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

By

Satoshi ICHIKAWA* and Hideto OHNISHI*
(Received December 23, 1988)

Abstract

This paper desbribes 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 characterisic 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[1)~5)]. 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 impendances. Recently, Nagono has reported a numerical method for this problem by applying the inverse Fourier transform[6)]. 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

* Department of Electrical Engineering II

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[7].

2. Analysis in complex frequency domain

2. 1 Induced voltage on coaxial cable

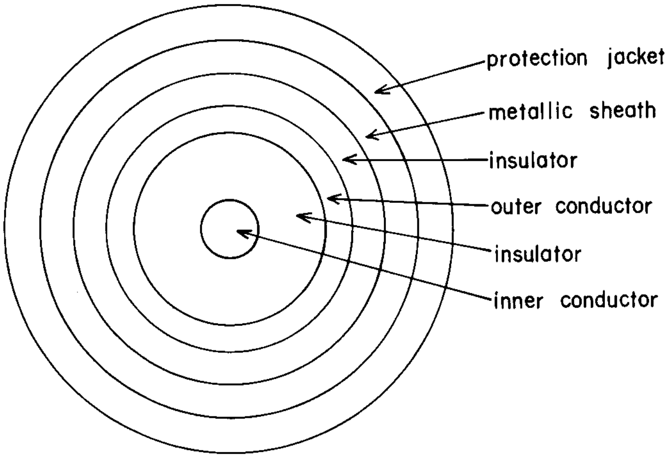

Figure 1 Cross-section of coaxial cable

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 ciecuit are given as follows.

metallic sheath--earth circuit : Γ, K, Z, Y, V_{se}, I_{se}

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

inner conductor--outer conductor circuit : Γ_c, K_c, Z_c, Y_c, V_{io}, I_{io}

Impendance 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_{st}

The metallic sheath--earth circuit and the outer conductor--metallic sheath circuit have an infinite length for the longitudal directin 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 longitudal 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 $x=q-p$.

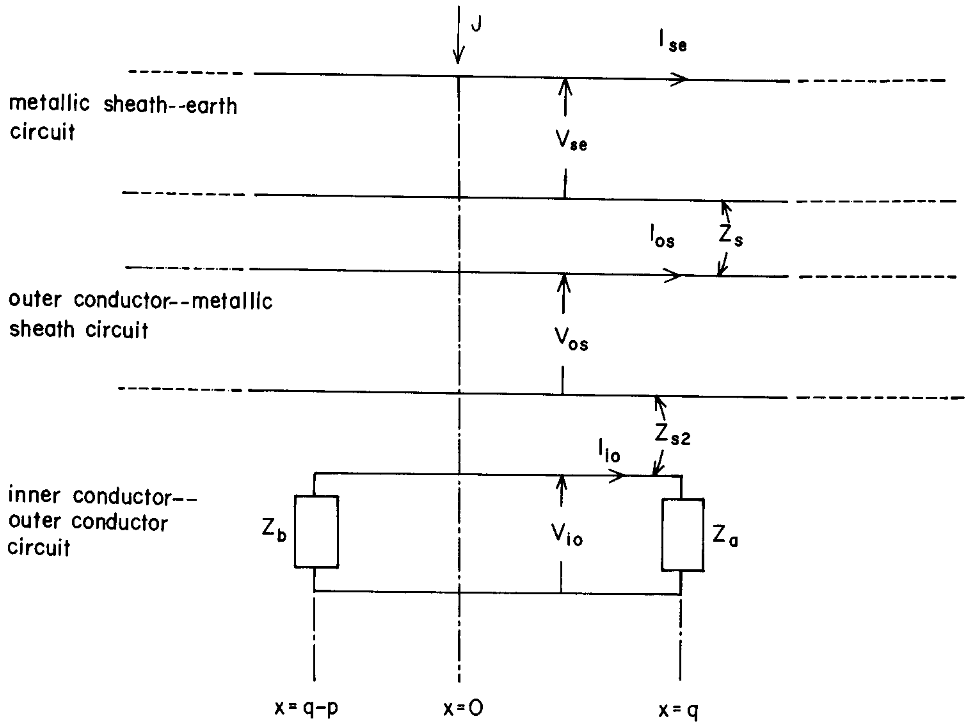

Figure 2 Circuit model of buried coaxial cable system

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

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

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

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

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 Γ 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

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

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.

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

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

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

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

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

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.

$$\left.\begin{array}{l} P_o(x)=\dfrac{1}{2K_o}\displaystyle\int_0^x E_o(x)\exp(\Gamma_o x)dx=\dfrac{Z_sJ}{2K_o(\Gamma-\Gamma_o)}\{1-\exp[-(\Gamma-\Gamma_o)x]\} \\ Q_o(x)=\dfrac{1}{2K_o}\displaystyle\int_0^x E_o(x)\exp(-\Gamma_o x)dx=\dfrac{Z_sJ}{2K_o(\Gamma+\Gamma_o)}\{1+\exp[-(\Gamma+\Gamma_o)x]\} \end{array}\right\} \quad (7)$$

Propagation constant Γ_o and characteristic impendance K_o are given as follows

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

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

$$B_o=-Q_o(\infty)=-\frac{Z_sJ}{2K_o(\Gamma+\Gamma_o)}\qquad(9)$$

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 determind as follows in this case.

$$\left.\begin{array}{l}V_{os}(x)=\dfrac{Z_sJ}{2(\Gamma^2-\Gamma_o^2)}\left[\Gamma_o\exp(-\Gamma_o x)-\Gamma\exp(-\Gamma x)\right]\\ I_{os}(x)=\dfrac{Z_sJ\Gamma_o}{2K_o(\Gamma^2-\Gamma_o^2)}\left[\exp(-\Gamma_o x)-\exp(-\Gamma x)\right]\end{array}\right\}\qquad(10)$$

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.

$$\left.\begin{array}{l}\dfrac{dV_{io}^+(x)}{dx}=-Y_c\cdot I_{io}^+(x)+E_c^+(x)\\ \dfrac{dI_{io}^+(x)}{dx}=-Z_c\cdot V_{io}^+(x)\end{array}\right\}\qquad(11)$$

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

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

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

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

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 Γ_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 condoctor 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.

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

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 simulataneous 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:

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

where

μ: permeability of soil [H/m]
ε: 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

$$\left.\begin{aligned}
&\Gamma^2(s)=Z(s)\cdot Y(s)\\
&Z(s)=Z_i(s)+(\mu s/\pi\hat{a}\gamma^2)\{\Gamma(s)\mathrm{K}_1[\Gamma(s)\hat{a}]-\sqrt{\gamma^2+\Gamma^2(s)}\mathrm{K}_1[\hat{a}\sqrt{\gamma^2+\Gamma^2(s)}]\}\\
&\hat{a}=\sqrt{a_o^2+4d^2}\\
&\gamma=\sqrt{\mu s(\varepsilon s+g)}\\
&Y(s)=\{Y_i^{-1}(s)+\mathrm{K}_0[\Gamma(s)\hat{a}]\}^{-1}
\end{aligned}\right\} \tag{20}$$

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

$$\left.\begin{aligned}
&Z_i(s)=\frac{\eta}{2\pi a_o D}[\mathrm{I}_0(\sigma_s a_o)\mathrm{K}_1(\sigma_s a_i)+\mathrm{K}_0(\sigma_s a_o)\mathrm{I}_1(\sigma_s a_i)]\\
&D=\mathrm{I}_1(\sigma_s a_o)\mathrm{K}_1(\sigma_s a_i)-\mathrm{K}_1(\sigma_s a_o)\mathrm{I}_1(\sigma_s a_i)\\
&\sigma_s^2=g_s\mu_s s\\
&\eta=\sigma_s/g_s
\end{aligned}\right\} \tag{21}$$

where

a_i: inner radius of metallic sheath [m]
g_s: conductivity of metallic sheath [S/m]

μ_s : permeability of metallic sheath [H/m]

and I_0 and I_1 are modified Bessel functions.

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

$$Y_t(s)=\frac{2\pi(g_c+\varepsilon_c s)}{\log(a_{co}/a_{ct})} \tag{22}$$

where

a_{co} : outer radius of protection jacket [m]
a_{ct} : inner radius of protection jacket [m]
g_c : conductivity of protection jacket [S/m]
ε_c : permittivity of protection jacket [F/m].

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

$$\Gamma(s)=F[\Gamma(s)\,;\,s,\,a_o,......] \tag{23}$$

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

This equation is solved by the interation 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;

$$Z_s=\frac{1}{2\pi g_s a_t a_o D} \tag{24}$$

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

where

a_{oo} : outer radius of outer conductor [m]
a_{ot} : inner radius of outer conductor [m]
g_{oc} : conductivity of outer conductor [S/m]
μ_{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}	4.700×10^{-3}	[m]
	: inner radius	a_{ci}	3.700×10^{-3}	[m]
matallic sheath	: outer radius	a_o	3.700×10^{-3}	[m]
	: inner radius	a_i	2.900×10^{-3}	[m]
outer conductor	: outer radius	a_{oo}	2.400×10^{-3}	[m]
	: inner radius	a_{oi}	2.220×10^{-3}	[m]
permittivity	: soil	ε	2.656×10^{-11}	[F/m]
	: protection jacket	ε_c	2.036×10^{-11}	[F/m]
conductivity	: soil	g	2.000×10^{-2}	[S/m]
	: protection jacket	g_c	1.000×10^{-14}	[S/m]
	: metallic sheath	g_s	3.731×10^{7}	[S/m]
	: outer conductor	g_{oc}	5.807×10^{7}	[S/m]
permiability	: soil	μ	1.256×10^{-6}	[H/m]
	: metallic sheath	μ_s	6.283×10^{-6}	[H/m]
	: outer conductor	μ_{oc}	1.256×10^{-6}	[H/m]
outer conductor--metallic sheath circuit				
	: resistance	R_o	5.694	[mΩ/m]
	: inductance	L_o	0.4690	[μH/m]
	: capacitance	C_o	294.0	[pF/m]
inner conductor--outer conductor circuit				
	: resistance	R_c	8.925	[mΩ/m]
	: inductance	L_c	0.2644	[μH/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 exponetial functions.

$$j(t)=1189.9[\exp(-1.3339\times10^4 t)-\exp(-3.3597\times10^4 t)] \tag{26}$$

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

$$J(s)=1189.9\left[\frac{1}{(s+1.3339\times10^4)}-\frac{1}{(s+3.3597\times10^4)}\right] \tag{27}$$

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.

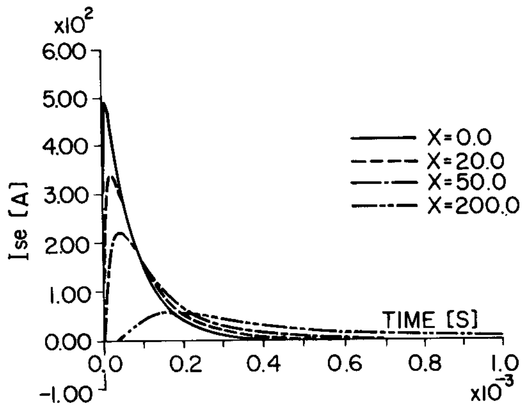

Figure 3 Calculated results when thickness of protection jacket is negligjble

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 $\sqrt{\ }$, 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 $\mu\varepsilon=3.34\times10^{-17}$ and the coefficient of the s term is $\mu g=2.51\times10^{-8}$. 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

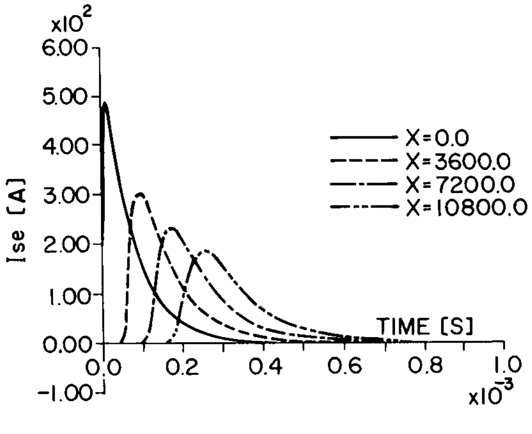

Figure 4 Calculated results when thickness of protection jacket is considered

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 admittnce $Y(s)$ 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 [Ω/m]		Y [S/m]	
	Real	Imag.	Real	Imag.
10	0.1631×10^{-2}	0.8902×10^{-4}	0.4661×10^{-12}	0.3362×10^{-7}
100	0.1718×10^{-2}	0.7332×10^{-3}	0.1840×10^{-10}	0.3362×10^{-6}
1000	0.2647×10^{-2}	0.5885×10^{-2}	0.1493×10^{-8}	0.3362×10^{-5}
10000	0.1313×10^{-1}	0.4297×10^{-1}	0.1107×10^{-6}	0.3360×10^{-4}
100000	0.1086×10^{0}	0.2619×10^{0}	0.7230×10^{-5}	0.3336×0^{-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 impednces and calculate the traveling wave characteristics of the induced voltages. We call the numerical solutions obtained by these impendances 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 ae 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.

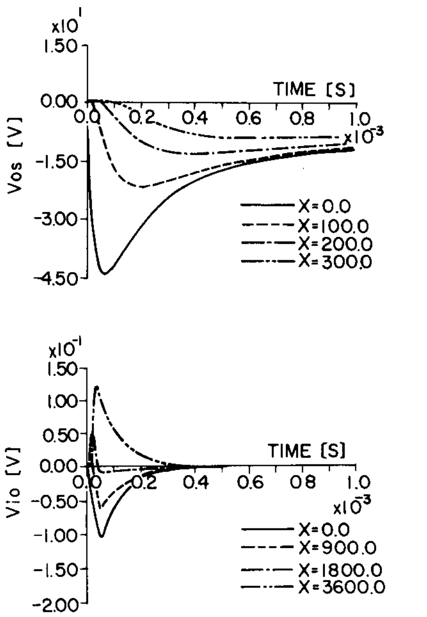

Figure 5 Approximate solutions (A, 1)

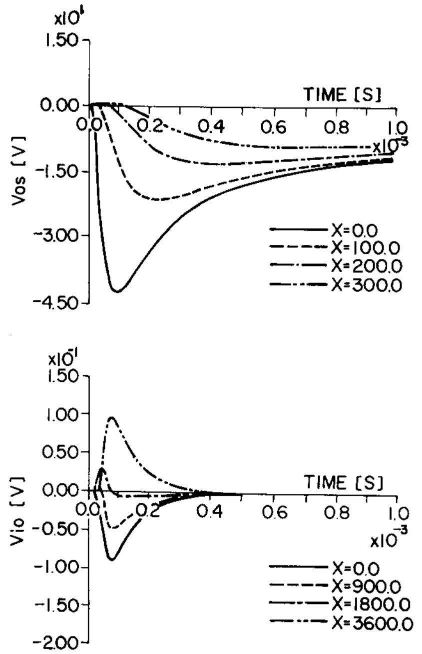

Figure 6 Precise solutions (A, 1)

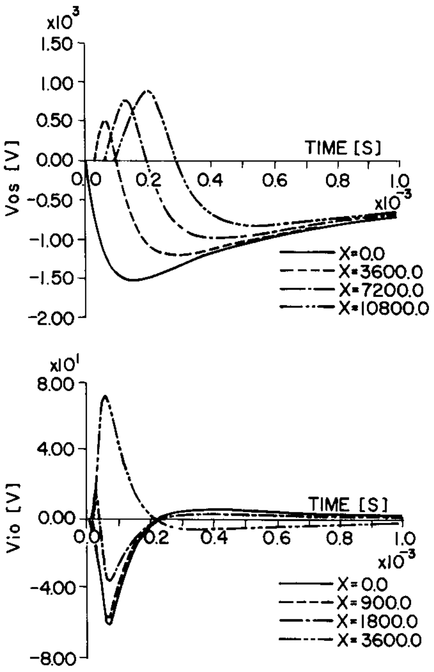

Figure 7 Approximate solutions (B, 1)

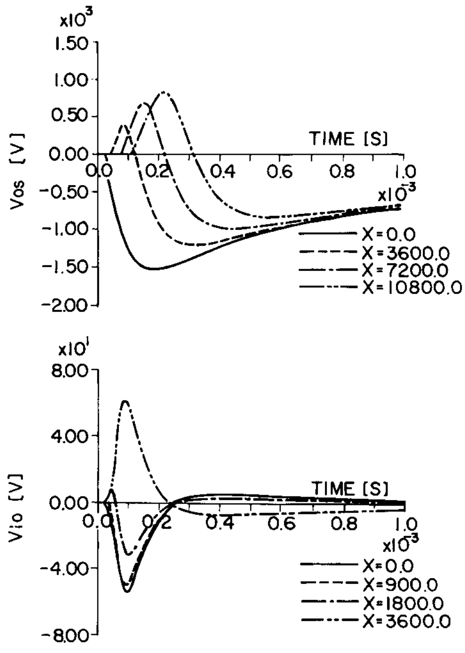

Figure 8 Precise solutions (B, 1)

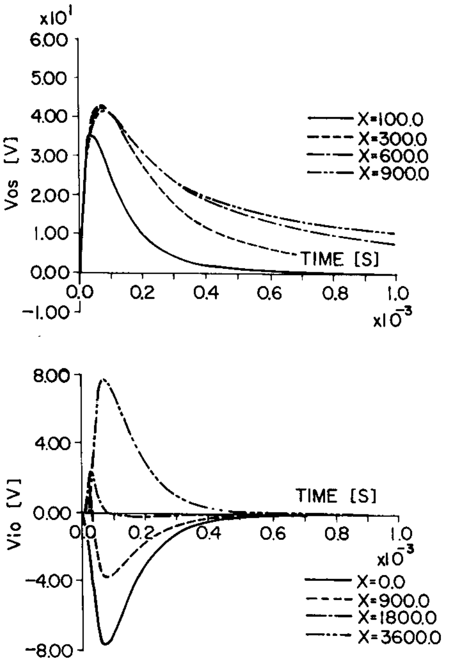

Figure 9 Approximate solutions (A, 2)

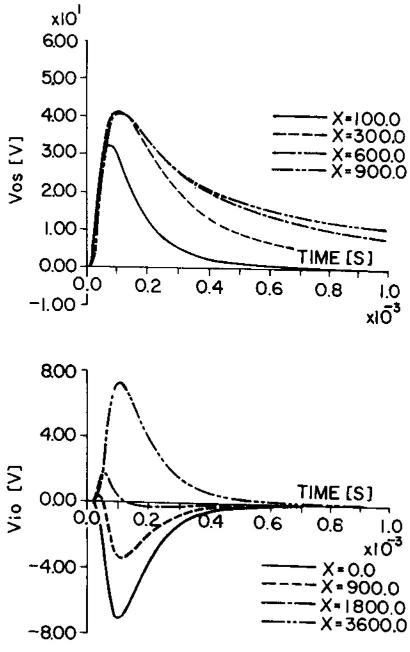

Figure 10 Precise solutions (A, 2)

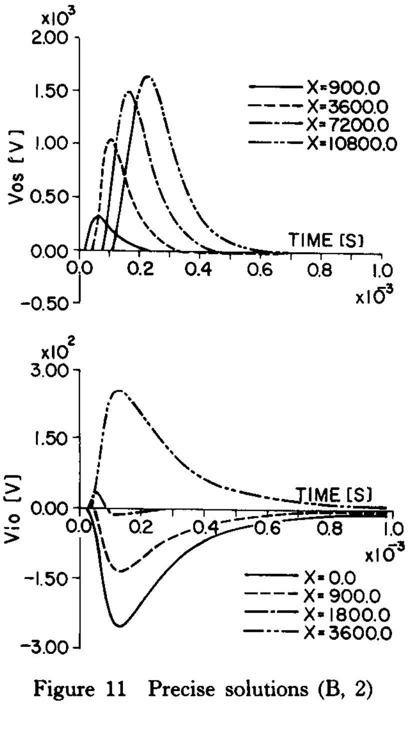

Figure 11 Precise solutions (B, 2)

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 importnt 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	0.437×10^{2}	236	0.425×10^{2}	422	2.72
		V_{io}	3600	0.125×10^{0}		0.097×10^{0}		30.0
	2	V_{os}	900	0.420×10^{2}	233	0.409×10^{2}	420	2.63
		V_{io}	3600	0.788×10^{1}		0.733×10^{1}		7.52
B	1	V_{os}	0	0.152×10^{4}	473	0.150×10^{4}	561	1.11
		V_{io}	3600	0.720×10^{2}		0.616×10^{2}		16.8
	2	V_{os}	10800	0.170×10^{4}	470	0.164×10^{4}	559	3.67
		V_{io}	3600	0.267×10^{3}		0.256×10^{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 cndition 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 resons, it may be valid to use Z_S and Z_{S2} as coupling impednces.

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 solove 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.

References

1) S. A. Schelkunoff : "The electromagnetic theory of coaxial transmission lines and cylindrical shields", BSTJ, 13, pp. 532-579 (1934)

2) S. A. Schelkunoff and T. M. Ondarenko : "Crosstalk between coaxial transmission lines", BSTJ, 16, pp. 144-164 (1937)

3) E. D. Sunde : "Lightning protection of buried toll cables", BSTJ, 24, pp. 253-300 (1945)

4) J. Kemp : "Estimation voltage surges on buried coaxial cable struck by lightning", Electrical Commu. 40, pp. 381-384 (1965)

5) S. G. Unger : "Effect of lightning puncture on the core-shield voltage of buried cable", BSTJ, 59, pp. 333-366 (1980)

6) T. Nagano : "Induced voltages on buried coaxial cable by direct lightning strokes", JIECE of Japan, J67-B, pp. 786-796 (1984).

7) S. Ichikawa : "Numerical analysis of traveling waves in transmission networks by numerical inversion of Laplace transform", JIEE of Japan, 102-B, pp. 785-792 (1982)