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# Modeling of Radio Frequency Electromagnetic Disturbances in Power Line Communication Networks

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**Abstract**—This paper proposes a new approach to modeling the radio frequency (RF) electromagnetic disturbances in broadband power line communication (PLC) networks using the multi-conductor transmission line (MTL) theory. The model includes a differential-mode (DM) current propagation model and a common-mode (CM) current propagation model. The frequency range of interest is from 1MHz to 30MHz. Practical measurements are carried out to compare with the simulation results as a form of verification of the accuracy of the proposed models.

## I. INTRODUCTION

Broadband Power Line Communications (BPLC) is a term used to describe the technology of using the existing power line cables to provide broadband Internet access. Currently, BPLC has already achieved a transmission rate of 200 Mbps [1] and is capable of transmitting High-Definition Television (HDTV) and Voice over Internet Protocol (VoIP) around the home unlike a few decades ago, in which where the applications were of narrowband and restricted to only power line signalling electricity meters.

The commercial potential of this technology would be greatly enhanced if the electromagnetic interference (EMI) problem is resolved. BPLC operates in the frequency band of 1 MHz to 30 MHz and is a concern for other users of these frequencies such as radio amateurs, military communications, aeronautical/maritime safety services and others [2]. The two forms of electromagnetic disturbances are the differential-mode (DM) and common-mode (CM) signals [3]. The DM signals are the PLC signals and the CM signals are the unwanted noise. Both of them contributed to the level of EMI radiation.

In this paper, a RF electromagnetic disturbance model for a three-wire power line cable is derived based on the Multi-conductor Transmission Line (MTL) theory. This model consists of a DM current propagation model and a CM current propagation model. The frequency of interest is from 1 MHz to 30 MHz. This model can be used to characterize and understand the behavior of DM and CM in the PLC network.

## II. DM AND CM PROPAGATION MODELS

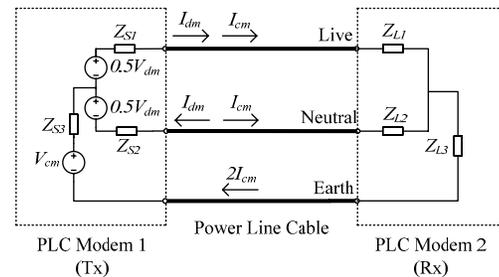


Fig.1. The current propagation paths in a PLC system.

Fig. 1 shows the current propagation paths in a PLC system with three wires when a PLC signal is injected by the PLC Modem 1 into the Live and Neutral wires. The wanted PLC signal is the DM current  $I_{dm}$  and the CM current  $I_{cm}$  is the unwanted signal.  $Z_{S1}$  and  $Z_{S2}$  are the DM source impedances and  $Z_{L1}$  and  $Z_{L2}$  are the DM load impedances. The CM source and load impedances are  $Z_{S3}$  and  $Z_{L3}$  respectively. The currents flowing in the Live, Neutral and Earth wires are given by

$$I_L = I_{dm} + I_{cm} \quad (1)$$

$$I_N = -I_{dm} + I_{cm} \quad (2)$$

$$I_E = -2I_{cm} \quad (3)$$

For the DM current  $I_{dm}$ , it flows into the Live wire from PLC Modem 1 to PLC Modem 2 and returns via the Neutral wire. PLC Modem 1 is the DM signal source and PLC Modem 2 is the load. The Neutral wire is taken as the reference for the DM current propagation model as shown in Fig. 2.

For the CM current  $I_{cm}$ , it flows from PLC Modem 1 to PLC Modem 2 in the Live and Neutral wires and returns to PLC Modem 1 via the Earth wire. PLC Modem 1 is taken as the CM noise source and PLC Modem 2 is taken as the load. The Earth wire is taken as the reference for the CM current propagation model as shown in Fig. 3.

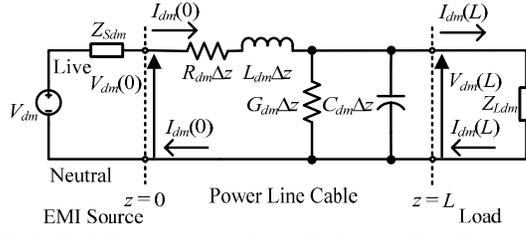


Fig. 2. The DM current propagation model of a power line cable.

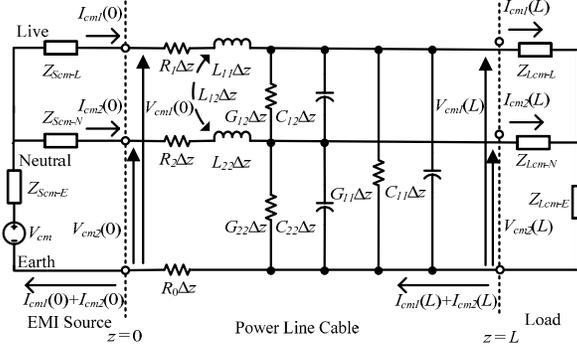


Fig. 3. The CM current propagation model of a power line cable.

The  $Z$  and  $Y$  matrices which are the per-unit-length impedance and admittance matrices respectively:

$$Z = R + j\omega L \quad (4)$$

$$Y = G + j\omega C \quad (5)$$

where  $R=R_{DM}$ ,  $L=L_{DM}$ ,  $G=G_{DM}$  and  $C=C_{DM}$  for DM current propagation model and  $R=R_{CM}$ ,  $L=L_{CM}$ ,  $G=G_{CM}$  and  $C=C_{CM}$  for CM current propagation model need to be computed.

The chain parameter matrix can be computed as

$$\Phi_{11}(L) = \cosh(\sqrt{ZY}L) = Y^{-1} \cosh(\sqrt{ZY}L)Y \quad (6)$$

$$\Phi_{12}(L) = -Z_0 \sinh(\sqrt{ZY}L) = -\sinh(\sqrt{ZY}L)Z_0 \quad (7)$$

$$\Phi_{21}(L) = -Z_0^{-1} \sinh(\sqrt{ZY}L) = -\sinh(\sqrt{ZY}L)Z_0^{-1} \quad (8)$$

$$\Phi_{22}(L) = \cosh(\sqrt{ZY}L) = Y \cosh(\sqrt{ZY}L)Y^{-1} \quad (9)$$

The DM and CM current propagation models of the power line cable in Figs. 2 and 3 can be represented by their chain parameter matrix as shown in Figs. 5 and 6.

The relationship between the injected voltage and the current at the source and at any point on the transmission line is given by the chain parameter matrix as follows:

$$\begin{bmatrix} V(L) \\ I(L) \end{bmatrix} = \Phi(L) \begin{bmatrix} V(0) \\ I(0) \end{bmatrix} \quad (10)$$

where  $L$  is the length of the power line cable.

The generalized Thevenin equivalent representations at the terminals relating the voltages and the currents are as follows:

$$V(0) = V_S - Z_S I(0) \quad (11)$$

$$V(L) = V_L + Z_L I(L) \quad (12)$$

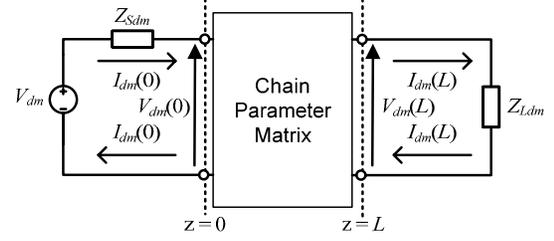


Fig. 5. DM current propagation model using the chain parameter matrix.

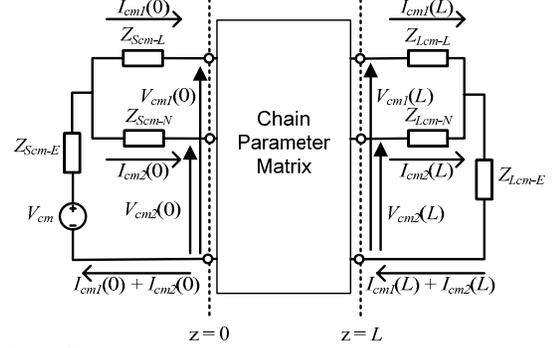


Fig. 6. CM current propagation model using the chain parameter matrix.

### III. DETERMINATION OF LINE PARAMETERS

The per-unit-length matrices of the power line cable need to be derived first in order to obtain the chain parameter matrix.

#### A. Resistance

When a high frequency current flows in the power line cable, we need to consider the skin effect. The skin depth  $\delta$  is given by [4]

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \quad (13)$$

where  $\mu$  is the permeability of the metal wire and  $\sigma$  is its conductivity. The high frequency per-unit-length resistance for a cable of radius  $R_{cable}$  in a homogeneous medium can be approximated by

$$R_{cable} = \frac{1}{2\pi r_{cable} \sigma \delta} \quad (14)$$

Since the wires are all identical, the per-unit-length DM and CM resistance matrices are obtained as

$$R_{DM} = [2R_{cable}] \quad (15)$$

$$R_{CM} = \begin{bmatrix} 2R_{cable} & R_{cable} \\ R_{cable} & 2R_{cable} \end{bmatrix} \quad (16)$$

### B. Inductance

The determination of the inductance requires the consideration of the magnetic flux  $\psi_i$  that penetrates a surface that is parallel to the cable when a current flows [4]. The details of the derivation can be found in [5].

The self-inductance  $L_{ii}$  is given as

$$L_{ii} = \frac{\mu}{2\pi} \ln \left( \frac{d_{i0}^2}{r_{wi} r_{w0}} \right) \quad (17)$$

and the mutual inductance  $L_{ij}$  is given as

$$L_{ij} = \frac{\mu}{2\pi} \ln \left( \frac{d_{i0} d_{j0}}{d_{ij} r_{w0}} \right) \quad (18)$$

Again, the skin effects need to be considered. According to [6], the self-inductance for conductor  $i$  can be corrected by multiplying it by a correction factor of

$$X_i = \frac{1}{0.315 \times 0.53 \times \frac{r_{wi}}{\delta}} \quad (19)$$

where  $r_{wi}$  is the radius of conductor  $i$ .

The corrected self-inductance is finally obtained as

$$L_{ii\text{corr}} = X_i \cdot \frac{\mu}{2\pi} \ln \left( \frac{d_{i0}}{r_{wi}} \right) + X_0 \cdot \frac{\mu}{2\pi} \ln \left( \frac{d_{i0}}{r_{w0}} \right) \quad (20)$$

where  $X_i$  is the correction factor for the Conductor  $i$  and  $X_0$  is the correction factor for the Conductor 0.

The mutual inductance also needs to be corrected in order to take into account the skin effects. The corrected mutual inductance is finally obtained as

$$L_{ij\text{corr}} = X_j \cdot \frac{\mu}{2\pi} \ln \left( \frac{d_{j0}}{d_{ij}} \right) + X_0 \cdot \frac{\mu}{2\pi} \ln \left( \frac{d_{i0}}{r_{w0}} \right) \quad (21)$$

where  $X_j$  is the correction factor for the Conductor  $j$ .

The per-unit-length DM and CM inductance matrices are finally written as

$$L_{DM} = [L_{ii\text{corr}} + L_{jj\text{corr}} - 2L_{ij\text{corr}}] \quad (22)$$

$$L_{CM} = \begin{bmatrix} L_{ii\text{corr}} & L_{ij\text{corr}} \\ L_{ji\text{corr}} & L_{jj\text{corr}} \end{bmatrix}_{i=1, j=2} \quad (23)$$

### C. Capacitance

The per-unit-length CM capacitance matrix for the power line cable is derived based on the principle of electrostatics.  $C_{pair}$  is the CM capacitance per-unit-length between any two parallel wires.

The capacitance between any two wires is given by [7]

$$C_{pair} = \frac{\pi \epsilon}{\ln \left[ (D/2a) + \sqrt{(D/2a)^2 - 1} \right]} \quad (24)$$

where  $D$  is the distance between any two wires and  $a$  is the radius of the wire. The per-unit-length DM and CM capacitance matrices are given by

$$C_{DM} = [C_{pair}] \quad (25)$$

$$C_{CM} = \begin{bmatrix} 2C_{pair} & -C_{pair} \\ -C_{pair} & 2C_{pair} \end{bmatrix} \quad (26)$$

### D. Conductance

From [7], if the surrounding medium is homogenous, we can obtain

$$\frac{C}{G} = \frac{\epsilon}{\sigma_d} \Rightarrow G = \frac{\sigma_d C}{\epsilon} \quad (27)$$

where  $\sigma_d$  and  $\epsilon$  are the conductivity and permittivity of the dielectric material respectively and  $G$  is the conductance of the wire.

We assume that the dielectric material is homogenous. Based on this assumption, and from (27), we get

$$G_{DM} = \frac{\sigma_d}{\epsilon} [C_{pair}] \quad (28)$$

$$G_{CM} = \frac{\sigma_d}{\epsilon} C = \frac{\sigma_d}{\epsilon} \begin{bmatrix} 2C_{pair} & -C_{pair} \\ -C_{pair} & 2C_{pair} \end{bmatrix} \quad (29)$$

## IV. EXPERIMENTAL VERIFICATION

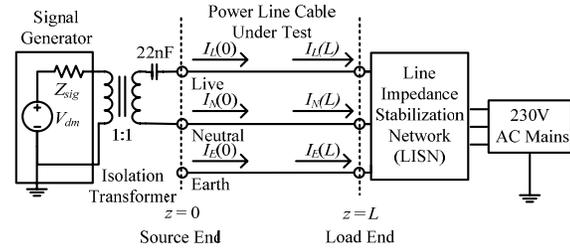


Fig. 9. Experimental setup.

The experimental setup is shown in Fig. 9. The DM and CM sources comprise of a signal generator, an isolation transformer and a 22 nF ‘Y’ class coupling capacitor. The power line cable is 3 m in length, and each wire is made up of copper conductors that are stranded and insulated with PVC. The power line cable is terminated with a line impedance stabilization network (LISN), which acts as the balanced load. The frequency range of interest is from 1 MHz to 30 MHz. The signal generator is configured to inject a 100mV into the Live and Neutral wires.

With the properties of the power line cable being defined as such, it becomes possible to calculate the chain parameter matrix. The currents  $I_L$ ,  $I_N$  and  $I_E$ , flowing in the Live, Neutral and Earth wires at the source and load ends are measured using the RF current probe. Given knowledge of the DM and CM sources, the CM current values for the Live, Neutral and Earth wires at the load end can be derived and compared to those measured using the RF current probe. This comparison serves as a verification of the DM and CM current propagation model.

We assume that the DM input voltage at the source end be 100mV. After measuring the currents  $I_L$ ,  $I_N$  and  $I_E$  at the source and the load ends with the RF current probe and using equations (1), (2) and (3), we can obtain the DM and CM currents at the source and load ends. This gives us  $V_{dm}(0)=100\text{mV}$ ,  $I_{dm}(0)$ ,  $I_{dm}(L)$ ,  $I_{cm1}(0)$ ,  $I_{cm2}(0)$ ,  $I_{cm1}(L)$  and  $I_{cm2}(L)$ .

Using the two-current-probe measurement methodology [8], we can find  $Z_{Ldm}$ ,  $Z_{Lcm-L}$ ,  $Z_{Lcm-N}$ ,  $Z_{Lcm-E}$  in which  $Z_{Ldm}=Z_{LN}$  and  $Z_{Lcm-L}=Z_1$ ,  $Z_{Lcm-N}=Z_2$  and  $Z_{Lcm-E}=Z_3$ . With the knowledge of these currents and impedances, we can find the voltages  $V_{dm}(L)$ ,  $V_{cm1}(L)$  and  $V_{cm2}(L)$  at the load end.

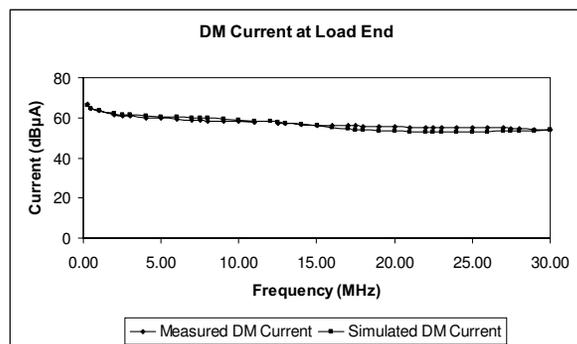


Fig. 13. Comparison of the measured and simulated DM currents in the Live wire at the load end.

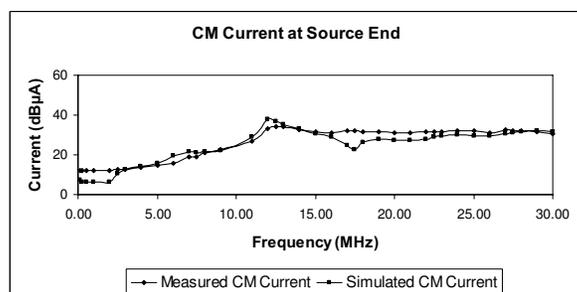


Fig. 14. Comparison of the measured and simulated CM currents in the Live wire at the source end.

With the properties of the cables known, we can calculate the chain parameter matrices for the DM and CM currents. Knowing  $V_{dm}(0)=100\text{mV}$ ,  $I_{dm}(0)$  and  $I_{dm}(L)$ , we can verify

the DM current propagation model by comparing the current at the load end. Fig. 13 shows the comparison of the measured and simulated DM currents at the load end. The two graphs almost close to each other serve as a verification of the DM current model.

For the CM current propagation model, we have  $I_{cm1}(0)$ ,  $I_{cm2}(0)$ ,  $I_{cm1}(L)$  and  $I_{cm2}(L)$ . After we get the impedances of the LISN, we can find  $V_{cm1}(L)$  and  $V_{cm2}(L)$  in which  $V_{cm1}(L)=(I_{cm1}(L)+I_{cm2}(L))*Z_3+I_{cm1}(L)*Z_1$  and  $V_{cm2}(L)=(I_{cm1}(L)+I_{cm2}(L))*Z_3+I_{cm2}(L)*Z_2$ . The unknowns are the  $V_{cm1}(0)$  and  $V_{cm2}(0)$ . To verify the CM current propagation model, we compare the CM currents at the source end. Since the LISN is balanced,  $V_{cm1}(L)$  and  $V_{cm2}(L)$  are almost equal and  $I_{cm1}(L)$  and  $I_{cm2}(L)$  are almost equal, so we just need to compare the simulated and measured currents for  $I_{cm1}(L)$ . Fig. 14 shows the comparison of the measured and simulated CM currents in the Live wire at the source end. The two graphs matching each other serve as a good verification for the CM current propagation model.

## V. CONCLUSIONS

In this research, a RF electromagnetic disturbance model for the PLC networks has been proposed based on the multi-conductor transmission line theory. This model uses a three-wire power line cable as it is a more accurate representation of the actual power line network. The distributed per-unit-length DM and CM propagation parameters for the power line cable are derived based on the properties of the power line cables. Next, the chain parameter matrix for any length of the power line cables can be calculated. Once we know the DM and CM currents and voltages at one end of the power line, the level of DM and CM voltages at any point of the power line cable for different loading conditions can be estimated with reasonable accuracy.

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