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TRANSIENT ELECTROMAGNETIC TOPOLOGY AND ITS EXPERIMENTAL VALIDATION

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Abstract—Transient electromagnetic topology (TEMT) method is presented briefly first and then three typical configurations, namely, a transmission line network, a wire penetrating a cavity aperture and then connecting to a device, and two systems connected by a shielded cable radiated by an electromagnetic pulse, are analyzed by using the TEMT method. The currents induced at the loads obtained by the TEMT method are compared with those from the experiment. The good agreement of the numerical results with the experimental ones validates the TEMT method.

1. INTRODUCTION

Electromagnetic pulse (EMP) interaction with electronic systems draws more and more attentions. The interaction is a complicated process and hard to analyze. The three-dimensional (3-D) electromagnetic numerical method, such as the finite-difference time-domain (FDTD) method, is usually used to compute some electromagnetic problems, for example, shielding effectiveness of cavities. However, the 3-D electromagnetic numerical method can not be able to solve the interaction alone, because there also are cables and integrated circuits in electronic systems which are difficult to analyze by using the 3-D electromagnetic numerical method. Experiments are often used to get the upset or damage thresholds of some elements and devices, but for the whole system, the cost and time this method takes can not be afforded.

The electromagnetic topology (EMT) is noted as a method to analyze the external electromagnetic fields interaction with complex systems and to predict the interferences generated by external

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electromagnetic fields in the complex systems [1–12]. From a quantitative point of view, the problem can be solved in two steps [6]. A 3-D numerical method is adopted to obtain the excitation fields of the transmission line network in the systems first and then the responses at the nodes of the network are computed. Under typically 500 MHz, the transmission line network in the systems can be treated as a shielding level which blocks the electromagnetic energy propagating from the exterior to the interior and satisfies the good shielding approximation [13], so the effect of the network on the incident fields can be ignored and the excitation fields of the network equaled the incident fields when the network is removed [6, 10]. In these steps, the Baum-Liu-Tesche (BLT) equation is utilized to compute the responses of the nodes in the network. However, the BLT equation was a frequency-domain equation, which implies the electronic system analyzed was linear and time invariant. But in fact, there are many nonlinear protection devices in the electronic system and even for the linear system, there are nonlinear processes taking place in the circuit element when some kinds of upsets or damages exist [3].

SPICE models of transmission lines excited by external electromagnetic fields have been recommended in the EMT method to obtain the responses of the network [14] and several SPICE models for multiconductor transmission lines and shielded cables excited by external fields have been developed in [15–17]. The EMT method with these SPICE models is referred to the transient electromagnetic topology (TEMT) because it can be used directly in the time domain and be utilized for the nonlinear or time-varying electronic systems. In the TEMT method, the FDTD method is employed to compute the excitation fields of the transmission line network and then the SPICE models of the lines are utilized to obtain the terminal responses. The applicability of the SPICE model of the lossless transmission line in the TEMT method has been studied in [18]. Later, the interferences on several simple electronic systems generated by an EMP have been analyzed by using the TEMT method and the results have been validated by comparing with the experimental ones [19]. However, more examples should be studied to validate the TEMT method.

In this paper, the TEMT method is introduced briefly and then three typical configurations excited by an EMP are studied and their results are compared with the experimental ones.

2. BRIEF INTRODUCTION OF THE TEMT METHOD

In the prediction of the interferences generated by an external source in the complex systems by using the EMT method, the transmission line network in the systems is treated as a shielding level. The excitation fields of the network can be obtained numerically or experimentally first and then the responses at the nodes of the networks are solved. In the conventional EMT method, the BLT equation, which is derived from the propagation and scattering equations, is employed to solve the responses at the nodes of the network [20]. The propagation equation describes the waves propagating on the tubes which represent multiwire transmission lines, given by

$$\mathbf{W}(l) = \mathbf{\Gamma} \cdot \mathbf{W}(0) + \mathbf{W}_s \tag{1}$$

where $\mathbf{W}(0)$ and $\mathbf{W}(l)$ are the voltage or current waves at the two ends of a tube, $\mathbf{\Gamma}$ is the propagation matrix, and $\mathbf{W}_s$ are the contribution of the equivalent sources on the tube to the waves. The scattering equation describes the scattering characteristics of the nodes, in other words, the connection between the tubes, given by

$$\mathbf{W}(0) = \mathbf{S}\mathbf{W}(l) \tag{2}$$

where $\mathbf{S}$ is the scattering matrix and $\mathbf{W}(0)$ and $\mathbf{W}(l)$ are the reflecting and incident waves at the nodes, respectively. From the propagation and scattering equations, the BLT equation can be obtained easily

$$[\mathbf{1} - \mathbf{S} \cdot \mathbf{\Gamma}]\, \mathbf{W}(0) = \mathbf{S}\mathbf{W}_s \tag{3}$$

In the TEMT method, the SPICE models of lines and cables excited by the external fields are utilized to obtain the responses of the lines and cables in the system. The excitation fields of the lines or cables, namely, the incident fields at the lines or cables when the lines or cables are removed, are obtained by using the FDTD method first. Then these excitation fields are integrated into the SPICE models of the lines or cables radiated as the driving sources. With the excitation fields and parameters of the lines or cables, the SPICE circuits of these lines or cables can be obtained [15–17]. In a SPICE model of the line or cable, the line or cable is modeled as a port device, where the port voltages and currents are the voltages and currents at the two ends of the line or cable. The SPICE model converts the problem of field coupling into the problem of circuit analysis, which makes the combination of the field analysis and the circuit analysis easily. Any network in an electronic system is composed of lines and cables, so the SPICE equivalent circuit of the whole network can be made up of the SPICE circuits of the lines and cables. In the BLT equation, the scattering matrix characterizes the connection between the lines and cables. However, in the TEMT method, the connection can be easily realized by connecting the nodes of the lines in a SPICE software. These SPICE models can be used in the time domain analysis [15–17]. In addition, there are many SPICE circuits of nonlinear elements and devices in the SPICE libraries and they can be incorporated into the circuit of the network easily. With the SPICE circuits of the lines, cables, and terminal devices, the voltages and currents induced at the ports of the devices can be obtained easily.

In the process of using the TEMT method, the excitation fields can be obtained numerically and experimentally first. Then with the excitation fields and the parameters of the lines and cables, the SPICE models of lines and cables are generated. After defining the connection between the lines, cables, and terminal loads in a SPICE software, the voltages and currents of the loads can be obtained.

3. EXPERIMENTAL VALIDATION

The experiments are carried out in an asymmetrical flat-plate guided-wave EMP simulator, which can simulate the vertically polarized EMP defined by IEC61000-2-9, namely, 2.5 ns rise-time and 23 ns pulse-width [19, 21]. The electric field of the EMP simulated by the simulator is measured by a unipole antenna, as shown in Figure 1, and is used as the input sources in the SPICE models or in the FDTD method later [19].

The first configuration is a multiconductor transmission line network, which is a common configuration in the electronic systems, excited by the EMP. This configuration is utilized to study the ability of the SPICE models for analyzing the transmission line network. This network consists of three transmission lines over the ground. The height of the network over the ground is 0.3 m, the radii of all the wires in the network are 0.7 mm, and all the loads of the network are 100 Ω. Figure 2 shows the model of the transmission line network. In this configuration, the network has no shieldings and the external

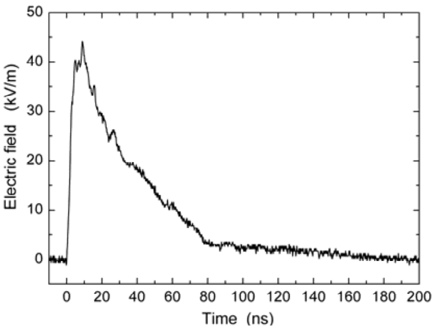


Figure 1. The waveform of the electric field simulated by the simulator.

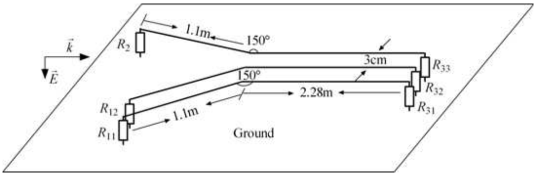


Figure 2. A multiconductor transmission line network excited by the EMP.

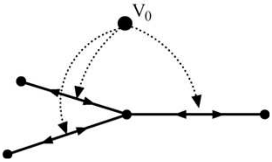


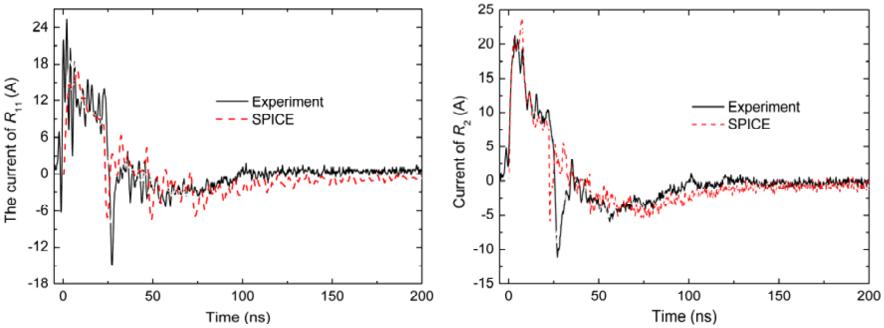
Figure 3. Interaction graph for the network.

field couples onto the network directly. Figure 3 shows the interaction graph of the network, where the large solid point denotes the external volume V_0, the small solid points represent the nodes in the network, and the arrowheads indicate the direction of the energy flow.

For this configuration, all the wires are irradiated by the plane-wave field and there are SPICE models for multiwire transmission lines excited by plane-wave fields [22], so the FDTD method is not needed to compute the excitation fields of the lines. In the simulation, the SPICE circuits of the three lines are generated first with the waveform of the plane-wave field and the parameters of the lines, then the connections between the lines are defined, and the whole circuit is run in a SPICE software. The currents of R_{11} and R_2 obtained by the SPICE models are shown in Figure 4, which agree well with the experimental results. In the experiment, the currents of the loads are obtained by a measurement system consisting of Rogowski coils, attenuators, convertors converting the electric signals to optical signals, etc.

The second configuration studied consists of two systems connected by a SYV-50-5-1 shielded cable, as shown in Figure 5, where the devices within the systems are represented by two resistances R_1 and R_2. The loads R_1 and R_2 are both $50\,\Omega$. The shielded cable in this configuration can denote communication lines in reality. The dimensions of the two cavities are $41.0\,\text{cm} \times 10.5\,\text{cm} \times 27.3\,\text{cm}$. The cable between the two cavities is 3 m long and the wires, which connect the cable and the loads, are 0.13 m long. The height of the cable above the ground is 0.15 m.

The interaction graph for this configuration is shown in Figure 6.



(a) (b)

Figure 4. The terminal currents of the transmission network. (a) The current of the load R_{11}. (b) The current of the load R_2.

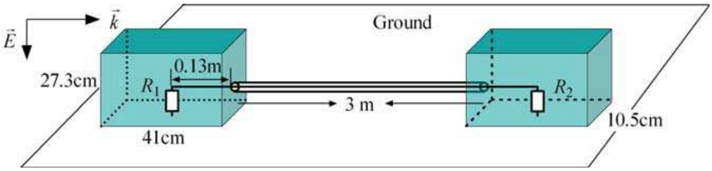


Figure 5. Two systems connected by the SYV-50-5-1 shielded cable.

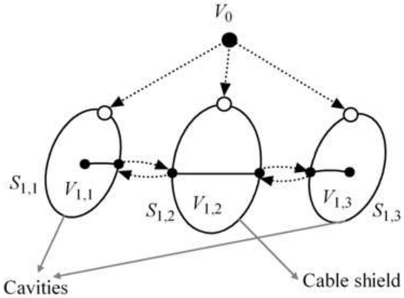
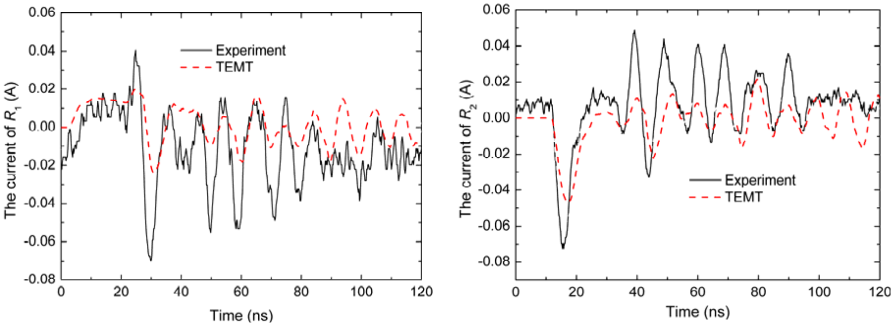


Figure 6. The interaction graph for the configuration in Figure 5.

$S_{1,1}$, $S_{1,3}$, and $S_{1,2}$ are the two systems' metal cavities and the cable shield. $V_{1,1}$, $V_{1,3}$, and $V_{1,2}$ are the volumes inside the cavities and the cable shield. The hollow points on the $S_{1,1}$, $S_{1,2}$, and $S_{1,3}$ denote the surface nodes. The inner wire in $V_{1,2}$ are the inner conductor of the cable and the wires inside $V_{1,1}$ and $V_{1,3}$ are those connecting the cable and the loads. The external field couples into the inner system mainly through the cable shield. If there are other apertures or slots on the cavities, then the field can also couple into the system via these



(a) (b)

Figure 7. The currents of the two systems connected by the shielded cable. (a) The current of the load R_1. (b) The current of the load R_2.

apertures or slots. Due to the topology decomposition, the excitation fields of the cable and the wires inside the cavities can be calculated independently. Because there are no other apertures or slots on the cavities, the excitation fields of the connecting wires can be neglected. The connecting wires and the inner conductor of the cable interact with each other, so they should be considered together when the responses of the loads are calculated.

In the simulation, the excitation fields of the cable is calculated by using the FDTD method first, then the SPICE circuits of the cable and wires are generated, and at last the responses are obtained through a SPICE software. The currents of the loads R_1 and R_2 obtained by using the TEMT method are shown in Figure 7. The currents show that the numerical results have similar waveshapes and pulse-widths as the experimental results, but have different magnitudes. The reason for these differences may be that the transfer impedance and admittance of the cable needed by the SPICE model are obtained by using the analytical equations [23, 24]

$$R_{dc} \approx \frac{4}{\pi d^2 N \mathcal{C} \sigma \cos\alpha}, \tag{4}$$

$$L_t \approx \frac{\pi\mu_0}{6\mathcal{C}} (1-K_C)^{3/2} \frac{e^2}{E(e)-(1-e^2)K(e)} \quad (\alpha < 45^\circ) \tag{5}$$

$$C_t \approx \frac{\pi C_{out} C_{in}}{3(\varepsilon_{out}+\varepsilon_{in})\mathcal{C}} (1-K_C)^{3/2} \frac{1}{E(e)} \quad (\alpha < 45^\circ). \tag{6}$$

However, these equations have some limitations and the values they provide are not very accurate.

The third configuration is a wire penetrating a cavity aperture and then connecting to a device, which is protected by a transient

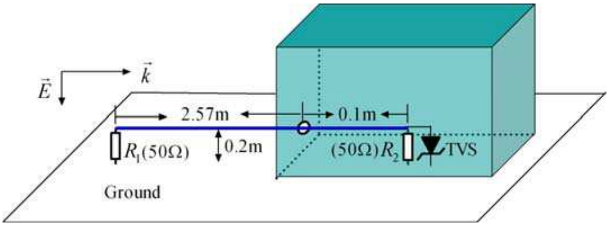


Figure 8. A wire penetrates a cavity aperture and then connects to a device.

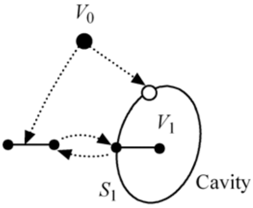
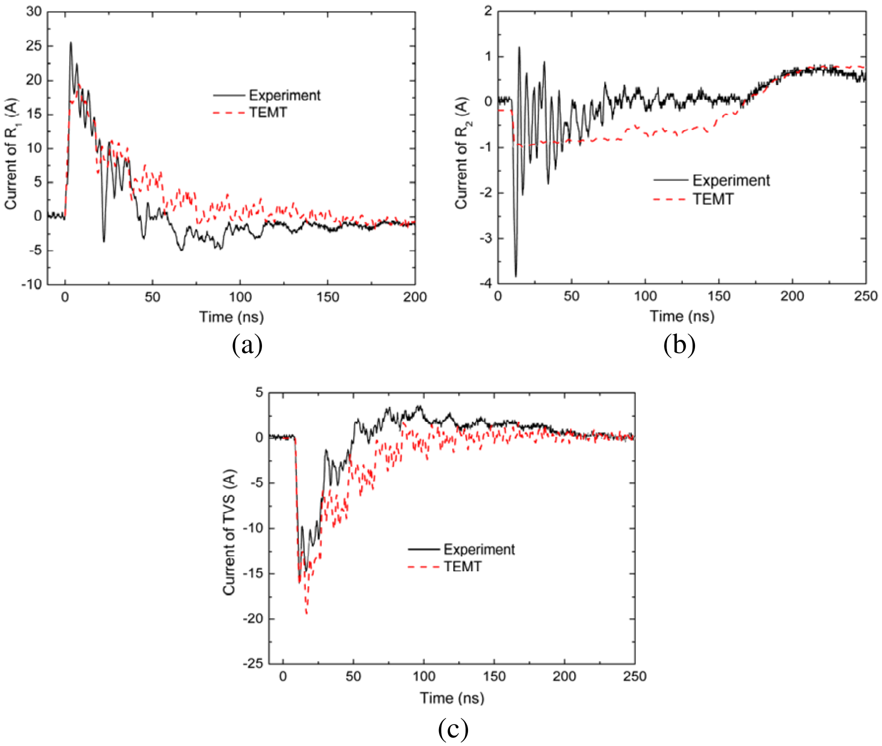


Figure 9. The interaction graph for the configuration in Figure 8.

voltage suppressor (TVS), as shown in Figure 8. The cavity in this configuration has the same size with the one in the above configuration. The wire is 2.57 m long outside the cavity and 0.1 m long inside the cavity, with the height of 0.2 m above the ground. The device is represented by a resistance R_2 (50 Ω) here, and the part number of the TVS diode is 1.5KE39CA. This configuration is utilized to validate the capability of the TEMT method to analyze the nonlinear systems. The interaction graph of this configuration is shown in Figure 9. The external pulse can couple onto the wire directly. If there are other apertures or slots on the cavity, the external field can penetrate through the apertures or slots and then couple onto the wire. In the simulation, the excitation fields of the wire are computed by using the FDTD method first and then the SPICE circuits of the wire and the TVS diode are employed to obtain the terminal currents [19]. The currents of R_1, R_2, and the TVS obtained by the TEMT method are shown in Figure 10. The numerical results of the currents of the load R_1 and the TVS diode agree well with the experimental results. However, there are some discrepancies between the numerical and experimental results of the R_2's current in early time. This is due to the SPICE circuit of the TVS diode, which is downloaded from the internet of the factory, is suitable for low frequency signals, and the clamping voltage obtained by this circuit may be much smaller than its true value when the frequency is high [25]. Consequently, the current of the load R_2 obtained by the experiment is larger than the numerical one when the TVS diode's current varies fast.



(a)

(b)

(c)

Figure 10. The current responses of the third configuration. (a) The current of the load R_1. (b) The current of the load R_2. (c) The current of the TVS diode.

4. CONCLUSION

The TEMT method has been briefly introduced and three typical configurations excited by the EMP defined by the IEC have been studied by using this method. The results have been compared with those obtained by the experiment and the good agreement is obtained. It can be tentatively concluded that the good agreement validates the availability of the TEMT method.

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