High-frequency characterization of a Medium Voltage PLC transmission system

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Abstract

The applications of Power-line communication (PLC) technology in medium voltage (MV) distribution networks are mainly related to the monitoring, control and metering functionalities. In order to design a robust communication system for MV-PLC grid, the frequency response of the channel and coupling devices has to be investigated. Scope of this paper is to present a theoretical model for a MV power-line system based on transmission line theory and to demonstrate its correctness by means of measurement results; the obtained results are in good agreement with the theoretical predictions.

Index Terms

MV-PLC, MV cable, transmission line theory.

I. INTRODUCTION

In the last years, medium voltage (MV) power network has changed its primary role. Its passive architecture has been replaced by an active one due to the wide diffusion of the dispersed generation (DG) [1]. Moreover it has been seen a progressive distribution of the protection, automation and control functions needed for its management. In order to support this evolution, a distributed reliable and broadband communication network is needed as well. This can be implemented using different transmission technologies like fiber optic, Global System for Mobile communications (GSM) or power line communication (PLC) systems. Among these, PLC system has the main advantage to be a low cost solution as it provides communication services through an existing infrastructure. Moreover, PLC system can be owned by the power suppliers. The drawback is that the power line has not been designed for communication purpose. As a consequence, in order to design a robust communication scheme over a medium voltage network, the knowledge of the frequency response of the channel and the coupling devices is of primary interest. In the distribution network, the coupling devices are an important element as they are the physical connection between the PLC device and the power line. Compared to the inductive couplers, the capacitive devices are more intrusive but their behaviour is independent from the status of the switches. Furthermore, in order to provide a broadband communication channel, the frequency range of $1 − 20$ MHz needs to be characterized. A similar work on the CENELEC bands [2] has been proposed in [3].

This paper is organised as follow: first, a theoretical model of the communication system is presented, subsequently the experimental measurements are exposed and compared with the model.

II. THEORETICAL MODEL

Fig. 1 shows the block diagram of the analyzed PLC system. At the transmitter side, in order to link the signal generator to the MV PLC channel, a capacitive coupling device, represented by means of three functional blocks, has been used. An impedance adapter device, shown in Fig. 1 by the non-ideal transformer with transmission matrix $[T]_T^T$ and turns ratio $N_1/N_2$ is used to match the complex impedance of the MV line and the output impedance $Z_S$ of the signal generator. Moreover, the high-pass filtering behaviour of the coupling circuit, formed by the drain coil $L_T$ and the coupling capacitor $C_T$, is modeled as a cascade of the transmission matrices $[T]_L^T$ and $[T]_C^T$. When the signal wavelength is significantly longer than the conductor length, a
Finally, given a section has been carried out with a network analyzer HP 8753C by Agilent. The transmission line parameters R, L, C, and G of per unit length are modeled as

$$Z = \sqrt{(R(f) + j\omega L)/(G(f) + j\omega C)}$$

and the propagation coefficient

$$\gamma = \sqrt{(R(f) + j\omega L)(G(f) + j\omega C)}$$

The ABCD coefficients [6] of the transmission matrix $[T]_h$ take on the following expression:

$$[T]_h = \begin{bmatrix}
\cosh(\gamma \ell) & z_C \sinh(\gamma \ell) \\
\frac{1}{z_C} \sinh(\gamma \ell) & \cosh(\gamma \ell)
\end{bmatrix}$$  \hspace{1cm} (1)

where $\ell$ is the length of the considered line. At the receiver side, an equivalent scheme used at the transmitter is considered. As a consequence, the overall transmission matrix can be written as

$$[T] = [T]_F^T \cdot [T]_E^T \cdot [T]_h \cdot [T]_R^T \cdot [T]_L^T$$

Finally, given $[T]$, it is possible to write the scattering parameter $S_{21}$ of the overall system in terms of its element $t_{i,j}(f, \ell)$ with $i, j = 1, 2$ [6], as

$$S_{21}(f, \ell) = \frac{2Z_0}{t_{11}(f, \ell)Z_0 + t_{12}(f, \ell) + t_{21}(f, \ell)Z_0^2 + t_{22}(f, \ell)Z_0}$$  \hspace{1cm} (2)

where $Z_0$ is equal to the source and load impedances (i.e., $Z_0 = Z_S = Z_L$). It is worth highlighting that each element $t_{i,j}(f, \ell)$ of the overall transmission matrix $[T]$ is a function of the frequency along with the length $\ell$ of the MV PLC channel.

### III. Simulation and Measurement Results

First of all, a characterization of MV RG7H1R cable insulated with polyethylene with an aluminium core of 95 mm$^2$ cross-section has been carried out with a network analyzer HP 8753C by Agilent. The transmission line parameters R, L, C, and G of a 10 m length cable have been measured with the open-short circuit method [5]. Given the measurement results, the resistance per unit length $R(f)$ is assumed proportional to the square root of the frequency, i.e., $R(f) = \sqrt{0.0012 \cdot 10^{-6} f}$ Ohm/m, the conductance per unit length is modeled as $G(f) = 0.24 \cdot 10^{-6} + 1.072^{-5} \cdot 10^{-6} f$ S/m whereas the inductance $L$ and the capacitance $C$ per unit length are almost constant in the explored frequency range, respectively 170 nH/m and 240 pF/m. Figures 2 and 3 show the measured and the calculated $R(f)$ and $G(f)$ in the frequency range of 300 kHz-30 MHz.

Moreover, Fig. 4 compares measured and simulated values of the characteristic impedance $Z_C$ for the considered 10 m length MV RG7H1R cable: Table I lists the parameters of the coupling devices used in the experiment.

Finally, the model depicted in Fig. 1 has been simulated with the values of R, L, C, and G previously calculated and the results have been compared with the measurements carried out over a real system using a MV cable of length $\ell = 0$ m (i.e., coupling devices only) and $\ell = 150$ m. Fig. 5 compares the values of the two port scattering parameter $S_{21}$ measured with the network analyzer HP 8753C with the simulated ones: from Fig. 5 one can conclude that the theoretical model and the experimental results are in good agreement for frequencies up to 20 MHz. Furthermore, given the correctness of the proposed model, it has been possible to predict the $S_{21}$ parameter for cables of $\ell = 1000$ m length.

### TABLE I: Capacitive coupling device parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Transformer ratio ($N_1/N_2$)</td>
<td>0.5</td>
</tr>
<tr>
<td>$C_T = C_R$</td>
<td>260 pF</td>
</tr>
<tr>
<td>$L_R = L_T$</td>
<td>20 µH</td>
</tr>
</tbody>
</table>

Fig. 2: Comparison between the calculated and measured resistance per unit length for a 10 m length MV RG7H1R cable.

Fig. 3: Comparison between the calculated and measured conductance per unit length for a 10 m length MV RG7H1R cable.
Fig. 4: Characteristic impedance $Z_C$ for the MV RG7H1R cable.

Fig. 5: Power-line MV cable $S_{21}$ parameter obtained from the theoretical model and measurement results.

IV. Conclusion

A theoretical model for a medium voltage (MV) power-line system (coupling circuit and MV cable) has been derived in terms of its transmission matrix and scattering parameters. In order to validate the theoretical model, the scattering parameter $S_{21}$ of a real power-line MV cable has been measured: the obtained results are in good agreement with the theoretical predictions up to 20 MHz.

References