Efficient Method for Field Coupling to Nonuniform Transmission Line Using Cascaded SPICE Model

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Abstract— This paper presents a method of equivalent cascaded SPICE model for external field coupling with nonuniform transmission line. Two nonuniform transmission lines excited by an external EMP with different incidences have been studied to validate its accuracy and efficiency. The results show that the induced voltages obtained by the proposed method agree well with those via the software CST even when the segment number is up to three and the proposed method has higher efficiency. Due to the application of SPICE model and directly computation in the time domain, this method allows for the analysis of nonuniform transmission line terminated with nonlinear loads and integrated circuits.

1. INTRODUCTION

External field coupling through wires or cables is an important coupling path for external field interaction with electronic systems and has attracted many attentions [1, 2].

Due to the fact that many transmission lines are nonuniform, fields coupling to nonuniform transmission lines should be studied. External field coupling with nonuniform transmission lines has been studied by some researchers in the frequency domain, where the method of equivalent cascaded network chain [3], the electromagnetic topology method [4], and transmission-line super theory [5] have been applied. These methods are the frequency-domain method and are not suitable for nonuniform transmission line with nonlinear loads. Three dimensional (3D) numerical method, such as finite-difference time-domain (FDTD) method [6], has been employed to compute lightning-induced voltages on an overhead line [7]. The FDTD method can be applied to compute field coupling with nonuniform transmission line with nonlinear loads. However, the meshes are determined by the minimum size of the line and thus this method is inefficient. To analyze field coupling with transmission lines efficiently in the time domain directly, some SPICE models for external field coupling with transmission lines have been developed [2, 8, 9]. However, these SPICE models are only suitable for uniform transmission lines and nonuniform transmission lines have not been considered.

This paper presents a method of equivalent cascaded SPICE model for external field coupling with nonuniform transmission lines. The accuracy and the efficiency of the proposed method are validated by comparing with the commercial software CST. Due to the direct computation in time domain, this method can be used for the analysis of nonuniform transmission line with nonlinear loads. Moreover, this method allows the analysis of nonuniform transmission line loaded by integrated circuit due to the application of SPICE model.

2. METHOD OF EQUIVALENT CASCADED SPICE MODEL

For transmission line with weak nonuniformity, the coupling with external field can be described by

$$\begin{array}{l} \dfrac{\partial}{\partial z}\mathbf{V}\left(z,t\right)+\mathbf{L}\left(z\right)\dfrac{\partial}{\partial t}\mathbf{I}\left(z,t\right)=\mathbf{V}_F\left(z,t\right) \\ \dfrac{\partial}{\partial z}\mathbf{I}\left(z,t\right)+\mathbf{C}\left(z\right)\dfrac{\partial}{\partial t}\mathbf{V}\left(z,t\right)=\mathbf{I}_F\left(z,t\right) \end{array}. \tag{1}$$

Here $\mathbf{V}(z)$ and $\mathbf{I}(z)$ are the line voltage vector and the line current vector, respectively. $\mathbf{L}(z)$ and $\mathbf{C}(z)$ are the per-unit-length (p.u.l.) inductance and capacitance matrices of the line, which are not constant but the functions of the z axis. $\mathbf{V}_F$ and $\mathbf{I}_F$ are distributed voltage and current source vectors which denote the effect of the external fields.

Because $\mathbf{L}(z)$ and $\mathbf{C}(z)$ are the functions of the z axis, (1) can not be decoupled by similarity transformation for general configurations of nonuniform transmission line but only for some certain configurations of nonuniform transmission line [11]. As a result, different modes are coupled together on nonuniform transmission line and the SPICE model for general nonuniform transmission line can not be derived directly from (1).

Because transmission line equation can not be decoupled by similarity transformation for general configurations, we divide nonuniform transmission lines into several sections and each section are approximated by a uniform transmission line, as shown in Figure 1. Consequently, the nonuniform line can be seen as cascaded series of segments of uniform lines.

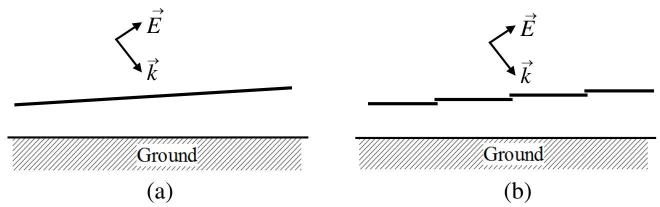


Figure 1: Nonuniform transmission line approximated by cascaded series of many short sections of uniform lines. (a) Nonuniform transmission line. (b) Cascaded series of segments of uniform lines.

The equation for the nth section of uniform line can be written as

$$\begin{array}{l} \frac{\partial}{\partial z}\mathbf{V}_n(z,t) + \mathbf{L}_n\frac{\partial}{\partial t}\mathbf{I}_n(z,t) = \mathbf{V}_{Fn}(z,t) \\ \frac{\partial}{\partial z}\mathbf{I}_n(z,t) + \mathbf{C}_n\frac{\partial}{\partial t}\mathbf{V}_n(z,t) = \mathbf{I}_{Fn}(z,t) \qquad (n=1,\ldots,N) \end{array}. \tag{2}$$

$\mathbf{L}_n$ and $\mathbf{C}_n$ are the inductance and capacitance matrices of nth section and they are constant. N is the number of the sections. For this segment of uniform line, a similar transformation can be applied to decouple the Equation (2) to mode quantities as

$$\begin{array}{l} \mathbf{V}_n(z,t) = \mathbf{T}_{Vn}\mathbf{V}_{mn}(z,t) \\ \mathbf{I}_n(z,t) = \mathbf{T}_{\mathrm{I}n}\mathbf{I}_{mn}(z,t) \end{array}. \tag{3}$$

Then the relation between the terminal mode voltages and currents of the nth section of uniform line can be written as

$$\begin{array}{r} \left[\mathbf{V}_{mn}(0,t) - \mathbf{Z}_{Cmn}\mathbf{I}_{mn}(0,t)\right]_i = \left[\mathbf{V}_{mn}(l_n, t-T_{in}) - \mathbf{Z}_{Cmn}\mathbf{I}_{mn}(l_n, t-T_{ni})\right]_i + \left[\mathbf{V}_{0n}(t)\right]_i \\ \left[\mathbf{V}_{mn}(l_n,t) + \mathbf{Z}_{Cmn}\mathbf{I}_{mn}(l_n,t)\right]_i = \left[\mathbf{V}_{mn}(0, t-T_{in}) + \mathbf{Z}_{Cmn}\mathbf{I}_{mn}(0, t-T_{ni})\right]_i + \left[\mathbf{V}_{ln}(t)\right]_i \end{array}. \tag{4}$$

Here l_n is the length of the nth section of uniform line. $\mathbf{Z}_{Cmn}$ is the mode characteristic impedance diagonal matrix. T_{ni} is the one-way time delay of the ith modal line of the nth section. $\mathbf{V}_{0n}$ and $\mathbf{V}_{ln}$ are the additional source due to external excitation field, which can be realized through delay lines and controlled sources for plane-wave excitation [2] and should be computed numerically for nonuniform-field excitation [8]. Then the SPICE model for the nth segment of uniform line can be developed and is shown in Figure 1.

Because these uniform segments are cascaded to approximate nonuniform transmission line. The voltages and currents at the node, which connects two adjacent segments of uniform line, and terminals satisfy the relation defined by

$$\begin{array}{ll} \mathbf{V}_{n-1}(l_{n-1}) = \mathbf{V}_n(0), & \mathbf{I}_{n-1}(l_{n-1}) = \mathbf{I}_n(0) \\ \mathbf{V}_1(0) = \mathbf{V}(0), & \mathbf{I}_1(0) = \mathbf{I}(0) \\ \mathbf{V}_N(l_N) = \mathbf{V}(l), & \mathbf{I}_N(l_N) = \mathbf{I}(l) \end{array}, \tag{5}$$

where l is the length of the nonuniform transmission line. As a result, the equivalent cascaded SPICE model for nonuniform transmission line is given in Figure 1.

The segment number N is an important parameter for this method, which determines the accuracy and efficiency of this method. Enough sections should be divided to ensure the good approximation of the nonuniform transmission line. However, some researches do not show that the more segments the better [12]. Too much segments will increase the computation complexity and numerical faults. Thus an appropriate segment number N should be chosen to ensure the accuracy

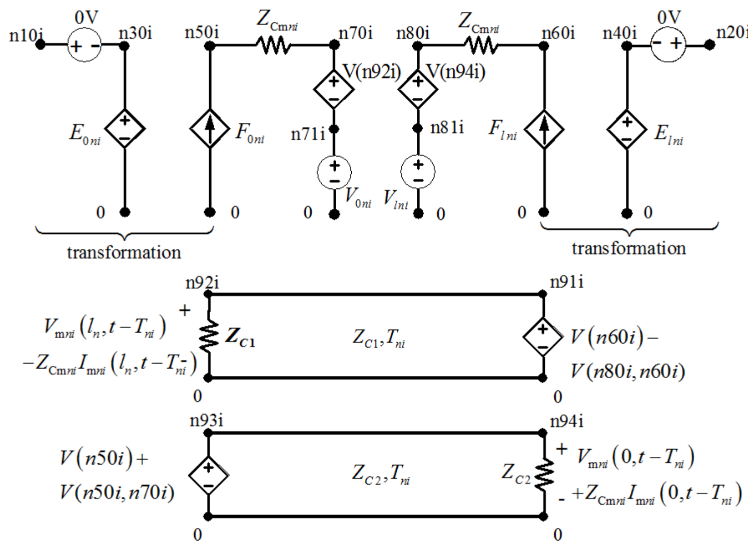


Figure 2: SPICE model for nth section of uniform line.

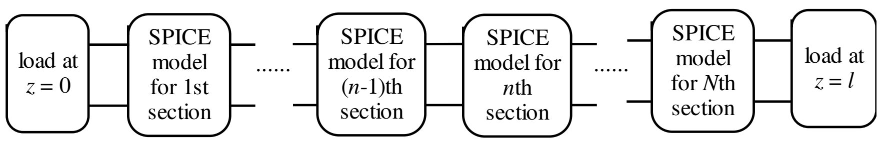


Figure 3: Cascaded SPICE model for nonuniform transmission line.

and efficiency. In this paper, the self-adapting method is applied to determine the segment number N.

After the equivalent cascaded SPICE model for nonuniform transmission line is developed and the terminal connections are defined, a SPICE software can be employed to obtain the voltages induced on the loads by an external field.

3. NUMERICAL VALIDATION

Nonuniform single-conductor and multiconductor transmission lines excited by an external electromagnetic pulse (EMP) have been studied by using the proposed method. The external EMP is a bi-exponential pulse and defined by $E(t) = kE_0[\exp(-\beta t) - \exp(-\alpha t)]$, where $k = 1.3$, $E_0 = 50\,\mathrm{kV/m}$, $\alpha = 6.0 \times 10^8\,\mathrm{s}^{-1}$, and $\beta = 4.0 \times 10^7\,\mathrm{s}^{-1}$. In order to validate the accuracy and efficiency of the proposed method, the results of different segment numbers are compared with those via the microwave studio of CST. All the computations are carried out on a personal desktop.

A nonuniform single-conductor transmission line with the radius of 1 mm and the length of 1 m excited by the EMP with a perpendicular incidence is shown in Figure 4. The heights of the line over the ground at the near and far ends are $h_1 = 0.5\,\mathrm{cm}$ and $h_2 = 3.5\,\mathrm{cm}$, respectively. The terminal loads R_1 and R_2 are $50\,\Omega$.

Figure 1 shows the induced voltages at R_1 and R_2 obtained by the cascaded SPICE model when the segment number N equals 1, 3, and 5, comparing with those via the software CST. When the segment number $N = 1$, the whole nonuniform line is considered as a uniform transmission line. The results show that the induced voltages at R_1 and R_2 obtained by the proposed method are in

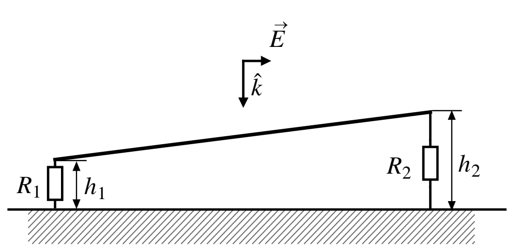


Figure 4: Nonuniform single-conductor transmission line excited by an EMP with perpendicular incidence.

a good agreement with those via CST even when the segment number N equals 3 and the results when $N = 3$ have little difference with those when $N = 5$. This implies that the approximation of three segments of uniform line is sufficient for this nonuniform line.

The time taken by the proposed method and CST is compared in Table 1. The cost time of the proposed method when $N = 3$ and $N = 5$ are 1.92 s and 2.88 s, respectively, while the time taken by CST is 4.2 h, where the smallest mesh size is 2 mm and the number of mesh cells is 215,136. It can be concluded from these results that the proposed method has good accuracy and efficiency for the nonuniform single-conductor transmission line.

A nonuniform multiconductor transmission line excited by the EMP with a horizontal incidence, as shown in Figure 6, are also studied by using the proposed method to validate its ability for nonuniform multiconductor transmission line. The nonuniform multiconductor transmission line consists of two wires with the radius of 1 mm, the length l of 2 m, and the height h of 2 cm. The distances between the two wires at the near and far ends are $D_0 = 1$ cm and $D_l = 5$ cm, respectively. All the loads are 50 Ω.

Figure 7 shows the induced voltages at R_{01} and R_{l1} obtained by the cascaded SPICE model when the segment number N equals 1, 3, and 5, comparing with those via the software CST. The results show that the induced voltages at R_{01} and R_{l1} obtained by the proposed method when $N = 3$ have little difference with those when $N = 5$ and they agree well with those via the software CST.

The time taken by the two method are given in Table 2. The time taken by the proposed method when $N = 3$ and $N = 5$ are 3.91 s and 7.61 s, respectively, much shorter than 8.8 h taken by CST, where the smallest mesh size is 1 mm and the number of mesh cells is 257,040. It can be concluded from these results that the proposed method also has good accuracy and efficiency for the nonuniform multiconductor transmission line.

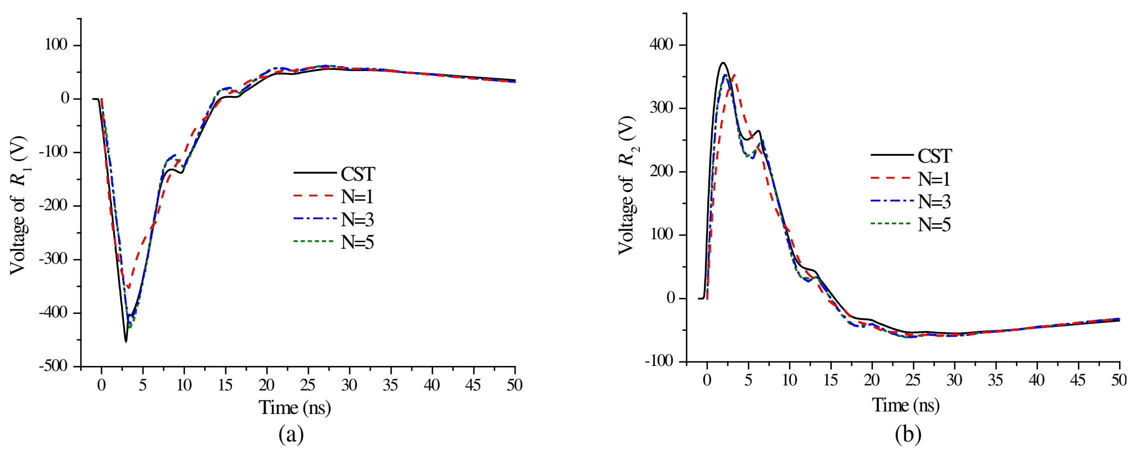


Figure 5: Induced voltages of nonuniform single-conductor transmission line when the EMP has a perpendicular incidence. (a) Voltage of R_1. (b) Voltage of R_2

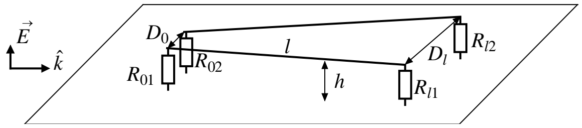
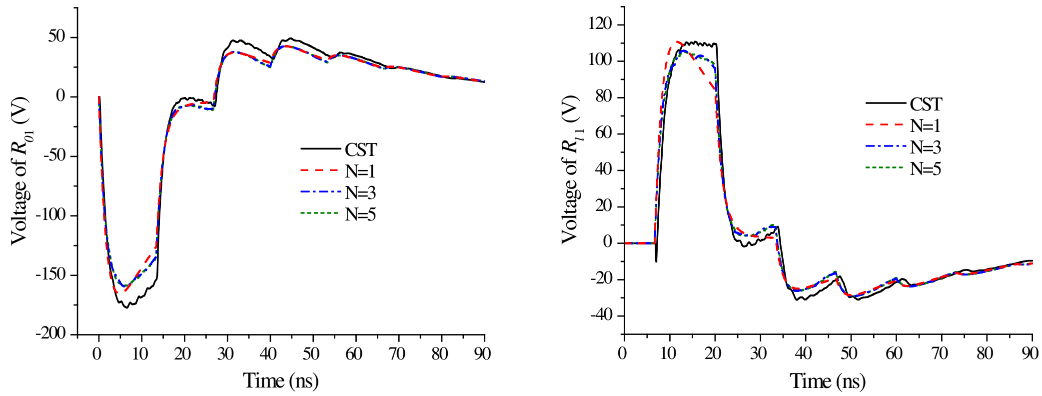


Figure 6: Nonuniform multiconductor transmission line excited by an EMP with horizontal incidence.

Table 1: Cost time of the proposed method and CST for nonuniform single-conductor transmission line.

	Cost time
Proposed method ($N = 3$)	1.92 s
Proposed method ($N = 5$)	2.88 s
CST	15061 s ≈ 4.2 h



(a) (b)

Figure 7: Induced voltages of nonuniform muticonductor transmission line when the EMP has a horizontal incidence. (a) Voltage of R_{01}. (b) Voltage of R_{l1}.

Table 2: Cost time of the proposed method and CST for nonuniform multiconductor transmission line.

	Cost time
Proposed method ($N = 3$)	3.91 s
Proposed method ($N = 5$)	7.61 s
CST	31514 s ≈ 8.8 h

4. SUMMARY AND CONCLUSION

A method of equivalent cascaded SPICE model has been presented for external field coupling to nonuniform transmission line. Nonuniform single-conductor and multiconductor transmission lines excited by an external EMP with different incidences have been studied by using this method. The results show that the induced voltages obtained by the proposed method are in a good agreement with those via the software CST even the segment number N is up to 3 and the proposed method is more efficient than CST. Due to the application of SPICE model, this method can be employed in time domain directly and allows for the analysis of nonuniform transmission line loaded with nonlinear loads and integrated circuits.

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