The Modeling and Experimental Investigation on Coupling of Transmission Line Network with Electromagnetic Pulse (EMP)

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Abstract: With the development of high power electromagnetic pulse (EMP) resources, intentional electromagnetic interference (IEMI) has become a practical threaten to power line network and SCADA system because of their sensitivity and vulnerability to EMP attack. In this paper, the transmission line models are built for two parallel power lines and several transmission line network models. The coupling of EMP (HEMP, square wave EMP) with transmission line network is simulated and the dependences of induced current and voltage are investigated. The results show that the proposed models of transmission line and network can predict the coupling process with EMP and the coupling mechanism can provide useful information for the protection, reliability of power line network.

Keywords: intentional electromagnetic interference, modeling, coupling, transmission line, EMP,

1、Introduction

With the wildly application of electronic technology, the electromagnetic environments became more and more complex. The electromagnetic pulse (EMP) is one important part of electromagnetic environments, which includes Electrostatic discharge EMP (ESD EMP), Lightning electromagnetic pulse (LEMP), Nuclear electromagnetic pulse (NEMP), High power microwave (HPM) and Ultra-wide band (UWB) etc. Due to the high power and wide frequency band, EMP can make interfere, latent or permanent failure to the transmission line, electrical devices, and the destroy capacity exceed far more than other normal electromagnetic environments.

Therefore, it is an effective technique to attack the transmission lines, especially the sensitive SCADA system. According to the predictions of American AD report, EMP weapon would be the most possible and valuable attacking weapon in the near future years [1]. In addition, with the development of electronic technology, there is a trend that the high power microwave and Ultra-wide band devices is becoming smaller, cheaper and easier to be manufactured and has become a means for terrorism attack on the government, national infrastructures, weapon system and military command authority. This kind of EMP attack or electromagnetic interference is called Intention Electromagnetic Interference (IEMI) or electromagnetic terrorism.

In 2007, D. Mansson from Uppsala University and T Nilsson from National Defense Technology Agency began to investigate the transmitting process of UWB in electric-power line and some preliminary research of propagation and attenuation dependences in different coupling modes, shapes and lengths of wires has been carried out.

Currently, IEC are working on relevant international standards and propose specification for the evaluation methods, immunity test requirements and protective measures [3].

The previous research in the this area mainly focuses on the direct radiation effect of HEMP to sensitive circuitry or device, but ignored the systematic research on the transmitting of EMP in transmission networks.

By using the transmission line theory and electromagnetic topology, the coupling model of transmission line with EMP radiation and injection are built in this paper, and so the transmission line coupling laws of EMP is investigated. This paper provides useful results for further investigations of EMP with different transmission line networks, response prediction and electromagnetic protection.

2、Modeling of coupling between overhead transmission line and EMP and Simulation of responses

According Agrawa's modeling principle [8], for a double-conductor transmission line under radiation of electromagnetic field, its equivalent model is as Fig. 1. Supposing that two conductors are same ideal conductors with radius *a*, and the distance *d* of two conductors is far greater than radius and far smaller than incident length of wave. Furthermore, suppose that the media around the line is non-magnetized and the permittivity is $\mu=\mu_0=4\pi\times10^{-7}$H/m. Since a<<d, the quasi-static field produced by the charges and current in the space can be ignored. Then the total magnetic field and electric field can be decomposited into two components, one is the incident field (E^{inc} and H^{inc}) when the transmission lines are absent and another one is that produced by the chages and current of the transmission lines.

Using matrix to represent the voltage and current of transmission lines,

$$\frac{d}{dx}\begin{bmatrix} V^{sca}(x) \\ I(x) \end{bmatrix} + \begin{bmatrix} 0 & Z' \\ Y' & 0 \end{bmatrix}\begin{bmatrix} V^{sca}(x) \\ I(x) \end{bmatrix} = \begin{bmatrix} V'_{S2} \\ 0 \end{bmatrix} \tag{1}$$

The boundary condition is,

$$V^{sca}(0) = -Z_1 I(0) + \int_0^d E_z^{inc}(0,z)dz \tag{2}$$

$$V^{sca}(L) = -Z_1 I(L) + \int_0^d E_z^{inc}(L,z)dz \tag{3}$$

The integrate item in the boundary condition can be considered to be produced by the additional voltage resource in both end of the transmission line,

$$V_1 = -\int_0^d E_z^{inc}(0,z)dz \tag{4}$$

$$V_2 = -\int_0^d E_z^{inc}(L,z)dz \tag{5}$$

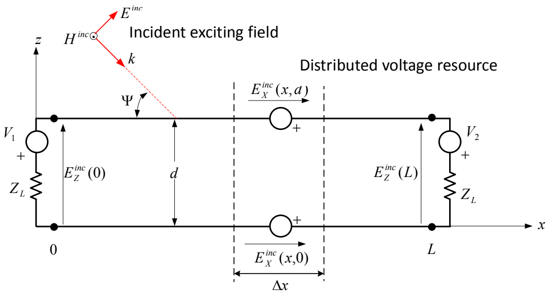

Fig.1 Equivalent transmission line mode of Agrawal law

Currently， there are svarious form of expression for HEMP. But it is mostly expressed using double exponential function.,

$$E_{inc}(t) = kE_0(e^{-\alpha t} - e^{-\beta t}) \tag{6}$$

Where k is correction coefficient, E_0 是 peak value of field, which is normally take the value of $50kV/m$， α、β r represent rise and drop time. In this sample, set the incident field as Bell wave，and its waveform is as Fig.2. The transient response can be calculated as Fig. 3.

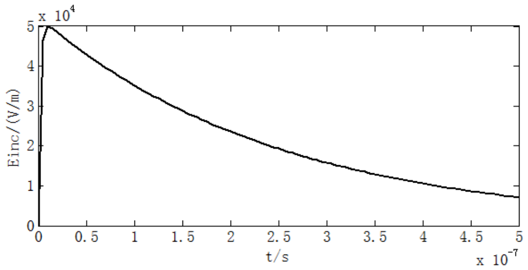

图 2 Incident waveform (Bell wave)

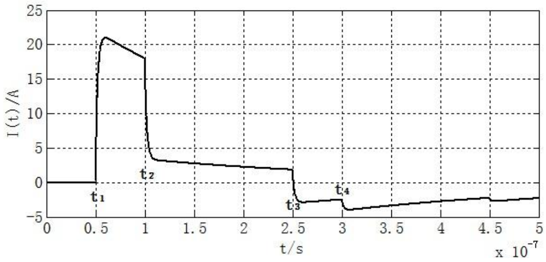

Fig.3 Waveform of transient current induced at x=L

From Fig. 3, it can be seen that this current waveform is an un-continuous one. This comes from different parts of transmission line structure. At $x = L$ and time $t_1 = (L/c)\cos\psi = 0.5\times10^{-7}s$,, the incident wave moves along transmission line at the velocity of $v = c/\cos\psi$ 。The following un-continuous waveform arrives at the time of $t_2 = L/c = 1\times10^{-7}s$. At this time, the observer at $x = L$ firstly notice that, the length of the transmission line is limited. ,Before this time, the observer obtains only the response of half unlimited transmission line. After t_1 and t_2, there are many reverse wave and the return time interval is $2L/c = 2\times10^{-7}s$. So the response time of t_3 should be $t_1 + 2L/c = 2.5\times10^{-7}s$. This corresponding to a returning time from the end of $x = L$. The response time at t_4 时 should be 1.5 time of return time from the end of x = 0. The time of above waveform are all indicated in Fig.3.

The following are the analysis of dependences of induced current

(1)Dependence on length L

Fig.4 gives the waveforms of induced current at load Z_2 when the lengths are 15m, 30m, 45m, 90m. It indicated that, with the increase of length, the peak value of induced current does not change and only the arriving time to load varies and this result agrees to the above analysis.

(2)Dependences on the hight h from ground

Set the height of transmission lines above the ground as 0.1m, 0.2m, 0.4m, the induced

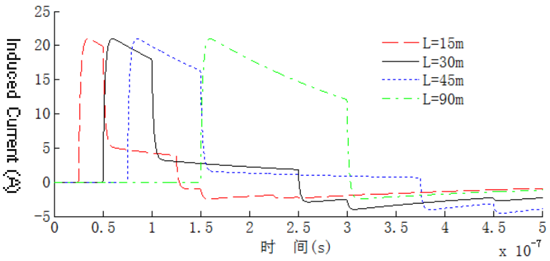

Fig.4 Induced current of edge loading with different length

current in load Z_2 is shown in Fig. 5. It can be seen that the current peak increases with the increase of height. This is because, with the increase of height, the area of return circuit formed by conductor and ground also increases and the coupling energy increases.

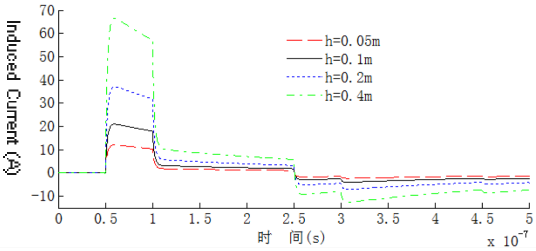

Fig.5 Induced current of edge loading with different height

(3)Dependence on the radius r

Set the radius of transmission line is 0.05cm、0.1cm、0.15cm、0.3cm. The induced current on Z_2 is shown by Fig.6. The results show that the peak values of current increase with the increase of radius. But the radius will not affect the magnitude of current after 100ns.

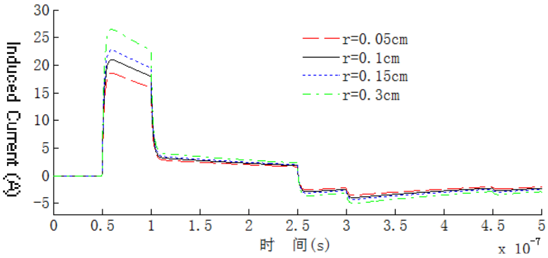

Fig.6 Induced current of edge loading with different radius

(4) Dependence of impedance Z_1.

The induced current on Z1 is shown in Fig. 7

when Z_1 is 0Ω、50Ω、159Ω. and infinite large. The figure shows that the first peak of current is independent on Z_1. But after the reflection by Z_1, the peak value will increase with the increase of Z_1. This is caused by the variation of reflection index.

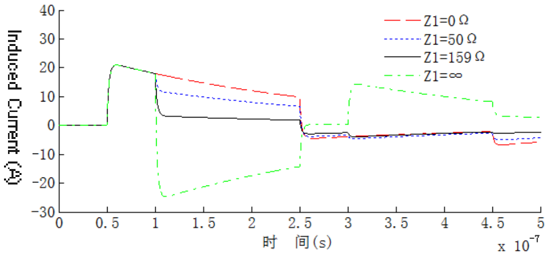

Fig.7 Induced current of edge loading with different Z1

(5) Dependences on **impedance** Z_2 value

The load Z_2 is set to be 0Ω, 50Ω, 159Ω (half of the characteristic impedance) and infinite large. The results show that that waveform of the induced current increases with the increase of Z_2. and the current approaches zero when the Z_2 changes to infinite large.

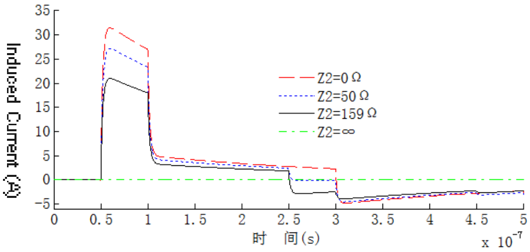

Fig.8 Induced current of edge loading with different Z2

(6) Dependences on polarization angle α

Fig.9 indicates the induced current of Z_2 when the polarization angle α is 0°, 30°, 60°, 90°. It can be concluded that the peak of induced current will decrease when the Z2.increase and if the polarization angle equals is 90°.

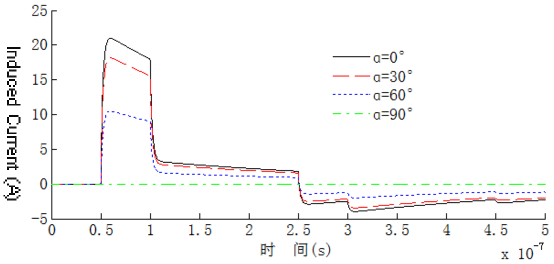

Fig.9 Induced current of edge loading with different Brewster angle

(7)Dependences on the variation of azimuth

Set the azimuth angle ϕ to be 0º, 30º, 60º, 90º. Fig 10 and gives the induced current. It is seen that the peak value of the induced current decreases when the azimuth angle increase.

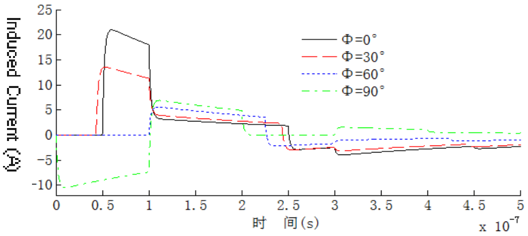

Fig.10 Induced current of edge loading with different azimuth angle

(8)Dependences on incident elevation angle ψ

When ψ is set to be 0°、30°、60°、90°, the induced current as Fig. 11. From the figure it can be concluded that the induced current decreases with the increase of ψ.

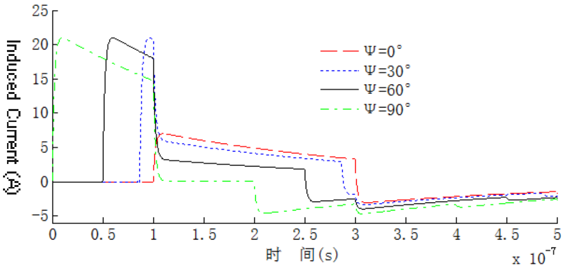

Fig.11 Induced current of edge loading with different elevation angle

3 Coupling of transmission line network with EMP

For the interferences caused by outer interferences through power line, signal line or exposed conductors to interior electronic system, we can build the topological structure using junctions and tubes. And the incident and reflection components of wave can be analyzed using the charge at start and end points in one dimension axes and using superposition of voltage wave. [9-10].The following is a one kind of frequency domain expression of BLT hypermatrix equation of transmission line network. [11].

$$\left[\left(\left(\mathbf{1}_{\mathbf{n,m}}\right)_{\mathbf{u,v}}\right)-\left(\left(\mathbf{S}_{\mathbf{n,m}}\right)_{\mathbf{u,v}}\right)\left(\left(\boldsymbol{\Gamma}_{\mathbf{n,m}}\right)_{\mathbf{u,v}}\right)\right]\left(\left(\mathbf{V}_{\mathbf{n}}(\mathbf{0})\right)_{\mathbf{u}}\right)$$

$$=\left(\left(\mathbf{S}_{\mathbf{n,m}}\right)_{\mathbf{u,v}}\right)\left(\left(\mathbf{V}^{(\mathrm{s})}{}_{\mathbf{n}}\right)_{\mathbf{u}}\right)。\qquad(7)$$

where：

$\left(\left(\mathbf{1}_{\mathbf{n,m}}\right)_{\mathbf{u,v}}\right)$ is unit hypermatrix；

$\left(\left(\mathbf{S}_{\mathbf{n,m}}\right)_{\mathbf{u,v}}\right)$ scattering hypermatrix；

$\left(\left(\boldsymbol{\Gamma}_{\mathbf{n,m}}\right)_{\mathbf{u,v}}\right)$ propagation hypermatrix

$\left(\left(\mathbf{V}_{\mathbf{n}}(\mathbf{0})\right)_{\mathbf{u}}\right)$ is super vector of leaving superposition voltage wave at junctions (can be simply expressed by $\left(\mathbf{W}_{\mathbf{u}}\right)$)；

$\left(\left(\mathbf{V}^{(\mathrm{s})}{}_{\mathbf{n}}\right)_{\mathbf{u}}\right)$ is the super vector of exciting resource in network.

Through calculation of inverse matrix, superposition voltage wave vector can be derived for each junction as following,

$$\left(\left(\mathbf{V}_{\mathbf{n}}(\mathbf{0})\right)_{\mathbf{u}}\right)=\left[\left(\left(\mathbf{1}_{\mathbf{n,m}}\right)_{\mathbf{u,v}}\right)-\left(\left(\mathbf{S}_{\mathbf{n,m}}\right)_{\mathbf{u,v}}\right)\left(\left(\boldsymbol{\Gamma}_{\mathbf{n,m}}\right)_{\mathbf{u,v}}\right)\right]^{-1}\cdot$$

$$\bullet\left(\left(\mathbf{S}_{\mathbf{n,m}}\right)_{\mathbf{u,v}}\right)\left(\left(\mathbf{V}^{(\mathrm{s})}{}_{\mathbf{n}}\right)_{\mathbf{u}}\right)\qquad(8)$$

However, the solution of equation (8) is not the real voltage at each junction of network. So we must rebuild the real voltage of load at each junction based on the superposition of networks. The real voltage super vector of each junction is the superposition of leaving wave supermatrix and coming wave super matrix at x = 0.

$$\left(\mathbf{V}_{\mathbf{n}}(\mathbf{0})\right)=\frac{\mathbf{1}}{\mathbf{2}}\left[\left(\mathbf{V}_{\mathbf{n}}(\mathbf{0})\right)_{\mathbf{u}}+\left(\mathbf{V}_{\mathbf{n}}(\mathbf{L}_{\mathbf{v}})\right)_{\mathbf{v}}\right]\qquad(9)$$

where： $\left(\mathbf{V}_{\mathbf{n}}(\mathbf{0})\right)$ is the real hyper-vector of voltage wave at junction of $x=0$； $\left(\mathbf{V}_{\mathbf{n}}(\mathbf{0})\right)_{\mathbf{u}}$ is the hyper-vector of leaving voltage wave at junction of $x=0$； $\left(\mathbf{V}_{\mathbf{n}}(\mathbf{L}_{\mathbf{v}})\right)_{\mathbf{v}}$ 为 is superposition vector of coming voltage waveat junction of $x=0$.

It is known in the electromagnetic topological theory that the relationship between leaving and coming wave is as following,

$$\left(\left(\mathbf{V}_{\mathbf{n}}(\mathbf{L}_{\mathbf{u}})\right)_{\mathbf{u}}\right)=\left(\left(\boldsymbol{\Gamma}_{\mathbf{n,m}}\right)_{\mathbf{u,v}}\right)\left(\left(\mathbf{V}_{\mathbf{n}}(\mathbf{0})\right)_{\mathbf{u}}\right)+\left(\left(\mathbf{V}_{\mathbf{n}}{}^{(\mathrm{s})}\right)_{\mathbf{u}}\right)(10)$$

For the simply purpose for programming, we introduce correlation matrix of wave-wave tube. It is defined as,

$$\left(\left(\mathbf{T}_{\mathbf{n,m}}\right)_{\mathbf{u,v}}\right)=\begin{cases}\left(\mathbf{1}_{\mathbf{n,m}}\right)_{\mathbf{u,v}} & \mathbf{W}_{\mathbf{u}},\mathbf{W}_{\mathbf{v}}\text{」 same tube, and ⌊}\boldsymbol{\mu}=\mathbf{v}\\ \left(\mathbf{0}_{\mathbf{n,m}}\right)_{\mathbf{u,v}} & \mathbf{W}_{\mathbf{u}},\mathbf{W}_{\mathbf{v}}\text{ different tube, or ¿}\boldsymbol{\mu}\neq\mathbf{v}\end{cases}$$

(11)

By considering equation (10) and (11), and also considering equation (6) of total voltage， we have

$$\left(\mathbf{V}_{\mathbf{n}}(\mathbf{0})\right)=\frac{\mathbf{1}}{\mathbf{2}}\left[\left(\left(\mathbf{S}_{\mathbf{n,m}}\right)_{\mathbf{u,v}}\right)+\left(\left(\mathbf{T}_{\mathbf{n,m}}\right)_{\mathbf{u,v}}\right)\right]\cdot$$

$$\bullet\left[\left(\left(\mathbf{1}_{\mathbf{n,m}}\right)_{\mathbf{u,v}}\right)-\left(\left(\mathbf{S}_{\mathbf{n,m}}\right)_{\mathbf{u,v}}\right)\left(\left(\boldsymbol{\Gamma}_{\mathbf{n,m}}\right)_{\mathbf{u,v}}\right)\right]^{-1}\left(\left(\mathbf{V}_{\mathbf{n}}{}^{(\mathrm{s})}\right)_{\mathbf{u}}\right)\quad(12)$$

So we can obtain the voltages at each junction of network by solving equation (12)

The above derivations is based on frequency domain. But, the EMP signal normally has the property of wide frequency band and normally expressed in time domain waveform. So when the exciting signal is pulse, we normal transfer time domain signal into frequency domain signal, then solve the above equations to find the voltage response in time domain and finally find the time domain voltage using inverse Fourier transform. In this way, greater error may be caused. So in this paper, the complex Fourier transform and inverse transform are improved [21-23]. The proposed method is as following, find the transfer function using frequency BLT matrix equations first and then using find the solution by convolution method. Through comparison, the solution by this new method is more accurate compared to experimental results.

In an electromagnetic topological network as Fig 12, J_i represents junctions, w_i represents the propagation within network and Z_L is terminal load. The lengths of tube are set to be $T_1 = 2$m, $T_2 = 3$m, $T_3 = 3$m and $T_4 = 1$m. The characteristic impedance of each tube are same and equal to 50 Ω and the terminal load is also 50 Ω .We inject a square wave pulse as indicated Fig. 13 at junction 1 from a square wave resource (high frequency noise generator INS-4040, pulse width 50ns, Amplitude 300V). We analyze the response at terminal load of junction 4 to EMP injection (Fig.14).

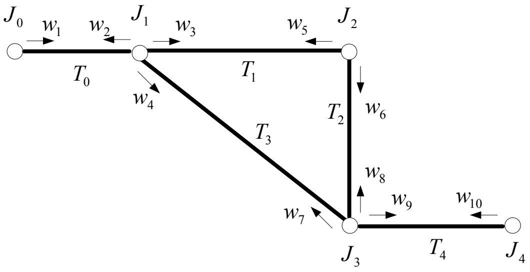

Fig. 12 Electromagnetic topological model of Circle network #1

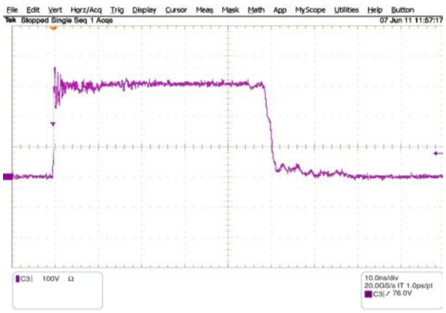

Fig.13 The injected square wave

Fig.15 and Fig.16 show the responses when terminal loads and tube 3 varies.

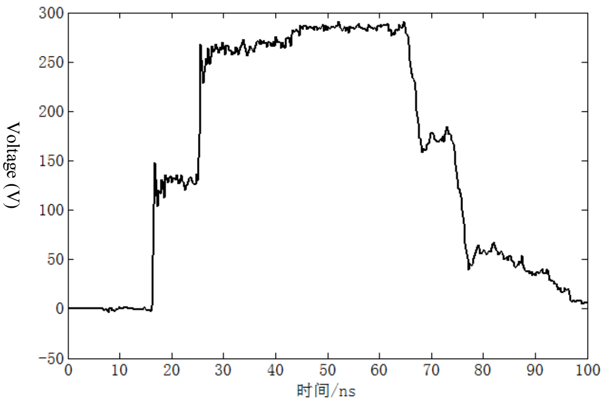

Fig.14 The response voltage waveform at junction 4

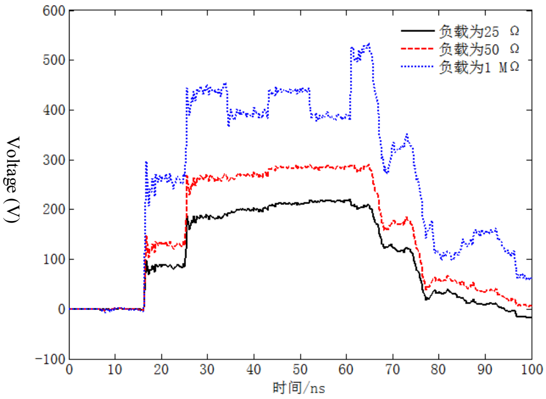

Fig.15 The voltage response at junction 4 when the load varies.

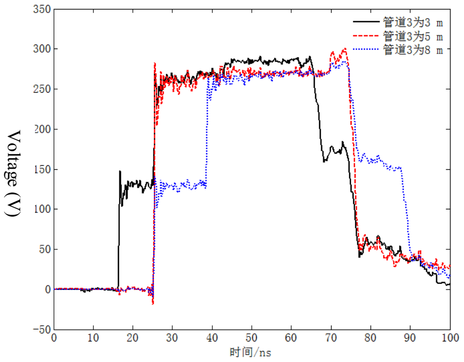

Fig.16 The voltage response at junction 4 at deferent wire lengths

From the results above, we can find that the amplitude of response voltage increase with the increase ofr load and reach a maximum value at 1MΩ or above. At other times, new pulse response also appear. These new responses possible caused by mismatch load. When the length of tube 3 increases, the variation of response at junction 4 is small and only a time delay appeared. When the length of tube 3 is 5m, the response waveform is almost same with the injected waveform. This is because that the propagating times of pulse to junction 4 are same although they go along with different path after junction 1.

According to above methods, we can analyze another topological structure #2 as shown in Fig.17, in which a load R = 50 Ω. Is added to the structure shown in Fig.12.

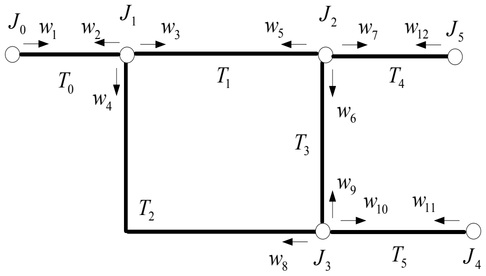

Fig.17 The topological model of circle network #2

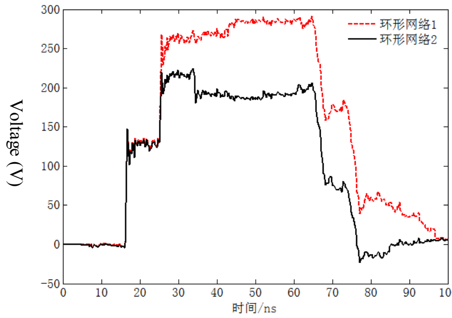

Fig.18 The voltage response at junction 4 for different network structures

From the above figure, it can be find that, when network varies, the response at junction 4 also varies. After a load R=50 Ω is added, the amplitude of response voltage decreased and the decrease value is greater at the time of 34.34 ns. The results show that the network structure and terminal load will affect the response simultaneously.

Fig.19 and Fig.20 give the response at junction 4 when the load *R* at junction 2 and the length of tube 3 vary.

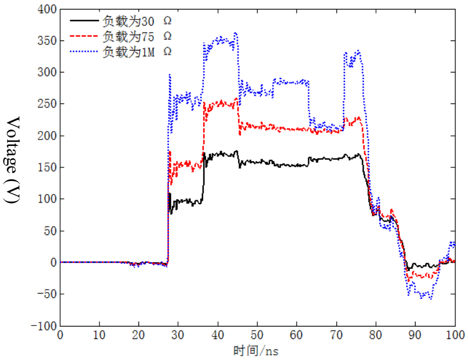

Fig.19 The voltage response at junction 4 at different loads.

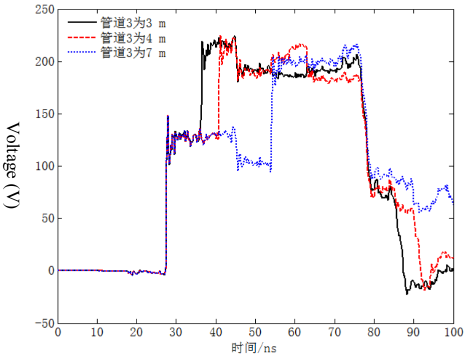

Fig.20 The voltage response at junction 4 at different wire lengths

From Fig.19 and Fig 20, we can find that the response at junction 4 will appear great variation when other loads vary. This is mainly cause by the reflection at junction 2 and circle network. With the increase of load value, not only the amplitude will increase, but the variation will increase. But the variation of load does not affect pulse width. The variation of length of wires, such as tube 3 is 7m or above, may cause new step variation of response besides the time delay.

4. Conclusions

In this paper, the BLT equations are built for double parallel conductor line and two typical networks and the EMP responses are also investigated under the conditions of injection and radiation of EMP. The dependences of propagation of EMP on the wire parameters, height from ground and network structures are analyzed. These models and results have been proved to be good agreement with experimental results [8] and they are also useful to investigate the response processes and coupling of transmission line network with other kind of EMPs and provide a effective theory for predicting the EMP hazards to transmission line networks. The research on the coupling between EMP and wire network (such as power line network and SCADA system) is very important for reducing electromagnetic interferences and improve the protection against possible EMP attack.

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