Journal of Computers Vol. 28, No. 4, 2017, pp. 122-128
doi:10.3966/199115592017082804013

Transmission Line Theory Application in Strong Electromagnetic Pulse Coupling

Cui Hao[1*], and Denghua Li[1]

1 Electronic Information and Control Experiment Teaching Center, Beijing Information Science & Technology University, Beijing, 100101, China
haocui0433234@163.com

Received 25 October 2016; Revised 13 June 2017; Accepted 26 June 2017

Abstract. For the problem of strong electromagnetic pulse gets into the electronic equipment through the double conductor, the model of parallel double conductor under the strong electromagnetic pulse was proposed in this paper. In the modeling of the electromagnetic pulse source, horizontal angle, vertical angle and polarization angle were bringing in, which makes the strong electromagnetic pulse illuminate double conductor with any angle. The conductivity, permeability, and characteristic impedance of the metal wire were bring in the model, which makes the model suitable for the high frequency and low frequency (<100MHz). The voltage produced on the double conductor under the strong electromagnetic pulse was calculated using transmission line theory. The simulation analyzed different horizontal angle, vertical angle and polarization angle impact on the coupling voltage peak. Then, the maximum coupling voltage was determined under the same strong electromagnetic pulse, which provided good basic research for the further protection circuits' research.

Keywords: double conductor, electronic equipment, MATLAB, strong electromagnetic pulse, transmission line theory

1 Introduction

As the development of the electronic information technology, more and more electronic products in our life, and people more and more depend on electronic products. There are more country strengthen the development of the electromagnetic pulse weapons. If the electronic products didn't install protection circuits, the inside circuits of the products will be failure or damage [1-5]. So, the electronic products' protection from the intensive electromagnetic pulse is important. There are some basic research on the protection circuits now [6-10], but there is rarely thorough modeling research on the two-conductor line's coupled voltage under the intensive electromagnetic pulse. The thorough modeling of the two-conductor line under the intensive electromagnetic pulse is established in this paper. The peak value of the coupled voltage produced on the conductor line will be calculated, which provides protective order of magnitude for the protection circuits, and provides good theoretical reason.

The model of the electromagnetic pulse is established in the second section. For simulating the electromagnetic pulse radiating in any direction, the vertical angle and horizontal angle of incidence are introduced. The thorough modeling of the two-conductor line under the intensive electromagnetic pulse is established with transmission line theory, which solves the coupled voltage produced on the two-conductor line. The third section does the simulation analyses. The last section summarizes the whole paper.

[*] Corresponding Author

2 Physical Modeling

The thorough modeling of the two-conductor line under the intensive electromagnetic pulse is established in this paper. Suppose that the electromagnetic pulse wave is Transverse Electric and Magnetic (TEM) plane electromagnetic wave. For simulating that the electromagnetic pulse wave radiating the two-conductor line in any angle, the horizontal angel ϕ, vertical angel ψ of the electromagnetic wave, and polarization angle α of the electric field are introduced in the model. The voltage produced on the transmission lines is calculated with telegraph equation.

The sketch of two-conductor line under plane electromagnetic wave is shown in Fig. 1. The coordinate axes in the sketch are not placed by right-hand corkscrew rule, but it will not affect the final result. The length of the conductor in the sketch is l. The distance between the two conductors is w. The radius of the conductor is a. The circuits at the end of the conductors are modeled as equivalent load impedance Z_{L1} and Z_{L2}.

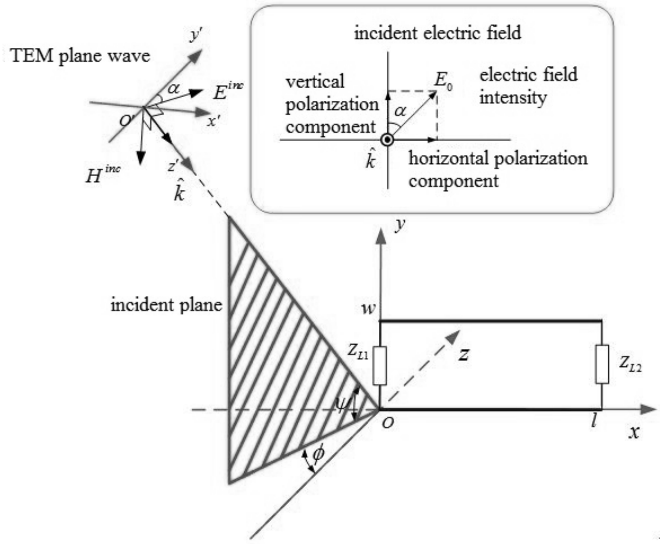

Fig. 1. Sketch of two-conductor line under plane electromagnetic wave

2.1 Incident Electric Field Modeling

Suppose that $\hat{j}_x$, $\hat{j}_y$ and $\hat{j}_z$ are the electromagnetic wave's unit vectors under the x', y' and z' axes' direction respectively in the $O'-x'y'z'$ coordinate system. The electric field of the incident electromagnetic pulse wave can be expressed as below:

$$\boldsymbol{E}^{inc} = (E_0 \sin\alpha \hat{j}_x + E_0 \cos\alpha \hat{j}_y) e^{-jk_0 z'} . \quad \textbf{(1)}$$

Thereinto, E_0 is the amplitude of the incident electric field, k_0 is the propagation constant of the plane electromagnetic wave in the vacuum.

Suppose that $\hat{i}_x$, $\hat{i}_y$ and $\hat{i}_z$ are the unit vectors under the x, y and z axes' direction respectively in the $O-xyz$ coordinate system. Changing the incident electric field from $O'-x'y'z'$ coordinate system to $O-xyz$ coordinate system has to do the below transformation.

$$\begin{aligned} \hat{j}_x &= -\cos\phi \hat{i}_x + \sin\phi \hat{i}_z \\ \hat{j}_y &= \sin\psi \sin\phi \hat{i}_x + \cos\psi \hat{i}_y + \sin\psi \cos\phi \hat{i}_z \\ \hat{j}_z &= \cos\psi \sin\phi \hat{i}_x - \sin\psi \hat{i}_y + \cos\psi \cos\phi \hat{i}_z \end{aligned} \quad \textbf{(2)}$$

Taking equation (2) into equation (1), the expression of the incident electric field under the $O-xyz$

coordinate system is shown as below:

$$\boldsymbol{E}^{inc} = \begin{bmatrix} (E_0 \cos\alpha \sin\psi \sin\phi - E_0 \sin\alpha \cos\phi)\hat{i}_x \\ +E_0 \cos\alpha \cos\psi \hat{i}_y \\ +(E_0 \sin\alpha \sin\phi + E_0 \cos\alpha \sin\psi \cos\phi)\hat{i}_z \end{bmatrix} e^{-jk_0 \begin{bmatrix} (\cos\psi \sin\phi)x \\ -(\sin\psi)y \\ +(\cos\psi \cos\phi)z \end{bmatrix}} . \quad \textbf{(3)}$$

2.2 Transmission Line Model's Solving

Agrawal has given the telegraph equation using scattering variable and incident variables [11]. Suppose that $V(x)$ is the voltage of the transmission line at point whose x-coordinate is x. $V^{inc}(x)$ is the incident voltage produced on the conductor line radiated by the incident electromagnetic wave. $V^{sca}(x)$ is the scattering voltage produced by the electric current and electric charge in the conductor. The transmission line model under electromagnetic pulse is shown in Fig. 2.

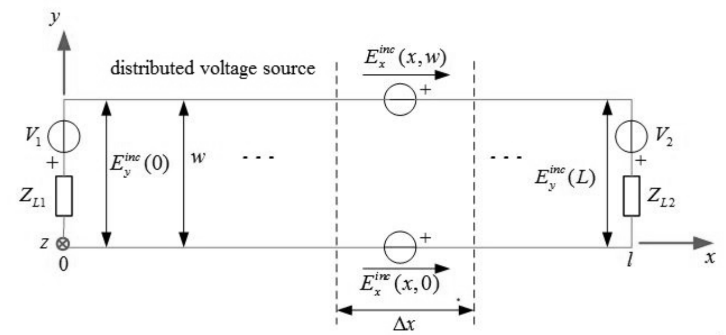

Fig. 2. Transmission line model under electromagnetic pulse

In the $O-xyz$ coordinate system, the whole voltage is:

$$\begin{aligned} V(x) &= V^{sca}(x) + V^{inc}(x) \\ &= V^{sca}(x) - \int_0^w \boldsymbol{E}^{inc} \bullet d\hat{y} \\ &= V^{sca}(x) - \int_0^w E_0 \cos\alpha \cos\psi e^{-jk_0 x(\cos\psi \sin\phi)} e^{jk_0 y(\sin\psi)} dy \\ &= V^{sca}(x) - E_0 \cos\alpha \cos\psi e^{-jk_0 x(\cos\psi \sin\phi)} \frac{e^{jk_0 w(\sin\psi)} - 1}{jk_0(\sin\psi)} \\ &\approx V^{sca}(x) - E_0 w \cos\alpha \cos\psi e^{-jk_0 x(\cos\psi \sin\phi)} \end{aligned} \quad \textbf{(4)}$$

The scattering voltage $V^{sca}(x)$ can be shown in Green function [12].

$$V^{sca}(x) = \int_0^l G_V(x; x_s) V_{S2} \mathrm{d}x_s - G_V(x;0)V_1 + G_V(x;l)V_2 . \quad \textbf{(5)}$$

Thereinto, voltage's Green function is:

$$G_V(x; x_s) = \frac{\delta e^{-\gamma l}}{2Z_c(1 - \rho_1 \rho_2 e^{-2\gamma l})} [e^{-\gamma(x_> - l)} + \delta\rho_2 e^{\gamma(x_> - l)}](e^{\gamma x_<} - \delta\rho_1 e^{-\gamma x_<}) . \quad \textbf{(6)}$$

In the above function, define that $\delta = 2U(x - x_s) - 1$. $U(x - x_s)$ is the unit Heaviside step function. $x_<$ is the little one of the variable x and x_s. $x_>$ is the bigger one of the variable x and x_s. When $x < x_s$, $\delta = -1$. When $x > x_s$, $\delta = 1$. Some electromagnetic pulse interference's frequency is lower 100MHz, which belongs to low frequency area. For the universality of the model, suppose that the characteristic impedance of the transmission line is Z_c.

$$Z_c = \sqrt{\frac{R + j\omega L}{G + j\omega C}} . \quad \textbf{(7)}$$

Thereinto, $\omega = 2\pi f$, which is the angular frequency of the electromagnetic pulse wave. R, G, L and C are the resistance, leakage conductance, inductance and capacitance in the unit transmission line's equivalent circuit respectively. Suppose that $w \gg 2a$, the resistance should be [13]

$$R = \frac{1}{a}\sqrt{\frac{\mu f}{\pi\sigma}} . \quad \textbf{(8)}$$

μ is the permeability of the metal, σ is the conductivity of the metal, and f is the frequency of the electromagnetic wave.

$$L = \frac{\mu_0}{\pi}\ln(\frac{w}{a}) . \quad \textbf{(9)}$$

$$G = \frac{\pi\sigma_0}{\ln(w/a)} . \quad \textbf{(10)}$$

$$C = \frac{\pi\varepsilon_0}{\ln(w/a)} . \quad \textbf{(11)}$$

Thereinto, $\mu_0 = 4\pi \times 10^{-7}(\mathrm{H/m})$ is the permeability of the vacuum, and $\varepsilon_0 = \frac{1}{36\pi} \times 10^{-9}(\mathrm{F/m})$ is the permittivity of the vacuum. $\sigma_0 = 0$ is the conductivity of the vacuum. So, $G = 0$.

The propagation constant of the electromagnetic wave under the transmission line is:

$$\gamma = \sqrt{(\mathrm{R} + \mathrm{j}\omega \mathrm{L})(\mathrm{G} + \mathrm{j}\omega C)} . \quad \textbf{(12)}$$

Thereinto, w is the distance between the two conductors' center, a is the radius of the conductor. The equivalent load impedances at the end of the conductor line are Z_{L1} and Z_{L2}. So, the voltage reflection coefficients at the end of the conductor line are:

$$\rho_1 = \frac{Z_{L1} - Z_c}{Z_{L1} + Z_c} \quad \textbf{(13)}$$

$$\rho_2 = \frac{Z_{L2} - Z_c}{Z_{L2} + Z_c} \quad \textbf{(14)}$$

The distribution voltage source is:

$$\begin{aligned} V_{S2} &= E_x^{inc}(x,w) - E_x^{inc}(x,0) \\ &= \left(E_0 \cos\alpha \sin\psi \sin\phi - E_0 \sin\alpha \cos\phi\right)\left(e^{jk_0 w(\sin\psi)} - 1\right)e^{-jk_0 x(\cos\psi \sin\phi)} \\ &\approx \left(E_0 \cos\alpha \sin\psi \sin\phi - E_0 \sin\alpha \cos\phi\right) jk_0 w(\sin\psi)e^{-jk_0 x(\cos\psi \sin\phi)} \end{aligned} \quad \textbf{(15)}$$

Thereinto, $k_0 = \omega / c$, $k_0 w \ll 1$. c is the speed of the light in the vacuum. ω is the angular speed. Voltage source V_1 and V_2 are shown as below:

$$\begin{aligned} V_1 &= -\int_0^w E^{inc}(0,y,0) \bullet \mathrm{d}\hat{y} \\ &\approx -E_y^{inc}(0,0,0)w \\ &= -E_0 w \cos\alpha \cos\psi \end{aligned} \quad \textbf{(16)}$$

$$\begin{aligned} V_2 &= -\int_0^w E^{inc}(l,y,0)\bullet \mathrm{d}\hat{y} \\ &\approx -E_y^{inc}(l,0,0)w \\ &= -E_0 w\cos\alpha\cos\psi e^{-jk_0 l\cos\psi\sin\phi} \\ &= V_1 e^{-jk_0 l\cos\psi\sin\phi} \end{aligned} \quad \mathbf{(17)}$$

3 Simulation and Analysis

The model is simulated with matlab in this paper. Suppose that the incident intensive electromagnetic pulse electric field value is $E_0 = k_1\left(\left(\frac{10^8\,\mathrm{t}}{\tau}\right)^2 - 1\right)e^{-\left(\frac{10^8\,\mathrm{t}}{2b}\right)^2}$. Thereinto, $k_1 = \frac{2}{3}\times10^{-14}$, $\tau = 5\times10^{-10}$, $b=1$. The amplitude of the intensive electromagnetic pulse changing with time is shown in Fig. 3.

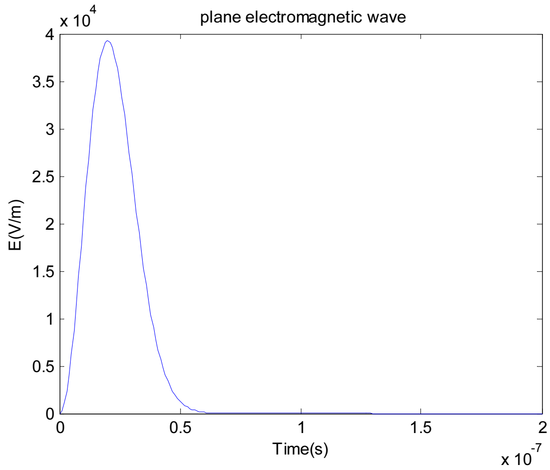

Fig. 3. Amplitude of the intensive electromagnetic pulse changing with time

Fig. 3 shows that the biggest amplitude of the intensive electromagnetic pulse is 38kV/m, the rise time is 25ns, and the duration of the whole electromagnetic pulse is 50ns.

Suppose that the horizontal angle of the electromagnetic wave is $\phi = 180^\circ$, the polarization angle of the electric field is $\alpha = 0^\circ$. The frequency of the electromagnetic wave is f=50MHz. The radius and length of the conductor line is $a = 1.5\mathrm{mm}$ and $l = 50\mathrm{mm}$. The distance between the two conductor line is $w = 20\mathrm{mm}$. The equivalent load impedance at the end of the conductor line is Z_{L1}=$Z_{L2} = 50\Omega$. The material of the conductor line is copper. The permeability and conductivity of the copper are $\mu = 0.99999\mu_0$ and $\sigma = 5.8\times10^7\mathrm{S/m}$. When $x = l$, the coupled voltage in the conductor line is $V(x = l)$. The coupling voltage on the wire with different vertical angle of incidence ψ is shown in Fig. 4.

When the vertical angle of incidence $\psi = 180^\circ$, the coupling voltage on the wire with different horizontal angle of incidence ϕ is shown in Fig. 5.

When the horizontal angle of incidence $\phi = 180^\circ$, the coupling voltage on the wire with different polarizing angle α is shown in Fig. 6.

As the simulation results show, the peak value of the coupled voltage on the conductor line is ±780V when the peak value of the electric field is 38KV/m. When the vertical angle of the electromagnetic wave and the polarizing angle of the electric field take different values, the coupled voltage in the two-conductor line will be changing with the angle.

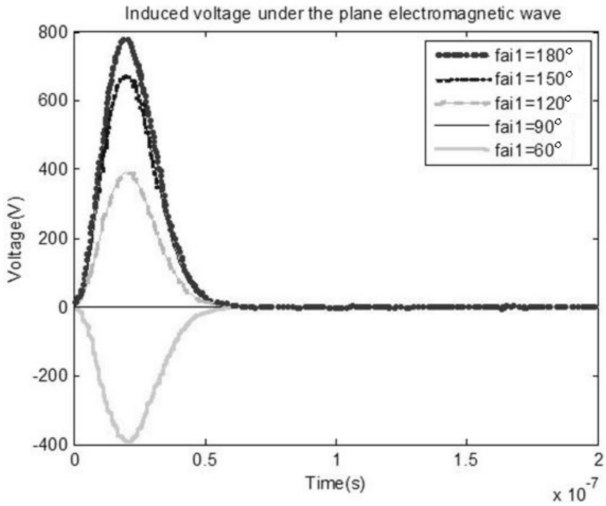

Fig. 4. The coupling voltage on the wire with different vertical angle of incidence ψ

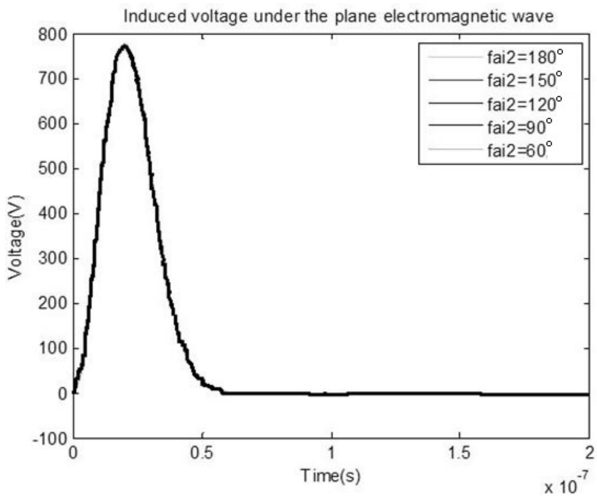

Fig. 5. The coupling voltage on the wire with different horizontal angle of incidence ϕ

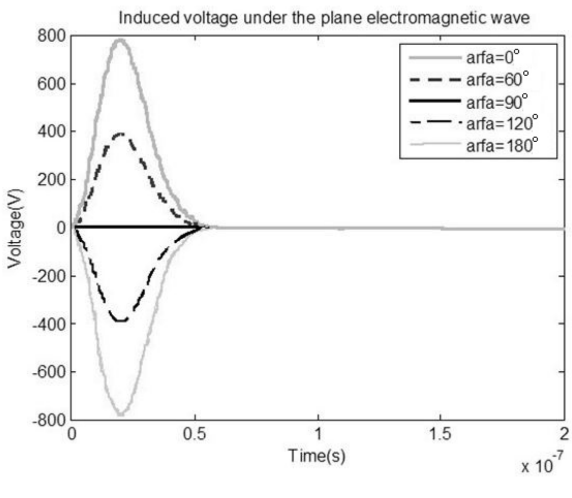

Fig. 6. The coupling voltage on the wire with different polarizing angle α

4 Conclusions

The model of parallel double conductor under the intensive electromagnetic pulse was proposed in this paper. The coupled voltages were calculated with different horizontal angle, vertical angle and polarization angle of the electromagnetic wave. The peak value of the coupled voltage is defined at last, which did a pioneering work for the future electromagnetic pulse protection research, and provided theory for the engineering practice. In the following work, the coupled voltage should be taken as a reference value, and the protection circuit will be designed based on this value.

Acknowledgement

This work is supported by General armament department pre-research fund project (9140A11030214 DZ03001).

References

[1] X.-R. Ren, C.-C. Chai, Z.-Y. Ma, Y.-T. Yang, L.-P. Qiao, C.-L. Shi, The damage effect and mechanism of bipolar transistors induced by injection of electromagnetic pulse from the base, Acta Physica Sinica 62(6)(2013) 068501-1~068501-6.

[2] Y.-J. Chai, D. Meng, J.-J. Li, Z. Li, Study on electromagnetic pulse effect of complex electronic systems, Radio Engineering 41(1)(2011) 38-40.

[3] S.-Q. Zheng, X.-G. Wu, Y.-F. Zhu, Electromagnetic pulse threats to ship-flat and requirements of protection, Journal of Microwaves 8(2010) 101-104.

[4] H. Meng, Experimental study of wireless sensor networks' communication performance in electromagnetic interference environment, Microcontrollers and Embedded Systems 5(2015) 24-27.

[5] F. Zhuang, Y. Xu, R. Yu, F. Lei, W. Chen, Advanced active gate drive for switching performance improvement and overvoltage protection of high-power IGBTs, IEEE Transactions on Power Electronics 99(2017) 1-1.

[5] A.K. Agrawal, H.J. Price, S.H. Gurbaxani, Transient response of multiconductor transmission lines excited by a nonuniform electromagnetic field, IEEE Trans. Electromagnetic Compatibility 22(2)(1980) 119-129.

[7] J. Y. Lin, W.-J. Dong, C.-X. Zhang, C.-M. Zhou, J.-F. Ma, Investigation of injury effects to strong electromagnetic pulse on typical flying control system, in: Proc. 2012 Second International Conference on Instrumentation, Measurement, Computer, Communication and Control (IMCCC), 2012.

[8] C. Liu, B. Cao, W. Jiang, Effects of convex platform structure on couplings of strong electromagnetic pulse, in: Proc. Conference on Consumer Electronics, Communications and Networks (CECNet), 2011 International, 2011.

[9] C. Wang, C. Zhu, Z. Gu, D. Liu, Research on electromagnetic protection of mobile power station's generator, in: Proc. 2011 Second International Conference on Mechanic Automation and Control Engineering (MACE), 2011.

[10] X.-L. Chang, S.- H. Liu, F.-F. Xie, M.-H. Man, The research of bio-inspired electromagnetic protection based on pulse coupled neural network, in: Proc. 2012 5th International Conference on Biomedical Engineering and Informatics (BMEI), 2012.

[11] M.-S. Lin, Y.-H. Huang, C.-I. G. Hsu, Design a dual-band high-impedance surface structure for electromagnetic protection in WLAN applications, in: Proc. 2014 International Symposium on Electromagnetic Compatibility, Tokyo (EMC'14/Tokyo), 2014.

[12] F.M. Tesche, Handbook of Electromagnetic Compatibility, Acdemic Press, New York, 1995.

[13] A.R. Luria, The Mind of a Mnemonist (L. Solotarof, Trans.), Avon Books, New York, 1969 (Original work published 1965).