Transient Electromagnetic Topology Method for Complex Wiring Consisting of Random and Nonuniform Transmission Lines

Haiyan Xie[1], **Yong Li**[1], **Hongfu Xia**[1], **Chun Xuan**[1], **and Jianguo Wang**[2]

[1]Northwest Institute of Nuclear Technology, P. O. Box 69-12, Xi'an, Shaanxi 710024, China
[2]Northwest Institute of Nuclear Technology, P. O. Box 69-1, Xi'an, Shaanxi 710024, China

Abstract— The transient electromagnetic topology (TEMT) method is improved to include random and nonuniform transmission lines first and then is applied for the analysis of a car with complex wiring, which is composed by two random and a nonuniform transmission lines, under an electromagnetic pulse (EMP). In the TEMT method, the SPICE model for the nonuniform transmission line is composed by cascading the SPICE models for the segments of uniform lines, which compose the nonuniform transmission line. For the random transmission line, the average parameters are computed first and then the SPICE model is developed as the usual transmission line. The study on the car with complex wiring show that the improved TEMT method can deal well with the nonuniform and random transmission lines and the induced voltages of the devices generated by the EMP can be up to 100 V, which may cause upsets or damages to the devices.

1. INTRODUCTION

External high power electromagnetic pulse (EMP) interaction with electronic systems has attracted extensive attentions due to the development of the EMP sources [1] and the wide usage of electronic systems. External EMP can couple with systems through many paths (such as antennas, cables, and apertures) into interior subsystems or circuits and generates interferences and damages to them. The problem is complicated due to it relates to electromagnetic coupling, where the cable is hard to fix and can be random or nonuniform, and circuit or device effects.

The electromagnetic topology (EMT) method has been applied to analyze this problem since it was proposed. A car with complex wiring under EMP has been analyzed by using the EMT method in 2002 [2]. Kirawanich et al. have applied it to study EMP coupling with cables of communication systems [3]. In these researches, the Baum-Liu-Tesche (BLT) equation was employed to obtain voltages or currents generated by EMP at the terminals of transmission lines and it can not be used for transmission lines with nonlinear loads. In order to allow for the analysis of the nonlinear loads, the transient electromagnetic topology (TEMT) method was proposed [4]. The TEMT method applies the SPICE models of transmission lines and has been applied in EMP interaction with nonlinear systems [5]. However, the TEMT method has only considered uniform transmission lines. In reality, the transmission lines of systems are hard to fix and can be random or nonuniform.

In this paper, the TEMT method is extended to include random and nonuniform transmission lines and then is applied for the analysis of a car with complex wiring, which is composed by random and nonuniform transmission lines, under an EMP.

2. TEMT METHOD INCLUDING RANDOM AND NONUNIFORM TRANSMISSION LINES

2.1. Concept of TEMT Method

External EMP interaction with electronic system is a complex problem due to that: 1) the pulse width is short and the interaction is a transient process; 2) there are many coupling paths, including "front-door" and "back-door" couplings; 3) the configuration of electronic system is complex, including not only electromagnetic structures (cavities, apertures) but also wires, PCB, integrated circuits, and semiconductor devices; and 4) the nonlinear effect should be considered due to the high intensity of EMP. Due to the complexity, It is nearly impossible to solve this problem with only one numerical or experimental method.

Electronic systems include electromagnetic structures (cavities, antennas, and apertures, et al.), transmission line structures (such as wires and cables), and circuit structures (such as integrated circuits and semiconductor devices). The governing equations of these structures are different and their dimensions differs a lot. As a result, different methods and techniques are needed for different structures. This is the main reason that the interaction of EMP with electronic systems is difficult to solve. As a result, how to decompose the whole problem into the analyses of electromagnetic structures, line structures, and circuit structures apart and combine them effectively is the key.

The TEMT method assumes that the effect of transmission lines on the incident wave can be ignored [6] and transforms the problem of electromagnetic field coupling with transmission line structures into the problem of circuit analysis. This realizes the effective decomposition and combination of the analyses of different structures. In order to transform the problem of electromagnetic field coupling with transmission lines into the problem of circuit analysis, the SPICE models for several types of uniform transmission lines have been developed [7, 8].

2.2. Including Random and Nonuniform Transmission lines

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

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

where $\mathbf{V}(z)$ and $\mathbf{I}(z)$ are the line voltage and current vectors, 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 effects of the external fields. Due to the inductance and capacitance matrices are the functions of the z axis, (1) can not be decoupled by similarity transformation for general configurations of nonuniform transmission line. However, they can be approximated by cascaded series of segments of uniform lines [9]. Thus nonuniform transmission line is divided into segments of uniform lines first, then the SPICE model for each segment of uniform line is developed according to [7, 8], and at last the SPICE model for the nonuniform transmission line is composed by connecting the SPICE model of each segment.

Random transmission lines may be nonuniform ones. Because nonuniform transmission lines can be approximated as cascaded series of many short sections of uniform lines, random uniform transmission lines are the basis. The equation for field coupling with random uniform transmission lines can be written as

$$\begin{array}{l} \dfrac{\partial}{\partial z}\mathbf{V}(x,y,z) + \mathbf{L}(x,y)\dfrac{\partial}{\partial t}\mathbf{I}(z) = \mathbf{V}_F(x,y,z) \\ \dfrac{\partial}{\partial z}\mathbf{I}(x,y,z) + \mathbf{C}(x,y)\dfrac{\partial}{\partial t}\mathbf{V}(z) = \mathbf{I}_F(x,y,z) \end{array}. \tag{2}$$

Where the coordinates x and y are random. [10] and [2] point out that the average voltage can be approximated by the voltage when the average parameters (inductance, capacitance, et al.) are applied, that is, the average voltage and current satisfy the equation approximately as

$$\begin{array}{l} \dfrac{\partial}{\partial z}\bar{\mathbf{V}}(z) + \bar{\mathbf{L}}\dfrac{\partial}{\partial t}\bar{\mathbf{I}}(z) = \bar{\mathbf{V}}_F(z) \\ \dfrac{\partial}{\partial z}\bar{\mathbf{I}}(z) + \bar{\mathbf{C}}\dfrac{\partial}{\partial t}\bar{\mathbf{V}}(z) = \bar{\mathbf{I}}_F(z) \end{array}. \tag{3}$$

Here $\bar{\mathbf{L}}$ and $\bar{\mathbf{C}}$ are the average inductance and capacitance. $\bar{\mathbf{V}}_F$ and $\bar{\mathbf{I}}_F$ can be computed from the electromagnetic fields at the average position. As a result, with the average parameters and the excitation fields at the average position, the SPICE model for the random line can be developed from [7, 8].

3. NUMERICAL SIMULATION

Figure 1 shows a car with complex wiring inside under an EMP. The wiring consists of a three-wire transmission line, a two-wire transmission line, and singe-wire transmission line, with the radius of 0.75 mm and the lengths of 0.4 m, 0.6 m, and 0.5 m, respectively. The average height of these lines to the bottom of the car are 30 mm and all the terminal loads are 50 Ω. The load R_{11} connects with R_{21}, R_{12} connects with R_{22}, and R_{13} connects with R_3. The EMP is a biexponential pulse defined by $E(t) = kE_0[\exp(-\beta t) - \exp(-\alpha t)]$, where $k = 1.3$, $E_0 = 50\,\text{kV/m}$, $\alpha = 6.0e8\,\text{s}^{-1}$, and $\beta = 4.0e7\,\text{s}^{-1}$.

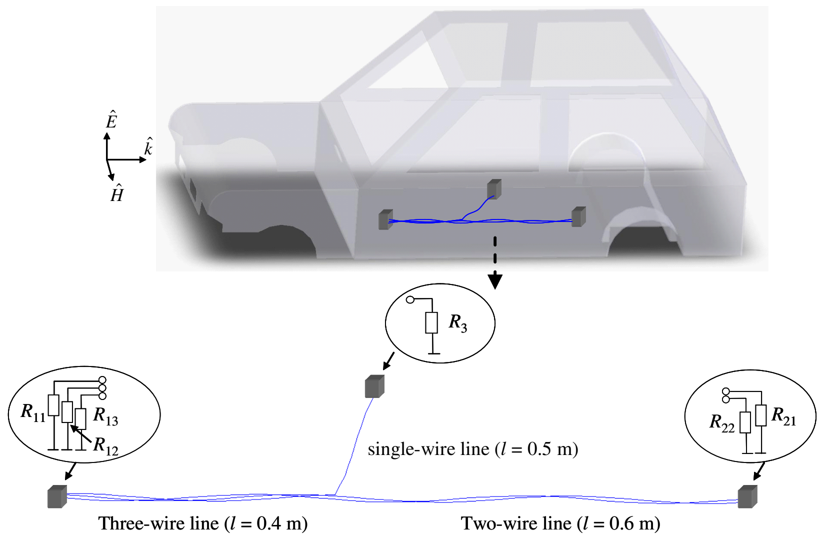


Figure 1: Car with complex wiring under an EMP.

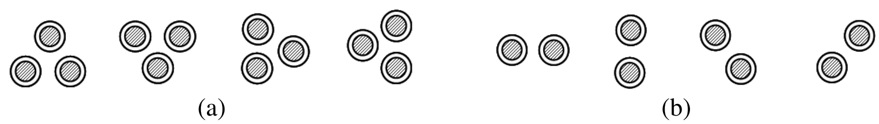


Figure 2: Different appearances of the transmission line cross section. (a) Three-wire transmission line. (b) Two-wire transmission line.

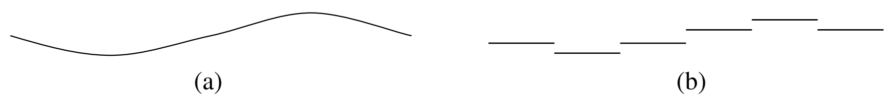


Figure 3: (a) Single-wire transmission line is approximated by cascaded series of sections of (b) uniform lines.

Due to that the wires are hard to fix exactly, the three-wire and two-wire transmission lines are random and their cross sections may have several different appearances, as shown in Figure 2, and the single wire is a nonuniform transmission line, as shown in Figure 3.

For this problem, the three-dimensional (3D) finite-difference time-domain (FDTD) method is applied to obtain the excitation fields along the lines at the average height. Then the inductance and capacitance matrices for the three-wire and two-wire transmission lines are computed according to the method described in Section 2, which are

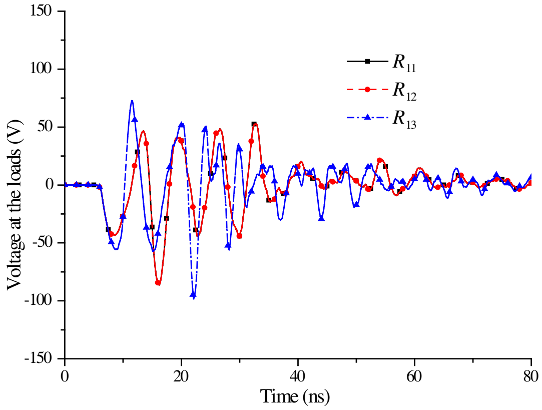
$$\mathbf{L}_1 = \begin{bmatrix} 0.876 & 0.571 & 0.571 \\ 0.571 & 0.876 & 0.571 \\ 0.571 & 0.571 & 0.876 \end{bmatrix} \mu H, \quad \mathbf{C}_1 = \begin{bmatrix} 26.11 & -10.29 & -10.29 \\ -10.29 & 26.11 & -10.29 \\ -10.29 & -10.29 & 26.11 \end{bmatrix} p\mathbf{F} \tag{4}$$

and

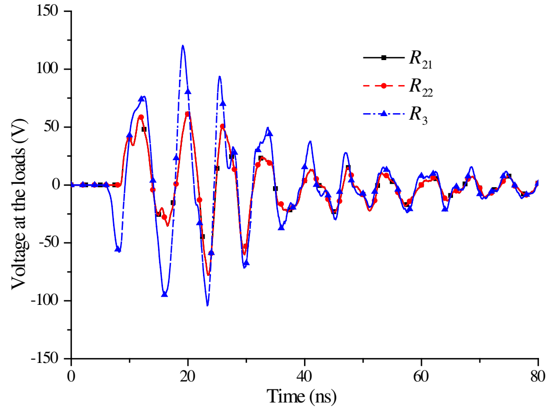
$$\mathbf{L}_2 = \begin{bmatrix} 0.876 & 0.571 \\ 0.571 & 0.876 \end{bmatrix} \mu H, \quad \mathbf{C}_2 = \begin{bmatrix} 26.11 & -10.29 \\ -10.29 & 26.11 \end{bmatrix} p\mathbf{F}, \tag{5}$$

respectively. The single-wire transmission line is approximated by six segments of uniform lines, as shown in Figure 3, and the inductance and capacitance of each section is computed. For the three-wire and two-wire transmission lines, the excitation fields are the fields at the average height of the lines, but for the single-wire transmission line, linear interpolation is applied to get the excitation fields of each segment from the fields at the average height. With the per-unit-length parameters and excitations fields, the SPICE models for these transmission lines can be developed according to [7]. Then a SPICE software can be employed to obtain the voltages induced at the loads.

Figure 4 shows the average voltages at the loads of the near and far ends of the wiring induced by external fields. The results show that the loads R_{11} and R_{12} have the same average voltages with the loads R_{21}, R_{22}, respectively. This is because the lines connecting them have the same statistical property. The magnitudes of these induced voltages can up to 100 V, which implies that the external EMP can generate interferences on the car's system.



(a)



(b)

Figure 4: Voltages induced at the loads of (a) the near end (b) the far end.

4. SUMMARY AND CONCLUSION

The TEMT method has been improved to include random and nonuniform transmission lines in this paper. Then the improved TEMT method is applied for the analysis of a car with complex wiring, which is composed by two random and a nonuniform transmission lines, under an EMP. The results show that the improved TEMT method can deal well with the nonuniform and random transmission lines and the induced voltages at the inside devices of the car generated by the EMP can be up to 100 V, which may cause upset or damage to the devices.

ACKNOWLEDGMENT

Acknowledgement is made to National Natural Science Foundation of China for the support of this research through Grant No. 61231003 and No. 61201090.

REFERENCES

1. Baum, C. E., "From the electromagnetic pulse to high-power electromagnetics," *Proceedings of the IEEE*, Vol. 80, No. 6, 789–817, 1992.
2. Paletta, L., J. P. Parmantier, F. Issac, et al., "Susceptibility analysis of wiring in a complex system combing a 3-D solver and a transmission-line network simulation," *IEEE Trans. Electromagn. Compati.*, Vol. 44, No. 2, 309–317, 2002.
3. Kirwanich, P., N. Kranthi, N. E. Islam, et al., "Electromagnetic topology-based analysis of coupling through small apertures on cables on communications systems," *Electromagnetics*, Vol. 25, Nos. 7–8, 589–602, 2005.
4. Xie, H., J. Wang, D. Sun, R. Fan, and Y. Liu, "Analysis of EMP coupling to a device from a wire penetrating a cavity aperture using transient electromagnetic topology," *Journal of Electromagnetic Waves and Applications*, Vol. 23, Nos. 17–18, 2313–2322, 2009.
5. Xie, H., J. Wang, D. Sun, R. Fan, and Y. Liu, "SPICE simulation and experimental study of transmission lines with TVSs excited by EMP," *Journal of Electromagnetic Waves and Applications*, Vol. 24, Nos. 2–3, 401–411, 2010.
6. Parmantier, J. P. and P. Degaugue, "Topology based modeling of very large systems," *J. Hamelin. Modern Radio Science*, 151–177, Oxford Univ. Press, Oxford, UK, 1996.
7. Xie, H., J. Wang, R. Fan, et al., "A hybrid FDTD-SPICE method for transmission lines excited by a nonuniform incident wave," *IEEE Trans. Electromagn. Compat.*, Vol. 51, No. 3, 811–817, 2009.
8. Xie, H., J. Wang, R. Fan, et al., "SPICE models to analyze radiated and conducted susceptibilities of shielded coaxial cables," *IEEE Trans. Electromagn. Compat.*, Vol. 52, No. 1, 215–222, 2010.
9. Omid, M., Y. Kami, and M. Hayakawa, "Field coupling to nonuniform and uniform transmission lines," *IEEE Trans. Electromagn. Compati.*, Vol. 39, No. 3, 1997.
10. Xie, H., J. Wang, Y. Li, and C. Xuan, "Influence analysis of stochastic translation of transmission lines over ground," *Progress In Electromagnetics Research Letters*, Vol. 44, 53–61, 2014.