Modeling of Power Line Transfer of Data for Computer Simulation

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Abstract: The paper deals with problems of data communication over power lines. This technology is referred to as PLC (Power Line Communication). A wider deployment of this technology in practice is currently hampered by a number of drawbacks. They are, in particular, interference with useful signal on lines, interference radiation, limited range of useful signal, and power grid elements that affect the transfer. It results from an analysis of partial problems that it is of advantage to have available a computer model of power line, which would enable simulating appropriately the data transfer over power lines. Two different, in a way conflicting, requirements need to be reconciled. Primarily, power lines are not designed for data transfer while data lines, in turn, are not adapted for power transmission. Although the two types of line are represented by the same parameters, their operation is completely different. A number of papers have been devoted to potential models of power lines for data communication. The present paper is an attempt to cope with these problems.

Keywords: Power line communication, PLC data communication, model of power line.

1. Introduction

The PLC (Power Line Communication) technology exploits power lines for data transfer. The need to use the distribution of electric power also for the transmission of control signals, telephony, etc., has appeared almost concurrently with the development of power grids. Today, this technology is growing in importance. They are expected to further develop with the introduction of the AMR (Automated Meter Reading) and AMM (Automated Meter Management) systems, as part of the latest trend in metering and management, the so-called Smart Metering systems. The PLC technology is a certain alternative to the other existing data channels.

![Figure 1. Model of a section of homogeneous line](image)

Relatively different and rather conflicting demands are made on power lines in this case. In energetics, power lines are mainly monitored from the viewpoint of power transmission (maximum transmission of power, quality, losses, cost, etc.) with 50 Hz (for U.S.A. 60 Hz) network frequency. In the PLC technology, the transmission of HF signals has to be assured. In the case of AMR and AMM systems, a limited band of narrow-band PLC will obviously be concerned, using the 3 – 148.5 kHz band. Efforts are therefore being made to describe power lines from the viewpoint of both power engineering (transmission of electric power) and telecommunications (data transfer). Currently, the PLC technology counts on the application of power lines at low-voltage (LV) levels 230/400 V and high-voltage (HV) levels up to 35 kV.

The power line is only one of the numerous elements of power grids, which contain further elements such as transformers, protective devices, generators, compensators, choke coils, various loads, etc. Power lines transmit and distribute electric power. They connect two nodes of the power grid. A node is the site where a source, electrical appliance, or transformer is connected, the site of network branching or switching station, the site where the type of line is changed. For the description and modeling of a power line, the papers focuses only on the description of a power line between two network nodes, connected by one type of line and considered at the low-voltage level 230/400 V. In view of the real range of PLC technology signals and the communication channel requirements it is the LV level where maximum development and exploitation can obviously be expected.

At the low-voltage level, there are two possible ways of connecting a power line: via outdoor lines or via cable lines. Outdoor and cable lines are further subdivided by the manner of placing, execution of phase conductors, etc. But this is of no fundamental effect from the viewpoint of modeling for the PLC technology. Although the descriptions of outdoor and cable lines are identical as regards the basic parameters, the description and parameters given below are considered for cable lines.

In both energetic and communications, four principal parameters are used in the basic description of power lines. These parameters determine the basic properties of a power line and they also form the basic model of a power line. The following primary parameters describing electrical properties are considered:

- specific resistance $R$ [Ω/km],
- specific inductance $L$ [H/km],
- specific conductance $G$ [S/km],
- specific capacitance $C$ [F/km].

These parameters can be used to establish the operation parameters of a line, in particular the characteristic (wave) impedance and transmission coefficient (propagation constant). In power lines, the system is considered in steady state, with 50 Hz (60 Hz) alternating current.
The basic network model of a two-conductor homogeneous line, of elementary length \( l \), described by primary parameters, is known in the form of equivalent schematic given in Fig. 1. Based on the primary parameters, other parameters of a line can be determined such as:

- specific transmission coefficient (propagation coefficient)

\[
g = \sqrt{Z \cdot Y} = \sqrt{(R + j\omega L) \cdot (G + j\omega C)} = \alpha + j\beta , \tag{1}
\]

where \( \alpha \) is the specific attenuation in dB/km, and \( \beta \) is the specific phase shift in rad/km, and

- characteristic impedance

\[
Z_u = \frac{\sqrt{Z \cdot Y}}{\sqrt{(R + j\omega L)}} . \tag{2}
\]

These parameters are the secondary parameters of a line; see, for example, [2], [8], [9], etc.

2. PLC communication system

To build a complete PLC communication system it is necessary to model, in addition to line models, also the coupling elements, interference sources, models of signal transmitters and receivers, and a number of other devices that affect communication. Composing these individual models gives a model of the PLC communication system. Based on the simulation of this entire model including various models of lines and component parts, it is possible to make an analysis of a concrete power grid from the viewpoint of possible deployment of various combinations of PLC technologies, ciphering, modulations, coding, etc., in order to obtain the best possible data-transfer parameters in the above systems.

To be able to simulate PLC communication, it is thus necessary to create appropriate models of component parts and of the power line itself such that they can be used in the available simulation programs. There are several possibilities how to model power lines. One of them models the power line as an environment with multipath signal propagation. The parameters of this power line are obtained from the power grid topology or on the basis of measurement. Another possibility of modelling the power line consists in using cascade parameters, which describe the values of input and output voltages and currents by means of two-ports. Yet another possibility is to create an equivalent power line model, described by primary and secondary parameters.

In each case it is necessary to obtain a relation that expresses the transfer function of the whole transfer chain, which is a filter by nature. Circuit quantities at the beginning and end of the transfer chain are of primary interest. It is usually not necessary to know the conditions along the power line. When modelling with the aid of two-ports it appears to be of advantage to describe individual blocks separately and to use the mathematical apparatus for the solution of classical circuit structures. Here it seems to be of benefit to use simulation programs for the solution of electronic circuits; these programs can usually work very well with two-ports while the description of power lines in them is usually very limited.

When designing PLC systems it is necessary to bear in mind the nature of the transmission medium and potential interference that affect PLC communication. It is necessary to find adequate security codes, select a suitable modulation technique and possibly also ciphering for the communication between the data source and the receiver to be without problems and with the least possible error rate.

For modelling purposes, the PLC communication can be divided into the following parts:

- PLC communication model,
- Power line models
  - equivalent model described by primary and secondary parameters,
  - multipath signal propagation environment,
  - two-ports described by cascade parameters,
- Interference sources.

Most of the methods described in the literature that deal with the modelling and simulation of power lines are based on time-dependent telegraph equations. These equations are designed for an elementary power line section.

A power line can be regarded as a multipath channel since multipath propagation is caused by line branches with non-adapted impedances. The heterogeneous structure of a power line with many branches and non-adapted impedances causes reflections. For this reason, the multipath propagation environment describes a typical power line. This approach to power line modelling is characterized by precision and simplicity. However, its disadvantage is the high computation complexity, where a high number of signal propagation paths need to be considered.

3. Models of power lines in energetic

The model of a power line with uniformly distributed parameters is not much used in energetic. This is mainly given by what parameters should be monitored from the viewpoint of power transmission. For this reason, a two-port replacement of power line is used as a model. For the purpose of electric power transmission this replacement is sufficiently precise. The line parameters are concentrated into only one point, and current and voltage at one particular time are the same at all points of the line. The most frequently used two-ports are the \( \Pi \)-element, \( \Gamma \)-element and T-element. Using these two-ports, both the whole element and a certain section of the element can be replaced. To model further properties or connected devices, the networks can be connected in cascade, yielding a whole section of the power chain, e.g. from the transformer to a model of loading, as given, for example, in [2]. The description of two-ports therefore uses the cascade form of equation, based on a common two-port, see Fig. 2.
Unlike the description of the properties of common two-port as used in circuit theory, in the case of power line description the output current $I_2$ is of opposite direction. In the solution of the equivalent schematic of homogeneous line (see Fig. 1) the chosen direction of output current is opposite to that in the description of circuits. In the case of power line description, the chosen voltage and current orientations are for the description of relations along the line more logical. The matrix equations of the two-port are then in the form:

$$Z = VAa V = \begin{bmatrix} R+joL \end{bmatrix} \begin{bmatrix} G+joC \end{bmatrix} .$$

(3)

In [9], which deals with the description of power line, matrix $A$ is referred to as matrix $ABCD$ of transmission parameters, and individual members of the matrix are given in capital letters $A$, $B$, $C$ and $D$. In energetic, these members are referred to as the so-called Blondel constants. In circuit theory, the matrix contains linear cascade parameters, denoted $a_{11}$ to $a_{22}$. The above relations serve to determine voltage and current at the beginning of the power line, if the relations at the end of the power line are known. If the relations at the beginning of the power line are known and we calculate voltage and current at the end of the power line, the cascade equation is changed accordingly. The physical meaning of cascade parameters is obvious and it expresses the no-load and short-circuit conditions of the line.

$$A = a_{11} = \frac{V_1}{V_2} \bigg|_{t_0}, \quad B = a_{12} = \frac{V_1}{I_2} \bigg|_{t_0} ,$$

$$C = a_{21} = \frac{I_1}{V_2} \bigg|_{t_0}, \quad D = a_{22} = \frac{I_1}{I_2} \bigg|_{t_0} .$$

(4)

Parameter $a_{11}$ is the return voltage transfer function, $a_{12}$ is the transmission impedance, $a_{21}$ is the return current transmission. In the simulation of general circuits, most of the circuit simulation software for the simulation of electronic circuits (such as PSpice, MicroCap, etc.) can use two-ports represented by matrix $a_{11}$ to $a_{22}$. In the computer modeling of parts of a line, inclusive of the elements connected to the power grid, it is therefore of advantage to represent individual blocks by cascade parameters and to model the whole chain using cascaded two-ports. This enables modeling the line as a whole and also examining the effect of individual parts.

**II-element two-port**

This two-port is the most frequently used model of electric lines. It consists of the direct-axis impedance $Z$ and two line shunt admittances $Y/2$, usually of identical magnitude. The model is indicated in Fig. 3. This model of line can be used for lines of up to 400 km.

$$a_{11} = 1 + \frac{Z \cdot Y}{2},$$

(5)

$$a_{12} = Z,$$

(6)

$$a_{21} = Y + \frac{Z \cdot Y^2}{4},$$

(7)

$$a_{22} = a_{11} .$$

(8)

The model of the power line itself can be obtained by multiple cascade connection of elementary two-ports represented by matrix $A$. Consider an electrically long line when it holds

$$|d| > 1$$

(9)

In this case, determining the number of elementary two-ports is an important step in designing the model of line. It is obvious that the greater the number of elementary two-ports, the more precise the model of line will be. But increasing disproportionately the number of elementary networks makes the calculations rather complicated or, if the equivalent line is realized, makes its design difficult. When determining the minimum number of two-ports, it appears sufficient to consider the line delay and the maximum frequency range for which the model will be used. A simple criterion is the ratio of the period of the highest frequency $f_s$ being transmitted to the delay of one network $t_0$; it should be at least twice the number of elementary circuits used $n_e$. This condition seems to be sufficient in most cases. For sufficiently high frequencies, the total delay $T_D$ of the specific line section can be determined from the specific inductance and specific capacitance according to the well-known relation

$$T_D = \sqrt{LC} .$$

(10)

If the model of line is made up of $n_e$ elementary sections, then the delay of one section will be
The number of elementary two-ports can, for the highest frequency being transmitted, be determined from the relation

\[ n_s > \frac{1}{2\pi f_c \sqrt{LC}}. \]  

(12)

Solving the line models with the aid of cascaded elementary two-ports brings some advantages when computer simulation programs are made use of. In the simulation program, we can work with elementary parts, the two-ports, which are represented by cascade parameters. Cascade solution offers the possibility of choosing a certain degree of complexity and precision of the line being modelled. It is also possible to define individual blocks as macromodels describing a data channel. An example can be seen in the solution given in [2], [3], and shown in Fig. 4.

As is obvious, each part of the line with connected elements (in this case they are two coupling elements of PLC modems, lead-in cable, and the motor itself) is described by a separate cascade matrix \( A_1 \) to \( A_4 \). Internal series impedance \( Z_s \) of signal source \( U_s \) and parallel impedance of load \( Z_L \) can also be described by cascade parameters and included in the resultant transfer function. The resultant cascade matrix of the line being modeled is obtained simply as the product of partial cascade matrices, i.e.

\[ A = \prod_{i=1}^{n} A_i \]  

(13)

where \( n \) is the number of parts described by the cascade matrix.

This approach provides the possibility of working in the simulation program with parameters and a representation that is used in the solution of “classical” electronic circuits. It is easy to obtain the transfer function of not only the line but also of the whole transmission chain. These programs provide appropriate tools for working with elements defined in this way, and they possess tools for transfer function analysis, sensitivity function calculation, and tolerance analysis in the frequency and time domains.

4. Transfer functions of cascade model of power line

The cascade model of a power line was indicated in the previous part. It follows from the model that the line is divided into individual parts, which are described by frequency-dependent parameters \( a_{11} \) to \( a_{22} \). The resultant transfer cascade matrix is given by relation (13); it enables obtaining the transfer functions of the line model on the basis of knowing the parameters \( a_{11} \) to \( a_{22} \) of individual parts. For example, Table 1 gives the relations for voltage transfer in dependence on the cascade parameters for four individual parts of the elementary two-ports considered.

As follows from Fig. 4, the model of a line is divided into a certain number of parts, with individual parts described by cascade matrices. Devices connected to the power grid substantially affect the data transfer of PLC systems. It is therefore important to determine the parameters of individual parts comparatively well. In the following text, a simplified model formed by three blocks will be considered. The load considered in the model given above is an electric motor, which represents the impedance connected to the line. Also modeled are the coupling element and a power line, the parameters of which are obtained for a certain frequency range by measurement. For all the models, the cascade parameters can be calculated for the resultant cascade matrix of the whole power line that is being modeled.

![Figure 4. Cascade model of line, with connected motor](image-url)

Table 1. Calculation relations for voltage transfer

<table>
<thead>
<tr>
<th>( n )</th>
<th>( K_V ) voltage transfer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( \frac{1}{a_{11}} )</td>
</tr>
<tr>
<td>2</td>
<td>( \frac{1}{a_{11} \cdot a_{12} + a_{21} \cdot a_{22}} )</td>
</tr>
<tr>
<td>3</td>
<td>( \frac{1}{a_{11} \cdot a_{12} \cdot a_{13} + a_{21} \cdot a_{22} \cdot a_{23} + a_{31} \cdot a_{32} \cdot a_{33} + a_{41} \cdot a_{42} \cdot a_{43}} )</td>
</tr>
<tr>
<td>4</td>
<td>( \frac{1}{a_{11} \cdot a_{12} \cdot a_{13} \cdot a_{14} + a_{21} \cdot a_{22} \cdot a_{23} \cdot a_{24} + a_{31} \cdot a_{32} \cdot a_{33} \cdot a_{34} + a_{41} \cdot a_{42} \cdot a_{43} \cdot a_{44}} )</td>
</tr>
</tbody>
</table>

\( a_{11} \) to \( a_{22} \) refers to cascade parameters of the \( n \)-th elementary two-port.

5. Model of electric motor

Impedance of an electric motor depends on a number of parameters, in particular on induction magnetization and leakage inductance of stator winding, resistance of stator...
winding, leakage inductance and resistance of rotor winding, and mechanical loading of electric motor. At higher frequencies, leakage capacitance and other leakage inductances influence the total impedance of electric motor. Moreover, due to the skin effect, all resistances of electric motor increase and depend on frequency.

Impedance of electric motor is mainly affected by the following parameters:
- capacitance between adjacent stator and rotor coils rotating in phase,
- capacitance between rotating winding and stator,
- capacitance between neighbouring rotor windings,
- mutual inductance between adjacent stator and rotor coils rotating in phase,
- mutual inductance between neighbouring rotor windings, and,
- resistance of stator frame and stator coil.

Various models of electric motors are given in the literature. Now, we are considering the model given, for example, in [2], [4], which is shown in Fig. 5.

![Impedance model of electric motor](image)

**Figure 5.** Impedance model of electric motor [2], [4]

The above model is thus greatly simplified and models the basic parameters, where \( C_{hf} \) is the capacitance at high frequencies, \( R_{z0} \) is the characteristic resistance, \( L_{lf} \) is the inductance at low frequencies, and \( R_{lf} \) is the resistance at low frequencies, given by the resistance of stator winding.

To examine phenomena in low-voltage power grids, the above impedance model must be made more specific. The model indicated in Fig. 5 is suitable for use in the frequency band of up to ca. 1 MHz. To be able to model PLC systems, the respective loading (electric motor) and its impedance should be modeled in the frequency band 3-30 MHz, which is used by PLC systems. In this band, parallel and series resonances appear in the loading mentioned (electric motor).

For modeling with PLC systems, the models described in [2] and [6] and shown in Fig. 6 are therefore more suitable. The utilization of individual models depends on the type of signal coupling to power-line phase conductors. The model in Fig. 6a is suitable when signal coupling to phase conductors L1, L2 and L1, L2+L3 is used while the model in Fig. 6b is suitable for signal coupling to phase conductors L1, PE and L1+L2+L3, PE.

![Modified impedance model of electric motor](image)

**Figure 6.** Modified impedance model of electric motor, a) model A (L1, L2 a L1, L2+L3), b) model B (L1, PE a L1+L2+L3, PE) [2].

Individual parameters in the model (Fig. 6) mean the following:
- \( L_{lf} \) – inductance of stator winding at low frequencies,
- \( R_{lf} \) – resistance of stator winding at low frequencies,
- \( C_{hf} \) – capacitance with current flowing, at high frequencies,
- \( L_{hf} \) – inductance with current flowing, at high frequencies,
- \( R_{hf} \) – resistance with current flowing, at high frequencies.

Impedance \( Z_A \) of model (A) acc. to Fig. 6a is given by the relation

\[
Z_A = \frac{R_z + s(C_{hf}R_zR_{hf} + L_{hf}) + s^2(C_{hf}L_{hf}R_z + C_{hf}L_{hf}R_{hf}) + sC_{hf}L_{hf}R_{hf}}{1 + s^2(C_{hf}R_zR_{hf}R_{hf} + C_{hf}L_{hf}R_{hf}) + s^2(C_{hf}L_{hf}R_z + C_{hf}L_{hf}R_{hf})},
\]

while impedance \( Z_B \) for model (B) acc. to Fig. 6b is determined by the relation

\[
Z_B = \frac{1 + sC_{hf}R_{hf} + s^2C_{hf}L_{hf}}{sC_{hf}}.
\]

If a cascade model of power line with connected loadings acc. to Fig. 4 is considered, then the cascade parameters of models A and B of the given electric motor are \( ^a a \) for model A and \( ^b a \) for model B (Fig. 6).

\[
\begin{align*}
^a a_1 &= 1, \\
^a a_2 &= 0, \\
^a a_3 &= -\frac{1 + s(C_{hf}R_zR_{hf} + C_{hf}R_{hf}) + s^2(L_{hf}C_{hf} + L_{hf}C_{hf})}{R_z + s(C_{hf}R_zR_{hf} + L_{hf}) + s^2(C_{hf}L_{hf}R_z + C_{hf}L_{hf}R_{hf}) + sL_{hf}C_{hf}}, \\
^a a_4 &= 1,
\end{align*}
\]

\[
\begin{align*}
^b a_1 &= 1, \\
^b a_2 &= 0, \\
^b a_3 &= -\frac{1 + s(C_{hf}R_zR_{hf} + C_{hf}R_{hf}) + s^2(L_{hf}C_{hf} + L_{hf}C_{hf})}{R_z + s(C_{hf}R_zR_{hf} + L_{hf}) + s^2(C_{hf}L_{hf}R_z + C_{hf}L_{hf}R_{hf}) + sL_{hf}C_{hf}}, \\
^b a_4 &= 1.
\end{align*}
\]
6. Model of coupling element

The coupling element is an important part of PLC channel from the transfer point of view. In contrast to other elements of the power grid, the properties of coupling element can be modified via a suitable circuit solution. An added coupling element entails further attenuation and contributes to the total attenuation, which is seen as essential in data transfer via the PLC technology. In [2], a model of the coupling element is given and, based on measurement, the parameters of individual elements of the model are determined. The model is given in Fig. 7 and its application is mainly in the frequency band 100 kHz – 30 MHz.

![Figure 7. Model of coupling element (fons et origo [2])](image)

With a view to the above-considered cascade model of power line and connected devices acc. to Fig. 4, the required calculated cascade parameters $a_{11}$ to $a_{22}$ of the model of the whole coupling element are

$$a_{11} = 1, \quad a_{12} = 0, \quad a_{21} = \frac{sc_m}{1 + sc_m R_m + s^2 L_m C_m}, \quad a_{22} = 1.$$  

(17)

Now it is necessary to either obtain the parameters of power line cable on a specific frequency that the PLC system operates on or analytically describe the frequency dependence of the primary parameters. Fig. 8 gives the waveforms of primary parameters measured on two types of power line cable: CYKY 3x1.5 (three-conductor cable with copper core, core cross-section 1.5 mm²) and AYKY 3x2.5 (three-conductor cable with aluminum core, core cross-section 2.5 mm²). The parameters measured have been recalculated per 1 km of length. To measure the frequency dependence of the primary parameters, the HP/AGILENT 4192A impedance analyzer was used. The analyzer measures $|Z|, |Y|, R, X, G, B, L, C, D, Q,$ and others. The frequency band is given by the analyzer range.

7. Power line model

If we again consider cascade arrangement in the model according to Fig. 3, the block described by cascade matrix $A_4$ represents an elementary network of the power line proper. According to Fig. 3, the power line proper can be modeled by a $\Pi$-network, while relations (5) to (8) determine the calculation of individual cascade parameters $a_{11}$ to $a_{22}$. If the longitudinal impedance $Z$ represents a series combination of resistance $R$ and inductance $L$, and the transverse admittance $Y$ represents a parallel combination of capacitance $C$ and conductance $G$, all of which represent the primary parameters of the power line, then in this case it holds for the cascade parameters:

$$a_{11} = 1 + \frac{RG + s(LG + CR) + s^2LC}{2},$$  

(20)

$$a_{12} = R + sL, \quad a_{21} = \frac{4G + RG^2 + s(4C + 2RC + GL) + s^2(CRC + 2GL) + s^3CL}{4},$$  

(22)

$$a_{22} = a_{11}.$$  

(23)

The values of elements in the model are: $C_1 = 374 \ \mu F$ (capacitance of coupling capacitor), $L_1 = 1.3 \ \mu H$ (leakage inductance of the transformer), $R_1 = 4.5 \ \Omega$ (resistance of the winding), $L_2 = 1.5 \ \mu H$ (magnetization inductance of the transformer and parallel inductances), $C_0 = 56 \ \mu F$ (leakage capacitance of the transformer winding and diodes), $R_0 = 15 \ \Omega$ (series resistance of the leakage capacitance), $R_3 = 10 \ \kO$ (resistance of the loading). Then the values of the cascade parameters of coupling element are

$$a_{11} = 8.67 \times 10^{-3} \frac{2.44 \cdot 10^{-10} + 6.53 \cdot 10^{-12} \cdot s + 2.77 \cdot 10^{-9} \cdot s^2 + 2.67 \cdot 10^{-7} \cdot s^3 + s^4}{[1.19 \cdot 10^{-10} \cdot s^4 + s^5]},$$  

(19)

$$a_{12} = 1.3 \times 10^{-3} \frac{2.44 \cdot 10^{-10} \cdot s + 6.17 \cdot 10^{-12} \cdot s^2 + 1.19 \cdot 10^{-9} \cdot s^3 + s^4}{[1.19 \cdot 10^{-10} \cdot s^4 + s^5]},$$  

$$a_{21} = 0.0667 \frac{1.18 \times 10^{-10} \cdot s + 1.8 \times 10^{-12} \cdot s^2 + s^3}{[1.19 \cdot 10^{-10} \cdot s^4 + s^5]},$$  

$$a_{22} = 1.$$

To obtain true parameters of a power line cable, the primary parameters were measured of a four-conductor cable with 2.5 mm² cross-section of each conductor with PVC insulation and PVC sheath, designed for a rated voltage of 450/750 V. The values of primary parameters measured have been recalculated for a cable length of 1 km; they are:

\[ R = 100 \, \Omega, \quad L = 650 \, \mu H, \quad C = 65 \, nF \text{ and } G = 0.002 \, mS \text{ at a frequency of } 150 \, kHz. \]

If the cable line is modelled by a two-port, then for the given values of primary parameters the corresponding cascade parameters of the cable are

\[ a_{11} = 4.225 \times 10^{-11} (2.84 \times 10^6 + 1.84 \times 10^5 \cdot s + s^2), \]
\[ a_{12} = 0.00065 (1.53 \times 10^3 + s), \]
\[ a_{21} = 6.5 \times 10^{-8} (3.07 \times 10^4 + s), \]
\[ a_{22} = 1. \quad (24) \]

8. Example of simulation of cascade model

Based on the determined cascade parameters of parts of the model given in Fig. 4 the resultant transfer function of the transfer path can be established using relation in Table 1. In the simulation programs, use can be made of, for example, the Laplace controlled sources connected in series and the respective calculated partial transfer functions. The frequency characteristics of a model set up in this way and having the parameters of individual parts as considered above are given in Fig. 9.

It is evident from the waveforms that for the narrow-band PLC (3–148.5 kHz) considered the transfer over the above power-line cable is possible but the coupling element cannot be used for the given band. The above method can easily be used to examine separately individual parts and then to verify the function of the whole and thus arrive at a design of an acceptable solution for the given requirements.

9. Conclusion

In the paper, a possible method for modeling data communication over power lines is suggested. The starting point is the description of partial elements, using cascade matrices. Individual elements are then analyzed and modeled. The models given are based on models reported in the literature; in the paper, a calculation method is proposed for cascade arrangement of partial models, and elements of partial cascade matrices of the basic elements of the total model are calculated. Some of the simulations given in the paper confirm the conclusions given in the literature and indicate good reproducibility of the results. The paper follows up on these conclusions and provides a calculation apparatus for the construction of models of power lines for the simulation of data transfer by the PLC technology. This method of modeling then enables a relatively easy insertion of blocks into the model that provide for modeling in
particular the problematic area of this technology such as the range of useful signal, interference with useful signal along the line or the effect of individual elements of the power grid on data transfer. The present paper is intended as a contribution to solving these problems.

References


