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Investigation of Electromagnetic Field Coupling with Twisted Conducting Line by Expanded Chain Matrix

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Abstract – In the current paper, we propose a new modeling algorithm to analyze the coupling between an incident electromagnetic field (EMF) and a twisted conducting line, which is a kind of non-uniform line. Typically, analysis of external field coupling to a uniform transmission line (TL) is implemented by the Baum-Liu-Tesche (BLT) equation so that the induced load responses can be obtained. However, it is difficult to apply this method to the analysis of a twisted conducting line. To overcome this limitation, we used a chain matrix composed of ABCD parameters. The proposed algorithm expands the dimension of the previous chain matrix to consider the EMF coupling effectiveness of each twisted pair, which is then applied to multi-conductor transmission line (MTL) theory. In addition, we included a comparative study that involves the results of each method applied in the conventional BLT equation and new proposed algorithm in the uniform two-wire TL case to verify the proposed method.

Keywords: Coupling, Electromagnetic field (EMF), Twisted conducting line, Transmission line (TL), Baum-Liu-Tesche (BLT) equation, Chain matrix, Multi-conductor transmission line (MTL)

1. Introduction

An important aspect of electromagnetic interference (EMI) is the determination of electromagnetic coupling to TLs and the terminal responses of the lines illuminated by an incident EMF [1-2]. In general, the behavior of the induced responses can be evaluated using electromagnetic scattering theory. This paper considers the important parts of the electromagnetic compatibility (EMC) problem of high-frequency EMF coupling to both uniform and non-uniform lines based on electromagnetic scattering theory. In case of conducted interference, it is modeled using circuit theory that is valid for low frequencies where the wavelength is much larger than the size of the system being considered. At high frequencies, however, due to the wave-propagation effects, it is difficult to apply the conventional circuit model to the EMF coupling problem [3]. Hence, we used TL theory and models for lines that have lumped excitation sources. The EMF coupling to a uniform TL can be analyzed by applying the BLT equation that uses a general scattering matrix form [4-5]. However, there is a limit to use of the BLT equation to analyze EMF coupling with a twisted conducting line because of repeatedly changing coupling components of each twisted pair.

In this paper, the proposed algorithm solves the problem of EMF coupling to twisted conducting lines as a kind of non-uniform line above a ground plane using an expanded chain matrix algorithm applied to MTL theory. The fundamental chain matrix formulation allows an efficient numerical solution for the terminal responses when the uniform MTL is excited, whereas non-uniform lines cannot be analytically solved, in general [1, 6]. So the purpose of this paper is to propose a new method for analyzing non-uniform line such as twisted conducting line. The proposed method uses ABCD parameters, which consider the coupling component of each line, and the twisted conducting line is modeled by dividing twisted pairs into a finite number of small sections. From this, the induced load voltage and current responses can be determined using an expanded chain matrix which is combined from each small section modeled. The result from the proposed method was compared with a reference result implemented by the conventional BLT equation method.

2. Conventional Analysis Based on BLT Equation

A general approach for the determination of the load responses of the two-wire TL illuminated by an incident field uses the BLT equation.

Fig. 1 shows the field excitation of an isolated two-wire TL using distributed sources. The distributed voltage and current source terms can be calculated by:

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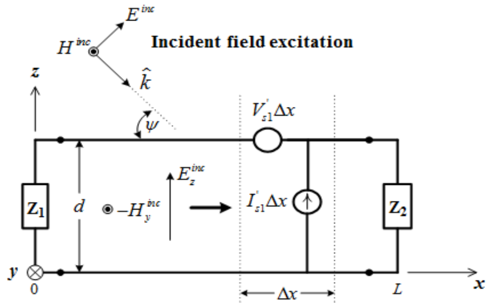


Fig. 1. Modeling of external field excitation of a TL using distributed voltage and current sources.

$$V'_{s1}(x) = -j\omega\mu\int_0^d H_y^{inc}(x,z)\,dz \quad (1)$$

$$I'_{s1}(x) = -j\omega C'\int_0^d E_z^{inc}(x,z)\,dz \quad (2)$$

where μ is the magnetic permeability of the material around the wires, ω is angular frequency, H_y^{inc} is the y-axis incident magnetic field, E_z^{inc} is the z-axis incident electric field, and *C'* is the per-unit-length capacitance discussed in chapter 4 [7]. The BLT equations for the load responses of the voltage and current are written in compact matrix form as:

$$\begin{bmatrix} V(0) \\ V(L) \end{bmatrix} = \begin{bmatrix} 1+\rho_1 & 0 \\ 0 & 1+\rho_2 \end{bmatrix} \begin{bmatrix} -\rho_1 & e^{\gamma L} \\ e^{\gamma L} & -\rho_2 \end{bmatrix}^{-1} \begin{bmatrix} S_1 \\ S_2 \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} I(0) \\ I(L) \end{bmatrix} = \frac{1}{Z_c} \begin{bmatrix} 1-\rho_1 & 0 \\ 0 & 1-\rho_2 \end{bmatrix} \begin{bmatrix} -\rho_1 & e^{\gamma L} \\ e^{\gamma L} & -\rho_2 \end{bmatrix}^{-1} \begin{bmatrix} S_1 \\ S_2 \end{bmatrix} \quad (4)$$

where Z_c is the characteristic impedance, ρ_i is the reflection coefficient at each load, γ is the propagation constant along the two-wire TL, and the source vectors are given by:

$$\begin{pmatrix} S_1 \\ S_2 \end{pmatrix} = \begin{pmatrix} \frac{1}{2}\int_0^L e^{\gamma x_s}\left[V'_{s1}(x_s) + Z_c I'_{s1}(x_s)\right]dx_s \\ -\frac{1}{2}\int_0^L e^{\gamma(L-x_s)}\left[V'_{s1}(x_s) - Z_c I'_{s1}(x_s)\right]dx_s \end{pmatrix} \quad (5)$$

where x_s is the position of the distributed sources.

The vector *S* is the excitation term in terms of the distributed source terms. Finally, the load responses can be implemented by solving Eqs. (3) and (4).

As an example of the time-domain response calculated by inverse Fourier transform of the frequency-domain response of the BLT equation for the two-wire TL, consider the line shown in Fig. 1 with the following parameters: *L*=30*m*, each conductor separation *d*=20*cm*, and each wire radius $a_{1,2}$=0.15*cm*. For this line geometry, the characteristic impedance is Z_c≈586Ω. The termination impedances at *x*=0 and *x*=*L* are set to the values $Z_1=Z_2=Z_c/2$≈293Ω. The incident electric field that strikes the line with an angle of incidence ψ=30° is defined as a

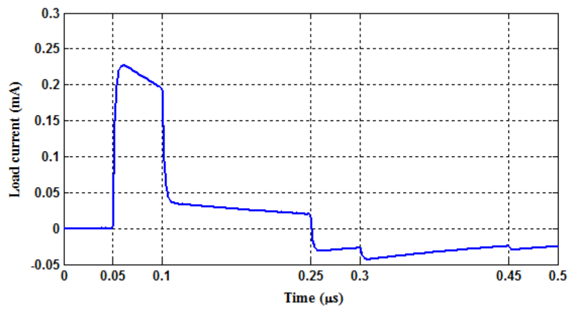


Fig. 2. Induced current at *x*=*L* for the two-wire TL obtained from BLT equation method.

double exponential waveform called HEMP (High altitude Electromagnetic Pulse) described by $E_{inc}(t)=E_0\times(e^{-at}-e^{-bt})$ V/m, E_0=1.05, *a*=4 × 10^6, *b*=4.76 × 10^8, and the field components are discussed in section II [8]. As a result, the induced current at *x*=*L* can be obtained using Eq. (4), which is shown in Fig. 2. It is a conventional method for analyzing EMF to uniform TL coupling based on BLT equations.

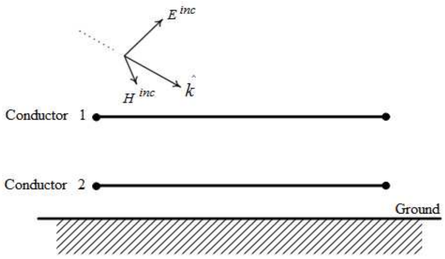
3. Analysis of Uniform/Non-uniform line over Ground Based on Proposed Method

As for the case of EMF coupling in a two-wire line above a ground plane, the ground plane plays a role in analyzing load responses of the line. It can be considered as a reference conductor so that one can apply MTL theory to analyze this phenomenon.

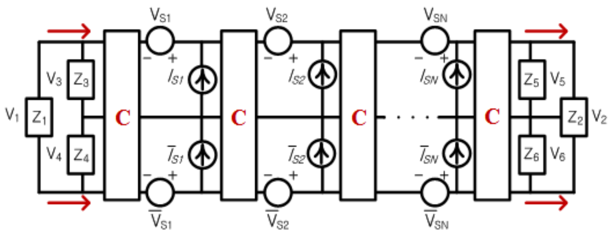
3.1 Analysis of uniform line above ground plane

Fig. 3 shows the real situation in external field excitation of a uniform two-wire TL above ground plane and the proposed modeling structure. To solve the load responses in this problem, we considered the line with the following parameters: *L*=30*m*, each conductor separation *d*=20*cm*, the distance from ground to conductors 1, 2 $h_{1,2}$=4*mm*, and each wire radius $a_{1,2}$=0.15*cm*. For this line geometry, termination impedances at each load are set to the values $Z_1=Z_2$=50Ω, $Z_3=Z_4=Z_5=Z_6=\infty$. And for the ground plane, in many practical applications, the ground plane is the earth, for which ε_r≈10, thus we use this value for considering the ground plane as a reference conductor [10].

The external incident electric field is defined as a double exponential waveform in the same manner as section 2, but each parameter is defined by E_0=6.5, *a*=4× 10^7, *b*=6× 10^8. In the case of aerial lines as shown in Fig. 3(a), the total field above the ground plane is the sum of the incident fields and the reflected field from the ground plane, which are expressed by Eqs. (6) and (7) in section III [8]. Also, the model of the EMF in free space is presented in section II [8]. Because the incident electric field has a wide band



(a) EMF coupling to uniform line on ground plane



(b) Proposed modeling structure by chain matrix

Fig. 3. EMF coupling to uniform two-wire TL on ground plane and proposed modeling configuration.

range of approximately 500MHz in which the wavelength is much smaller than the total length of the uniform two-wire TL, we divided the whole structure of the uniform two-wire TL into small sections. These small sections are modeled by a cascaded identical chain matrix as shown in Fig. 3(b).

There is a difference between two-wire TLs in Fig. 1 and 3(a). It requires additional per-unit-length parameters to consider the EMF coupling of each line to the ground plane. So, this paper proposes an expanded (4 by 4) chain matrix that contains all coupling effectiveness. In the expanded chain matrix, each parameter involves the per-unit-length capacitances C_{1g} and C_{2g} induced by the electric coupling of conductor lines 1 and 2, inductances L_{1g} and L_{2g} induced by the magnetic coupling of ground to conductor lines 1 and 2, and mutual coupling terms C_m and L_m. These parameters can be calculated using equations presented in chapter 5 [7].

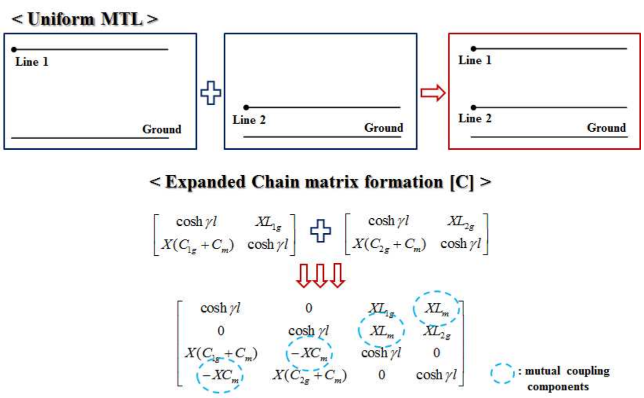


Fig. 4. The expanded chain matrix C in uniform MTL.

$$\frac{(V_4 - V_3)}{Z_1} - I_3 = \frac{V_3}{Z_3} \tag{6}$$

$$\frac{(V_3 - V_4)}{Z_1} - I_4 = \frac{V_4}{Z_4} \tag{7}$$

$$\frac{(V_6 - V_5)}{Z_2} - I_5 = \frac{V_5}{Z_5} \tag{8}$$

$$\frac{(V_5 - V_6)}{Z_2} - I_6 = \frac{V_6}{Z_6} \tag{9}$$

Fig. 5 shows an equivalent circuit for the two-wire TL above ground plane to apply boundary conditions at each load. The node equations are calculated by Eqs. (6) to (9) using simple circuit theory, and the final equation for the relationship between load responses and distributed sources can be expressed by:

$$\begin{bmatrix} V_3 \\ V_4 \\ I_3 \\ I_4 \end{bmatrix} = C^N \times \begin{bmatrix} V_5 \\ V_6 \\ I_5 \\ I_6 \end{bmatrix} + C^{N-1} \times \begin{bmatrix} -V_{SN} \\ -\bar{V}_{SN} \\ -I_{SN} \\ -\bar{I}_{SN} \end{bmatrix} + C \times \begin{bmatrix} -V_{S1} \\ -\bar{V}_{S1} \\ -I_{S1} \\ -\bar{I}_{S1} \end{bmatrix} \tag{10}$$

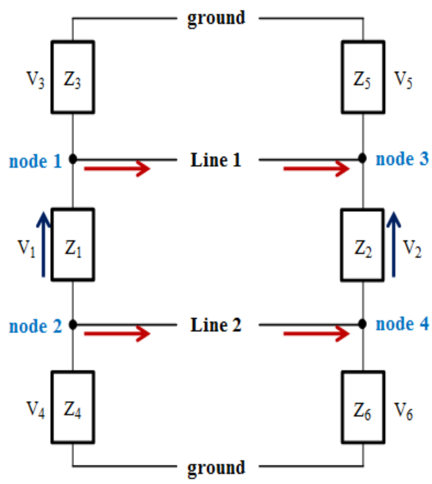


Fig. 5. Boundary conditions at each termination load.

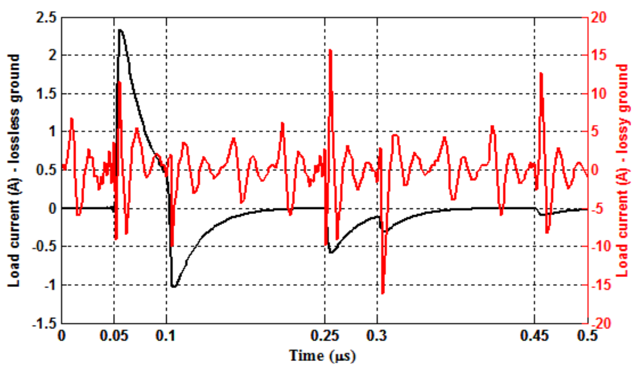


Fig. 6. Induced current at load $x=L$ for the two-wire TL above ground plane in various cases.

where N is the number of resolved small sections.

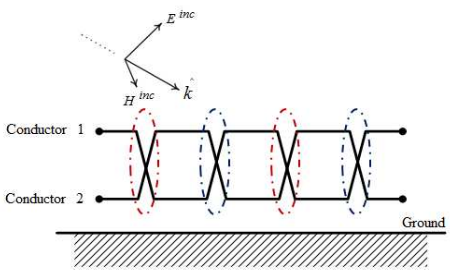
Fig. 6 shows the result of induced current responses at $x=L$, which is applied with different conductivities of ground planes. The effect of loss in the ground plane increases the amplitude of current induced in the line. It can be found that the response is smaller due to the fact that the tangential excitation electric field along the horizontal section of the line is smaller for the case of the perfectly conducting ground plane.

3.2 Analysis of non-uniform line above ground plane

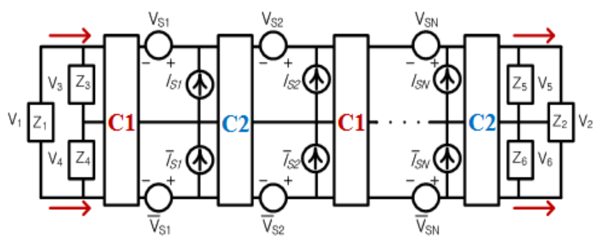
When the non-uniform line having iterative twisted pairs is analyzed, it requires a modeling algorithm different from the uniform MTL analysis, because the cross domain of the twisted pair must be considered. Most importantly, the distances from ground to each line are changed iteratively, which can be identified by Fig. 7(a). So, the twisted conducting line can be modeled by a cascaded structure that consists of odd and even numbers of each twisted pair, as shown in Fig. 7(b). The odd number twisted pairs have different values of height $h+d$, d in line 1 and d, $h+d$ in line 2. In this view, the expanded chain matrix C1 can be obtained interacting with each chain matrix in order, as shown in Fig. 8(a). In contrast, the even number twisted pairs have structure opposite from the odd number of twisted pairs. It is just a different point. Also, the expanded chain matrix C2 can be obtained by the same method as C1 calculation, as shown in Fig. 8(b).

To solve the load responses in this problem, we applied the line parameter, termination impedances, and incident electric field in the same way as section 3.1.

The final equation, which is described by multiplying the expanded chain matrices C1 and C2 repetitively, is given by

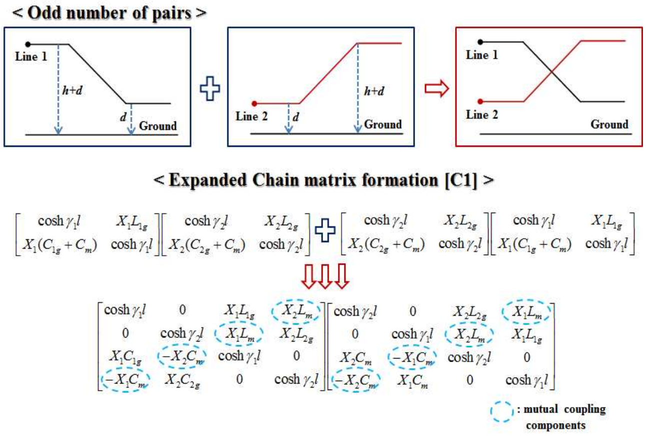


(a) EMF coupling to non-uniform line on ground plane

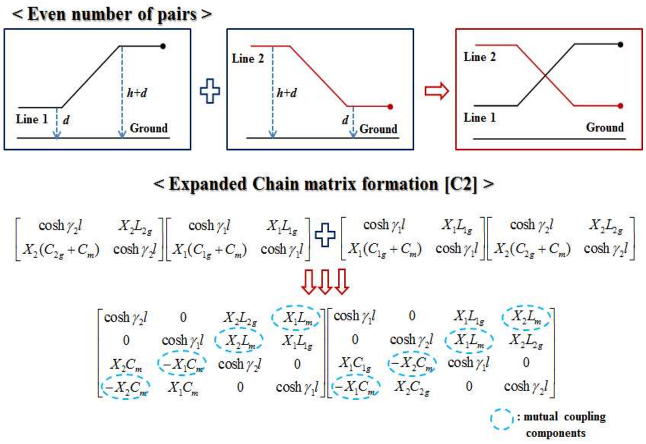


(b) Proposed modeling structure by chain matrix

Fig. 7. EMF coupling to twisted conducting line on ground plane and proposed modeling configuration.



(a) Expanded chain matrix C1 at odd number of pairs



(b) Expanded chain matrix C2 at even number of pairs

Fig. 8. The expanded chain matrices C1 and C2 in twisted pairs.

$$\begin{bmatrix} V_3 \\ V_4 \\ I_3 \\ I_4 \end{bmatrix} = [C1 \cdot C2]^{\frac{N}{2}} \times \begin{bmatrix} V_5 \\ V_6 \\ I_5 \\ I_6 \end{bmatrix} + [C1]^{\frac{N}{2}} [C2]^{\frac{N}{2}-1} \times \begin{bmatrix} -V_{SN} \\ -\bar{V}_{SN} \\ -I_{SN} \\ -\bar{I}_{SN} \end{bmatrix} \cdots + [C2] \times \begin{bmatrix} -V_{S1} \\ -\bar{V}_{S1} \\ -I_{S1} \\ -\bar{I}_{S1} \end{bmatrix} \quad (11)$$

where N is total number of twisted pairs.

Fig. 9 shows the result of induced current at load for the twisted conducting line above ground plane in the lossless case. Because the magnetic fields are countervailed by the opposite direction of the induced currents in the twisted pairs of each section, it can be found that the induced current is significantly decreased in comparison with the result of EMF coupling to uniform MTL shown in Fig. 6.

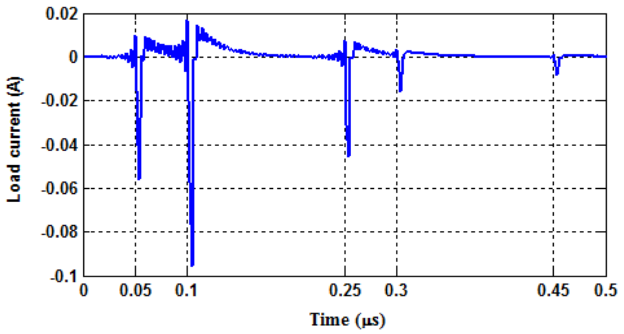


Fig. 9. Induced current at $x=L$ for the twisted conducting line above ground plane about lossless cases.

4. Verification of Proposed Algorithm

To verity proposed modeling method, we applied it to the two-wire TL case introduced in section 2 as basic structure, and it can be modeled by a cascaded identical chain matrix as shown in Fig. 10. A useful set of parameters for circuits that are cascaded together are the original 2 by 2 chain parameters [9]. Also known as the ABCD or transmission parameters, these are defined by the matrix expression as:

$$\begin{bmatrix}V_1\\I_1\end{bmatrix}=\begin{bmatrix}A\,B\\C\,D\end{bmatrix}\begin{bmatrix}V_2\\I'_2\end{bmatrix} \tag{12}$$

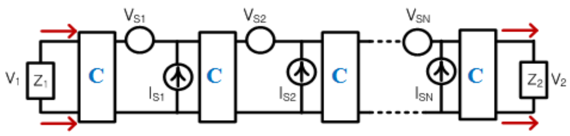
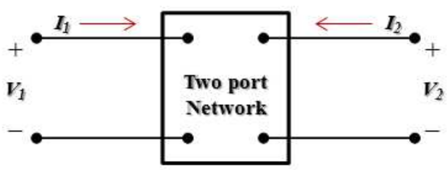
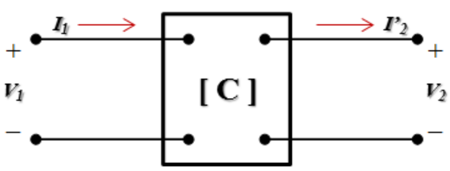


Fig. 10. Proposed modeling structure by chain matrix in two-wire TL.



(a) General two port network system



(b) Chain matrix system

Fig. 11. Comparison of general two port network system and original chain matrix system.

The location and orientation of the port voltages and currents for the chain parameters and two port network systems are shown in Fig. 11. As shown in Fig. 11(a), the direction of the current at port 2 is reversed from that in the definitions of the general two port network systems in Fig. 11(b), and this current is denoted as I'_2.

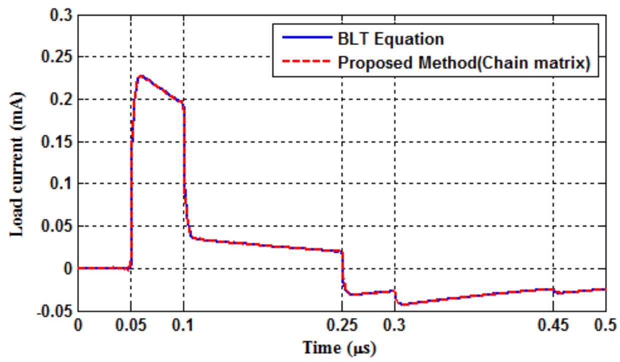


Fig. 12. Results for verification of proposed algorithm.

Table 1. Comparison of calculation time in two-wire TL.

Two-wire TL analysis	Calculation time [second]
Conventional method (BLT equation)	10.43 sec
Proposed method (Chain Matrix algorithm)	14.45 sec

5. Conclusion

The current study shows a new modeling method for analyzing EMF coupling to a twisted conducting line, and the method has been verified in comparison with results of the BLT equation. The expanded chain matrix algorithm can be applied to the analysis of EMF coupling with uniform TL as well as non-uniform TL analysis. In case of uniform line analysis, the BLT equation is a little more effective in terms of calculation time as indicated in Table 1. However, it is difficult to apply to non-uniform line analysis. So, this paper proposed the expanded chain matrix algorithm as a new modeling method to overcome the shortcomings of the conventional method.

Accordingly, we can analyze the load response of twisted conducting line as a non-uniform line by the proposed modeling method, and it is possible to identify that the twisted pairs have a great effect on shielding effectiveness in terms of magnetic coupling.

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