Power Line Communication Design and Implementation Over Distribution Transformers

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Abstract

Recently, communication requirements assumed a greater importance following interest in smart grid and cities. This type of communication is simply aimed to facilitate a wide range of applications, i.e. from metering to protection purposes. The traditional power line communication (PLC) has been used for many years over high voltage power lines but there is a need for expanding PLC applications for a more reliable operation of smart grids. For this purpose, this paper seeks to examine PLC application at the medium and low voltage sides over distribution transformers and proposes the transmission line model (TLM) technique to develop high frequency models of power apparatus (line and distribution transformer). The models are then verified by real time experiments on a distribution transformer (50kVA, 34.5/0.4 kV, 50Hz, oil insulated, delta/star connected). Laboratory experiments show that the proposed TLM model is suitable for high frequency modeling of a distribution transformer. Furthermore, the suggested technique is also compared to Matlab simulations.

1. Introduction

Unlike the traditional distribution networks in the past, today's distribution systems are planned to be 'smart' with the capability of communication techniques as a bridge between medium and low voltages. To have such a system is a prominent issue for distribution companies in most countries due to the need for supplying reliable energy. This will also allow an effective way of monitoring the distribution system where loss-leakage rate and power flow assume high importance. A distribution system operator can also make an efficient power flow prediction and work for quality issues with the help of communication schemes. Communications for power systems consists of, media, basic data (transmitted or received), data interface, scada systems, home automation, power system relaying and signaling, distribution management, automatic generation control, energy management, railway signaling, and substation automation [1]. To achieve these requirements some modern approaches such as GSM based monitoring can be used but result in high cost.

PLC offers a low cost solution compared to GSM based approaches because of its access up to the end-users. Communication media can be either metallic cable pairs or fiber optic cables but preferably metallic cables are used due to not having extra signaling costs. Metallic cable pairs consist of twisted pair conductors or coaxial cables, which are suitable for point-to-point communication, and do not require licensing. One such pair can be used for simplex and half-duplex transmission at a speed up to 2.4 kbps. If the impedance changes dynamically especially in case of switching events, it seriously affects the performance. Alternatively, fiber optic cables present a wider bandwidth, immunity against lightning and electromagnetic inferences but require high installation cost [2,3].

To sum up, PLC can be negatively affected by the power lines and transformers connecting the lines. Cable structure and connecting points at the buses, line capacitances, and environmental conditions are the factors that affect the performance of PLC. Furthermore, transformers under rated working conditions severely attenuate the communication and behave like a low-pass filter up to kHz ranges. Therefore, overall and transformers affect the PLC negatively and further studies are needed to improve the PLC performance.

This paper addresses a novel modeling and simulation technique for line and distribution transformers based on TLM. To the authors' knowledge, it is the first study these simulations are then verified by a two of laboratory experiments. Computer simulations have random data, text message, and voice message as input signals and associated bit error rate (BER) values are calculated. A three phase distribution transformer in service is used for real time experiments.

2. Power Line Communication

PLC is a traditional communication method that uses the existing cable pairs to send and receive data simultaneously while the network is running. This is basically achieved on metallic cable pairs which enable simplex and half-dublex transmission at a speed up 2400bps over a pair. There are three kinds of PLC i.e. ultra narrow band, narrow band, and broad band. PLC has some advantages i.e. fully control over communication, no licensing, and suitable for point to point communication. However, some external conditions may affect the carrier signal. Besides, network impedance changes dynamically and it affects the transmitted data. Furthermore, switching transients and lightning phenomena also have adverse effects on PLC. These disadvantages can be overcome using additional filter circuits and reliability can be maximized [4]. Traditional PLC has been used for many years through the power lines but it is not compatible for smart metering due to the use of distribution transformers under service. This is explained in Fig. 1.

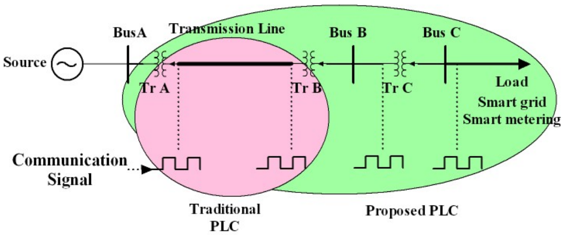

Fig. 1. Demonstration of traditional and proposed PLC schemes

In Fig. 1; traditional PLC scheme consists of only a power cable while the proposed one consists of a power cable and a distribution transformer. The main purpose of the suggested technique is to send the data from substation/generation side and to retrieve it from the consumer side which is the background of smart metering and grid. To achieve this goal it requires a complex modeling of transformers under high frequency conditions. The following section describes the modeling procedure.

3. TLM Model of a Distribution Transformer

The TLM technique was first introduced for modeling two dimensional electromagnetic field problems and then developed for three dimensional problems and circuit simulations [5]. Since TLM proposes discrete modeling without setting up any integro-differential equations, it is easy to implement in computers. TLM models reactive components as transmission line segments so called stubs. Inductor element is terminated by short circuit to emphasize storage in the magnetic field while a capacitor is modeled by an open-circuit stub to emphasize storage in the electric field. By doing so, the linear inductive and capacitive behaviors are obtained and these can be extended to nonlinear modeling adding additional techniques such as Jiles-Atherton and Lucas based formulations. As in case of transformer modeling, magnetic coupling is modeled using current controlled voltage source in TLM [6,7].

Fig.2 shows a simple TLM modeling of a single phase transformer under rated frequency. It is noted that it is valid up to a few kHz.

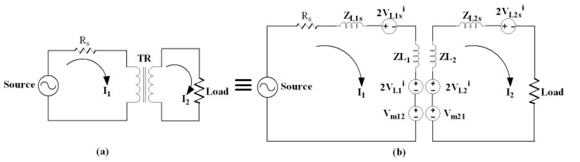

Fig. 2. (a) general view of a single phase transformer, (b) TLM representation

The controlled sources representing mutual terms of $M\dfrac{di}{dt}$ are as follows:

$$V_{m12} = Z_m I_2 + 2V^i_{m12} \quad (1)$$

$$V_{m21} = Z_m I_1 + 2V^i_{m21} \quad (2)$$

where $Z_m = \dfrac{2M}{\Delta t}$.

The following equations are solved to find I_1 and I_2.

$$(R_s + ZL_1 + ZL_{1s})I_1 - Z_m I_2 = Vs - 2(V^i_{L1} - V^i_{m12} - V^i_{L1s}) \quad (3)$$

$$-Z_m I_1 + (Z_{L2} + Z_{L2s} + R_2 + R_L)I_2 = 2(V^i_{m21} - V^i_{L2} - V^i_{L2s})$$
(4)

Characteristic impedances in Eqs. (3,4) are calculated as follows.

$$Z_{L1s} = \frac{2L_{1s}}{\Delta t} \quad Z_{L2s} = \frac{2L_{2s}}{\Delta t} \quad Z_{L1} = \frac{2L_1}{\Delta t} \quad Z_{L2} = \frac{2L_2}{\Delta t} \quad (5)$$

where Δt is sampling interval.

All TLM voltages are calculated as follows:

$$V_{L1} = 2V^i_{L1} + I_1 Z_{L1} \quad (6)$$

$$V_{L2} = 2V^i_{L2} + I_2 Z_{L2} \quad (7)$$

$$V_{m12} = 2V^i_{m12} + I_2 Z_m \quad (8)$$

$$V_{m21} = 2V^i_{m21} + I_1 Z_m \quad (9)$$

$$V_{L1s} = 2V^i_{L1s} + I_1 Z_{L1s} \quad (10)$$

$$V_{L2s} = 2V^i_{L2s} + I_2 Z_{L2s} \quad (11)$$

The incident voltages at the next time step:

$${}_{k+1}V^i_{L1} = {}_kV^i_{L1} - {}_kV_{L1} \quad (12)$$

$${}_{k+1}V^i_{L2} = {}_kV^i_{L2} - {}_kV_{L2} \quad (13)$$

$${}_{k+1}V^i_{m12} = {}_kV^i_{m12} - {}_kV_{m12} \quad (14)$$

$${}_{k+1}V^i_{m21} = {}_kV^i_{m21} - {}_kV_{m21} \quad (15)$$

$${}_{k+1}V^i_{L1s} = {}_kV^i_{L1s} - {}_kV_{L1s} \quad (16)$$

$${}_{k+1}V^i_{L2s} = {}_kV^i_{L2s} - {}_kV_{L2s} \quad (17)$$

The simulation is run until the desired number of iteration is achieved. High frequency modeling of a transformer is a bit complex due to stray capacitances of primary, secondary, and between the primary and secondary windings (Fig. 3).

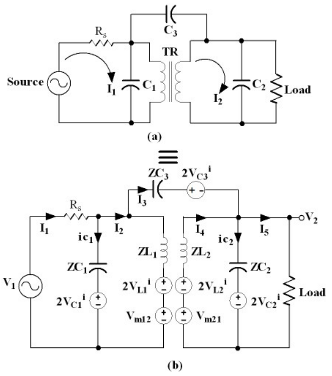

Fig. 3. High frequency transformer modeling, a) general representation, b) TLM concept

The following circuit equations are obtained and solved for I1, I2, I3, I4, and I5.

$$V_1 - 2V^i_{C1} = I_1(R_s + ZC_1) - I_2 ZC_1 \quad (18)$$

$$2V_{C1}^{i} + 2V_{L1}^{i} - 2V_{m12}^{i} = -I_1 ZC_1 + I_2(ZC_1 + ZL_1) - I_4 Z_m - I_3 ZL_1 \tag{19}$$

$$2V_{m12}^{i} - 2V_{L1}^{i} + 2V_{C3}^{i} - 2V_{L2}^{i} - 2V_{m21}^{i} = -I_2 ZL_1 + I_3(ZL_1 + ZC_3 + ZL_2) - I_4 ZL_2 \tag{20}$$

$$2V_{m21}^{i} - 2V_{L2}^{i} - 2V_{C2}^{i} = -I_2 Z_m + I_3 ZL_2 + I_4(ZL_2 + ZC_2) - I_5 ZC_2 \tag{21}$$

$$2V_{C2}^{i} = -I_4 ZC_2 + I_5(R_{load} + ZC_2) \tag{22}$$

The next procedure is to calculate TLM voltages and updates as in the case of Eqs. (6-17).Voltage gain is then calculated as in Eq. 23.

$$G = \frac{V_2}{nV_1} \tag{23}$$

where n is turn ratio.

If a more detailed modeling is desired, magnetic behavior can be obtained using Jiles-Atherton approach in TLM simulations [8].

4. Laboratory Experiments

4.1. Measuring and estimating the frequency response of a distribution transformer

In order to send data over transformers, the process will require additional circuit devices both in primary and secondary sides to maintain data reliability [9,10]. This causes additional cost as well as security concerns for high voltage side. However, the suggested method of using PLC does not need to have any additional device except for frequency behavior to define maximum gain at a specific frequency. In real life experience, the distribution transformers are fed through power cables/lines which have specific high frequency characteristics. To obtain a more realistic results, a π line model, which has 137 km, 77kV, 100A rated values, is used (Fig. 4).

Fig. 4. 50kVA, delta/star, 34.5/0.4kV distribution transformer for PLC. (1) distribution transformer, (2) line model

Transmission line model has line – line capacitances as well as line – ground capacitances. The effects of these capacitances are also taken into account in computer simulations. The transmission line is modeled as a 2-port network and its related coefficients are calculated as below

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} \tag{24}$$

where A=D=-1.0144-j*0.0209, B=Z=3.012+j*4.455 Ω , C=0.009 $(1/\Omega)$. These parameters are obtained experimentally, i.e. no-load and short circuit tests, and used in TLM simulations. The TLM of line is given in Fig. 5.

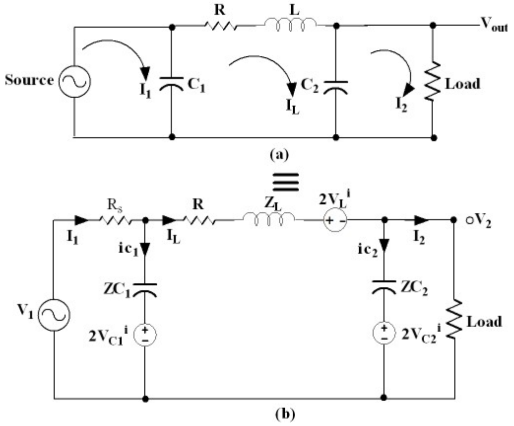

Fig. 5. TLM model of 137 km, 77kV, 100A line section, a) general view, b) TLM representation

The following equations are solved for I_1 , I_L , and I_2 .

$$\begin{bmatrix} R_s + ZC_1 & -ZC_1 & 0 \\ -ZC1 & R + Z_L + ZC_1 + ZC_2 & -ZC_2 \\ 0 & -ZC_2 & R_L + ZC_2 \end{bmatrix} \begin{bmatrix} I_1 \\ I_L \\ I_2 \end{bmatrix} = \begin{bmatrix} V_1 - 2V_{C1}^{i} \\ 2V_{C1}^{i} - 2(V_L^{i} + V_{C2}^{i}) \\ 2V_{C1}^{i} \end{bmatrix} \tag{24}$$

The performance of the TLM modeling and PSIM solutions are given in Fig. 6. As seen in Fig. 6, TLM presents a close frequency response compared to real time and PSIM solutions.

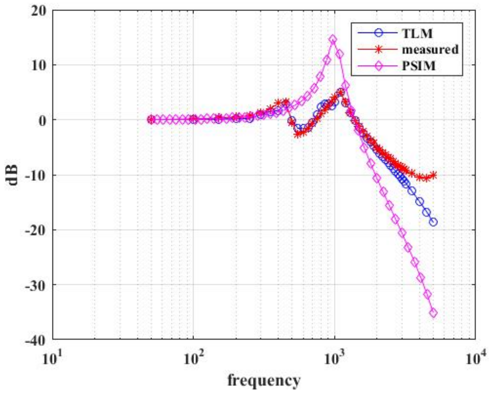

Fig. 6. Performance of TLM modeling of a line section

In Fig. 6, the real time frequency response is obtained by changing the frequency of the input signal (constant) and reading voltage of output signal. The frequency response of the transformer along with the transmission line model from high voltage to low voltage side was obtained experimentally. Sweep

Frequency Response Analysis (SFRA) technique was used to characterize the frequency response. The studied transformer showed a resonance of bandwidth of 34 kHz centered at 210 kHz as shown in Fig. 7. The resonance bandwidth will be used as communication channel to transmit messages from the utility to the customer. The proposed channel has gain of 12 V/V which acts as an amplifier circuit to the transmitted message. Therefore, it will be expected that the BER of the transmitted signal will be better than the AWGN theoretical limits. In other words, the gain of the communication channel will amplify the message increasing the SNR which will make the BER to look better than the theoretical limits.

Using the TLM model from section 3, the frequency response of same transformer was estimated and plotted with respect to the real measured data as depicted in Fig. 7.

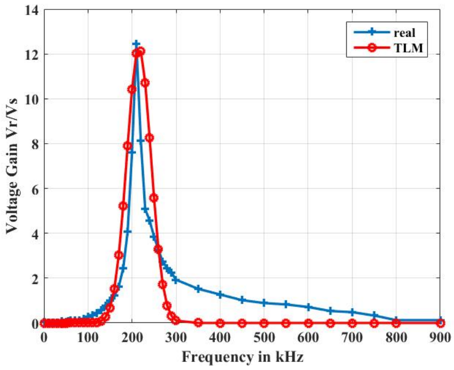

Fig. 7. Comparison between TLM model results with respect to real measurements of frequency response for distribution transformer.

By comparing the TLM model and the measured frequency response, it can be concluded that TLM modeling estimates the high frequency behavior of the distribution transformer in a similar manner to real time experimental SFRA results.

4.2. Sending data through resonance bandwidth

As illustrated in section 4.2, the resonance can form a reliable communication channel. By truncating the bandwidth of the resonance to be 34 kHz around the center frequency, the channel will be presented as band-pass filter with amplification gain as shown in Fig. 8.

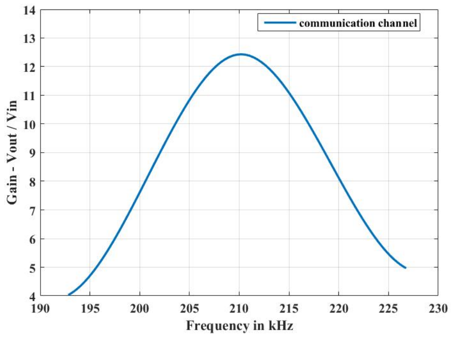

Fig. 8. Communication channel of the distribution transformer

By looking at the truncated channel in frequency domain, the filter response can be visualized; consequently, for better performance, the carrier frequency (sinusoidal waveform in time domain) should be sent at the channel center frequency as shown in Fig. 9. In other words, the message should be modulated at the resonance frequency to utilize the bandwidth fully and optimize the SNR values.

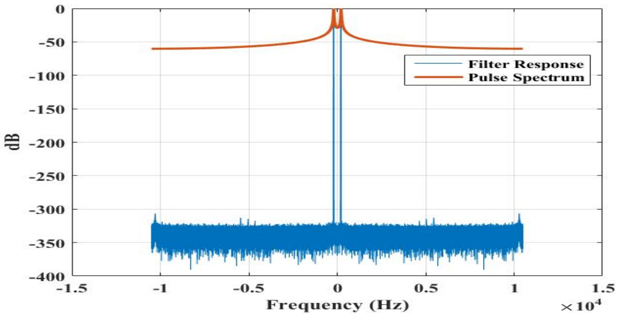

Fig. 9. Filter response and pulse spectrum at center frequency.

The data (text message) sent through the transformer channel is "**This is PLC study over distribution transformer for ELECO 2017**" and converted into 8 bits binary data and then BPSK modulated. Signal to noise ratio (SNR) is selected between -10:1:10 and Monte Carlo method is used for obtaining BER values (Fig. 10). In Fig. 10, simulation results are given. BER values related to transformer channel are not seen since they have zero values. White noise with a SNR of -10:1:10 is added to simulations.

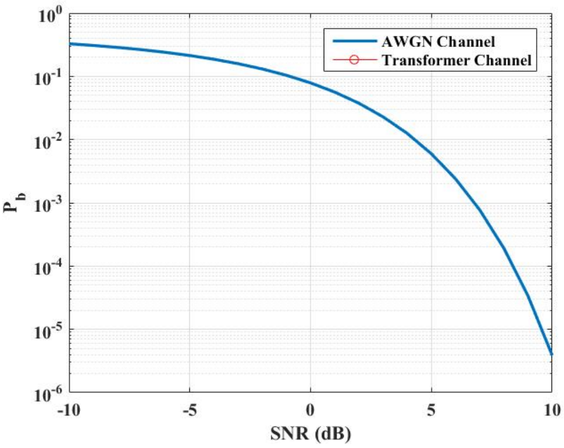

Fig. 10. BER values of transformer channel vs AWGN channel

The following example is a bit complex due to size of the data. A 10kbit data generated randomly was sent through the transformer channel with an 800 bps and the BER values are seen in Fig. 11. The performance of transformer channel is slightly better than the theorical channel even in low SNR values.

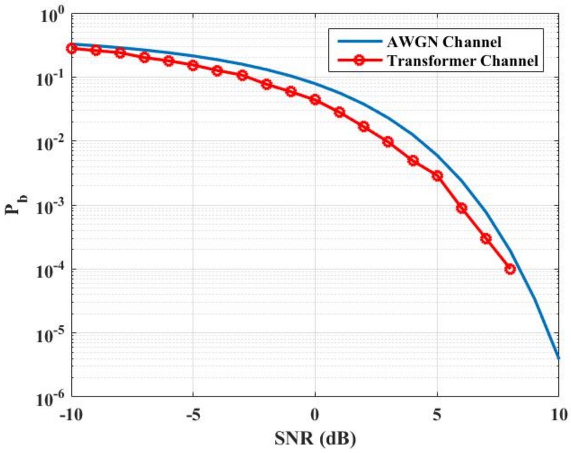

Fig. 11. Sending random generated data and related BER values

5. Conclusions

Due to transformer high frequency behavior sending the data through magnetic coupled transformers cannot be easily achieved. One of the possible reason is that transformer itself behaves as a low pass filter circuit under high frequency. Therefore, its high frequency modeling plays an important role to have a suitable communication channel.

This paper presents an alternative and computationally cost effective method based on TLM to model a distribution transformer under high frequency. The TLM based model is then used as a communication channel to enable data transfer bilaterally. The associated BER values show that the proposed model is suitable for data communication even for sending large amounts of data.

In future studies, data length and bit rate will be investigated and more real time measurements will be included.

6. References

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