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Modeling Low Voltage Power Line as a Data Communication Channel

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Abstract**—** Power line communications may be used as a data communication channel in public and indoor distribution networks so that it does not require the installing of new cables. Industrial low voltage distribution network may be utilized for data transfer required by the on-line condition monitoring of electric motors. This paper presents a pilot distribution network for modeling low voltage power line as data transfer channel. The signal attenuation in communication channels in the pilot environment is presented and the analysis is done by varying the corresponding parameters for the signal attenuation.

Keywords**—**Data communication, indoor distribution networks, low voltage, power line.

I. INTRODUCTION

Typical power line cable consists of three conductors: a phase, a neutral, and ground. Two of these three conductors suffice to create a communication channel. Since the phase and neutral conductors have equal wire gauge, we use these two conductors as the communication channel. Power lines have been used for low speed (<30 kbps) data communication in applications like power distribution automation and remote meter reading and local area networks for many years [1]. Nowadays, due to the increasing importance of networking in homes, offices and industrial buildings, power lines are being considered as a candidate for medium and high speed (> 2 Mbps) data transmission. [2, 3, 4]. The term "low-voltage power line communication system" refers to transmission over the existing power lines, which would normally require additional hard ware installation. This system is attractive because it reuses the existing lower voltage distribution network; hence, new cabling installation can be avoided. Therefore, small investment and cost savings can be achieved [5]. The main driving force lies in that it can provide good business opportunities for a variety of different areas including electrical power engineering, communication networks as well as building automation, because the networks are almost universal in coverage and are easily accessed by wall plugs [6]. However, unlike the other wired communication mediums such as the unshielded twisted pair (UTP) and coaxial cables, LV power lines present an extremely harsh environment for channel parameters namely, noise(background noise, narrow noise & impulse noise), impedance mismatch and attenuation are found to be highly unpredictable and variables with time, frequency and location. Therefore, it is a real challenge to realize high rate data transmission over the low-voltage distribution network. One of the most important problems to solve is to find the appropriate modulation technique. In order to overcome these difficulties, a lot of efforts have been undertaken to characterize and model the LV power line channel [4]. The objective of this paper is to model low voltage power line channel as a series combination of T or Π sections and derive its transfer function with given length and size based on the transmission line theory. This model will help the PLC system designer to better understand the channel behaviors and to engineer the channel performance under unpredictable load conditions. That is followed by the plotting the transfer function that show how much in magnitude and angle loss a signal suffers passing through this line and also show the loading effect on a signal along with the signal reflection. At the end of the paper, it has been demonstrated the results in graphs which are obtained by Matlab.

II. POWER LINE CHANNEL MODELING

In order to simulate power-line communications, a channel model has to be formed. There are two main methods used to model power line channels [7]. The first one applies the methods used for the modeling of radio channels. It assumes the distribution network as a multi-path propagation channel. The parameters of the channel are acquired based on the topology of the distribution network or based on the channel measurements and optimization algorithm [8]. The second approach applies to the methods used to model long electricity distribution networks. This kind of approaches to model power line channel when the topology of the network and high frequency parameters of the components are known and the high frequency characteristics of the individual network components can be obtained [8]. Figure 1 shows an equivalent II model for transmission line which is used for the study. Figure 2 depicts a two-port representation for the modeled power-line channel which consists of two transmission matrices and the load impedance. The first transmission

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matrix represents the electric motor connected in parallel with the signal source. Respectively, the second transmission matrix represents the low voltage power cable between signal source and load.

The parameters of the model are obtained. The detailed is shown in appendix.

$$Z' = Z_C \sinh\gamma l = Z \sinh\gamma l/\gamma l$$
$$Y'/2 = 1/Z_C \tanh\gamma l/2 = Y/2\ (\tanh\gamma l/2)/\ (\gamma l/2) \qquad (1)$$

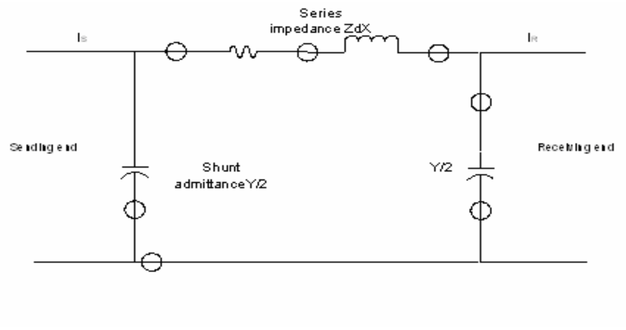

Fig. 1 Equivalent Π model for transmission line

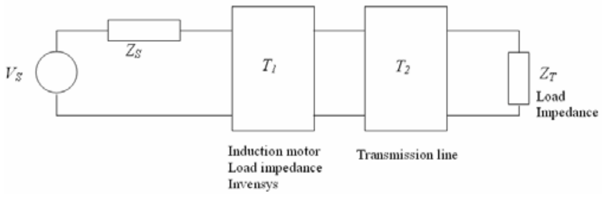

Fig. 2 Two-port Modeled of Power-line As Data Channel

III. IMPLEMENTATION

A pilot network is developed to analyze the high frequency characteristics of a complete distribution network and the effect of individual components which is shown in Figure 3. The signal attenuation coefficient of the cabling is calculated based on an experimentally acquired equation by:

$$\alpha(f) = 0.5 \cdot 10^{-6} \cdot \frac{1}{m} \cdot \left(f \cdot \frac{1}{Hz} \right)^{0.6}$$

The motors were modeled using the input impedance model introduced by Aloha et al. [8] which is shown in Figure 4. The parameters for both 15 kW motors in signal coupling (L1, PE) are: L_{hf} = 159nH, C_{hf} = 2.5nF and R_{hf} = 3Ω. Transmission matrix $T_1(f)$ is formed for the electric motor.

$$T(f) = \begin{bmatrix} 1 & 0 \\ \dfrac{1}{Z_{M,1}(f)} & 1 \end{bmatrix}$$

Where $Z_{M,1}(f)$ represents the input impedance of the electric motor, which is calculated by using the equation.

$$Z_{M,1}(f) = R_{hf,1} + j2\pi f L_{hf,1} + \frac{1}{j2\pi f C_{hf,1}}$$

The next transmission matrix T_2 is formed for motor cable (MCCMK 3x35+16), which is connected in series with the signal source:

$$T_2(f) = \begin{bmatrix} \cosh[\gamma_1(f)L_1] & Z_{0,1}\sinh[\gamma_1(f)L_1] \\ \dfrac{1}{Z_{0,1}}\sinh[\gamma_1(f)L_1] & \cosh[\gamma_1(f)L_1] \end{bmatrix}$$

where the propagation constant for the cable is:

$$\gamma_1 = \alpha_1(f) + j\beta_1 = \alpha_1(f) + j2\pi f\sqrt{l_1 c_1}$$

And the characteristic impedance of the cable is:

$$Z_{0,1} = \sqrt{\frac{l_1}{c_1}}$$

The distributed capacitance of the cable is increased 25% in order to match the simulation with the measurement. Both transmission matrices are combined using chain rule:

$$T(f) = T1(f)T2(f) = \begin{bmatrix} 1 & 0 \\ \dfrac{1}{Z_{M,1}(f)} & 1 \end{bmatrix} \begin{bmatrix} \cosh[\gamma_1(f)L_1] & Z_{0,1}\sinh[\gamma 1(f)L_1] \\ \dfrac{1}{Z_{0,1}}\sinh[\gamma_1(f)L_1] & \cosh[\gamma_1(f)L_1] \end{bmatrix}$$
$$= \begin{bmatrix} \cosh[\gamma_1(f)L_1] & Z_{0,1}\sinh[\gamma_1(f)L_1] \\ \dfrac{\cosh[\gamma_1 L_1]}{Z_{M,1}(f)} + \dfrac{1}{Z_{0,1}}\sinh[\gamma_1(f)L_1] & \dfrac{Z_{0,1}\sinh[\gamma 1(f)L_1]}{Z_{M,1}(f)} + \cosh[\gamma 1(f)L_1] \end{bmatrix}$$

The received voltage is measured over the load impedance Z_L which consists of two load impedances connected in parallel. The first one is the serial connection of the motor cable (EMCMK 3x16+16, length 9.7 m) and the electric motor (Invensys, 15 kW). The second one is the input impedance of the distribution transformer (France Transform, 50 kVA). The impedance formed by the cable and motor is:

$$Z_{eq}(f) = Z_{0,2}\frac{Z_{M,2}(f) + Z_{0,2}\tanh[\gamma_2(f)L_2]}{Z_{0,2} + Z_{M,2}(f)\tanh[\gamma_2(f)L_2]}$$

The propagation constant for the cable is calculated using equation:

$$\gamma_2 = \alpha_2(f) + j\beta_2 = \alpha_2(f) + j2\pi f\sqrt{l_2 c_2}$$

The characteristic impedance of the cable is calculated using equation:

$$Z_{0,2} = \sqrt{\frac{l_2}{c_2}}$$

The parameters for the input impedance model of the electric motor and for the power cable are in table [6].

The distributed capacitance of the cable is increased 40% in order to match the simulation with the measurement. For simplicity, the input impedance for the distribution transformer (France Transform, 50kVA) in signal coupling (L1, PE) is assumed to be equal to 60Ω.

The total load impedance is given by equation:

$$Z_L(f) = \frac{Z_T(f)Z_{eq}(f)}{Z_T(f) + Z_{eq}(f)} = \frac{Z_T(f)Z_{0,2}\dfrac{Z_{M,2}(f) + Z_{0,2}\tanh[\gamma_2(f)L_2]}{Z_{0,2} + Z_{M,2}(f)\tanh[\gamma_2(f)L_2]}}{Z_T(f) + Z_{0,2}\dfrac{Z_{M,2}(f) + Z_{0,2}\tanh[\gamma_2(f)L_2]}{Z_{0,2} + Z_{M,2}(f)\tanh[\gamma_2(f)L_2]}}$$

The transfer function for the voltage attenuation of the communications channel is given by equation:

$$H(f)=\frac{V_2(f)}{V_S(f)}=\frac{Z_L(f)}{A(f)Z_L(f)+B(f)+C(f)Z_L(f)Z_S+D(f)Z_S}$$
$$=\frac{Z_L(f)}{\cosh[\gamma_1(f)L_1]Z_L(f)+Z_{0,1}\sinh[\gamma_1(f)L_1]}$$

IV. SIMULATION

The amplitude responses for power-line channel and for the frequency band 100 kHz – 20 MHz are calculated. In addition, the gains of the simulated and measured channel behave similarly. The effect of length to the signal voltage attenuation is shown in Figure *5*. The distance between receiver and transmitter is 50, and 100 respectively and the signal coupling is (L1, PE). The effect of capacitance and inductance to the signal voltage attenuation is shown in Figure 6. The capacitance and inductance of MCCMK transmission line are 83nH and 313pF, and 41.5nH and 156.5pF, respectively.

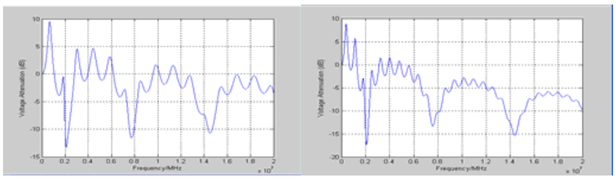

Fig. 5 Simulated amplitude response for the frequency band 100 kHz – 20 MHz

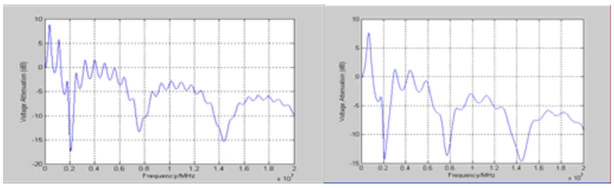

Fig. 6 Simulated amplitude response for the frequency band 100 kHz – 20 MHz

V. CHANNEL CAPACITY ANALYSIS AND BIT ERROR POSSIBILITY

The information capacity of a communications channel describes the number of independent symbols that can be transmitted through the channel in a given unit of time. The basic symbol in digital communications is the bit. In communication, the transmitter injects a signal into the channel. The channel filters the transmitted signal and at the receiver noise is added to the transmitted signal.

The capacity of the channel is dependent on the signal to noise ratio at the receiver and the bandwidth available for data transfer. C.E. Shannon from Bell Telephone Laboratories presented in 1948 the mathematical formula for the information capacity of a communications channel:

$$C=B\log_2\left(1+\frac{S}{N}\right)$$

where C represents the information capacity of the channel (bits/second), B is the available bandwidth and the symbols S and N represent the signal and the noise power at the input of the receiver. Shannon's theorem is not directly applicable for the capacity analysis of a power-line channel, because the signal to noise ratio is frequency variant with practical channels.

The output voltage amplitude of the transmitter $U_{TX}(f)$ can be presented with the output power of the transmitter $P_{tx}(f)$ and the input impedance of the communications channel at the transmitter $Z_{in,tx}(f)$:

$$|U_{tx}(f)|=\left|\sqrt{\frac{P_{tx}(f)}{\cos\phi(f)}}\cdot Z_{in,tx}(f)\right|$$

where cos $\varphi(f)$ is the phase angle of the input impedance $Z_{in,tx}(f)$. The voltage amplitude of the received signal at the receiver $U_{rx}(f)$ can be written as:

$$|U_{rx}(f)|=|H(f)|\cdot|U_{tx}(f)|$$

where $H(f)$ is the transfer function of the communications channel. The information capacity of the channel presented with the signal voltage and noise voltage amplitudes is:

$$C=\int_{f1}^{fh}\log_2\left[1+\left(\frac{|Urx(f)|}{|U_n(f)|}\right)^2\right]df$$

where $B=f_h-f_l$ and $|U_n(f)|$ is the amplitude of the noise voltage at the receiver. The noise voltage amplitude can be calculated applying the noise current amplitude $|I_n(f)|$ and the input impedance at the receiver:

$$|U_n(f)|=|Z_{in,rx}(f)|\cdot|I_n(f)|$$

Shannon's theorem gives the theoretical data transfer rate of the communications channel that can be achieved at a low probability of data transfer errors. Another quantity to estimate the quality of the communications channel and the receiver is the bit error ratio (BER). It describes the probability of error per received bit. Theoretically, the bit error ratio is dependent on the signal to noise ratio at the receiver and on the used modulation method. The bit error ratio for binary FSK can be estimated using equation:

$$BER=\frac{1}{2}erfc\left(\sqrt{\frac{\gamma_b}{2}}\right)$$

where γ_b is the signal to noise ratio per received bit and

$$erfc(x)=\frac{2}{\sqrt{\pi}}\int_x^{\infty}e^{-t}dt$$

VI. DISCUSSION

We simulate load impedance as a function of frequency from there we can see that load impedance plays an important role in determining the location and amplitude of notches and peaks in the signal voltage attenuation. If we increase the frequency, there is a very little effect of load impedance. We plot signal attenuation co-efficient as a function of frequency and the magnitude of signal attenuation will increase with the increasing of frequency almost linearly. Furthermore, we simulate voltage attenuation with frequency after varying the length of cable, where it shows if we increase the length of wire then the signal will suffer a lot of its phase and magnitude. At the end, we plot signal attenuation as a function of frequency by varying the capacitance and inductance of transmission line. We can see the values of the distributed inductance and capacitance of this transmission line is reduced, the notches and peak still occurs at the same frequency except that there will be less ripple on the signal attenuation and the magnitude of the signal attenuation is reduced. However, the ripples in the voltage attenuation reduces as the value of inductance and capacitance is reduces, but the voltage attenuation will be more after reducing of that value of MCCMK transmission line at frequency band 100 kHz – 20 MHz.

VII. CONCLUSION

The amplitude responses of the power-line channels in the pilot distribution network can be modeled using two-port models and simple high frequency models for the power cables and electric motors. Similar models can be applied in the power-line communications and electro-magnetic interference. Moreover, a proper noise model is required for the simulation of the power-line as a communication channel. From the above model and simulation, we can see that load impedance plays an important role in determining the location and amplitude of notches and peaks in the signal voltage attenuation with frequency as well as changing the value of load impedance will cause effect on attenuation.

APPENDIX

The series impedance per unit length is shown by ‘z’ and the shunt admittance per phase is shown by ‘y’, where z = r + jwL and y = g + jwc. Consider a small segment of line Δx at a distance x from the receiving end of the line. From Kirchhoff’s voltage law

$$V(x + \Delta x) = V(x) + z\Delta x I(x)$$

$$\frac{V(x+\Delta x) - V(x)}{\Delta x} = zI(x)$$

Taking the limit as Δx→0, we have, $\frac{dV}{dx} = zI(x)$

Also, from Kirchhoff’s current law

$$I(x+\Delta x) = I(x) + y\Delta x V(x+\Delta x)$$

$$\frac{I(x+\Delta x) - I(x)}{\Delta x} = yV(x)$$

So $dI(x)/dx = yV(x)$

Finally, we get

$$\frac{d2V(x)}{dx2} = zy\, V(x)$$

Let $\gamma = zy$

The following second-order differential equation will result

$$d^2V(x)/dx^2 - \gamma^2 V(x) = 0$$

The solution of equation (2) is

$$V(x) = A_1e^{\gamma x} + A_2e^{-\gamma x}$$

Where γ = Propagation constant

$$= \alpha + j\beta = \sqrt{zy} = \sqrt{(r + jwL)(g + jwc)}$$

Where α → Attenuation constant and β→ Phase constant

$$I(x) = \frac{1}{z} \cdot \frac{dV(x)}{dx} = \frac{\gamma}{z}(A_1e^{\gamma x} - A_2e^{-\gamma x})$$

$$I(x) = \sqrt{y/z(A1e\gamma x - A2e - \gamma x)}$$

$$I(x) = 1/Zc(A_1e^{\gamma x} - A_2e^{-\gamma x})$$

Where Zc = Characteristic impedance = $\sqrt{y/z}$

To find the constants A_1 and A_2, consider when x = 0, V(x) = V_R, and I(x) = I_R. From above equation we can find

$$A_1 = (V_R + Z_CI_R)/2$$

$$A_2 = (V_R - Z_CI_R)/2$$

The general expressions for voltage and current along any transmission line become

$$V(x) = (V_R + Z_CI_R)/2 * e^{\gamma x} + (V_R - Z_CI_R)/2 * e^{-\gamma x}$$

$$I(x) = (V_R/Z_C + I_R)/2 * e^{\gamma x} - (V_R/Z_C - I_R)/2 * e^{-\gamma x}$$

The equations for voltage and current can be rearranged as follows

$$V(x) = (e^{\gamma x} + e^{-\gamma x})/2 * V_R + Z_c * ((e^{\gamma x} + e^{-\gamma x})/2) * I_R$$

$$I(x) = 1/ Z_c * (e^{\gamma x} + e^{-\gamma x})/2 * V_R + (e^{\gamma x} + e^{-\gamma x})/2 * I_R$$

i.e.

$$V(x) = \cosh\gamma x V_R + Z_c \sinh\gamma x I_R$$

$$I(x) = 1/Z_C \sinh\gamma x V_R + \cosh\gamma x I_R$$

We are particularly interested in the relation between the sending end and the receiving end of the line. Setting x = l, V (l) = V_s and I (l) = I_S, the result is

$$V(l) = \cosh\gamma l V_R + Z_c \sinh\gamma l I_R$$

$$I(l) = 1/Z_C \sinh\gamma l V_R + \cosh\gamma l I_R$$

Rearranging the above equations in terms of the ABCD constant,

$$\begin{vmatrix} Vs \\ Is \end{vmatrix} = \begin{vmatrix} A & B \\ C & D \end{vmatrix} \begin{vmatrix} V_R \\ I_R \end{vmatrix}$$

Where,

$A = \cosh\gamma l$ $\quad B = Z_c \sinh\gamma l$

$C = 1/Zc \sinh \gamma l$ $\quad D = \cosh\gamma l$

It is now possible to find an accurate equivalent Π model, shown in figure below to replace the ABCD constants of the two-port network.

$$V_S = (1 + Z'Y'/2)\, V_R + Z'I_R$$

$$I_S = Y'(1 + Z'Y'/4)\, V_R + (1 + Z'Y'/2)\, I_R$$

The parameters of the equivalent Π model are obtained

$$Z' = Z_C\sinh\gamma l = Z \sinh\gamma l/\gamma l$$

$$Y'/2 = 1/Z_C\tanh\gamma l/2 = Y/2\, (\tanh\gamma l/2)/ (\gamma l/2)$$

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