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Time-Domain Coupling Analysis of Shielded Cable on the Ground Excited by Plane Wave

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Abstract—This paper presents an efficient hybrid method consisting of finite-difference time-domain (FDTD) method, transmission line (TL) equations, and a fast calculation method for excitation fields, which can be applied to the coupling analysis of the shielded cable on the ground excited by plane wave rapidly. It can avoid modeling the infinite ground and the structure of the shielded cable directly. In this hybrid method, the shielded cable is decomposed into external and internal transmission line models, and the corresponding TL equations for the external and internal TL models are established necessarily. Then the FDTD method is utilized to solve the TL equations to obtain the transient responses on the shielding layer and core wires of the cable. A numerous examination of the coupling of coaxial cable exhibits that this hybrid method has very high accuracy and efficiency compared with the SPICE method. Finally, the methods of effective shielding protection of the cable have been proposed by analyzing the influences of the grounding states of the shielding layer, the electromagnetic parameters of the ground and the heights of the cable on the transient responses of the cable.

1. INTRODUCTION

In practical engineering applications, cables are usually located on the ground for the data transmission between electronic systems. The intense electromagnetic waves in the environment will couple strong interference signals on the cables, and then enter the terminal devices to disturb the proper functioning of the devices [1–3]. To suppress the interference of the ambient electromagnetic waves to the cables, the usual method of protecting the cables is adding a shielding layer. In general, the shielding layer is a weave structure, which cannot completely shield wide-band signals, such as nuclear electromagnetic pulse (NEMP), and high power microwave (HPM). Therefore, it has great application prospect to simulate and analyze the coupling characteristics of the shielded cable on the ground excited by plane wave.

The preferred method used to simulate the coupling problem of the shielded cable on the infinite ground excited by plane wave is the full-wave algorithm, such as FDTD method and MOM method. However, due to the complex structure of the shielding layer of the cable, it is difficult to model the cable with these methods directly. Meanwhile, the ground modeled in these methods needs to be meshed, and with the increase of cable length, the size of the ground should be enlarged too, which will cause the mesh number to increase greatly. Therefore, it is urgent to study efficient field-to-cable coupling methods to improve the computational efficiency of this coupling problem. At present, several field-to-cable coupling methods have been proposed, such as Baum-Liu-Tesche (BLT) equation, simulation program with integrated circuit emphasis (SPICE) methods, and FDTD-TL method. BLT equation [4–8] is a frequency domain method, which can only obtain the transient responses on the terminal loads of the cables, and the loads should be linear and time invariant. The SPICE methods [9–14] can be well

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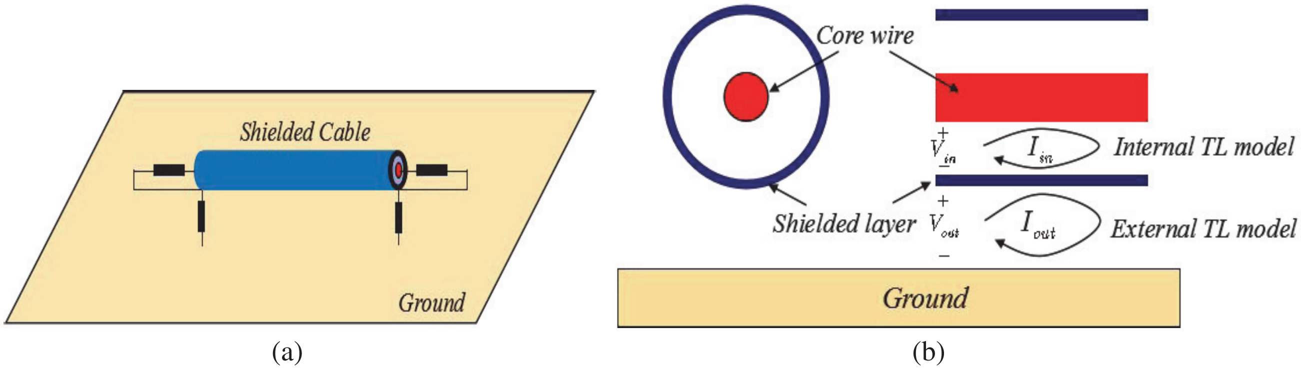
applied to the coupling analysis of nonuniform electromagnetic fields or plane wave to the cables on the ground. In these methods, the frequency domain math expressions of the incident and reflection waves are derived to obtain the excitation fields of the cables, and then the SPICE equivalent circuit models of the cables are established to simulate the transient responses on the terminal loads of the cables. However, these methods need costly formula derivation to establish the SPICE circuits of the cables, and the computational efficiency of the excitation fields of the cables is not high when the incident wave is a broadband signal or/and multiple wave sources. The research in this paper is based on a previous research on the FDTD-TL method proposed in [15]. It combines the FDTD method [16–18] with transmission line (TL) equations and a fast calculation method for the excitation fields of the cables to be used for the coupling analysis of the single or/and the multi-conductor transmission lines on the ground excited by plane wave, and can avoid modeling the ground and transmission lines directly. Moreover, the fast calculation method for the excitation fields of the cables is a time domain approach, which can avoid tedious derivation of math expressions and obtain the excitation fields of the cables excited by multiple pulse sources rapidly. However, this method cannot be applied to the coupling analysis of the shielded cable excited by plane wave currently.

In this paper, the FDTD-TL method proposed in [15] is improved to realize the rapid calculation of the coupling of the shielded cable on the ground excited by plane wave, and the influences of the grounding state of the shielding layer, the electromagnetic parameters of the ground and the heights of the cable on the transient responses of the cable are analyzed. Finally, the effective methods of shielding protection of the cable are given.

2. THEORY OF THE HYBRID METHOD

The coupling model of the shielded cable on the ground is shown in Fig. 1(a), where the location of the cable is parallel to the ground, and the shielding layer of the cable is connected to the ground by two loads. Meanwhile, the core wires are connected to the shielding layer by two loads too. The coupling of the shielded cable on the ground should be decomposed into internal and external transmission line (TL) models via the shielding layer, as shown in Fig. 1(b). The external TL model is composed of the shielding layer of the cable and the ground. The internal TL model is composed of core wires and shielding layer of the cable. The internal and external TL models are related by the transfer impedance and transfer admittance of the shielding layer.



(a) (b)

Figure 1. The model of the shielded cable on the ground. (a) 3D model. (b) 2D model.

The procedure of this hybrid method is shown in Fig. 2. The transmission line equations applied to the external and internal TL models should be established firstly. Then the equivalent distribution sources and distribution parameters are important factors of the TL equations, which should be obtained via the fast calculation method for the excitation fields, finite element method (FEM) software, and transfer impedance and admittance. Finally, the difference scheme of the FDTD method is used to discrete the TL equations to obtain the transient responses on the shielding layer and core wires. The coupling analysis of the external and internal TL models will be given in following sections.

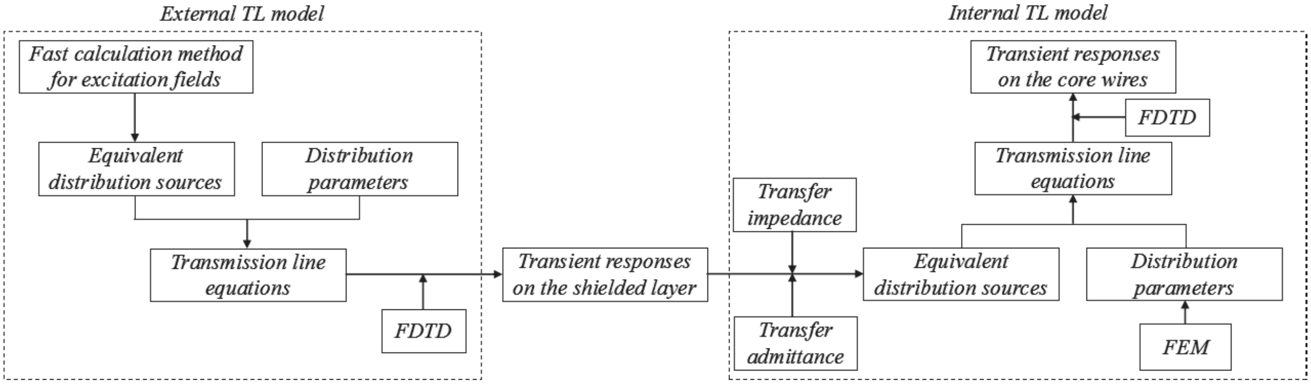


Figure 2. The procedure of this hybrid method.

2.1. The Coupling Analysis of the External TL Model

If the radiation of the core wires to the outer space is ignored, the shielded cable can be seen as a single line when we just analyze the coupling of the external TL model. The coupling of the single line excited by ambient electromagnetic wave can be described by the time domain TL equations [15] as

$$\frac{\partial}{\partial y}\mathbf{V}_{out}(y,t)+\mathbf{L}_{out}\frac{\partial}{\partial t}\mathbf{I}_{out}(y,t)+Z_g(t)*\mathbf{I}_{out}(y,t) = \mathbf{V}_F(y,t) \tag{1}$$

$$\frac{\partial}{\partial y}\mathbf{I}_{out}(y,t)+\mathbf{C}_{out}\frac{\partial}{\partial t}\mathbf{V}_{out}(y,t) = \mathbf{I}_F(y,t) \tag{2}$$

where $\mathbf{L}_{out}$ and $\mathbf{C}_{out}$ are the per-unit length inductance and capacitance of the line, respectively. $Z_g(t)$ is the time domain ground impedance, which stands for the influence of the electromagnetic parameters of the ground on the coupling of the cable. The frequency domain ground impedance $Z_g(\omega)$ can be expressed as

$$Z_g(\omega)=\frac{j\omega\mu_0}{2\pi}\ln\frac{1+\gamma_g h}{\gamma_g h} \tag{3}$$

where $\gamma_g = \sqrt{j\omega\mu_0(\sigma_g+j\omega\varepsilon_g)}$, here ε_g and σ_g are the permittivity and conductivity of the ground, respectively. h stands for the height of the cable.

$\mathbf{V}_F(y,t)$ and $\mathbf{I}_F(y,t)$ are the equivalent distribution voltage and current sources, which can be expressed as

$$\mathbf{V}_F(y,t) = -\frac{\partial}{\partial y}\mathbf{E}_T(y,t)+\mathbf{E}_L(y,t) \tag{4}$$

$$\mathbf{I}_F(y,t) = -\mathbf{C}\frac{\partial}{\partial t}\mathbf{E}_T(y,t) \tag{5}$$

where $\mathbf{E}_T(y,t)$ and $\mathbf{E}_L(y,t)$ can be expressed as

$$\mathbf{E}_T(y,t) = \int_0^h e_z^{ex}(x,y,z,t)\,dz \tag{6}$$

$$\mathbf{E}_L(y,t) = e_y^{ex}(x,y,h,t) \tag{7}$$

When the height of the cable to the ground is electrically small compared with the minimum wavelength of the ambient electromagnetic wave, the radiation of the cable can be neglected [15]. Therefore, the cable can be removed when calculating the excitation fields of the cable. In Equations (6) and (7), e_z^{ex} and e_y^{ex} stand for the incident electric field components vertical to the cable and along the position of the cable respectively. To avoid modeling the ground, a fast calculation method for the excitation fields of the cable is proposed in [15]. This method is based on the image theory, and the effect of the ground to the incident wave source is equal to a time-domain reflection wave source. The locations

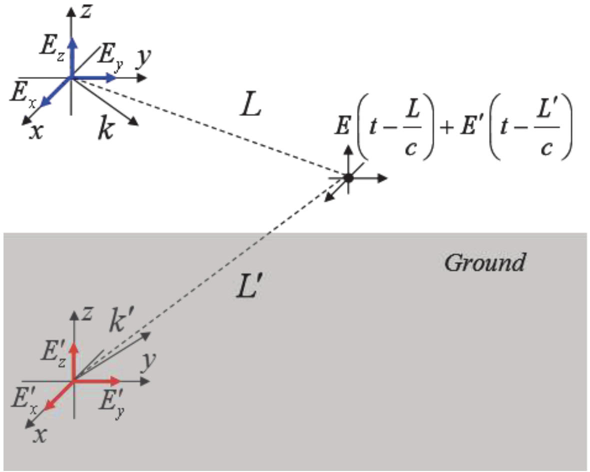


Figure 3. The Processing of the fast calculation method for excitation fields of the cable.

of the incident and reflection wave sources are symmetrical about the ground. Then the electric fields above the ground at any point can be obtained by the superposition of the incident wave source $E(t)$ and the reflection wave source $E'(t)$ propagating corresponding paths, as shown in Fig. 3.

At this point, TL equations of the external TL model are established. Then the difference scheme of the FDTD method is used to discrete Equations (1) and (2) to obtain the voltage and current responses on the shielding layer of the cable. The iteration formulas of the voltage and current responses can be found in [15].

2.2. The Coupling Analysis of the Internal TL Model

The coupling of the internal TL model can be described by the transmission line equations in frequency domain as

$$\frac{\partial \mathbf{V}_{in}(y,\omega)}{\partial y} + j\omega \mathbf{L}_{in}\mathbf{I}_{in}(y,\omega) = \mathbf{Z}_t(\omega)\,\mathbf{I}_{out}(y,\omega) \tag{8}$$

$$\frac{\partial \mathbf{I}_{in}(y,\omega)}{\partial y} + j\omega \mathbf{C}_{in}\mathbf{V}_{in}(y,\omega) = -\mathbf{Y}_t(\omega)\,\mathbf{V}_{out}(y,\omega) \tag{9}$$

where $\mathbf{L}_{in}$ and $\mathbf{C}_{in}$ are the per-unit length inductance and capacitance matrices of the internal TL model, respectively. They can be computed by the finite element method (FEM) software to simulate the two-dimension cross-section model of the core wires with the shielding layer. $\mathbf{V}_{out}(y,\omega)$ and $\mathbf{I}_{out}(y,\omega)$ are the voltage and current vectors of the shielding layer, respectively. $\mathbf{V}_{in}(y,\omega)$ and $\mathbf{I}_{in}(y,\omega)$ are the voltage and current vectors of the core wires, respectively. $\mathbf{Z}_t(\omega)$ and $\mathbf{Y}_t(\omega)$ are the transfer impedance and admittance of the shielding layer, respectively.

The correctness of the transient responses on the core wires depends on the accurate modeling of the transfer impedance and admittance of the shielding layer. The transfer impedance and admittance should be determined by the weave types of the shielding layer, which have several computational models. A common model given in [19] is used, which can be expressed as

$$\mathbf{Z}_t(\omega) = \mathbf{R}_{dc} + j\omega \mathbf{L}_t \tag{10}$$

$$\mathbf{Y}_t(\omega) = j\omega \mathbf{C}_t \tag{11}$$

where $\mathbf{R}_{dc}$, $\mathbf{L}_t$, and $\mathbf{C}_t$ are the transfer resistance, inductance and capacitance, respectively.

Then Equations (10) and (11) are substituted into frequency domain TL equations (Equations (8) and (9)), which are transformed to time domain as

$$\frac{\partial \mathbf{V}_{in}(y,t)}{\partial y} + \mathbf{L}_{in}\frac{\partial \mathbf{I}_{in}(y,t)}{\partial t} = \mathbf{R}_{dc}\mathbf{I}_{out}(y,t) + \mathbf{L}_t\frac{\partial \mathbf{I}_{out}(y,t)}{\partial t} \tag{12}$$

$$\frac{\partial \mathbf{I}_{in}(y,t)}{\partial y}+\mathbf{C}_{in}\frac{\partial \mathbf{V}_{in}(y,t)}{\partial t}=-\mathbf{C}_t\frac{\partial \mathbf{V}_{out}(y,t)}{\partial t} \tag{13}$$

The difference scheme of the FDTD method is utilized to discrete Equations (12) and (13) to obtain iteration formulas of the current and voltage responses on the core wires, which can be expressed as

$$\mathbf{I}_{in}^{n+\frac{1}{2}}\left(k+\frac{1}{2}\right)=\mathbf{I}_{in}^{n-\frac{1}{2}}\left(k+\frac{1}{2}\right)+\left[\frac{\mathbf{L}_{in}}{\Delta t}\right]^{-1}\left(\begin{array}{l}\left[\frac{\mathbf{R}_{dc}}{2}+\frac{\mathbf{L}_t}{\Delta t}\right]\mathbf{I}_{out}^{n+\frac{1}{2}}\left(k+\frac{1}{2}\right)+\left[\frac{\mathbf{R}_{dc}}{2}-\frac{\mathbf{L}_t}{\Delta t}\right]\mathbf{I}_{out}^{n-\frac{1}{2}}\left(k+\frac{1}{2}\right)\\ -\frac{\mathbf{V}_{in}^{n}(k+1)-\mathbf{V}_{in}^{n}(k)}{\Delta y}\end{array}\right) \tag{14}$$

$$\mathbf{V}_{in}^{n+1}(k)=\mathbf{V}_{in}^{n}(k)-\left[\frac{\mathbf{C}_{in}}{\Delta t}\right]^{-1}\left(\left[\frac{\mathbf{C}_t}{\Delta t}\right]\left[\mathbf{V}_{out}^{n+1}(k)-\mathbf{V}_{out}^{n}(k)\right]+\frac{\mathbf{I}_{in}^{n+\frac{1}{2}}\left(k+\frac{1}{2}\right)-\mathbf{I}_{in}^{n+\frac{1}{2}}\left(k-\frac{1}{2}\right)}{\Delta y}\right) \tag{15}$$

3. NUMERICAL SIMULATION

In this section, the time domain hybrid method is used for the coupling analysis of the RG-58 coaxial cable excited by ambient plane wave. Firstly, the accuracy and efficiency of this hybrid method are verified by comparing with the SPICE method in [9]. Then the influences of the grounding states of the shielding layer, electromagnetic parameters of the ground and heights of the cable on the transient responses of the cable are analyzed. Finally, the effective shielding protections of the cable are proposed.

3.1. Verification of the Hybrid Method

The coupling model of the RG-58 coaxial cable on the ground excited by plane wave is shown in Fig. 4, which is derived from [9]. In this case, the ground is assumed as perfect conductor. The cable is with height $h = 1\,\text{cm}$, length $l = 1\,\text{m}$, and radius $r = 1.52\,\text{mm}$. The grounding loads between the shielding layer and the ground are $R_{o1} = 100\,\Omega$, $R_{o2} = 150\,\Omega$, and the terminal loads R_{i1} and R_{i2} of the core wire are both $50\,\Omega$. The incident wave is a nuclear electromagnetic pulse, which can be described as $E_0(t) = kE_0[\exp(-\alpha t) - \exp(-\beta t)]$, where $k = 1.3$, $E_0 = 50\,\text{kV/m}$, $\alpha = 4 \times 10^7\,\text{s}^{-1}$, $\beta = 6 \times 10^8\,\text{s}^{-1}$. The propagation orientation of the wave is perpendicular to the cable. The transfer parameters of the cable are $R_{dc} = 0.0142\,\Omega/\text{m}$, $L_t = 1.0\,\text{nH/m}$, and $C_t = 0.091\,\text{pF/m}$, which are computed by the weave parameters of the shielding layer. The inductance and capacitance parameters of the core wire obtained by using the FEM software are $L_{in} = 0.0247\,\text{nH/m}$ and $C_{in} = 83.23\,\text{pF/m}$, respectively. The hybrid method and the SPICE method proposed in [9] are used to compute the transient responses on the terminal loads of the shielding layer and the core wire of the cable.

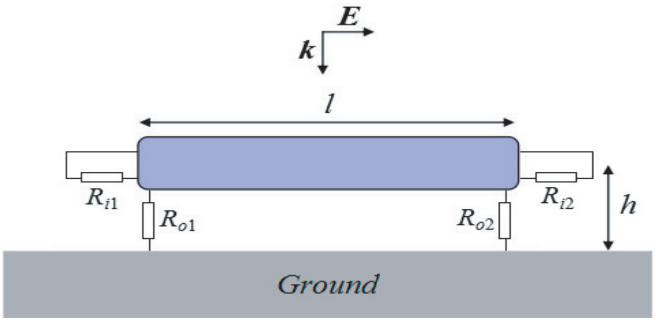
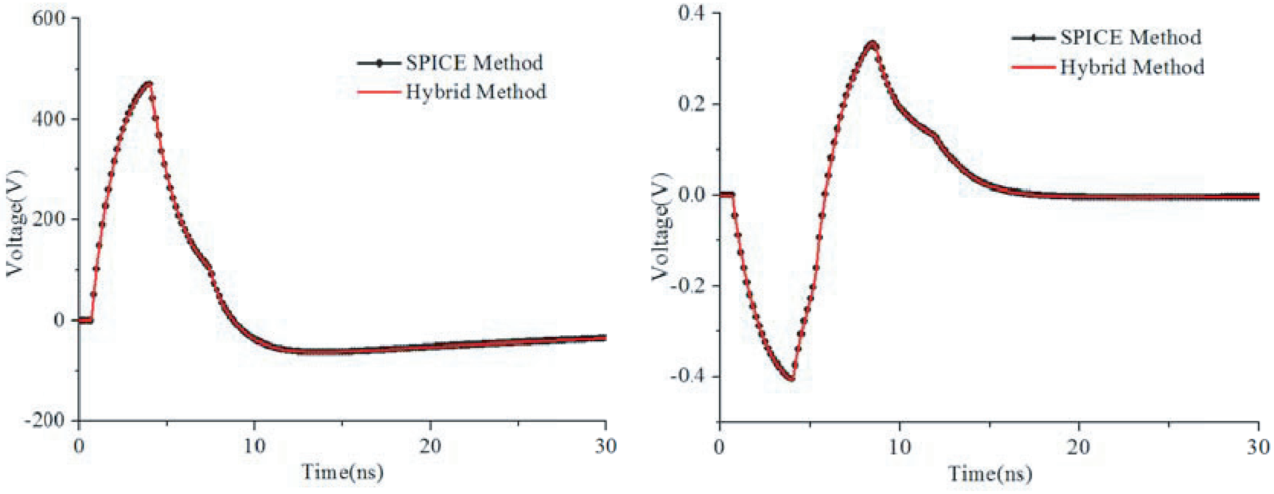


Figure 4. The model of the RG-58 coaxial cable excited by plane wave.

The voltage responses on loads R_{o2} and R_{i1} computed by the two methods are shown in Figs. 5(a) and (b), respectively. It can be seen that the results computed by the two methods agree well. Here the excitation fields of the cable in the SPICE method are computed by the superposition of the frequency domain incident and reflection waves via the reflection coefficient of the ground. The memory and computation time cost by the two methods are shown in Table 1. It can be seen that this hybrid



(a) (b)

Figure 5. The voltage responses on the shielding layer and the terminal loads of the core wire. (a) The voltage responses on the load R_{o2}. (b) The voltage responses on the load R_{i1}.

Table 1. The memory and time cost by the two methods.

Method	Memory (MB)	The cost time (s)
Hybrid Method	0.8	2.2
SPICE Method	10	40

method needs much less memory and computation time than the SPICE method, because it does not need tedious derivation to model the cable, and the computation efficiency of the excitation fields of the cable is higher.

3.2. The Coupling Analysis of the Shielded Cable

In this section, this hybrid method is used to analyze the coupling of the shielded cable via one case. In this case, the cable and incident wave are the same as the above case. The length and height of the cable are changed to 10 m and 2 cm, respectively. The electromagnetic parameters of the ground are $\varepsilon_r = 10$, $\sigma = 0.01\,\mathrm{S/m}$. The terminal loads of the core wire are still $50\,\Omega$.

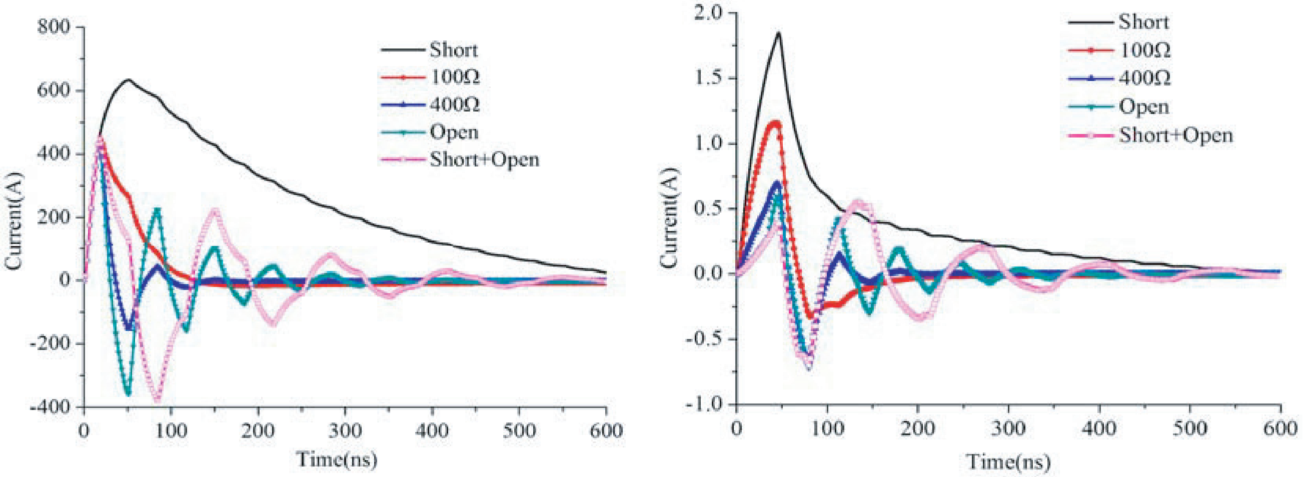
3.2.1. Different Grounding States of the Shielding Layer

Firstly, the hybrid method is used to compute the current responses on the center of the shielding layer and the terminal loads of the core wire with different grounding loads of the shielding layer, i.e., two loads are short, $100\,\Omega$, $400\,\Omega$, open, and one load is short and the other open, respectively.

From Figs. 6(a) and (b), we can see that the current responses on the center of the shielding layer are oscillated with the increase of the values of grounding loads, and the oscillations are continuously strengthened. It is worth mentioning that the current responses on the terminal loads of the core wire are basically consistent with the trend of the current responses on the shielding layer.

3.2.2. Different Parameters of the Ground

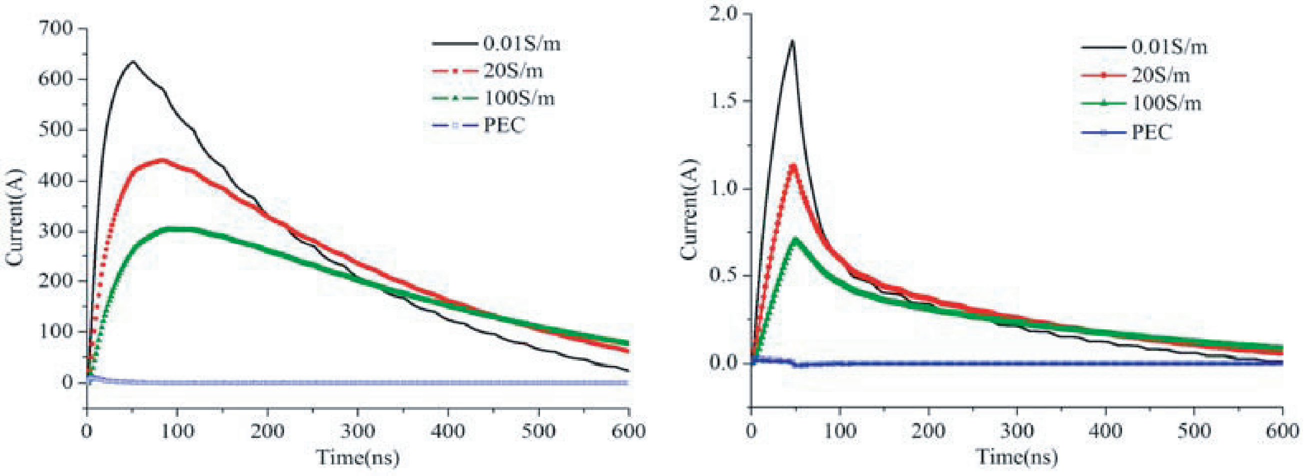
Then, the hybrid method is used to compute the current responses on the center of the shielding layer and terminal loads of the core wire with different electromagnetic parameters of the ground, i.e., $\varepsilon_r = 10$, $\sigma = 0.01\,\mathrm{S/m}$, $\varepsilon_r = 10$, $\sigma = 20\,\mathrm{S/m}$, $\varepsilon_r = 10$, $\sigma = 100\,\mathrm{S/m}$, and $\varepsilon_r = 1$, $\sigma = \mathrm{PEC}$ respectively, when the grounding loads of the shielding layer are short.



(a) (b)

Figure 6. The current responses on the cable with different grounding states. (a) Currents on the center of the shielding layer. (b) Currents on the terminal loads of the core wire.

From Figs. 7(a) and (b), we can see that the peak values of the current responses on the center of the shielding layer and the terminal load of the core wire are decreased with the increase of the conductivity of the ground. When the ground is a perfect conductor (PEC), the current responses on the shielding layer of the cable become very small.



(a) (b)

Figure 7. The current responses on the cable with different parameter of the ground. (a) Currents on the center of the shielding layer. (b) Currents on the terminal loads of the core wire.

3.2.3. Different Heights of the Cable

Finally, the hybrid method is used to compute the current responses on the shielding layer of the cable with different heights when the electromagnetic parameters of the ground are $\varepsilon_r = 10$, $\sigma = 0.01\,\mathrm{S/m}$ and $\varepsilon_r = 1$, $\sigma = PEC$, respectively. The heights of the cable are 2 cm, 5 cm, and 10 cm, respectively.

It can be seen from Figs. 8(a) and (b) that values of the current responses on the shielding layer become lower with the increase of height of the cable when the ground is treated as a low loss medium. On the other hand, the values of the currents on the shielding layer become higher with the increase of height of the cable when the ground is PEC.

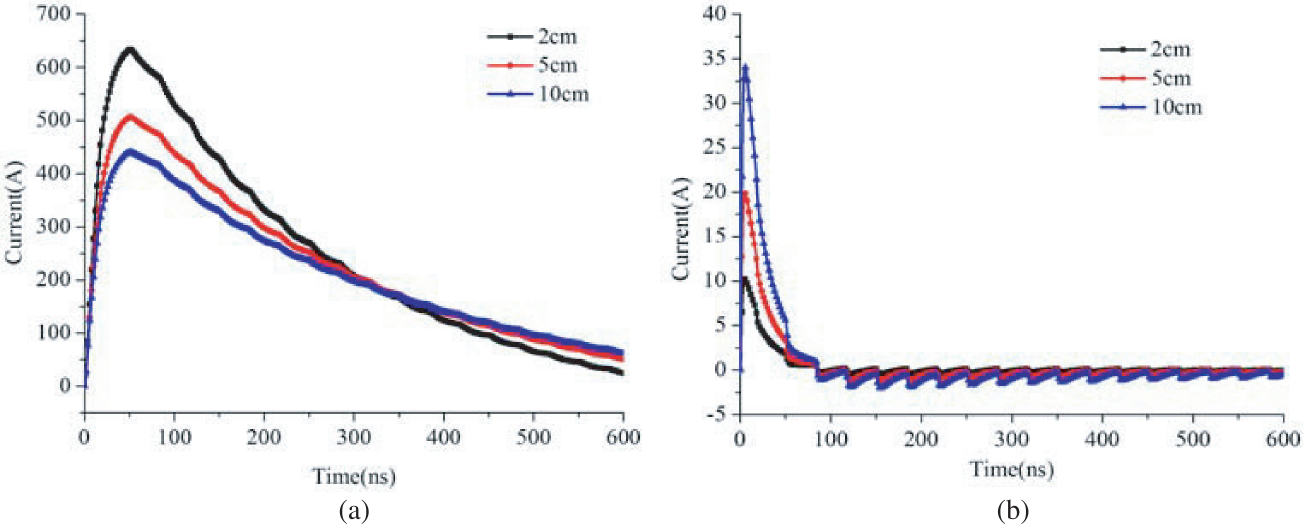


Figure 8. The current responses on the center of the shielding layer with different heights of the cable. (a) The ground is $\varepsilon_r = 10$, $\sigma = 0.01\,\mathrm{S/m}$. (b) The ground is $\varepsilon_r = 1$, $\sigma = PEC$.

Based on the above analysis, we can draw the conclusion that the effective shielding protections of the cable have three ways: The first is that the shielding layer of the cable should be connected to the ground by short circuit to avoid the oscillation of the interference signal, and the second is that metal nets should be laid on the ground near the cable to add conductivity of the ground. Finally, the cable should be close to the ground.

4. CONCLUSION

In this paper, an improved efficient time domain hybrid method has been proposed, which does not need to model the structures of the cable and the infinite ground directly, and can be used to solve the coupling problems of the shielded cable excited by ambient plane wave rapidly.

The accuracy and efficiency of this hybrid method have been verified by comparing with the SPICE method for the coupling analysis of the RG-58 coaxial cable. The results computed by the two methods agree well, and this method costs less computation time and memory than the SPICE method because the proposed method avoids tedious derivation to model the cable, and the efficiency of the fast calculation method for the excitation fields of the cable is high. In addition, the effective shielding protections of the cable are put forward via the analysis of the influences of the grounding states of the cable, the electromagnetic parameters of the ground, and the heights of the cable on the transient responses of the cable.

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