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Procedia Engineering 100 (2015) 1381 – 1388

Procedia Engineering

www.elsevier.com/locate/procedia

25th DAAAM International Symposium on Intelligent Manufacturing and Automation, DAAAM 2014

Modelling Transmission Lines for the Purpose of Data Transmission over Power Lines

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Abstract

The aim of the article is to create two models of power line communication. First model is called Multipath model and It is based on identifying the transfer function based on the measured values. Second model is called Transmission line model and It is useful if the topology of the network under consideration is known. Both models are useful to obtain information of the operation of outdoor networks.

Peer-review under responsibility of DAAAM International Vienna

Keywords: power line communication; modelling; smart grid; multipath model; transmission line model

1. Introduction

PLC (power line communication) is not new. It has been known for many years [1]. However, it never been deployed in large scale. There were only sporadic applications as an example of Czech HDO or remote control [2]. Currently PLC is experiencing a renaissance thanks to the advent of Smart Grid and Smart Metering [3]. PLC communication offers relatively low transmission speeds and relatively unreliable transmission, but these disadvantages compensate low costs to build communication infrastructure and it offers specific functionalities for use in Smart Grid [4]. The question is whether the declared parameters will be met in the real world. This article tries answering this question by creation of mathematical model of power line communication.

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Peer-review under responsibility of DAAAM International Vienna
doi:10.1016/j.proeng.2015.01.507

2. Motivation for the model PLC communication

Testing different kinds of standards of PLC communication is very expensive. This is necessary to test the communication system in which the distances should reach to kilometers, to achieve the meaningful data. There should be a wide range impedance unadapted branches and there should be different kinds of interference. It is practically impossible to achieve these conditions in the laboratory and must be tested on a real distribution system.

The values measured in one area are not possible to generalize, since there are areas with different densities, arrangement of branches and the occurrence of interference sources. It is also used various types of power lines.

Given these facts, it is advantageous to create a model of PLC communication, which in addition to the possibility of verification of existing standards provides additional major benefits.

The model is suitable to test the real possibility of certain standards in various areas. In addition to general conclusions which types of communication standards are suitable for urban or rural areas, it is possible to test technologies on specific areas before deploying this technology. So the distribution companies could verify if in specific area should be used the PLC technology, or if it is better to use alternative technologies such as mobile services.

It is possible to verify deployment of additional PLC communication supporting elements such as filters or repeaters.

In the case of a real deployment and problems of communication occurrence in individual cases or in certain areas, it is possible to verify whether the problem may be caused by a network configuration or if it is necessary to look for the problem elsewhere. For example, a faulty appliance issuing excessive interference to the network, other network arrangement than it anticipated and documented, hardware error on the transmitter or receiver.

This article focus on modeling of the distribution network belonging to a distribution companies where there are not frequent topology changes, as in the case of home networks where there is a topology change every time when light switch is turned on or off.

3. Modelling PLC

For modeling PLC communication via outside lines there are known two types of models. The first is multipath model suitable for models based on the measurements and identification. The second type is transmission line model, where the components are considered as two-port networks whose parameters can be obtained according to known parameters or identification. Transfer function of the whole system could be obtained by the product of these two-port transfer functions.

The bases of both models are telegraph equations describing the propagation of signals through homogeneous two-wire lines.

$$U(0) = U_k\,cosh(\gamma l) + Z_0 I_k\,sinh(\gamma l) \qquad I(0) = I_k cosh(\gamma l) + \frac{U_k}{Z_0} sinh(\gamma l) \tag{1}$$

Where U(0) and I(0) are voltage and current at the beginning of line, U_k and I_k are voltage and current at the end of line, γ is propagation constant of line, l is line's length, Z_0 is characteristic impedance of line.

3.1. Multipath model

Multipath model is particularly suitable if you are not aware of the exact parameters of the transmission channel primarily topology of the transmission system, but it is necessary to identify the transfer function based on the measured values.

Description of the model is also in publications [5], [6].

The transfer function is based on the assumption that the signal at the considered point is the sum of the forward signal components propagating in all possible paths to a destination whose level is reduced due to reflections on the individual impedance unadapted branches.

Mathematically, it can be written as:

$$H(f) = \sum_{i=1}^{N} \underbrace{g_i}_{\substack{attenuation\ due \\ to\ reflections}} \underbrace{A(f, d_i)}_{\substack{attenuation \\ on\ the\ line}} \underbrace{e^{-j2\pi f \tau_i}}_{\substack{delays\ due \\ to\ distance}} \tag{2}$$

where N is number of considered paths.

3.1.1. Attenuation due to reflections

In the case of branching lines, line termination with impedance mismatch or entering into lines an element reflections are formed on these interfaces. Part of the wave continues and part is reflected back. Express what part of the wave can be reflected is possible by the equation:

$$U(z) = C_1 e^{-\gamma z} + C_2 e^{\gamma z} \tag{3}$$

where part with C_1 represents forward wave and part with C_2 represents reflected wave. Subsequently, by substituting for C_1 and C_2 reflection coefficient in the appropriate place can be obtained:

$$r = \frac{C_2 e^{\gamma l}}{C_1 e^{-\gamma l}} = \frac{\frac{U_k - Z_0 I_k}{2} e^{-\gamma(l-l)}}{\frac{U_k + Z_0 I_k}{2} e^{\gamma(l-l)}} = \frac{\frac{U_k}{I_k} - Z_0}{\frac{U_k}{I_k} + Z_0} = \frac{Z_k - Z_0}{Z_k + Z_0} \tag{4}$$

Where Z_k is load impedance or impedance ongoing lines.
The remaining part of the wave continues, so the transmittance is:

$$t = 1 - r \tag{5}$$

The resulting attenuation due to reflections can be obtained from the product of the reflectance and transmittance according to the direction in which the wave propagates in respective route.

Data for the calculation of the reflection coefficient are often not known in the case of identification from the measured data. Therefore g_i is one of the identified parameter, whose value is different for each path and depending on the frequency. The absolute value must always be less than the 1. It is generally a complex number dependent on the frequency, but in order to simplify the model it is possible to omit the dependence on the frequency and g_i considered as a real number.

3.1.2. Attenuation on the line

Since it is considered only the forward wave, the line attenuation may be described by the equation:

$$e^{-\gamma l_i} \tag{6}$$

If line parameters are not known, it is possible to approximate function γ for electrical cables and the usual frequencies for PLC communication by function $\alpha(f)$ [1].

$$\alpha(f) = a_0 + a_1 f^k \tag{7}$$

Attenuation of the line can then be described by the equation:

$$A(f, l_i) = e^{-\alpha(f)l_i} = e^{-(a_0 + a_1 f^k)l_i} \tag{8}$$

where a_1, a_2, k are constants independent on path and frequency, which can be identified by measurement data. The parameter l_i is not dependent on frequency, but is dependent on the path length thus depends upon the path. This parameter could be also identified.

3.1.3. Delays due to distance

The individual waves on each path travel other distances to the finish, so they are also delayed in time. This delay can be expressed in the frequency domain as:

$$e^{-j2\pi f\tau_i} \tag{9}$$

where delay τ_i can be expressed as:

$$\tau_i = \frac{l_i\sqrt{\epsilon_r}}{c_0} \tag{10}$$

where ϵ_r is relative permittivity of the conductor insulation c_0 is speed of light, l_i is same as l_i in equation 8 and expresses the route length and differs for each path, but is independent of frequency. If the relative permittivity of the conductor insulation is not known it is possible ϵ_r and c_0 replace with constant v_p which expresses the speed of propagation in the conductor. This constant is independent of the frequency and path, and is often identified.

3.2. Transmission line model

Transmission line model is useful if we know the topology of the network under consideration.

Before using for modeling PLC communication, model was used to model the DSL communications. It is therefore possible to find description in other sources for example [7].

Description of the model is also in publications: [8], [9], [10]. Diagram of the simplest topology modeled using transmission line model can be found in Figure 1.

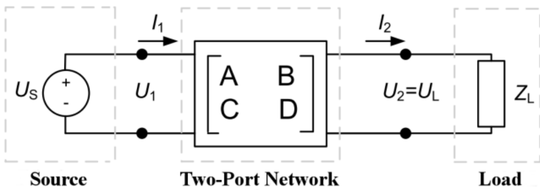

Fig. 1. the simplest topology of power line communication.

Two-port network is represented by equations that describe the dependence of the input and output voltage and current:

$$\begin{bmatrix} U_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} U_2 \\ I_2 \end{bmatrix} = \boldsymbol{M} \begin{bmatrix} U_2 \\ I_2 \end{bmatrix} \tag{11}$$

where **M** is a matrix expressing the two-port parameters.

If a network is formed by various two-ports connected in series. It is possible to replace them with one two-port, obtained as a product of individual matrices $\mathbf{M_i}$:

$$\boldsymbol{M} = \prod_{i=1}^{n} \boldsymbol{M_i} \tag{12}$$

where n is the number of series-connected two-ports.

Voltage transmission for each frequency can be expressed as the ratio of output voltage to input voltage. If the input voltage is expressed from equation 11 and load current is factored, voltage transmission can be described using only impedance load Z_L and final parameters of two-port network **M**.

$$H(f) = \frac{U_L}{U_S} = \frac{U_L}{AU_L + BI_L} = \frac{\frac{U_L}{I_L}}{A\frac{U_L}{I_L} + B} = \frac{Z_L}{AZ_L + B} \tag{13}$$

It will also be shown how to describe the most common network components such as two-ports:

3.2.1. Power lines as a two-port network

For modeling line as two-port can be used equation 1, which is in the shape that is needed, just need to convert it into matrix form:

$$\begin{bmatrix} U_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} cosh(\gamma l) & Z_0 sinh(\gamma l) \\ \frac{1}{Z_0} sinh(\gamma l) & cosh(\gamma l) \end{bmatrix} \begin{bmatrix} U_2 \\ I_2 \end{bmatrix} \tag{14}$$

3.2.2. The series impedance as a two-port network

For example it is a series resistor of non-ideal voltage source. The input and the output current equals, the output voltage is decreased by loss on impedance:

$$\begin{bmatrix} U_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} 1 & Z_s \\ 0 & 1 \end{bmatrix} \begin{bmatrix} U_2 \\ I_2 \end{bmatrix} \tag{15}$$

3.2.3. Parallel impedance as a two-port network

The input and output voltage are equal, input current is the sum of the output current and the current flowing through the impedance.

$$\begin{bmatrix} U_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ \frac{1}{Z_p} & 1 \end{bmatrix} \begin{bmatrix} U_2 \\ I_2 \end{bmatrix} \tag{16}$$

3.2.4. Branch in power line as a two-port network

Branch in power line ended with load Z_k (household). If power lines and termination load in branch are converted to impedance it is possible consider all branch as parallel impedance Z_p and use matrix from equation 16.

Express line and termination load as impedance is possible from relation:

$$Z_p = \frac{U_p}{I_p} = \frac{U_k cosh(\gamma l) + Z_0 I_k sinh(\gamma l)}{I_k cosh(\gamma l) + \frac{U_k}{Z_0} sinh(\gamma l)} = Z_0 \frac{Z_k + Z_0 tanh(\gamma l)}{Z_0 + Z_k tanh(\gamma l)} \tag{17}$$

3.3. Symmetry

Symetry means that the resulting transfer function does not depend on the direction. It must be possible to change transmitter and receiver and the resulting transfer function must remain the same. This problem is described in [2]. There is proof that the transfer function is symmetric only if the following conditions are met:

- The determinant of the resulting matrix **M** is equal to 1 |**M**|=1
- For all individual two-ports is true:

  - $A = D$ for any frequency
  - $B \neq C$ for any frequency
  - the determinant of matrix $\mathbf{M_i}$ is equal to 1 $|\mathbf{M_i}|=1$
- The internal resistance of the transmitter is the same as the load resistance of the receiver

4. Example of power line model

Unlike previous studies that focus on the modeling of indoor PLC, this example focuses on the modeling of the communication over high voltage line, which is currently experiencing a renaissance.

In the example, line is long 52 kilometers, the math cross section of each conductor is 3.75 cm^2. The resistivity of the conductors is 2.81E-8 Ωm. This is a 400 kV power line, which transfers power 640 MW. This example modelling power line in Europe, so considered frequencies are from 60 to 125 kHz [11]. The resulting transmission depending on the distance and frequency is shown at Figure 2..

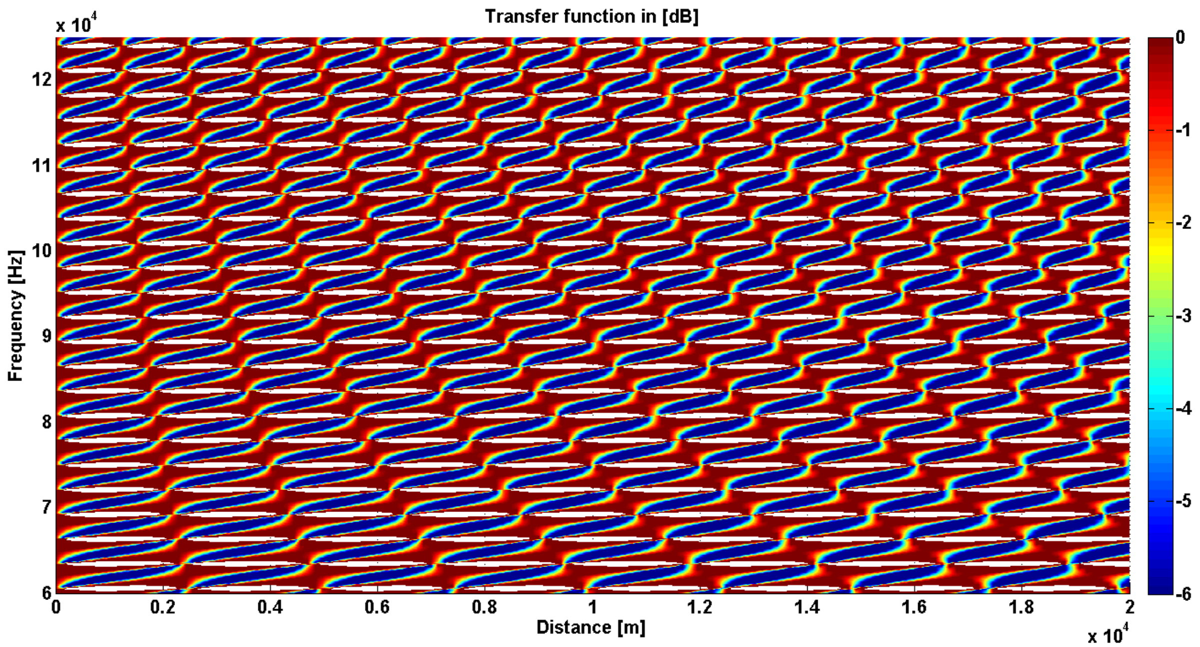

Fig. 2. Transfer function for communication over high voltage power lines.

5. Future improvements

The models described in this article are all designed for two wire lines. But power lines are very rarely realized as two wire line. The commonly are used three-phase lines, which are grounded in certain places or three phase line with neutral wire or three-phase line with neutral and earth wire, or the same in one phase variant. It is therefore necessary to convert models to form a multi-conductor model and add model of ground. It would be appropriate to extend the model with models of interference commonly found in electrical networks. Furthermore, in addition to modelling power lines and load impedances is suitable to deal with models of transformers, which are also located in the network. There is also no comparison with measurements in real transmission network yet.

Conclusion

Most of the current literature deals with the modelling of indoor PLC. But the communication over low and high voltage in Smart Grid and Smart Metering is experiencing the biggest boom in the present. This article is an introduction to this issue and shows the possibility of using well-known models for modelling outdoor networks by high voltage example. Article shows that modelling outdoor networks and high voltage lines is possible and could be very useful for improving power line communication. Future improvements of models are described in previous paragraph.

Acknowledgements

This work was partially realized Brno University of Technology, Faculty of Electrical Engineering and Communication and also by the project “TA02010864 - Research and development of motorized ventilation for the human protection against chemical agents, dust and biological agents” and project “TA03020907 - REVYT - Recuperation of the lift loss energy for the lift idle consumption” granted by Technology Agency of the Czech Republic (TA ČR).

Part of the work was supported by project “FR-TI4/642 - MISE - Employment of Modern Intelligent MEMS Sensors for Buildings Automation and Security” granted by Ministry of Industry and Trade of Czech Republic (MPO).

Part of the work was carried out with the support of core facilities of CEITEC – Central European Institute of Technology under CEITEC – open access project, ID number LM2011020, funded by the Ministry of Education, Youth and Sports of the Czech Republic under the activity „Projects of major infrastructures for research, development and innovations”.

This work was also supported by Operational Program Research and Development for Innovations; project CVVOZE – Center for Research and Utilization of Renewable Energy Sources no. of contract CZ.1.05/2.1.00/01.0014 and Faculty of Electrical Engineering and Communication, Brno University of Technology.

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