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Modeling and evaluation of power line for Smart grid communication

***Abstract**. This paper presents nowadays power line using for Smart grid application. Paper illustrated the development of theoretical and experimental study of power line cables characteristic in the frequency range 10 kHz–10 MHz. Primarily, it is focus on a realization of a power line model.*

***Streszczenie.** W artykule przedstawiono zastosowanie technologii Smart Grid na przykładzie sieci kablowej wykorzystywanej w paśmie 10 kHz – 10 MHz. **(Modelowanie i badanie sieci przesyłowej wykorzystywanej do komunikacji w technologii Smart Grid**)*

Keywords: Smart grid, power line, multipath propagation, two-port network.
Słowa kluczowe: Smart Grid. PLC – power line communication

Introduction

Power line communication (PLC) is a communication technology proposed as an integration service system on electric power networks for the transmission of information (voice, images, and data). This technology does not involve any installation costs or any special maintenance, because the existing cables of the power line are used. The operating rules of PLC systems can be summarized as follows: a high frequency signal is injected into a power line with a coupling device.

In Europe, the available frequency intervals for communication systems in low voltage (LV) and medium voltage (MV) power networks are established by CENELEC EN 50065-1 [1].

As a result of recent developments, the electrical power supply system is on the way to migrate from a pure energy distribution network to a multipurpose medium delivering energy, voice, and various data services [2]. Nowadays, most technical effort is concentrated on LV power line channels owing to the huge development of PLC in smart metering, smart grid and remote data acquisition [3].

The power line network differs considerably in topology, structure, and physical properties from conventional media such as twisted pair, coaxial, or fiber-optic cables. Therefore PLC systems have to encounter rather hostile properties [4]. For computer simulations oriented to appropriate system design, models of the transfer characteristics of the mains network are of major interest.

Although some model proposals can be found in literature, their practical value is generally very limited, because most of them represent only PLC model without noise model and assembling complex PLC communication model. The complex PLC communication model enables comparison of the performance of different modulation and coding schemes and for future standardization for Smart grid application.

In contrast to the known approaches, this paper outlines a top-down strategy considering the communication channel as a black box and describing its transfer characteristics by a frequency response $H(f)$. There are two possible methods for the modeling of power line channels as a black box. The first one applies the methods used for the modeling of radio channels. The power line channel is assumed to be a multipath propagation environment. The second alternative applies the methods used to model electricity distribution networks. The chain parameter matrices describing the relation between input and output voltage and current of two-port network can be applied for the modeling the transfer function of a communications channel.

In this paper, first the PLC using for Smart Grid is described. Secondly, a simplified model of transmission line is proposed. Thirdly, some theoretical observations are made on the parameters of PLC cables and relevant input parameters for power line model were calculated and measured for different cables. Finally, a power line model is design and simulation results are reported.

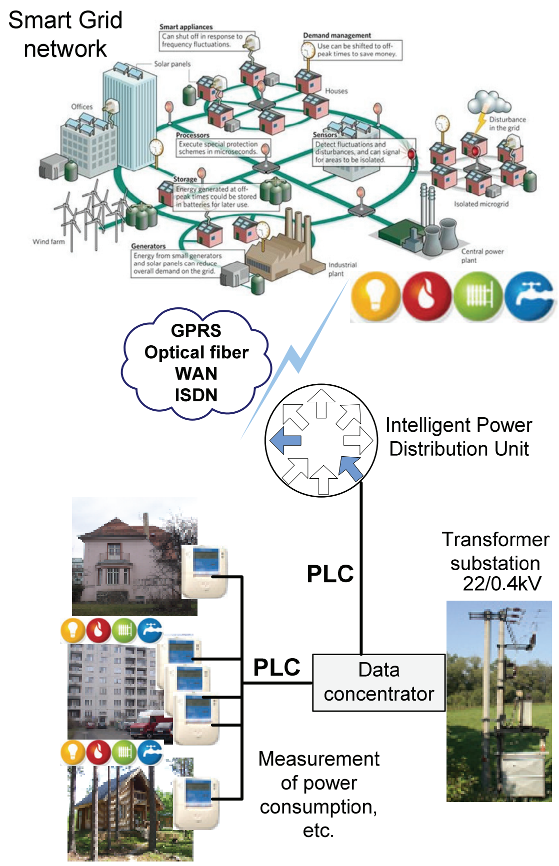

Fig.1. An example of the smart grid network

Smart grid

The term Smart Grids describes how to access the implementation of the processes of production, transmission, distribution and consumption of electrical energy (primary technology). Smart Grids affects processes in the primary technologies, but especially those related to secondary technologies - monitoring, management, process automation, diagnostics, and primary and secondary technology maintenance.

A specific feature of conventional energy grids is that they distribute energy in a one-way fashion. Communication infrastructure enables two-way communication of information in accordance with the transmission of electricity.

Increasing use of Smart grid is made of the possibilities of energy network management through telemetry, remote data acquisition of electrometers, power quality monitoring, on-line modes, supervisor centers for network operations, and unattended electric substation.

The Smart grids solution in power engineering deal with a large area, where is necessary to solve a number of problems. One of these problems are appropriate communication channels for two-way communication. Power lines, WAN, GPRS, ISND and fiber optic are possible, see Fig. 1. This article focuses on power line. PLC systems do not require any specific cabling because the terminal equipment is connected directly to the power network.

There are a lot of failings for widely using of this technology. An interference of useful signal, smaller range of useful signal and equipments of energy network are the main. From the analysis of partial problems, there is a better to have a mathematical computer model of power line which it would enable a simulation of data transmission with power lines.

Transmission line theory

In literature the methods used to simulate and to study the transmission line behavior are different [5]. Most of them are obtained from the time dependent telegrapher's equations which are for the elementary line transmission cell, shown in Fig.2, the following:

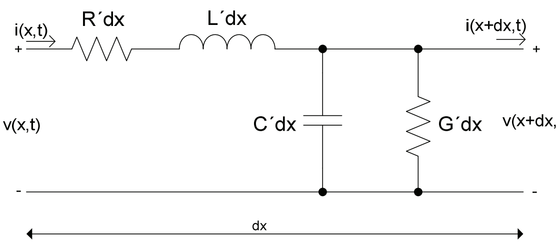

Fig.2. Elementary cell of a transmission line

(1) $$\frac{\partial v(x,t)}{\partial x} + R' i(x,t) + L' \frac{\partial i(x,t)}{\partial t} = 0$$

(2) $$\frac{\partial i(x,t)}{\partial x} + G' v(x,t) + C' \frac{\partial v(x,t)}{\partial t} = 0$$

In these equations *x* denotes the longitudinal direction of the line and *R', L', G'* and *C'* are the per unit length resistance (Ω/m), inductance (H/m), conductance (S/m) and capacitance (F/m) respectively. The electric quantities are dependent by the geometric and constitutive parameters.

The parameters to describe a transmission line are the characteristic impedance Z_c and the propagation constant γ:

(3) $$Z_C = \sqrt{\frac{R' + j\omega L'}{G' + j\omega C'}}$$

(4) $$\gamma = \alpha + j\beta = \sqrt{(R' + j\omega L')(G' + j\omega C')} \ .$$

Theoretical analysis of PLC cable

Considering the case of single-phase distribution, the structure depicted in Fig. 3 comprises a phase conductor, the neutral and the ground one. Each conductor is surrounded by its insulation coating.

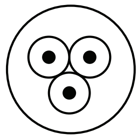

Fig.3. Cable cross-section

This cable is being described by distributed parameters *R', L', G' and C'* denoting respectively per unit length series resistance, series inductance, shunt conductance and shunt capacitance of the line, defined as in Fig.2. For modeling purposes, any of the cable types described above is regarded as a two-conductor plus reference wire transmission line, with surrounding dielectric material of relative dielectric constant ε_r.

Transmission line's configuration specified above – parallel two-conductor plus reference wire cable, having solid conducting cores and being surrounded by the same dielectric material – gives the following distributed parameters:

(5) $$R' = \sqrt{\frac{\mu_r \mu_0 f}{\pi \sigma a^2}} \left[\frac{\frac{d}{2a}}{\sqrt{\left(\frac{d}{2a}\right)^2 - 1}} \right]$$

(6) $$L_{ex} = \frac{\mu_r \mu_0}{\pi} cosh^{-1}\left(\frac{d}{2a}\right); L_{in} = \frac{R}{2\pi f}; L' = L_{in} + L_{ex}$$

(7) $$C' = \frac{\pi \varepsilon_r \varepsilon_0}{cosh^{-1}\left(\frac{d}{2a}\right)}$$

(8) $$G' = 2\pi f C \tan \delta$$

where α the conductors' radius (taken equal for all three), d the distance between the centres of phase and neutral conductors, ε_r the relative dielectric constant of the surrounding dielectric material, $\tan\delta$ its dissipation factor and μ_r its relative magnetic permeability [6].

Experimental set-up a measurement results

The measurements were carried out with a HP analyzer 4192A, operating in the frequency range 5 Hz–13 MHz. The frequency field investigated was from 10 kHz to 10 MHz according to the EN 50065-1 [1]. This frequency range includes the fixed CENELEC band 95 kHz–148.5 kHz.

Cable CYKY 3x1,5 , 3x2,5 a 3x4 [7] were examined. Fig. 4 shows the measurements of the longitudinal parameters *R'(f)* and *L'(f)* and cross parameters *C'(f)* and *G'(f)*.

There are two different approaches for calculation the parameters describing a transmission line. First, measuring the per-unit parameters *R'(f), L'(f), C'(f)* and *G'(f)* values to obtain the Z_C and γ parameters by using the expressions (3) and (4). Second, estimate the impedance magnitude Z_C and the propagation constant γ, (3) and (4) were employed, taking into account the geometrical dimensions [7] and equations (5-8).

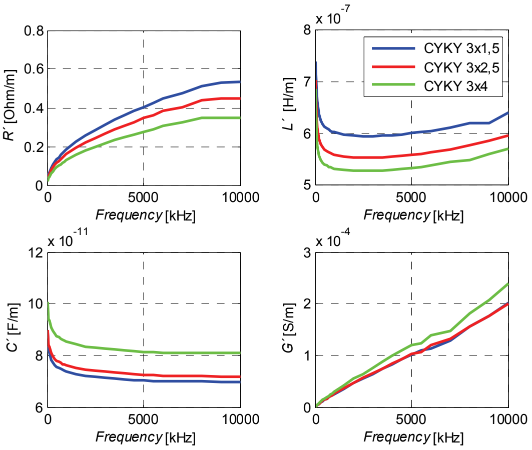

Fig.4. Measurement values of longitudinal parameters $R'(f)$ and $L'(f)$ and cross parameters $C'(f)$ and $G'(f)$.

Fig. 5 shows the magnitude of impedance Z_C and the propagation constant γ measured and estimated in the frequency range 10 kHz –10 MHz for the CYKY 3x2,5 cable.

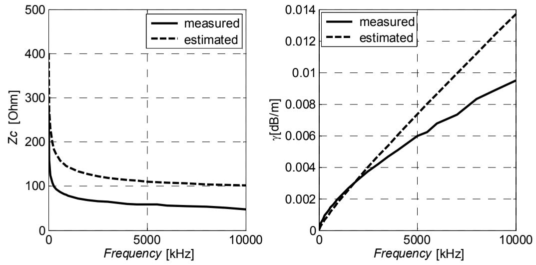

Fig.5. Magnitude of impedance Z_C and the propagation constant γ, measured and estimated for CYKY 3x2,5 cable

It can be observed that there is good agreement between the Z_C and γ values measured and estimated by the geometrical dimensions. A comparison shows that the magnitude characteristic and the propagation constant are slightly higher for estimated values.

Power line model for Smart grid network

The power line channel model is required to simulate PLC communications characteristic for Smart grid using. For the purpose of modeling, PLC communication system can be set up from PLC communication model, power line model and noise model. This article focuses on the realizations of power line model. Power line model is the main part of complex PLC communication system, other part are describe in [8].

Transfer function for multipath propagation environment

Multiple reflections at impedance discontinuities are typical for power line channels, there are caused multipath propagation. This behavior can be described by a model of the channel in Fig. 6 [4]. Each transmitted signal arrives in the receiver via N different paths. Each path i is defined by a certain delay τ_i and a certain attenuation factor C_i. The power line channel can be described by means of a discrete-time impulse response $h(t)$. The impulse response of the channel $h(t)$ can be written as a sum of the delayed and attenuated Dirac pulses:

(9) $$h(t)=\sum_{i=1}^{N} C_i\cdot\delta(t-\tau_i) \Leftrightarrow H(f)=\sum_{i=1}^{N} C_i\cdot e^{-j2\pi f\tau_i}.$$

The transfer function with multipath signal propagation can be written:

(10) $$H(f)=\sum_{i=1}^{N} g_i\cdot A(f,l_i)\cdot e^{-j2\pi f\tau_i},$$

where g_i is a weighting factor representing the reflection and transmission factors along the path and $A(f,l_i)$ is attenuation factor derived from characteristics of PLC transmission cable CYKY 3x2,5 (see Fig. 4, Fig. 5).

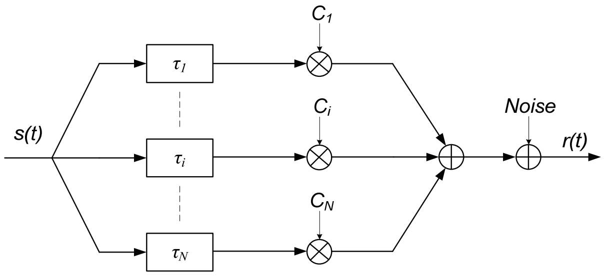

Fig.6. Multipath signal propagation representing power line channel

Transfer function of two-port network

The chain parameter matrices describing the relation between input and output voltage and current of two-port network can be applied for the modeling the transfer function of a power line channel.

In Fig. 7, the relation between input voltage and current and output voltage and current of a two port network can be represented as:

(11) $$\begin{bmatrix} U_1 \\ I_1 \end{bmatrix}=\begin{bmatrix} A & B \\ C & D \end{bmatrix}\begin{bmatrix} U_2 \\ I_2 \end{bmatrix}$$

where A, B, C and D are frequency dependent coefficients.

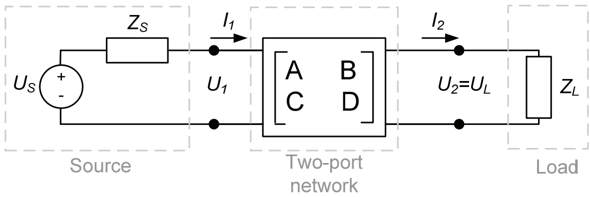

Fig.7. Two-port network connected to a source and load

The transfer function of two-port network is given by equation [9]:

(12) $$H=\frac{U_L}{U_S}=\frac{Z_C}{AZ_C+B+CZ_CZ_S+DZ_S}$$

The ABCD matrix for the transmission line with characteristic impedance Z_c, propagation constant γ and a length l can be calculated as [9]:

(13) $$\begin{bmatrix} U_1 \\ I_1 \end{bmatrix}=\begin{bmatrix} \cosh(\gamma l) & Z_C\sinh(\gamma l) \\ \frac{1}{Z_C}\sinh(\gamma l) & \cosh(\gamma l) \end{bmatrix}\begin{bmatrix} U_2 \\ I_2 \end{bmatrix}$$

Sample network

The simple distribution network topology is shown in Fig. 8. The link has one branch and consists of the segments (1), (2) and (3) with the lengths l_1, l_2 and l_3 and the characteristic impedance Z_{C1}, Z_{C2} a Z_{C3}.

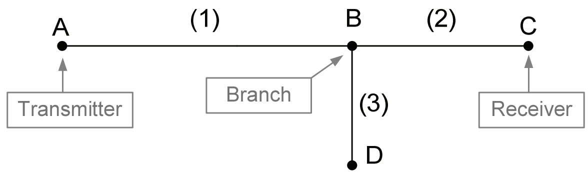

Fig. 8. Topology of the sample network

The transmitter and receiver are impedance matching, which means $Z_A=Z_{C1}$, $Z_C=Z_{C2}$. The appliance on the branch has different impedance than the cable, therefore the reflection occur here.

The parameters of the channel are acquired based on the topology of the distribution network and characteristics of PLC transmission cable CYKY 3x2,5 (see Fig. 4, Fig. 5). On the basis of these parameters we can make a calculation of characteristic impedance and propagation constant for each network segment.

The points for reflection are B and D with the reflection factor [10]:

$$r_{1B}=\frac{\dfrac{Z_{C2}\cdot Z_{C3}}{Z_{C2}+Z_{C3}}-Z_{C1}}{\dfrac{Z_{C2}\cdot Z_{C3}}{Z_{C2}+Z_{C3}}+Z_{C1}} \tag{14}$$

$$r_{3D}=\frac{Z_D-Z_{C1}}{Z_D+Z_{C1}} \tag{15}$$

$$r_{3B}=\frac{\dfrac{Z_{C2}\cdot Z_{C1}}{Z_{C2}+Z_{C1}}-Z_{C3}}{\dfrac{Z_{C2}\cdot Z_{C1}}{Z_{C2}+Z_{C1}}+Z_{C3}} \tag{16}$$

It is also necessary to calculate the transmission factor [10]:

$$t_{1B}=1-\left|r_{1B}\right|;t_{3B}=1-\left|r_{3B}\right| \tag{17}$$

The possible propagation paths from transmitter to receiver are shown in Table 1.

Table 1: Propagation paths.

Path No.	Way of the path	Weighting factor g_i	Length of path d_i
1	A→B→C	t_{1B}	l_1+l_2
2	A→B→D→B→C	$t_{1B}\cdot r_{3D}\cdot t_{3D}$	$l_1+2l_3+l_2$
N	A→B (→D→B)$^{N-1}$ →C	$t_{1B}\cdot r_{3D}\cdot (r_{3B}\cdot r_{3D})^{(N-2)}\cdot t_{3D}$	$l_1+2(N-1)l_3+l_2$

Each path i has a weighting factor g_i, representing the product of the reflection and transmission factors along the path. The delay τ_i of a path can be calculated from the length d_i, the speed of light c_0 and the isolation relative permittivity ε_r:

$$\tau_i=\frac{d_i\sqrt{\varepsilon_r}}{c_0} \tag{18}$$

The signal components of the paths have to be added due to superposition and the transfer function of sample network can be expressed as:

$$H(f)=\sum_{i=1}^{N} g_i\cdot A(f,d_i)\cdot e^{-j2\pi f\tau_i} \tag{19}$$

Due to the fact that longer paths have higher attenuation they contribute less to the overall signal at the receiving point, therefore was chosen six paths.

Transfer function for cascade two-port sample network

Fig. 9 shows the transmission line with one bridge tap. We replace the bridge tap with the equivalent impedance (see Fig. 10). The branch cable terminated by the load impedance Z_{br} can be considered to be equivalent load impedance Z_{eq} [9]:

$$Z_{eq}=Z_C\frac{Z_{br}+Z_C\,tanh(\gamma_{br}d_{br})}{Z_C+Z_{br}\,tanh(\gamma_{br}d_{br})} \tag{20}$$

where Z_{br} and γ_{br} are characteristic impedance and propagation constant of the branch.

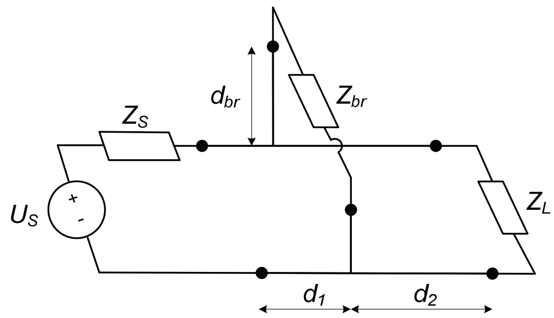

Fig. 9. Transmission line with one bridge tap connection

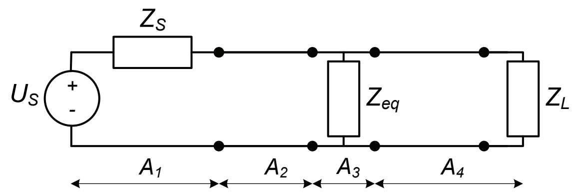

Fig. 10. Equivalent circuit for transmission line with one bridge tap connection

The channel from a source to a load consists of several network sections. Each section can be described with a single transmission matrix. The sections are serially connected. The transmission matrix A from the source to the load can be formed applying the chain rule:

$$A=\prod_{i=1}^{n} A_i \tag{21}$$

where n represents number of network sections. Fig. 10 illustrates the section for sample network. The matrices of the different sub circuits for sample network are [9]:

$$A_1=\begin{bmatrix}1 & Z_S\\ 0 & 1\end{bmatrix} \tag{22}$$

$$A_2=\begin{bmatrix}cosh(\gamma_1 d_1) & Z_1\,sinh(\gamma_1 d_1)\\ \dfrac{1}{Z_1}sinh(\gamma_1 d_1) & cosh(\gamma_1 d_1)\end{bmatrix} \tag{23}$$

$$A_3=\begin{bmatrix}1 & 0\\ \dfrac{1}{Z_{eq}} & 1\end{bmatrix} \tag{24}$$

(25) $$A_4 = \begin{bmatrix} cosh(\gamma_2 d_2) & Z_2\, sinh(\gamma_2 d_2) \\ \frac{1}{Z_2} sinh(\gamma_2 d_2) & cosh(\gamma_2 d_2) \end{bmatrix}$$

Simulation results

Fig. 11 shows the results of a simulation of the multipath signal propagation model based on transfer function (19) with six paths. The reflections at the open tap cause periodical notches in the frequency response, which can easily be seen in magnitude response in the Fig. 11.

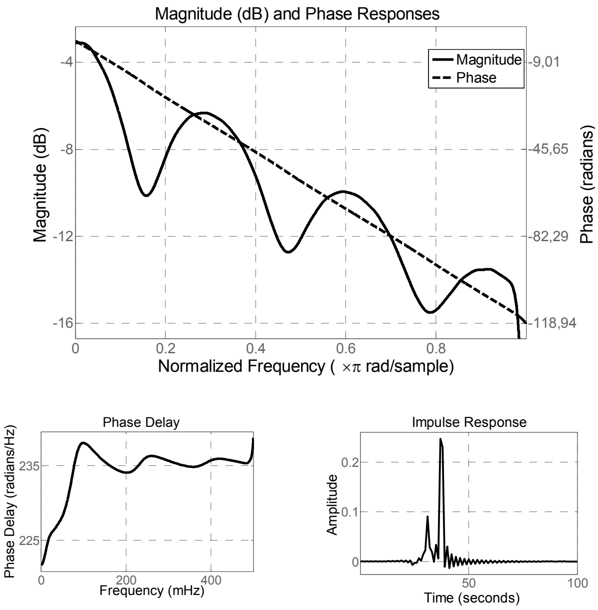

Fig.11. Simulation of the sample network with six paths

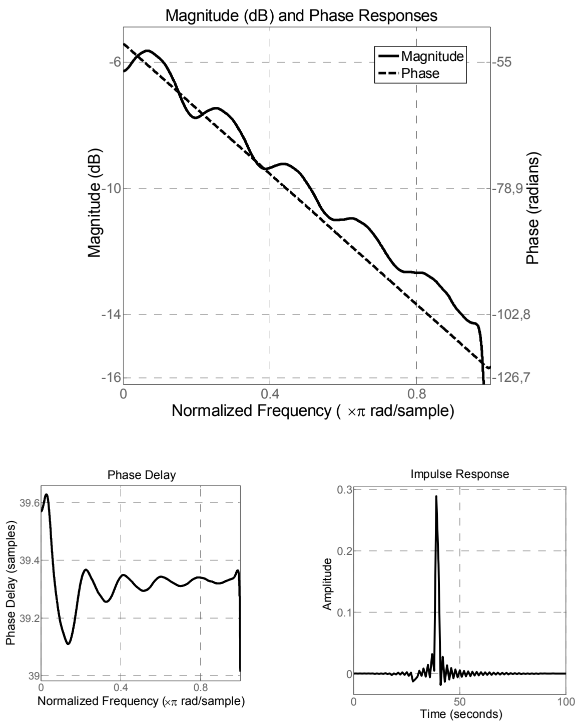

Fig.12. Simulation of the sample two-port network

Fig. 12 shows the results of a simulation of the sample network based on transfer function of two-port network model (21). The reflections at the open tap cause periodical notches in the frequency response, which can easily be seen in magnitude response in the Fig. 12.

Conclusion

The paper presents theoretical and experimental study on the characterization of PLC cables. The distributed parameters of the cable were evaluated in the frequency range 10 kHz–10 MHz. A simplified model of the transmission line is proposed, which allows one to evaluate the characteristic impedance and the propagation constant by means of the geometrical dimensions of the cable. The results of this experimental measurement and evaluation of PLC cables could be useful for power line modeling.

Next, the paper deals with design of the power line model. First, the power lines are modeled as an environment of multipath signal propagation. Second, the power lines are modeled through chain parameter describing the relation between input and output voltage and current of two-port network.

For the sample network topology was modeled power lines and the model simulation results are shown. The constructed power line model offers possibility to carry out investigations in different network topologies and study their effect on communication system.

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REFERENCES

[1] *CENELEC, "EN50065-1, Signalling on low-voltage electrical installations in the frequency range 3 kHz to 148.5 kHz".* 2008. Online: <http://www.cenelec.eu>.

[2] Mlynek, P.; Misurec, J.; Koutny, M. The communication unit for remote data acquisition via the Internet. In *Proceedings of the 7th WSEAS International Conference on Circuits, systems, electronics, control and signal processing (CSES'08).* Puerto de La Cruz, Spain: WSEAS Press, 2008. p. 168-173. ISBN: 978-960-474-035-2.

[3] Misurec, J. The Data Acquisition via PLC in Energetics. In *32nd International Conference on Telecommunications and Signal Processing - TSP' 2009. p.* 1-4. ISBN: 978-963-06-7716- 5.

[4] Hrasnica, H., Haidine, A., Lehnert, R. *Broadband Powerline Communications Network Design*. [s.l.] : Willey , c 2004. 275 p. ISBN 0-470-85741-2

[5] Dostert, K. M. Power Lines As High Speed Data Transmission Channels – Modelling the Physical Limits, *Proceedings of the 5th IEEE International Symposium on Spread Spectrum Techniques and Applications (ISSSTA 98*), 1998, pp. 585-589.

[6] Papaleonidopoulos, I.; Karagiannopoulos, C.; Theodorou, N.; Anagnostopoulos, C.; Anagnostopoulos, I. Modelling of indoor low voltage power-line cables in the high frequency range. *International Symposium on Power Line Communications and Its Applications (ISPLC).*

[7] Power cables and flexible cables. 2007. 104 p. Online:<www.draka.cz>.

[8] Koutny, M.; Misurec, J.; Mlynek, P. OFDM model for power line communication. In *Proceedings of the 4th International Communication and Technology(CIT'10).* Corfu Island, Greece: WSEAS Press, 2010. p. 161-165. ISBN: 978-960-474-207- 3.

[9] Esmailian, T; Kschischang, F; Gulak, G. In-building power lines as high-speed communication channels: channel characterization and a test channel ensemble. *International Journal of Communication Systems*. 2003.

[10] Zimmermann, M.; Dostert, K. A Multi-Path Signal Propagation Model for the Power Line Channel in the High Frequency Range. *Proceedings of the 3rd International Symposium on Power-Line Communications*, Lancaster, UK, 1999, pp. 45-51.

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