AN EFFICIENT METHOD FOR THE COMPUTATION OF ANTENNA-MODE CURRENTS ALONG TRANSMISSION LINES

Ana Vukicevic(1), Farhad Rachidi(2), Marcos Rubinstein(3), Sergey Tkachenko(4)

(1,2)Swiss Federal Institute of Technology, EMC Group, CH-1015 Lausanne, Switzerland
(3)University of Applied Sciences of Western Switzerland, Yverdon, Switzerland
(4)Institute for Fundamental Electrical Engineering, Otto-von-Guericke University, 39106 Magdeburg, Germany
1) Ana.Vukicevic@epfl.ch, 2) Farhad.Rachidi@epfl.ch, 3) Marcos.Rubinstein@eivd.ch, 4) Sergey.Tkachenko@E-Tecnik.Uni-Magdeburg.DE

ABSTRACT

In this paper, we present an integral equation describing the antenna-mode currents along a two-wire transmission line. When the cross-sectional dimensions of the line are electrically small, the integral equation reduces to a pair of transmission-line-like equations with equivalent line parameters (inductance and capacitance). The derived equations make it possible to compute the antenna-mode currents using a traditional transmission-line code with appropriate parameters. The derived equations are tested versus numerical results obtained using NEC, and good agreement is found.

INTRODUCTION

Transmission Line (TL) theory is a useful tool for the analysis of surge propagation along transmission lines. One of the basic assumptions of the TL theory is that the sum of the line currents at any cross section of the line is zero. Assuming that the sum of all currents is equal to zero, we only consider ‘transmission line-mode’ currents and neglect the so-called ‘antenna-mode’ currents (e.g. [1,2]). For a line consisting of a single conductor above ground, the quasi-symmetry due to the presence of the ground plane results in a very small contribution of antenna-mode currents and, consequently, the predominant mode on the line will be the transmission line mode [1]. For a two- (or multi-) conductor line, however, even for electrically small line cross-sections, the presence of antenna-mode currents implies that the sum of the currents in a cross section is not necessarily equal to zero [1,2]. If we desire to compute only the load responses of the line, consideration of only the TL model current is adequate, since the antenna-mode current response is small near the ends of the line. On the other hand, if we wish to evaluate the current along the line, the presence of antenna-mode currents needs to be taken into account, even for electrically small line cross sections. Therefore, to compute the fields radiated by power line communication signals from indoor low-voltage power lines or radiated emissions from printed circuit boards, one must take into account the contribution of the antenna-mode currents as these are often the predominant source of radiation.

To evaluate the antenna-mode currents, one has to apply general scattering theory. Recently, an integral equation describing the antenna-mode currents along a two-wire transmission line has been derived [3]. When the line cross-sectional dimensions are electrically small, the integral equation reduces to a pair of transmission-line-like equations with equivalent line parameters (inductance and capacitance per unit length). The derived equations make it possible to compute the antenna mode currents using a traditional transmission-line code with appropriate parameters. The aim of this paper is to test the accuracy of the derived equations by comparison versus numerical results obtained using the Numerical Electromagnetics Code (NEC2) [4].

INTEGRAL EQUATIONS FOR TRANSMISSION LINE MODE AND ANTENNA MODE CURRENTS

Consider a two-wire line of length L in free space, as shown in Fig. 1. The two conductors are separated by a distance d. The line is illuminated by an external electromagnetic field. The currents along the two conductors $I_1(z)$ and $I_2(z)$ can be decomposed as follows

$$I_1(z) = I_a(z) + I_{tl}(z) \tag{1}$$

$$I_2(z) = I_a(z) - I_{tl}(z) \tag{2}$$

where $I_a(z)$ and $I_{tl}(z)$ represent the antenna-mode and transmission-line-mode currents, respectively.

In [3], specific integral equations have been derived for both transmission line mode and antenna mode currents. These equations, written in a TL-like form are as follows.

Transmission Line Mode Current

$$\frac{dV^{s}(z)}{dz}+j\omega\frac{\mu}{2\pi}\int_{0}^{L}I_{tl}(z')\big(g_{1}(z,z')-g_{2}(z,z')\big)dz'=E_{z}^{i}(d,z)-E_{z}^{i}(0,z) \tag{3}$$

$$V^{s}(z)=-\frac{1}{2\pi\varepsilon\, j\omega}\frac{d}{dz}\int_{0}^{L}I_{tl}(z')\big(g_{1}(z,z')-g_{2}(z,z')\big)dz' \tag{4}$$

Antenna Mode Current

$$\frac{dV_{a}^{s}(z)}{dz}+j\omega\frac{\mu}{4\pi}\int_{0}^{L}I_{a}(z')\big(g_{1}(z,z')+g_{2}(z,z')\big)dz'=\frac{E_{z}^{i}(d,z)+E_{z}^{i}(0,z)}{2} \tag{5}$$

$$V_{a}^{s}(z)=-\frac{1}{4\pi\varepsilon\, j\omega}\frac{d}{dz}\int_{0}^{L}I_{a}(z')\big(g_{1}(z,z')+g_{2}(z,z')\big)dz' \tag{6}$$

in which the Green's functions are

$$g_{1}(z,z')=\frac{e^{-jk\sqrt{(z-z')^{2}+a^{2}}}}{\sqrt{(z-z')^{2}+a^{2}}}\quad\text{and}\quad g_{2}(z,z')=\frac{e^{-jk\sqrt{(z-z')^{2}+d^{2}}}}{\sqrt{(z-z')^{2}+d^{2}}} \tag{7}$$

and $V^{s}(z)$ and $V_{a}^{s}(z)$ are the scattered voltages associated respectively with the transmission line mode and the antenna mode, defined as

$$V^{s}(z)=\Phi(d,0,z)-\Phi(0,0,z)\quad\text{and}\quad V_{a}^{s}(z)=\frac{\Phi(d,0,z)+\Phi(0,0,z)}{2} \tag{8}$$

where Φ is the retarded scalar potential.

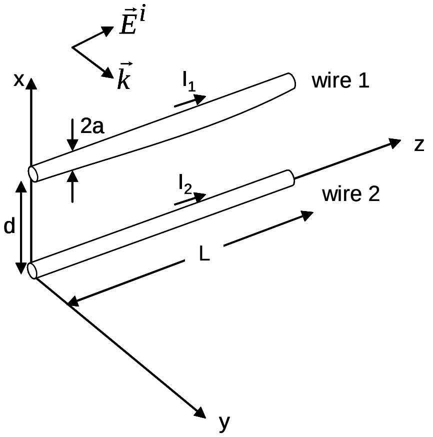

Fig. 1. Two-wire system in presence of an external electromagnetic field

SOLUTIONS FOR LINES WITH ELECTRICALLY-SHORT CROSS-SECTIONS

Under the TL approximation, it can be readily shown [5] that equations (3) and (4) reduce to the field-to-transmission line equations of Agrawal et al. [6]. For the antenna mode currents, it has been shown [3] that (5) and (6) reduce to

$$\frac{dV_{a}^{s}(z)}{dz}+j\omega L'_{a}\,I_{a}(z)=\frac{E_{z}^{i}(d,0,z)+E_{z}^{i}(0,0,z)}{2} \tag{9}$$

$$\frac{dI_{a}(z)}{dz}+j\omega C'_{a}\,V_{a}^{s}(z)=0 \tag{10}$$

where L'_{a} and C'_{a} are the equivalent per-unit-length inductance and capacitance for the antenna-mode current, respectively, given approximately by [3]

$$L'_{a}\cong\frac{\mu_{o}}{2\pi}\ln\frac{0.29L^{4}}{a^{2}d^{2}}\quad\text{and}\quad C'_{a}\cong\frac{2\pi\varepsilon_{o}}{\ln\frac{0.29L^{4}}{a^{2}d^{2}}} \tag{11}$$

SIMULATIONS AND COMPARISON WITH NEC

The proposed pair of transmission-line-like equations (9) and (10) for the computation of antenna-mode currents are tested here versus numerical results obtained using the Numerical Electromagnetics Code (NEC) [7]. The derived equations (9) and (10) are solved using a conventional transmission line code (e.g. [1]). The inductance and capacitance associated with the antenna-mode currents are determined using the approximate expressions (11).

We will consider a two-conductor line (as in Fig. 1) characterized by L = 31 m, d = 0.2 m, a = 1.5 mm. The wires are assumed to be perfectly conducting and the load impedances at the $z=0$ and $z=L$ ends are taken to be $Z_1 = Z_2 = 293\ \Omega$, which is approximately equal to one-half of the characteristic impedance of the line. This structure is excited by an incident plane wave that propagates in the plane of the line and strikes the line with an angle of incidence ψ.

Fig. 2 presents the computed results for the transmission-line mode and antenna-mode current magnitudes along the line, for a frequency f = 20 MHz and for the angle of incidence $\psi = 45^{o}$. Fig. 3 presents similar results, but for an angle of incidence $\psi = 90^{o}$ and a line length L = 41 m. In the same figures, we have also represented the transmission line mode current magnitudes calculated using both NEC and the TL approximation. It can be seen that the results obtained the proposed approach are in reasonably good agreement with those obtained using NEC. It is also worth noting that, even for the considered low frequencies, the antenna-mode currents are much larger than the transmission line mode currents.

CONCLUSIONS

We have presented integral equations describing the transmission line and antenna-mode currents along a two-wire transmission line. When the line cross-sectional dimensions are electrically small, the integral equation for the antenna mode current reduces to a pair of transmission line-like equations with equivalent line parameters (per-unit-length inductance and capacitance). The derived equations make it possible to compute the antenna mode currents using a traditional transmission line code with appropriate parameters. The derived equations were tested versus numerical results obtained using NEC and good agreement was found.

Acknowledgments – Interesting discussions with Prof. F.M. Tesche are greatly appreciated. Special thanks are due to Prof. J.B. Nitsch for his useful and precious comments on the manuscript. This work has been financially supported by the OPERA project (http://www.ist-opera.org), co-financed by the IST programme of the EC and the Swiss State Secretariat for Education and Research, Grant 030309-2.

REFERENCES

[1] F.M. Tesche, M.V. Ianoz, and T. Karlsson, “EMC Analysis Methods and Computational Models”, John Wiley & Sons, New York 1997

[2] C.R. Paul, Analysis of multiconductor transmission lines, John Wiley and Sons, 1994.

[3] A. Vukicevic, F. Rachidi, M. Rubinstein, S. Tkatcehnko, On the Evaluation of Antenna-Mode Currents along Transmission Lines, Submitted to IEEE Transactions on Electromagnetic Compatibility, 2005.

[4] G.J. Burke and A.J. Poggio, "Numerical electromagnetic code (NEC): Description theory", Lawrence Livermore Laboratory, 1981.

[5] S. Tkatchenko, F. Rachidi, M. Ianoz, "Electromagnetic field coupling to a line of finite length: theory and fast iterative solutions in frequency and time domains", IEEE Trans. on Electromagnetic Compatibility, Vol. 37, no 4, pp. 509-518, November 1995.

[6] Agrawal A.K., H.J. Price, S.H. Gurbaxani, "Transient response of a multiconductor transmission line excited by a nonuniform electromagnetic field", IEEE Trans. on EMC, Vol. EMC-22, No. 2, pp. 119-129, May 1980.

[7] G.J. Burke and A.J. Poggio, "Numerical electromagnetic code (NEC): Description theory", Lawrence Livermore Laboratory, 1981.

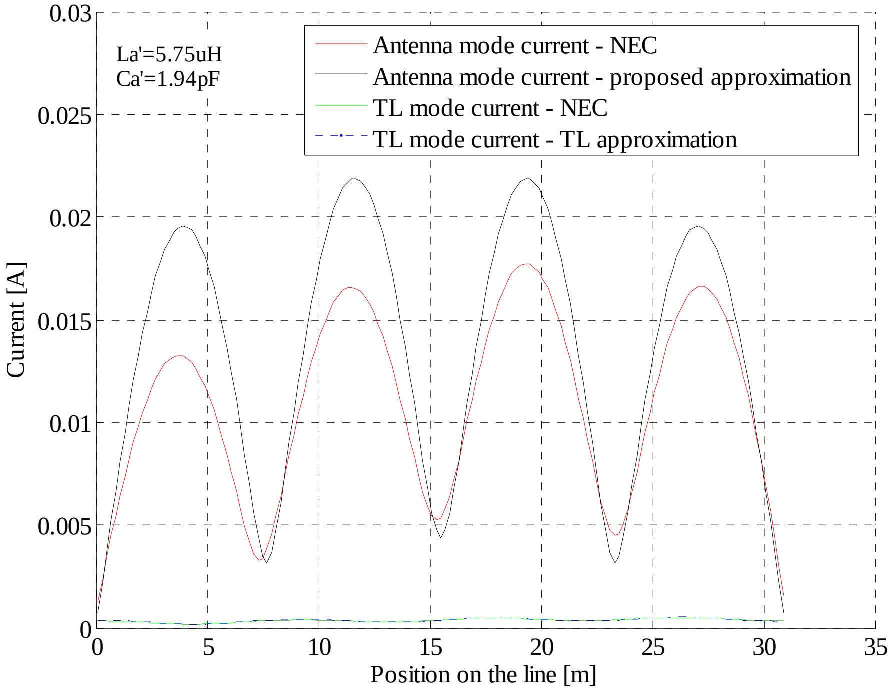

Fig. 2. Computed results for the transmission line mode and antenna mode current magnitudes along a 31-m long line, for an angle of incidence $\psi = 45^{o}$ and $f = 20$ MHz.

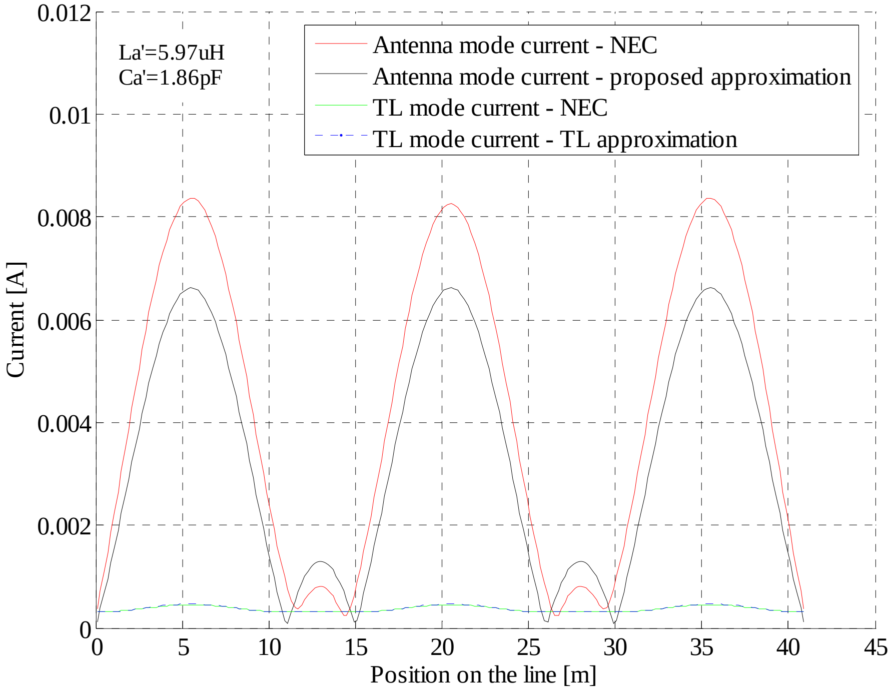

Fig. 3. Computed results for the transmission line mode and antenna mode current magnitudes along a 41-m long line, for an angle of incidence $\psi = 90^{o}$ and $f = 20$ MHz.