

Channel Modeling and Characterization of outdoor Low Voltage NB-PLC for AMI

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Abstract—This paper presents the analysis and modeling of real Low Voltage (LV) channel for Narrowband Power Line Communications (NB-PLC) by developing the Simulink and mathematical model of transmission line (TL) theory followed by their results discussion. The developed model allows the complete analysis and characterization of network impedances and channel transfer functions. The obtained results are validated by comparing the both models. Moreover the influence of constant and frequency selective impedances and, background noise on channel model has been evaluated. This research work will facilitate the International standardization process of LV power line transfer functions in the area of NB-PLC.

Keywords—Advanced metering infrastructure, smart grid, power line communications, two port network, all aluminium conductors, frequency selective impedances.

I. INTRODUCTION

The challenges being faced by existing power grid can be addressed by introducing the new emerging SG technologies. Currently global research in the area of SG communication emphasizes on the issues and opportunities to implement the ICT infrastructure that is advanced metering infrastructure (AMI) in SG. Over the past few years, metering devices have gone through the process of improvement and it is expected that these devices will be more sophisticated in order to offer good quality services. While considering the current scenario it has been observed that still today meters in a few countries are analog with lack of configurability and poor accuracy [1, 2]. Standards based on various communication technologies have emerged in recent past. IEEE P1901.1, P1901.2, G3, PRIME and IEC 61334 are some of the standards. SG communication products and technologies are emerging based on these standards. PLC is one of the most promising communication technologies for AMI because of its already existing infrastructure, due to which its installation cost reduces at least to 50% [3, 4].

Main characteristics of power line channel include the impedance matching & its continuously varying nature with respect to change in frequencies of the signal, channel multipath delay and various types of noises. Novel aspects presented in this research work pertains to the facts that we have modeled the LV NB-PLC coupler, introduces constant and frequency selective impedances and evaluated their influence on channel by comparing the channel transfer functions of both Simulink model and TL theory.

This paper is organized as follows. Section II sheds light on the proposed NB-PLC network by discussing the modeling of network parameters and proposed capacitive coupler device for NB-PLC signal transmission on LV network. Section III gives the comparative analysis of transfer functions obtained from proposed model and typical transmission line theory approach along with background noise of channel, followed by conclusions.

II. NB-PLC SYSTEM MODEL

PLC systems are operated by impressing a modulated carrier signal over the power line conductors of 50 Hz frequency. PLC is classified into two types: Narrowband PLC and Broadband PLC (BB-PLC) on the basis of frequency ranges. In this research paper channel modeling of LV transmission lines for NB-PLC is presented that supports the low data rate applications used for smart metering, home automation and control purposes.

Three major types of voltage levels i.e., low, medium and high exist in the power system for the sake of electricity transmission and distribution (T & D) towards the consumer side. This research work is focused on a case study that deals with the LV distribution network by taking the standard network values followed by Lahore Electric Supply Corporation (LESCO). Fig. 1 illustrates the complete simulation model in MATLAB/Simulink whose results are also verified by utilizing the concepts of transmission lines theory. According to data provided by National Transmission and Distribution Company (NTDC) and LESCO, the length of each HV transmission line installed ranges 3-18 km, MV ranges 1-6 km and LV distribution lines ranges 60-130 m. The voltage levels and conductor type of selected LV network consist of 400 V_{L-L} , 230 V_{L-N} via 11kV/0.4kV transformer, supplying through all aluminium conductors (AAC), standard BS-215, code name Wasp, with ampacity upto 286 A [3]. The length of main channel is 150 m terminated on 38 kW load with eight branches ranges 20 kW to 40 kW connected to it, each of which has 15 m length. After careful investigation about the frequency selective behaviour of domestic loads, RLC loads are used in the simulation model. Total harmonic distortion of NB-PLC channel using spectrum analyzer is measured as 4.6%.

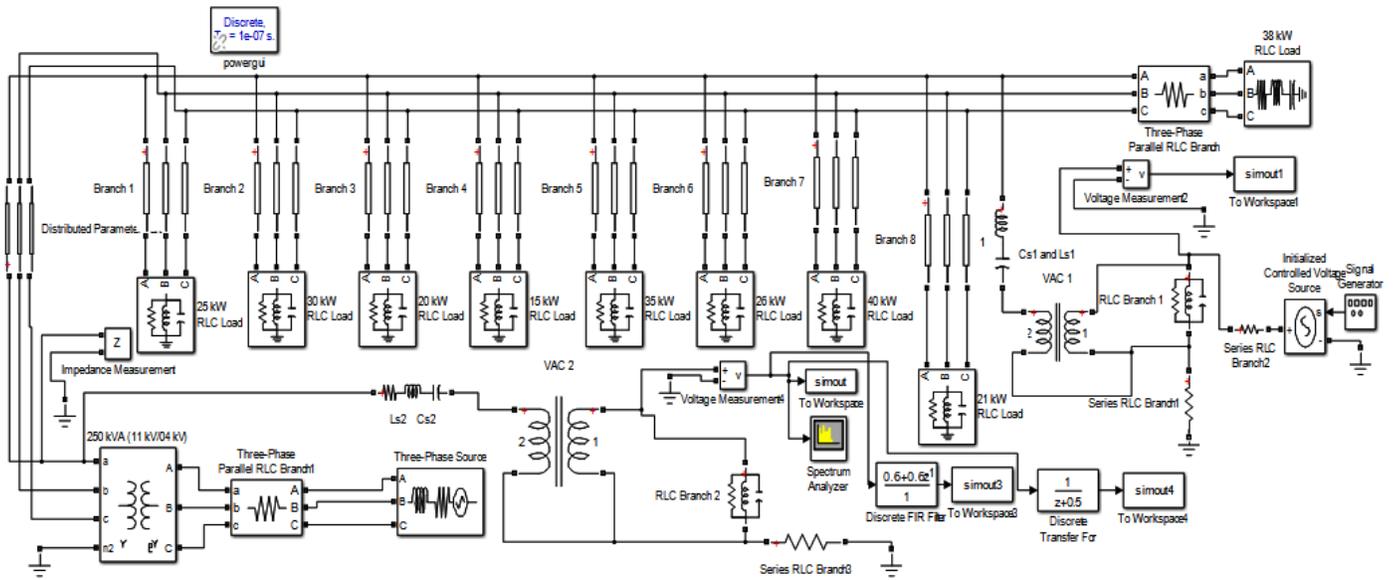


Fig. 1. Simulation Model of selected LV electrical network for modelling

A. Modeling of NB-PLC Channel Parameters

The electrical properties of any segment of transmission line are determined by its distributed parameters R , G , L and C (resistance, conductance, inductance and capacitance). The parameters of transmission lines such as propagation constant γ and characteristic impedance Z_c can be given as [5]:

$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)} \quad (1)$$

$$Z_c = \sqrt{(R + j\omega L)/(G + j\omega C)} \quad (2)$$

In above equations α and β are attenuation constant and phase constant of the propagation constant γ and ω is the angular frequency of channel under evaluation. Characteristic impedance Z_c of LV channel and each bridge tap is calculated as 220 Ω and 208 Ω respectively. A new concept of Frequency selectivity of resistance and conductance has been introduced in LV network to overestimate the cable and conductors losses which are given by [6]:

$$R = R_{dc} \cdot 10^{-5} \cdot \sqrt{f} (\Omega/m) \quad (3)$$

$$G = G_o \cdot 10^{-14} \cdot 2\pi f (S/m) \quad (4)$$

where f represents the frequency in Hz and R_{dc} is resistance of conductor. The value of each bridge tap's R_{dc} and G_o is taken as 7.55 Ω and 38.4 S respectively. For overhead lines, R_{dc} is 0.2720 Ω and G_o is close to zero because insulating material between conductors is free space, conductors spacing between transmission lines is 0.30 m. It is analyzed that resistance variations also satisfies the resistance variations law given by [1]:

$$R(f) = A_R f^2 + B_R f + C_R \quad (5)$$

where the values of A_R is $2 \times 10^{-11} m\Omega/(m * kHz^2)$, B_R is $1 \times 10^{-11} m\Omega/m * kHz$ and C_R is $2m\Omega/m$. Fig. 2

illustrates the resistance and conductance variations of each bridge tap or branch in which upper graph elucidates the resistance variations obtained from both methods as discuss above.

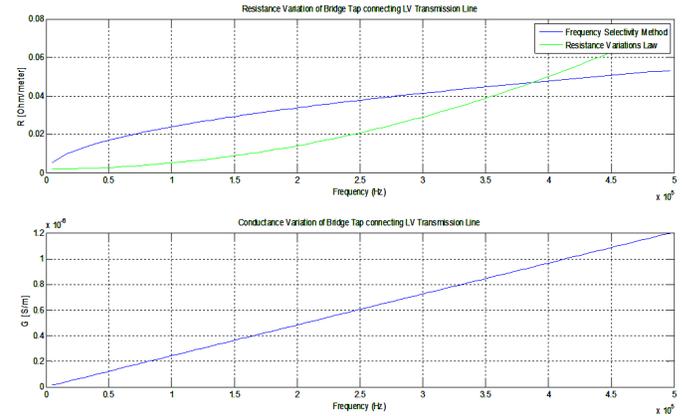


Fig. 2. R & G variations of each branch/bridge tap

The inductance of each phase and capacitance can be calculated as given by:

$$L_a = 2 \times 10^{-7} \ln(GMD/GMR) H/m \quad (6)$$

$$C = \frac{2\pi\epsilon_o}{\ln(GMD/r)} F/m \quad (7)$$

Where ϵ_o is 8.85×10^{-12} . Derived values of L and C of Wasp transmission line are 0.86 $\mu H/m$ and 13.6 pF/m respectively [7].

Impedance modelling is a very critical part for NB-PLC that can be modelled by sophisticated parallel resonant RLC circuit as:

$$Z(\omega) = \frac{R}{1 + jQ\left(\frac{\omega}{\omega_o} - \frac{\omega_o}{\omega}\right)} \quad (8)$$

where Q is a quality factor (selectivity), R represent the resistance at resonant and ω_o is representing angular resonant frequency [5]. From transmission line theory the input impedance Z_{in} of LV channel is calculated by:

$$Z_{in} = Z_{cbt} \frac{Z_{bt} + Z_{cbt} \tanh(\gamma_{bt} l_{bt})}{Z_{cbt} + Z_{bt} \tanh(\gamma_{bt} l_{bt})} \quad (9)$$

where Z_{bt} is impedance of bridge tap, Z_{cbt} represents characteristic impedance of bridge tap and γ_{bt} is reflection coefficient of bridge tap. Frequency selective behaviour of access impedances and input impedance (at LV side of 250 kVA transformer) along with their phase results of developed model are shown in Figs. 3 and 4 respectively.

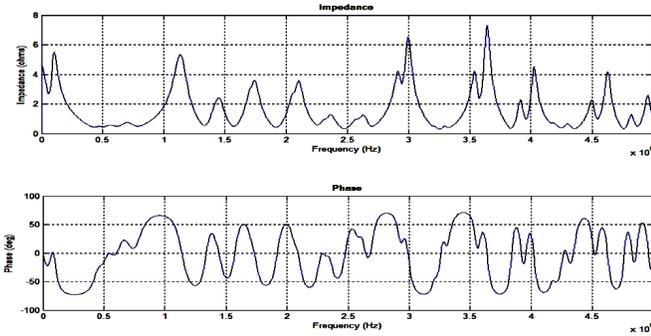


Fig. 3. Magnitude and phase of access impedances

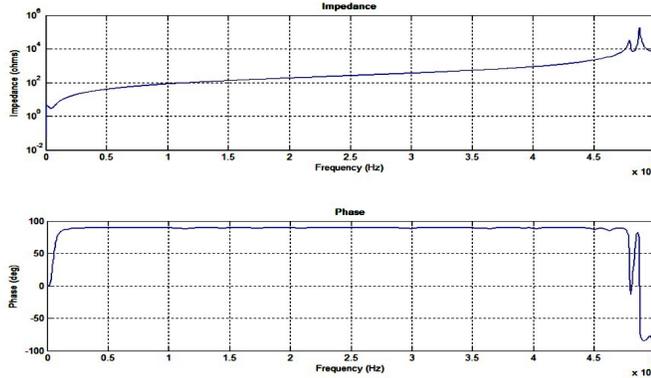


Fig. 4. Magnitude and phase of input impedance

Magnitude of source and load impedances are 50Ω and 4Ω respectively and impedances of bridge taps connected to LV lines ranges $4-8 \Omega$. It has been analysed that with impedances less than 0.5Ω , injection of significant amplitude of signals becomes a challenge [4].

B. Capacitive Coupling Device

A capacitive coupler is designed to connect the transceiver to LV network. The concept of capacitive coupler is taken from [1], [5] and [6] in which a capacitive coupler for MV

network has been introduced. We developed capacitive coupler for LV network in the simulink, in which a sinusoidal signal generator gives the signal to parallel RLC circuit with values $25 \text{ k}\Omega$, 135 H and 14 nF for R_p , L_p and C_p respectively. An isolation transformer of 1:1, operational frequency $10-500 \text{ kHz}$ and inductance 1.4 mH followed by a series tuned circuit with $L_s = 50 \text{ H}$ and $C_s = 1 \text{ nF}$ is used. The coupling interface used at the receiving end has same values as the capacitive coupler of transmitter side; both are shown in the developed model in Fig. 1.

III. TRANSFER FUNCTIONS AND RESULTS DISCUSSION

Transmission line theory has been used for the modeling of LV channel in order to obtain its transfer function, results are compared with transfer function obtained from Simulink model given as:

$$\text{Attenuation} = 20 \log_{10} \frac{V_{RX}}{V_{TX}} \quad (10)$$

Each segment of power grid can be approximated by utilizing the approach of ABCD matrix (transmission line parameters) which establishes a relationship of sending end voltage V_1 and current I_1 with the receiving end voltage V_2 and current I_2 given as:

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} \cosh(\gamma l) & Z_c \sinh(\gamma l) \\ \frac{1}{Z_c} \sinh(\gamma l) & \cosh(\gamma l) \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} \quad (11)$$

TL theory shows that every part of transmission line can be modeled in form of an appropriate two port network and their transfer function can be obtained as:

$$H = 20 \log_{10} \frac{Z_L}{AZ_L + B + CZ_L Z_S + DZ_S} \quad (12)$$

For the validation of results, comparative analysis of transfer functions obtained from both approaches mentioned above is presented in Figs. 5 and 6.

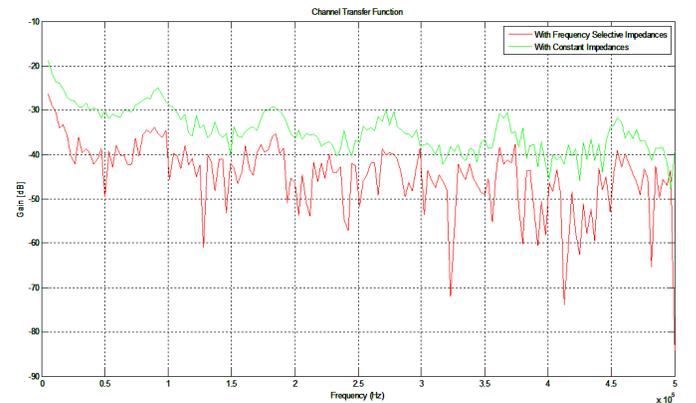


Fig. 5. Channel transfer function obtained from TL theory

Variations in signals attenuation caused by constant and frequency selective impedances revealed the fact that attenuation caused by constant impedances is about 10 dB lesser

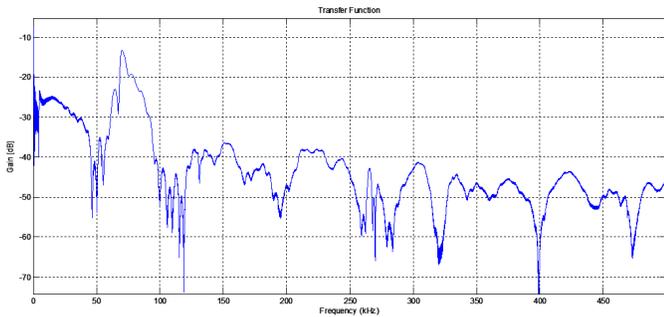


Fig. 6. Channel transfer function obtained from developed model

than frequency selective impedances. Transfer function result obtained by incorporating the frequency selective impedances is more similar with the results obtained from Simulink model shown in Figs. 5 and 6 respectively. Therefore it is suggested to add frequency selectivity into the network parameters in order to obtain more accurate results. Both plots (frequency selective and Simulink model) shows dips at the frequencies 125 kHz, 325 kHz, 400-410 kHz and then at 475 kHz. More rapid variations in attenuation have been found in the plot of Fig. 6 due to an additional attenuation caused by capacitive coupler device, however overall simulation plot shown in Fig. 6 is in good agreement with frequency selective transfer function plot of Fig. 5 thus validating the proposed procedure and techniques for the characterization and modelling of LV NB-PLC system.

A. Background Noise in NB-PLC Channel

Background noise is caused due to the frequency selectivity and time varying nature of loads that can create frequency disturbances in the frequency range up to 500 kHz in our case is shown in Fig. 7 [7]. As reported in literature, the power spectral density of background noise follows exponentially decaying function with frequency which can be modeled with the following expression:

$$PSD_W^{LV,MV} = a + be^{fc} \quad (13)$$

Where parameters a, b and c differs with respect to each model and scenario.

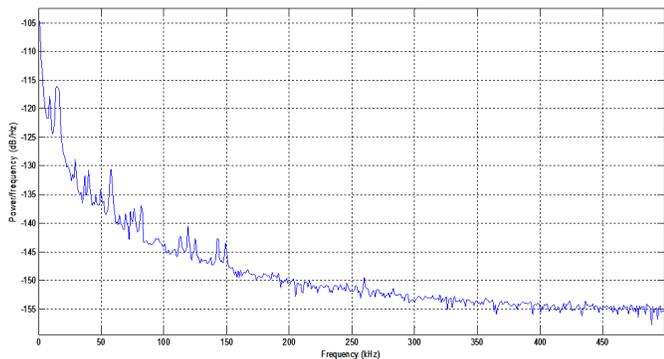


Fig. 7. Distribution of noise spectra in LV NB-PLC channel model

IV. CONCLUSION

In this research paper a comprehensive analysis of LV NB-PLC channel has been presented. The paper was focused on the modelling of LV channel parameters by incorporating new concepts to model them. A capacitive coupling device is designed to inject NB-PLC signal into the LV channel which was previously designed and implemented only for MV network. Frequency selectivity is observed in the developed Simulink model which was also modelled using TL theory by inducing the concept previously practiced in indoor PLC channel. In this perspective frequency dependent resistance and conductance were modelled. It is also shown that resistance variation plot also endorsed the resistance variations law. Frequency selective nature of loads has been analysed in the developed simulink model and after considering its frequency selectivity, a parallel RLC circuit was modelled with the help of equation 8 which added the frequency selectivity in the approach followed by TL theory. Then results of its transfer functions with both constant and frequency selective impedances were compared with the results of transfer function obtained from Simulink model. It has been observed that transfer function of simulink model that has frequency selective nature is approximately comparable with the TL theory transfer function that is based on frequency selective impedances but when it comes to compare with the constant impedance based transfer function of TL theory, lesser attenuations about 10-15 dB were observed in constant impedance model. Last but not least, the influence of background noise on LV NB-PLC network is obtained which is compared with existing noise models present in the literature.

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