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SIMULATION OF POWER LINE COMMUNICATIONS CHANNEL USING MATHEMATICAL MODEL

In the paper, the main factors degrading a telecommunication signal transmitted over the power grid wires are identified. A mathematical model of the PowerLineCommunication (PLC) channel reflecting signal multipath and attenuation is discussed. Simulation of a real PLC channel for broadband signals transmission carried out by the authors, based on the Dossert's model, is described and the results (true LV distribution network transmission parameters, transfer function characteristic) are reported.

1. Introduction

The PLC (Power Line Communication) system enables transmission of data signals over the low voltage segment of the electrical grid from the electricity substation to the customer's home or premises. A number of technologies already exist to turn existing electrical cables into LAN wiring [2]. PLC can be perceived as an IP-type service giving electricity customers access to the Internet via existing electrical supply system. Thus, the system should transmit both the low bandwidth signals for telephony or control and the broadband ones for image transmission over electrical wires.

Electrical grid has been designed and optimized for transmission of the high or low voltages, and, after implementing the PLC technology, it would become a shared medium. Therefore, there is a number of inherent limitations to overcome: susceptibility to electromagnetic interference which affects especially the overhead lines, high frequency interference, topology in which the bandwidth of received signal is reduced as the number of customers connected to the same electrical substation increases, power cable attenuation. The main factors degrading a telecommunication signal transmitted over the power grid wires are: multipath, attenuation and noise.

To describe and to forecast the transmission characteristics of a PLC system operating on a real low voltage (LN) network, a simulation could be helpful. Such a simulation of an existing distribution network containing one branch to the customer has been carried out by the authors. For simulation purposes, the PLC channel model reported by K.Dostert [1] has been chosen in which multipath, echoes and technical parameters of cables are taken into account. After calculation of the echo and individual paths factors as well as those for technical cable parameters according to the model requirements, the amplitude characteristic of the network has been obtained...

2. Model of PLC channel–mathematical description

The amplitude characteristic of physical channel constructed on the base of the power distribution network conductors or on connections to the building is a low-pass one. Particular components of the transmitted signal reach the receiver through different paths and show different delays. Regarding these features, a model of the PLC channel in the form of delay line incorporating N branches (echoes) with variable factors c_i. has been developed by K. Dostert [1]. Its basic structure is shown in Fig. 1.

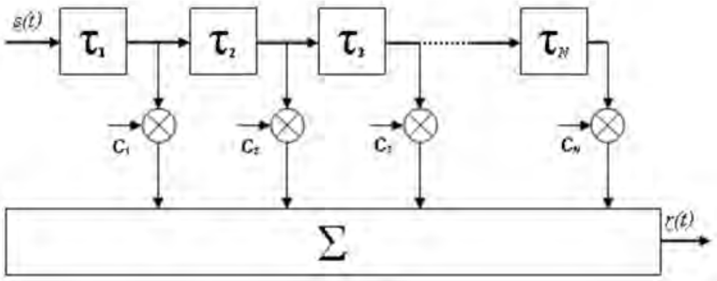

Fig. 1. Model of PLC channel with mulipath feature [1].
s(t) – input signal, r(t) – output signal, c_i. – echo attenuation factors

Input and output signals of the channel are *s(t)* and *r(t)*, respectively. Channel's impulse response to the *δ(t)* function input signal is:

$$h(t) = \sum_{i=1}^{N} c_i \cdot \delta(t - \tau_i)\,, \tag{1}$$

where t – actual time instant, N – number of echoes, τ_i – echo delay, c_i – echo attenuation.

From the channel impulse response given by (1), the channel transfer function can be found [1]:

$$H(f) = \sum_{i=1}^{N} c_i \cdot e^{-j2\pi f \tau_i}\;. \tag{2}$$

The c_i factor can be written as a function of the length l_i of the *ith* path and that of the frequency f [1]:

$$c(f, l_i) = a_i \cdot e^{-\alpha(f)\cdot l_i}\,, \tag{3}$$

where a_i – specific weighting factor reflecting network topology, and *α(f)* – product of the echo and transmission factors along the echo path.

By substituting (2) to (3) and replacing delay τ_i by quotient of the *i*-th cable length l_i and the phase velocity v_p, a complete transfer function of the modeled channel has been obtained [1]:

$$H(f) = \sum_{i=1}^{N} a_i \cdot e^{-\alpha(f)\cdot l_i} \cdot e^{-j2\pi f \frac{l_i}{v_p}}\;. \tag{4}$$

Expression (4) can be presented in more clear form:

$$H(f) = \sum_{i=1}^{N} a_i \cdot e^{-l_i(\alpha(f) + j\frac{\omega}{v_p})}\;. \tag{5}$$

Introducing physical line parameters: *R'*, *G'*, *L'* and *C'*, the propagation factor can be written down [1]:

$$\gamma = \sqrt{(R' + j\omega \cdot L')(G' + j\omega \cdot C')} = \alpha + j\beta\,, \tag{6}$$

where α – attenuation factor, β – phase factor. For frequencies of some to dozen MHz, we have $R' \ll \omega L'$ and $G' \ll \omega C'$, and the line can be considered as a weakly lossy one. For such a weakly lossy line, the complex propagation factor becomes [1]:

$$\gamma = \alpha + j\beta = \frac{1}{2}\cdot\frac{R'}{Z_c} + \frac{1}{2}\cdot G' Z_c + j\omega\sqrt{L' C'}\,. \tag{7}$$

First term of the (7) describes impact of the skin effect, second term – dielectric loss of the cable insulation. Z_c stands for characteristic impedance of the line which, for a weakly lossy line, takes more simple form given by:

$$Z_c = \sqrt{\frac{L'}{C'}}\,. \tag{8}$$

After substituting R', G', Z_c and technical transformations, the real part of (7) becomes a frequency dependent [1]:

$$\alpha(f) = \frac{1}{2} \cdot \frac{R'}{Z_c} + \frac{1}{2} \cdot G' \cdot Z_c \approx b_1 \sqrt{f} + b_2 \cdot f\,, \tag{9}$$

where factors b_1 and b_2 are of constant value depending on the cable type. Imaginary part of (9) can also be transformed in the frequency-dependent form [1]:

$$\beta = \omega \sqrt{L' \cdot C'} \approx b_3 \cdot f\,, \tag{10}$$

It is worth to note that the phase factor β changes with frequency in the linear way. Value of b_3 parameter depends on the cable type.

Regarding the equality:

$$\beta = \frac{\omega}{v_p}\,, \tag{11}$$

the quotation of pulsation and phase velocity in formula (5) can be replaced by linear frequency function given by (10).

Final form of the channel transfer function taking into account the transmission cable parameters is [1]:

$$H(f) = \sum_{i=1}^{N} a_i \cdot e^{-l_i (b_1 \cdot \sqrt{f} + b_2 \cdot f + j b_3 \cdot f)}\,. \tag{12}$$

K. Dostert explains in [1] that the characteristics of model reported before are similar to those for the real channel: it is sufficient to introduce not but 3-5 echoes of the signal into the formula (12) to obtain the transfer function similar to the real one[1]. It sounds to be true, as the reflected components (echoes) have to pass through the longer path than that of the primary wave; thus, they are respectively more attenuated. Also, their amplitude falls to the negligible level. Such a condition is proved by formula (3) showing that attenuation of each component depends also on the length of the path the component is going through.

It seems that the channel model as in Fig.1 can provide the approximation of a real channel of any assumed accuracy. Formula (12) can be also useful when plotting the phase characteristic and impulse response of the channel.

3. Simulation of a PLC channel

3.1 What is to be simulated. Referring to the model in shown in Fig.1, the authors decided to perform simulation of the PLC channel over the simple LV distribution line with one branch to the customer premises/building, in which HF signals are transmitted. Topology of the network is shown in Fig. 2.

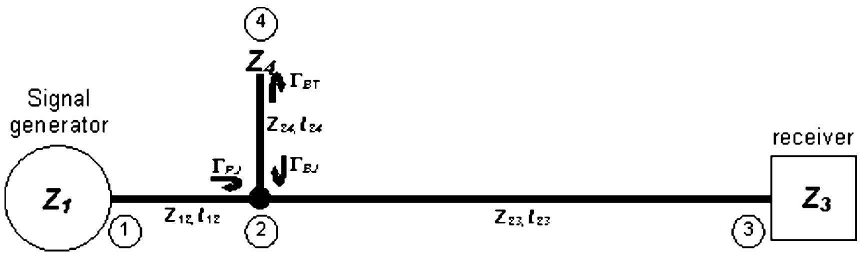

Fig. 2. Topology of distribution network containing one connection to the customer/building

As result of the simulation, the amplitude-frequency curve for the considered network should be obtained.

Network shown in Fig.2 utilizes a distribution line 200 m long (l_{12} + l_{23} = 200 m). The branch to the building is 11m long (l_{24} = 11 and is located 30m from the generator of the transmitted signal (l_{12} = 30 m). Both the distribution line and the branch to the customer are made of the same cable type (*Telefonika* YAKY4x150SE 4-sector power cable).

HF signal generator as well as the receiver are connected to the system by the interfaces matched to the distribution line; therefore, the signal will not be reflected at any of the line ends. In turn, the branch is loaded by an infinite impedance Z_4; it means that the signal reaching the end of branch will be entirely reflected (echoed). In fact, the branch to the building is loaded by an impedance $\neq \infty$. Nevertheless, in calculations, the branch line can be assumed to be open as the error is negligible.

3.2 Simulation procedure. Simulation procedure aiming to plot the amplitude-frequency curve for the described PLC channel includes the steps listed below:

– Calculation of the echo factors in the distribution network points where the lack of matching occurs

– Calculation of the weighting factors, $a_{1...}a_{4,}$ as in formula (12)

– Calculation of the length, $l_{1...}$ l_4, the transmitted signal is passing through

– Calculation of the factors, b_1, b_2 and $b_{3,}$ (formula (12)), referring to the parameters of a true 4-sector cable used in distribution networks [6]

– Plotting the amplitude-frequency characteristic for the PLC channel with multipath referring to the formula (12) and to the factors as mentioned above.

For analysis purposes, the network in Fig.2 was divided into three sections of length l_{12}, l_{23} and l_{24}. The characteristic impedances of sections are Z_{12}, Z_{23} and Z_{24}, respectively, and are equal to each other due to the same type of cable used in the entire network. Loading impedances are denoted Z_1, $Z_{3,}$ and Z_4, respectively, and the following equalities are valid: $Z_1 = Z_{12}$, $Z_3 = Z_{23}$ and $Z_4 = \infty$.

The echo factor at any x point of the line is defined by formula

$$\Gamma(x) = \frac{Z(x) - Z_c}{Z(x) + Z_c}, \tag{13}$$

where $Z(x)$ and Z_c stand for the line impedance at the x point and the characteristic line impedance, respectively[3].

Referring to the formula (13), the echo factors in the points **2** and **4** of the network (see Fig. 2) have been found:

$$\Gamma_{PJ} = \frac{Z_{24} // Z_{23} - Z_{12}}{Z_{24} // Z_{23} + Z_{12}}, \tag{14}$$

$$\Gamma_{BJ} = \frac{Z_{12} // Z_{23} - Z_{24}}{Z_{12} // Z_{23} + Z_{24}}, \tag{15}$$

$$\Gamma_{BT} = \frac{Z_4 - Z_{24}}{Z_4 + Z_{24}}, \tag{16}$$

where Γ_{PJ} – echo factor at the point **2** as seen by the frequency generator, Γ_{BJ} – echo factor at the point **2** as seen from the end of the branch line, and Γ_{BT} is the echo factor at the point **4**.

Referring to the scheme of the HF transmission line reported in [4] and to the formulas (14), (15) and (16), the weighting factor, $a_{i,}$ appearing in formula (12) for the *i*-th path on which the transmitted signal is passing, has been calculated. Forms of the weighting factor are presented in Table 1. To show better the path the signal is passing through (and how the total length of the *i*th path is being determined) , the arrows are plotted.

Table 1

Form of weighting factor, a_i, for the *i*th path [4]

Path No.	Path the signal is passing through	Weighting factor , a_i , of the *i*th path	Length of the *i*th path, l_i
1	(1)→(2) →(3)	$1 + \Gamma_{PJ}$	$l_{12} + l_{23}$
2	(1)→(2) →(4) →(2) →(3)	$(1 + \Gamma_{PJ}) \cdot \Gamma_{BT} \cdot (1 + \Gamma_{BJ})$	$l_{12} + 2 \cdot l_{24} + l_{23}$
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N	(1)→(2) →[(4) →(2)]$^{N-1}$ →(3)	$(1 + \Gamma_{PJ}) \cdot \Gamma_{BT} \cdot (\Gamma_{BT} \cdot \Gamma_{BJ})^{N-2} \cdot (1 + \Gamma_{BJ})$	$l_{12} + 2 \cdot (N-1) \cdot l_{24} + l_{23}$

From the formula (8), the characteristic impedance of the cable used in the network has been calculated (resulting value: Z_c = 16,797 Ω). Regarding the equalities: $Z_c = Z_{12} = Z_{23} = Z_{24}$, the weighting factors, a_i, for N = 4 different paths of the signal have been calculated. Calculation results are listed in the Table 2. Characteristic impedance was calculated for parameters of the *Telefonika* YAKY4x150SE 4-sector power cable.

For simulation and calculations, the *Mathcad2001Professional* program was used [6].

Table 2

Values of weighting factor, a_i, for the *i*th path

Path No.	Path the signal is passing through	weighting factor, a_i, for the *i*th path	Length of the *ith path*, l_i [m]
1	(1)→(2) →(3)	0,667	200
2	(1)→(2) →(4) →(2) →(3)	0,444	222
3	(1)→(2) →[(4) →(2)]^2 →(3)	-0,148	244
4	(1)→(2) →[(4) →(2)]^3 →(3)	0,049	266

To find the amplitude-frequency curve of the channel according to the formula (12), the factors: b_1, b_2 and b_3 , shall be found. The factors are calculated referring to the transmission line unit parameters. In turn, the form and values of the parameters depend on structure and dimensions of the cable used in the simulated network. The way of finding factors b_1, b_2 and b_3 as well as the role of constant values used in such calculations are presented in details in [6]. Calculated values of b_1, b_2 and b_3 for simulated network are $4.811 \cdot 10^{-7}$; $2.094 \cdot 10^{-10}$ and $4,189 \cdot 10^{-8}$, respectively**.**

3.3. Simulation results. On the base of transformations carried out referring to the formula (12) and referring to the values found, calculated and listed in tables 1 and 2, the amplitude characteristic of the transmission channel on the simulated LV distribution network (Fig. 2) can be plotted. The obtained curve is shown in Fig. 3. The shape of the characteristic shows intensive, temporary decays of amplitude in the channel resulting in a significant attenuation of the determined frequency components in transmitted signal. Also, the low-pass features of the channel are evident. There are two reasons for such a behavior:

– attenuation factor, $\alpha(f)$, increases with frequency

– attenuation factor increases as the length, l_i, of consecutive paths (which the transmitted signal is passing through) extends.

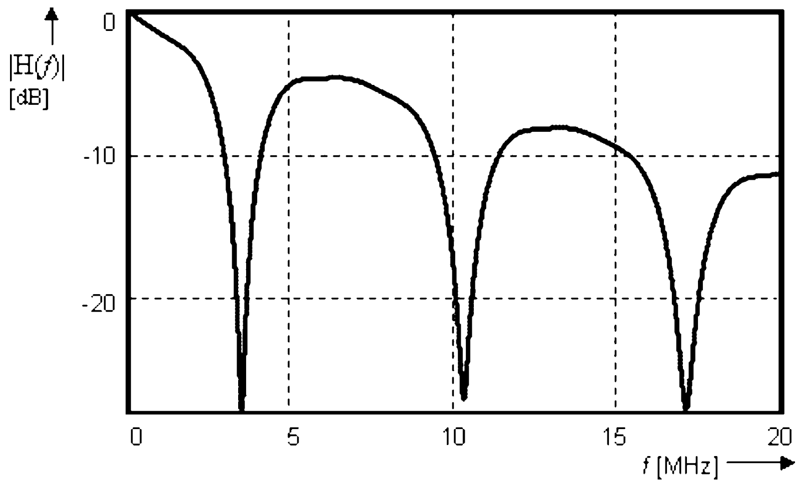

Fig. 3. Amplitude vs frequency curve for PLC channel for simulated distribution network of Fig. 3. H(f) – transfer function of transmission channel; f – transmitted signal frequency

4. Final remarks

– The main factors degrading a telecommunication signal transmitted in the power grid wires are: multipath, attenuation and noise.

– In multipath, the transmitted signal undergoes multiple reflections. Its components, attenuated and delayed, reach the receiver through various paths, and time delay between the first and last component exceeds several modulation intervals. It results in the inter-symbol interference. Thus, in models of the electrical power distribution infrastructure used for simulation of transmission of the narrow and broadband telecommunication signals, the signal paths are to be considered.

– To find the amplitude-frequency curve of a real PLC channel, the factors: b_1, b_2 and b_3 shall be found referred to the transmission line unit parameters which, in turn, should reflect structure/ dimensions of the cable in the simulated network.

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