{a}$  : effective radius of metallic sheath [m]

$a_o$  : outer radius of metallic sheath [m]

$d$  : buried depth of coaxial cable [m]

and  $K_0$  and  $K_1$  are modified Bessel functions.

$Z_i(s)$  is per unit length series impedance of the metallic sheath given by

$$\left. \begin{aligned} Z_i(s) &= \frac{\eta}{2\pi a_o D} [I_0(\sigma_s a_o) K_1(\sigma_s a_i) + K_0(\sigma_s a_o) I_1(\sigma_s a_i)] \\ D &= I_1(\sigma_s a_o) K_1(\sigma_s a_i) - K_1(\sigma_s a_o) I_1(\sigma_s a_i) \\ \sigma_s^2 &= g_s \mu_s s \\ \eta &= \sigma_s / g_s \end{aligned} \right\} \quad (21)$$

where

$a_i$  : inner radius of metallic sheath [m]

$g_s$  : conductivity of metallic sheath [S/m]



$\mu_s$ : permeability of metallic sheath [H/m]

and  $I_0$  and  $I_1$  are modified Bessel functions.

$Y_i(s)$  is per unit length parallel admittance of the protection jacket given by

$$Y_i(s) = \frac{2\pi(g_c + \epsilon_c s)}{\log(a_{co}/a_{ci})} \quad (22)$$

where

$a_{co}$ : outer radius of protection jacket [m]

$a_{ci}$ : inner radius of protection jacket [m]

$g_c$ : conductivity of protection jacket [S/m]

$\epsilon_c$ : permittivity of protection jacket [F/m].

From Eq. (20) ~ Eq. (22),  $\Gamma(s)$  can be expressed by

$$\Gamma(s) = F[\Gamma(s); s, a_o, \dots] \quad (23)$$

where  $F$  is a nonlinear function with respect to  $\Gamma(s)$ .

This equation is solved by the iteration method.

### 2. 3 Coupling impedance

The coupling impedances  $Z_s$  and  $Z_{s2}$  can be obtained to solve the impedance of the tubular conductor by the electromagnetic theory. They are given as follows ;

$$Z_s = \frac{1}{2\pi g_s a_i a_o D} \quad (24)$$

$$\left. \begin{aligned} Z_{s2} &= \frac{1}{2\pi g_{oc} a_{oo} a_{oi} D_o} \\ D_o &= I_1(\sigma_o a_{oo}) K_1(\sigma_o a_{oi}) - I_1(\sigma_o a_{oi}) K_1(\sigma_o a_{oo}) \\ \sigma_o^2 &= g_{oc} \mu_{oc} s \end{aligned} \right\} \quad (25)$$

where

$a_{oo}$ : outer radius of outer conductor [m]

$a_{oi}$ : inner radius of outer conductor [m]

$g_{oc}$ : conductivity of outer conductor [S/m]

$\mu_{oc}$ : permeability of outer conductor [H/m].

### 3. Traveling wave characteristic in time domain

Here we consider a buried coaxial cable system with the following conditions :

protection jacket	: outer radius	$a_{co}$	$4.700 \times 10^{-3}$	[m]
	: inner radius	$a_{ci}$	$3.700 \times 10^{-3}$	[m]
metallic sheath	: outer radius	$a_o$	$3.700 \times 10^{-3}$	[m]
	: inner radius	$a_i$	$2.900 \times 10^{-3}$	[m]
outer conductor	: outer radius	$a_{oo}$	$2.400 \times 10^{-3}$	[m]
	: inner radius	$a_{oi}$	$2.220 \times 10^{-3}$	[m]
permittivity	: soil	$\epsilon$	$2.656 \times 10^{-11}$	[F/m]
	: protection jacket	$\epsilon_c$	$2.036 \times 10^{-11}$	[F/m]
conductivity	: soil	$g$	$2.000 \times 10^{-2}$	[S/m]
	: protection jacket	$g_c$	$1.000 \times 10^{-14}$	[S/m]
	: metallic sheath	$g_s$	$3.731 \times 10^7$	[S/m]
	: outer conductor	$g_{oc}$	$5.807 \times 10^7$	[S/m]
permiability	: soil	$\mu$	$1.256 \times 10^{-6}$	[H/m]
	: metallic sheath	$\mu_s$	$6.283 \times 10^{-6}$	[H/m]
	: outer conductor	$\mu_{oc}$	$1.256 \times 10^{-6}$	[H/m]
outer conductor-metallic sheath circuit				
	: resistance	$R_o$	5.694	[m $\Omega$ /m]
	: inductance	$L_o$	0.4690	[ $\mu$ H/m]
	: capacitance	$C_o$	294.0	[pF/m]
inner conductor-outer conductor circuit				
	: resistance	$R_c$	8.925	[m $\Omega$ /m]
	: inductance	$L_c$	0.2644	[ $\mu$ H/m]
	: capacitance	$C_c$	49.54	[pF/m]
depth of buried cable		$d$	1	[m]
interval of communication instrument		$p$	3600	[m]
lightning point		$q$	3600	[m]

The waveform of lightning current is given in the following double exponential functions.

$$j(t) = 1189.9[\exp(-1.3339 \times 10^4 t) - \exp(-3.3597 \times 10^4 t)] \quad (26)$$

The theoretical consideration is done in the frequency domain and the Laplace transform of the lightning current is given as follows.

$$J(s) = 1189.9 \left[ \frac{1}{(s + 1.3339 \times 10^4)} - \frac{1}{(s + 3.3597 \times 10^4)} \right] \quad (27)$$

The numerical processing is carried out by the inverse Laplace transform, and the detailed procedure of the method is shown in reference (7).

### 3. 1 Influence of propagation constant of metallic sheath--earth circuit

Here, let us discuss the investigation on how far the difference of the propagation constants causes the difference of the traveling wave characteristics for the impulsive current on the metallic sheath--earth circuit.

The impulsive current of metallic sheath--earth circuit to propagate +x direction is given by the first relation of Eq. (3).

Fig. 3 shows a few results calculated when the influence of the thickness of the protection jacket is negligible.

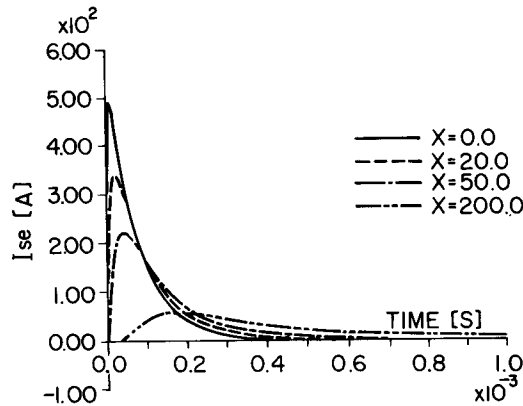


Figure 3 Calculated results when thickness of protection jacket is negligible

As is shown in these results, the peak values of the impulsive current decrease rapidly as  $x$  increases. In this case the propagation constant is given by Eq. (19). If the  $s^2$  term is dominant in the symbol of the square root  $\sqrt{\quad}$ , the traveling wave characteristic of this circuit tends to that of the loss-less transmission line, and if  $s$  term is dominant, to the RC transmission line. In our case, the coefficient of the  $s^2$  term is  $\mu \epsilon = 3.34 \times 10^{-17}$  and the coefficient of the  $s$  term is  $\mu g = 2.51 \times 10^{-8}$ . From this fact, it can be concluded that the  $s$  term is dominant. Calculated results indicate the validity of this consideration.

Fig. 4 shows a few results calculated when the influence of the thickness of the protection jacket is considered.

As is shown in these results, the peak values of the impulsive current does not

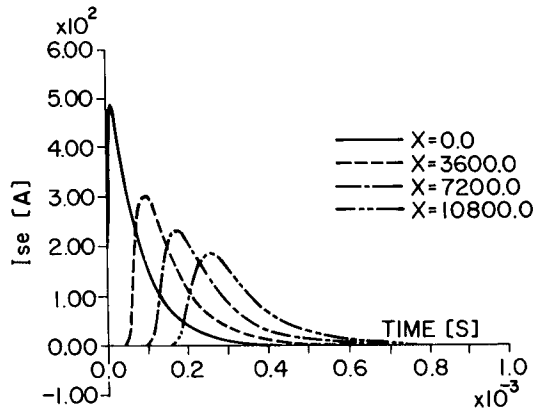


Figure 4 Calculated results when thickness of protection jacket is considered

decrease much as  $x$  increases, and the time delay of the beginning points of the impulsive current becomes large as  $x$  increases.

In this case, the propagation constant  $\Gamma(s)$ , series impedance  $Z(s)$  and parallel admittance  $Y(s)$  can be obtained by Eq. (20). Some values of  $Z(s)$  and  $Y(s)$  are listed in Table 1 as functions of  $s = i2\pi f$ .

Table 1 Calculated values of  $Z$  and  $Y$

$f$ [Hz]	$Z$ [ $\Omega/m$ ]		$Y$ [S/m]	
	Real	Imag.	Real	Imag.
10	$0.1631 \times 10^{-2}$	$0.8902 \times 10^{-4}$	$0.4661 \times 10^{-12}$	$0.3362 \times 10^{-7}$
100	$0.1718 \times 10^{-2}$	$0.7332 \times 10^{-3}$	$0.1840 \times 10^{-10}$	$0.3362 \times 10^{-6}$
1000	$0.2647 \times 10^{-2}$	$0.5885 \times 10^{-2}$	$0.1493 \times 10^{-8}$	$0.3362 \times 10^{-5}$
10000	$0.1313 \times 10^{-1}$	$0.4297 \times 10^{-1}$	$0.1107 \times 10^{-6}$	$0.3360 \times 10^{-4}$
100000	$0.1086 \times 10^0$	$0.2619 \times 10^0$	$0.7230 \times 10^{-5}$	$0.3336 \times 10^{-3}$

From these results, the property of this circuit tends to that of the distortion-less transmission line.

### 3. 2 Influence of coupling impedances

Here, we use  $Z_s$  and  $Z_{s2}$  of Eq. (24) and Eq. (25) as coupling impedances and calculate

the traveling wave characteristics of the induced voltages. We call the numerical solutions obtained by these impedances as precise solutions.

In reference (6), the resistances of the metallic sheath and the outer conductor at the direct current are used as coupling impedances. We call the numerical solutions obtained by these resistances as approximate solutions.

If sufficient results can be obtained by the approximate solutions, it may be concluded that the approximate solutions can be used satisfactorily because the execution time in the computation can be reduced.

In various cases, we calculated the approximate and precise solutions of the traveling wave characteristics of the induced voltages. Some results are shown in Fig. 5 ~ Fig. 11 with the following conditions :

- 1 : Breakdown of insulation of outer conductor--metallic sheath circuit did not occur at the origin.
  - 2 : Breakdown of insulation of outer conductor--metallic sheath circuit occurred at the origin.
- A : Thickness of protection jacket is not considered.  
B : Thickness of protection jacket is considered.

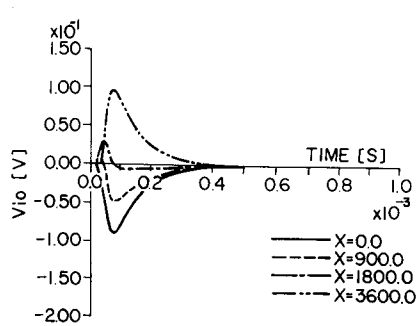
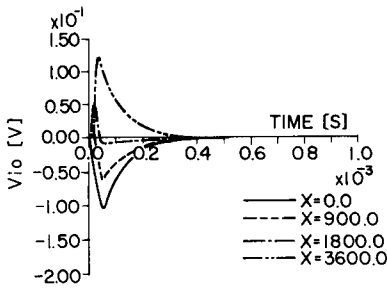
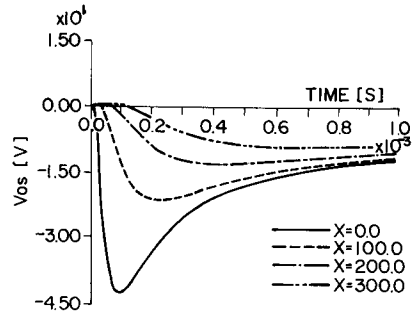
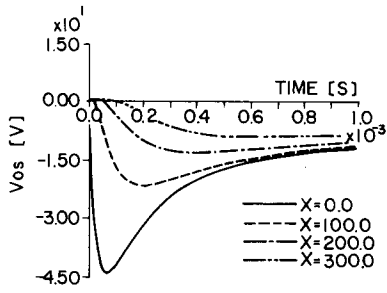


Figure 5 Approximate solutions (A, 1)

Figure 6 Precise solutions (A, 1)

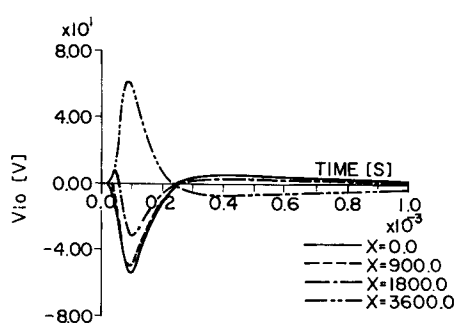
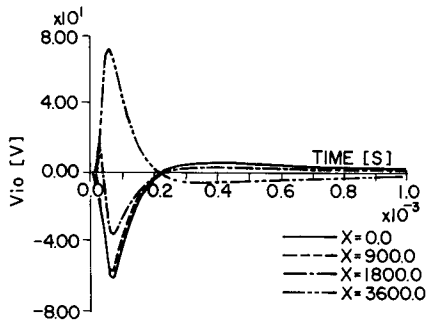
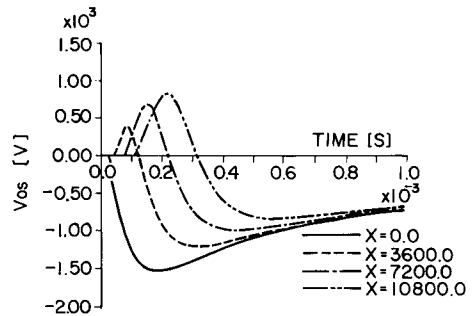
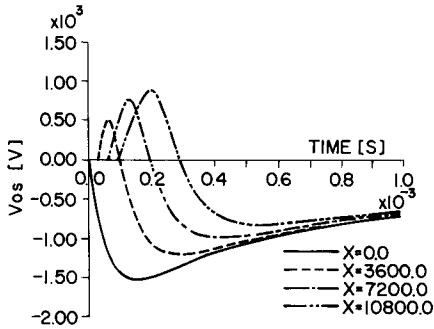


Figure 7 Approximate solutions (B, 1)

Figure 8 Precise solutions (B, 1)

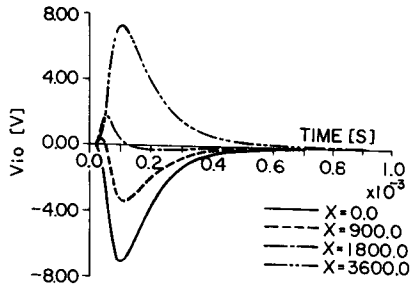
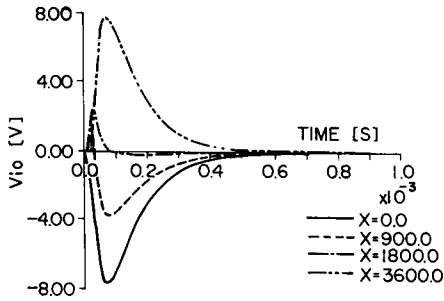
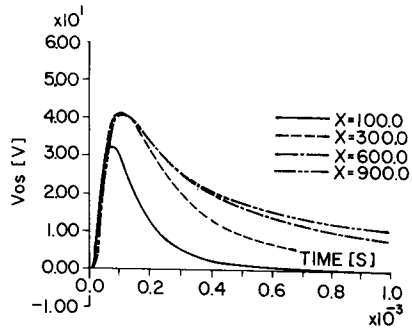
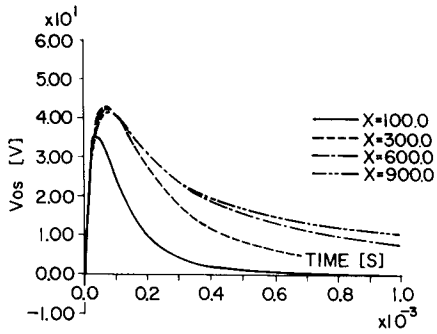


Figure 9 Approximate solutions (A, 2)

Figure 10 Precise solutions (A, 2)

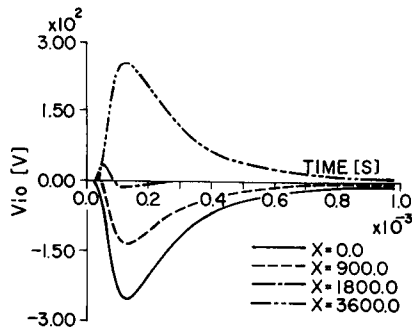
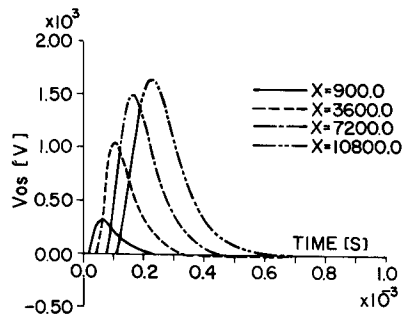


Figure 11 Precise solutions (B, 2)

As is seen from these results, the differences of the coupling impedances affect the peak values and waveforms of the induced voltages. The main purpose of this paper is to get useful information about induced voltages on a buried coaxial cable system. It becomes an important problem to get the peak values of the induced voltages.

In Table 2, the peak values of the induced voltages in various case are listed together with CPU times used and errors defined by  $|(precise\ solution - approximate\ solution) / precise\ solution|$ .

Table 2 Comparison of approximate solutions and precise solutions

			Distance [m]	Approximate solution		Precise solution		Error [%]
				Peak [V]	CPU [ms]	Peak [V]	CPU [ms]	
A	1	$V_{os}$	0	$0.437 \times 10^2$	236	$0.425 \times 10^2$	422	2.72
		$V_{io}$	3600	$0.125 \times 10^0$		$0.097 \times 10^0$		30.0
	2	$V_{os}$	900	$0.420 \times 10^2$	233	$0.409 \times 10^2$	420	2.63
		$V_{io}$	3600	$0.788 \times 10^1$		$0.733 \times 10^1$		7.52
B	1	$V_{os}$	0	$0.152 \times 10^4$	473	$0.150 \times 10^4$	561	1.11
		$V_{io}$	3600	$0.720 \times 10^2$		$0.616 \times 10^2$		16.8
	2	$V_{os}$	10800	$0.170 \times 10^4$	470	$0.164 \times 10^4$	559	3.67
		$V_{io}$	3600	$0.267 \times 10^3$		$0.256 \times 10^3$		4.01

For the coupling impedances  $Z_s$  and  $Z_{s2}$ , the real parts approach constant values in the low frequency region. They are resistances of the metallic sheath and outer conductor at the direct current, and the imaginary parts approach 0. In the high frequency region, the real parts of  $Z_s$  and  $Z_{s2}$  decrease, and the imaginary parts appear as the frequency increases. Thus, it may be concluded that the approximate solutions are used only for the low frequency region. The execution times can be reduced too much when the approximate solutions are used in condition A, but not so much in condition B.

In condition B, the propagation constants must be calculated by the iteration method, and at the same time, the coupling impedances can be calculated.

For practical purposes, the voltage of the inner conductor-outer conductor circuit must be calculated more precisely.

For these reasons, it may be valid to use  $Z_s$  and  $Z_{s2}$  as coupling impedances.



#### 4. Conclusion

In order to make clear traveling wave characteristics of induced voltages on a buried coaxial cable system, we investigated the factors giving serious influences to the results.

We used the circuit shown in Fig. 2 as a model of a buried coaxial cable system, There, it is important to calculate the following quantities precisely.

- (1) propagation constant of every circuit
- (2) coupling impedance between considered circuits

To solve these problems, the following procedures have been put into practice.

- (1) To calculate the propagation constant of the metallic sheath--earth circuit, the influence of the thickness of the protection jacket is considered.
- (2) The coupling impedances are calculated precisely by using the electromagnetic theory.

The numerical calculations in various conditions were done by the proposed method. From these results, it may be concluded that this method is useful to make a clear traveling wave characteristic in a buried cable system.

The numerical computations were done by FACOM-M382.

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