Experimental Characterization of Power Cables in the FCC Frequency Band

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Abstract

The measurements of common properties of the propagation channel is a topic of great importance for narrow band power line communication (PLC) systems in the frequency band between 9 kHz and 500 kHz (the larger FCC band). In this paper, we focus on the characterization of power distribution cables. The cable technology covered by this study is the important sub-group of underground cable. Two approaches to characterize the cable was presented. The approach that allows obtaining the complete model with the coupling phenomena is used to model the cable. The transfer functions of the different transmission lines including coupling between the lines are obtained and evaluated.

Index Terms

Attenuation, Coupling, Low voltage network, Modal transformation, Power cable, Power Line Communication, Primary parameters, Transfer function, Transmission Line Theory.

I. INTRODUCTION

Modeling the PLC channel (electrical networks) is a difficult task because the final channel model must take into consideration various parameters such as network topology, power cable technologies and length, as well as loads connected to the network [1-2]. The physical phenomena observed within the electric cables, such as the skin effect and proximity effects, are often represented by an equivalent circuit diagram with distributed primary parameters [3-4]. The primary parameters are matrices [R], [L], [C] and [G] of the circuit. Where [R], [L], [C] and [G] are matrices of linear resistance (Ohm / m), inductance (H / m), capacitance (F / m) and conductance (S / m) respectively. These frequency dependent parameters can be obtained in three different ways: by use of analytical formulations, simulations or from measurements. However, as the analytical formulations found in the literature do not fit the geometry of the studied power cables, we adopt the approach of measuring their primary parameters. The matrices of the primary parameters are considered balanced (assuming that the cable is reciprocal). The cable is composed of three different transmission lines (NPi) composed of a neutral and three phases. This characterization can be carried out in two ways:

- Characterization of simple lines (CSL): at low frequencies, power cables can be characterized as two-wire lines assuming that the coupling between adjacent conductors is negligible. The application of this approach to the characterization of power cables is shown in [3]
- Characterization of coupled lines (CCL): the power cable composed of 3 coupled transmission lines, where the coupling effect may be important in the larger FCC band. In the case of an N-conductors transmission line, the primary parameters become non-diagonal matrices because of the mutual inductive and capacitive components induced by the. We therefore consider a matrix model with a modal approach whose parameters are frequency-dependent [4-5]. In this paper, in order to define a complete model considering all phenomena, skin effect, proximity effect and coupling, the CCL approach is used to obtain the characteristics of the underground cable in the frequency band of interest.

II. MEASURING PRIMARY PARAMETERS

The primary parameters matrices are as follows:

$$[R]=\begin{bmatrix}R_1 & 0 & 0\\ 0 & R_2 & 0\\ 0 & 0 & R_3\end{bmatrix} \;;\; [L]=\begin{bmatrix}L_1 & M_{12} & M_{13}\\ M_{21} & L_2 & M_{23}\\ M_{31} & M_{32} & L_3\end{bmatrix} \;;\; [C]=\begin{bmatrix}C_1 & C_{12} & C_{13}\\ C_{21} & C_2 & C_{23}\\ C_{31} & C_{32} & C_3\end{bmatrix} \;;\; [G]=\begin{bmatrix}G_1 & 0 & 0\\ 0 & G_2 & 0\\ 0 & 0 & G_3\end{bmatrix}$$

Where Ri (i = 1, 2 or 3) corresponds to the resistance of conductor i. In the matrix L, the diagonal parameters Li correspond to the self-inductance of the conductors and non-diagonal terms Mij correspond to mutual inductance between two conductors i and j. In the matrices C and G, the terms Ci and Gi correspond to the capacity and conductance between the neutral and the conductor i, while the parameters Cij correspond to the capacity between the conductors i and j. The cable characterization method consist on measuring, with an LCR-meter, the access impedance of the transmission line inputs when the end is short circuited (Zin_cc), to obtain the resistance and the inductance, and open circuited (Zin_co), to obtain the capacity and the conductance [1]. Twelve measures are necessary to achieve the 18 parameters composing the CCL model: 3 resistances, 3 inductances, 3 mutual inductances, 3 capacitances, 3 mutual capacitances and 3 conductances.

The configuration measurement to obtain the resistances and the self-inductances is shown in Fig. 1-a. The resistance and inductance are obtained from equation 1 and the results are illustrated in Fig 3-a and 3-b respectively:

$$R_i = Real(Z_{in-cc}) \quad ; \quad L_i = \frac{Imag(Z_{in-cc})}{\omega} \; (1)$$

For the mutual inductances and as the procedure is the same to obtain all parameters: M12, M13 and M23, only the procedure to obtain M12 is presented. The configuration measurement is shown in Fig. 1-b. The voltages at the input of the lines 1 and 2 according to the configuration illustrated in Fig. 1-b are:

$$\begin{cases} V_1 = R_1 I_1 + jL_1\omega I_1 + jM_{12}\omega I_2 \\ V_2 = R_2 I_2 + jL_2\omega I_2 + jM_{12}\omega I_1 \end{cases} (2)$$

The transmission line NP2 is short-circuited:

$$I_2 = -\frac{jM_{12}\omega}{jL_2\omega + R_2} I_1 \;\; (3)$$

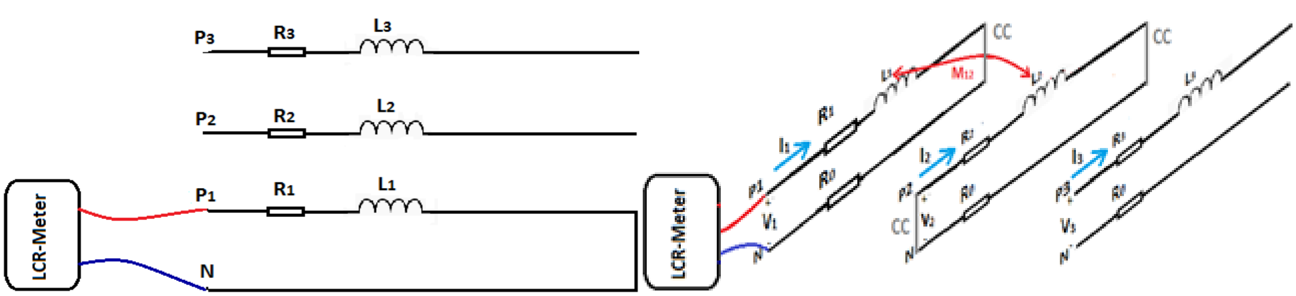
The inductance obtained from the measured access impedance in the configuration illustrated in figure 1-a is “Le1”. From (2) and (3), the mutual inductance M12 can be expressed as follows:

$$M_{12} = \sqrt{\frac{L_{e1}R_2^2}{L_2\omega^2} + L_{e1}L_2 - \frac{L_1R_2^2}{L_2\omega^2} - L_1L_2} \;\; (4)$$

Other mutual inductances are obtained by applying the same procedure:

$$M_{13} = \sqrt{\frac{L_{e2}R_3^2}{L_3\omega^2} + L_{e2}L_3 - \frac{L_1R_3^2}{L_3\omega^2} - L_1L_3} \quad ; \quad M_{23} = \sqrt{\frac{L_{e3}R_3^2}{L_3\omega^2} + L_{e3}L_3 - \frac{L_2R_3^2}{L_3\omega^2} - L_2L_3} \;\; (5)$$

The results of mutual inductances re illustrated in Fig. 3-b.



(a) (b)

Figure 1: configuration measurements to obtain resistance and inductance matrices

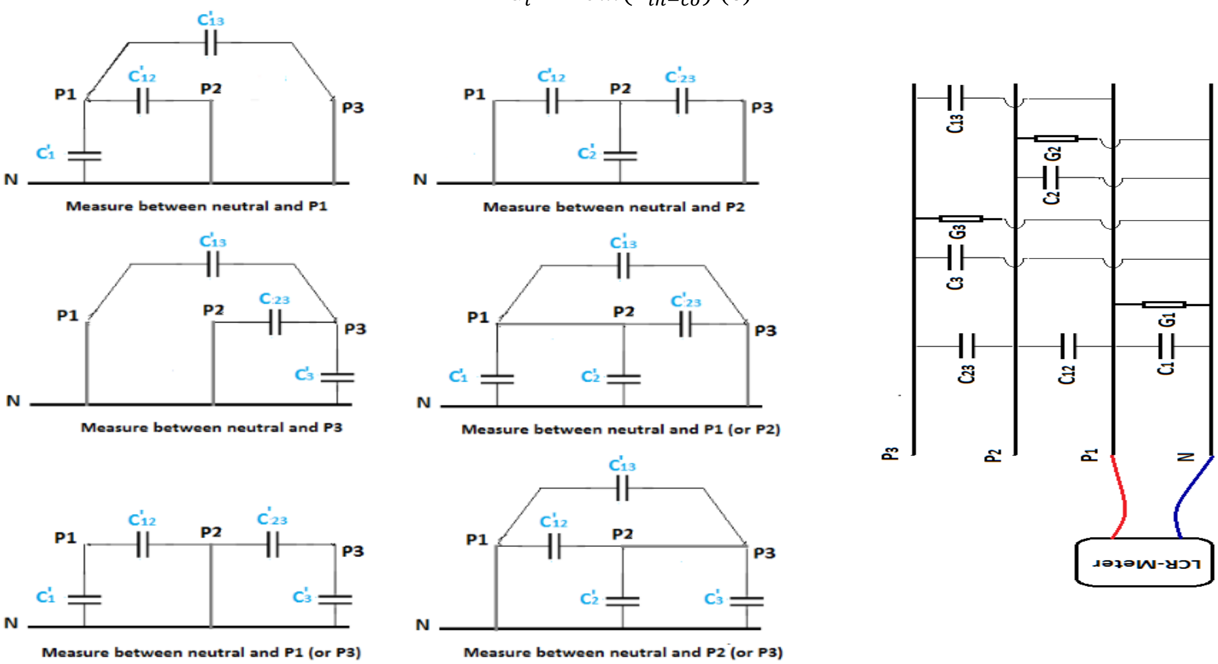
The matrix C is calculated from solutions of an electrostatic problem. The steps involve the resolution for loads on lines with voltages provided on the conductors [4]. The capacity matrix is therefore as follows:

$$[C] = \begin{bmatrix} C_1 & C_{12} & C_{13} \\ C_{21} & C_2 & C_{23} \\ C_{31} & C_{32} & C_3 \end{bmatrix} = \begin{bmatrix} \sum_{j=1}^{3} C'_{1j} & -C'_{12} & -C'_{13} \\ -C'_{12} & \sum_{j=1}^{3} C'_{2j} & -C'_{23} \\ -C'_{13} & -C'_{23} & \sum_{j=1}^{3} C'_{3j} \end{bmatrix} (6)$$

To obtain the 6 capacities, the corresponding configuration measurements is shown in Fig. 2-a. The result is illustrated in Fig. 3-c. The measurement procedure which allows to obtain the conductances is illustrated in Fig. 2-b and the results in Fig

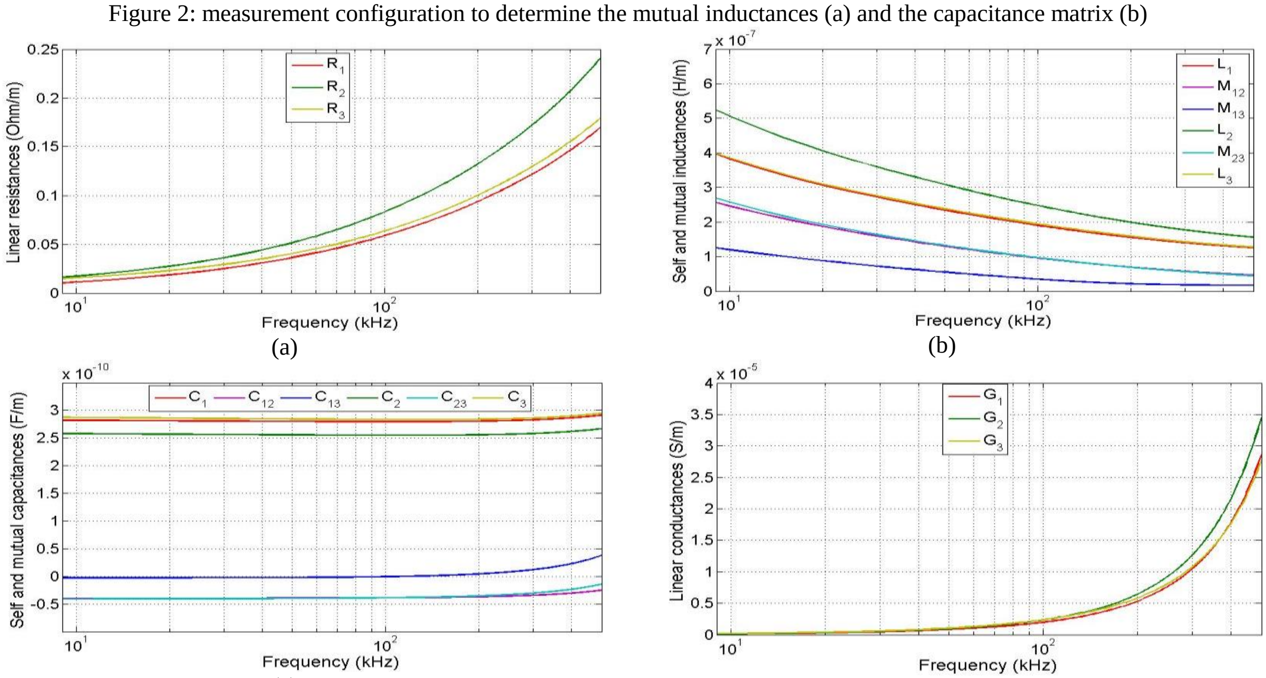
3-d. The conductances are obtained as follows:

$$G_i = Real(Z_{in-co}) \quad (6)$$



(a) (b)

Figure 2: measurement configuration to determine the mutual inductances (a) and the capacitance matrix (b)



(a) (b) (c) (d)

Figure 3: Resistance (a), inductance (b), capacitance (c) and conductance (d) matrices

The linear resistances increase fast with frequency because of the skin effect. Both self and mutual inductances decrease fast with frequency (factor 3 between 9kHz and 500kHz) because the skin effect decrease the magnetized volume and consequently the inductance. Both self and mutual capacitances increase at high frequencies. The mutual capacitances increase fast than self-capacitances. Which means that the difference between self and mutual capacitances decreases in high frequency that it results in higher capacitive coupling. The conductances increase fast with frequency because of the dielectric losses.

III. TRANSFER FUNCTION

The primary matrices will be used to obtain the transfer function model of the cable using ABCD matrices and the modal transformation [6]. The transfer function of the CCL approach for the underground cable is illustrated in Fig. 4. An assessment of the importance of coupling will be made from obtaining the transfer function between different lines. The transfer function will also be a matrix whose diagonal is the transmission between the inputs and outputs of the same transmission lines (NPi-NPi) and the non-diagonal parameters are the results of transmission due to coupling (NPi-NPj). The influence of the cable length on the coupling will also be presented. As the NP1 and NP3 are symmetric, only NP1 and NP2 are analyzed. Fig. 4-a illustrates the results of transmitting and receiving on NP1 (left) and NP2 (right). Fig. 4-b shows the result of the transfer function between NP1 and NP2/NP3 (left/right) when the generator is on NP1. Fig. 4-c is the result of the transfer function between NP2 and NP1/NP3 (left/right) when the generator is on NP2. It is observed that the coupling increases with frequency. It is also observed that in some conditions the coupling can be greater than the signal on the principal transmission line, e.g. at 500kHz for a cable of 500m, while transmitting on NP1, the signal received on NP2 is -32dB and the signal received on NP1 is -37dBm.

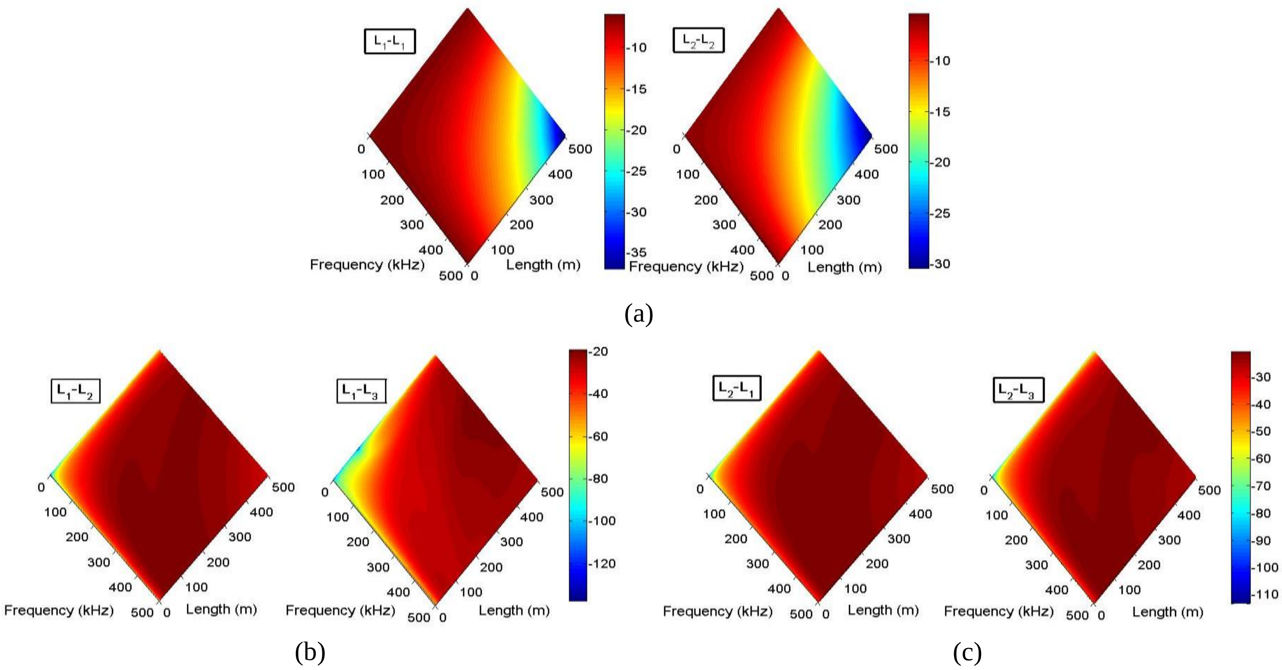


Figure 4: Transfer function when transmitting and receiving on the same line (a), coupling transfer function when transmitting on line 1 (a) and line 2 (b)

IV. CONCLUSIONS

This paper presents an experimental study on the characterization of low voltage distribution four-conductor underground cable in the frequency range 9 kHz – 500 kHz while the coupling between the transmission lines composing the cable is not neglected. The configuration measurements to obtain the primary parameters where presented and their frequency-dependent behavior was obtained. These parameters where then used to simulate the different transfer functions of the cable corresponding to transmission and reception between different transmission line. The results confirmed the importance of working with a model taking into account the coupling. These results can help the power line communications by providing a complete model of the cable network and to study in with configuration length/cable technology/boundary conditions the communication is optimized.

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