A Study of Impedance Matching Circuit Design for PLC

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Abstract**—**This paper presents two methods of designing a Broadband Impedance Matching (BIM) circuit for maximizing a power line communication (PLC) equipment (or Modem) signal injection into its load at any power line connection port. This optimal (BIM) circuit design is achieved in two phases: Butterworth gain function and Tchebycheff gain function. According to the comparison of simulation and practical results, the performances of two gain functions on BIM are discussed.

Index Terms— Power Line Communication (PLC), Tchebycheff Gain Function, Butterworth Gain Function, Broadband Impedance Matching (BIM)

I. INTRODUCTION

Power line communication (PLC) is a technique of using the existing power lines as communication media. Power utilities could use it not only for their power grid equipment monitoring, protecting and control, but also for home internet access [1]. In the areas where consumers already have cable modem or asymmetric digital subscriber line modem for internet access, PLC could provide another broadband medium alternative.

Due to the concern of radio frequency emission and interference, the permissible PLC modem's power injection into power line networks is very limited. If the impedance of a PLC modem mismatches the load impedance at a power line connection port, the PLC modem signal power injection into the power line connection port will further be reduced. This will not only limit the PLC modem signal delivery distance to next PLC modem hence more repeaters needed, but also will cause the PLC modem signal reflection (or radio frequency emission) from the power line connection port. The challenge of this research relies on finding a suitable Broadband Impedance Matching (BIM) circuit able to adapt the PLC physical layer to Modem. An excellent set of explicit formulas for the design of optimum Tchebysheff and Butterworth impedance filters based on Youla's theory [2] of broadband matching has been published by Chen [3].

In this paper, we use a Tchebycheff gain function [4] and Butterworth gain function algorithm to achieve broadband impedance matching for PLC networks. After the comparison simulation and practical results, the performances of two gain functions on BIM are discussed. We consider PLC signals in the [1-30 MHz] band and impedance matching at the emission port only. The proposed algorithms can be applied to both medium voltage (MV) and low voltage (LV) networks. An impedance matching circuit should definitively allow an enhancement of the performances of the PLC network thus including significant improvements of the data rates likewise the associated radiated emissions. The aim of this paper is to propose some algorithms for broadband impedance matching for various types of load. Using Tchebycheff gain function and Butterworth gain function to design a broadband impedance matching circuit is a quite well known issue. However, adapting the existing algorithms to PLC networks has never been done before due to a lack of knowledge of the distribution network, especially regarding the impedance of the emission port.

II. BROADBAND IMPEDANCE MATCHING THEORY

In Fig. 1, the general configuration of PLC system is represented. PLC modem is connected with standard data terminal such as PC, modulates and demodulates data signal from terminals. The modulated signals from modem will magnetically couple with power line through the Coupler, and it is sent to receiving terminal.

Manuscript received on September 21, 2009 ; revised November 30, 2009.

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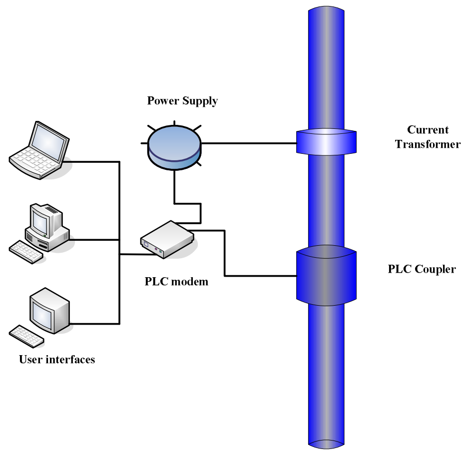


Fig. 1 PLC communication system

If the impedance of a PLC modem mismatches the load impedance at a power line connection port, the PLC modem signal power injection into the power line connection port will further be reduced. This will not only limit the PLC modem signal delivery distance to next PLC modem hence more repeaters needed, but also will cause the PLC modem signal reflection (or radio frequency emission) from the power line connection port. The problem could be solved by using a suitable BIM circuit

Let us consider the real condition of a PLC Coupler connected to the PLC network according to Fig. 2. We can see that the impedance matching circuit is a two port system to be inserted between the PLC modem and PLC Coupler. The BIM circuit will be called equalizer in the following. We can see that the equalizer is a two port system to be inserted between the source and the load.

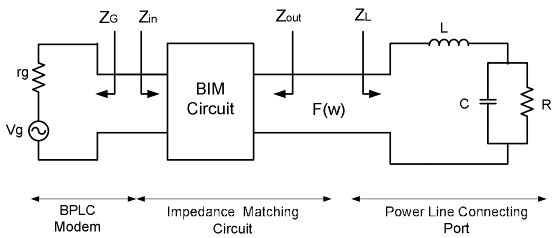


Fig. 2 Schematic of Impedance Matching

At each transmission port, a source (PLC modem in emission for instance) is used connected to a load (LV or MV networks), let us call Z_G the impedance of the source and Z_L the impedance of the load. In general, Z_G is a pure resistive load whereas Z_L is a complex one including resistive, inductive and capacitive components. The total active power delivered by the source can be completely transmitted to the load if and only if equation (1) is satisfied where ()* is for the complex conjugate.

$$Z_G = Z_L^* \tag{1}$$

Equation (1) shows there is definitively an impedan ce mismatch at the emission port, it means that the tota l active power P_L delivered by the PLC Coupler will b e partly transmitted to the Modem P_t and partly reflect ed P_r. So we have the equation (2).

$$P_g = P_t + P_r \tag{2}$$

Z_G is normally given by the PLC modem designer as a confirmed value; however, Z_L is much more complicated since we have to measure complex impedance in the [0.1~30MHz] band. It can be achieved using network analyzer.

The equalizer is necessary to minimize P_r and to maximize P_t, and perfect impedance matching will be reached if a total cancellation of P_r is achieved. This is exactly the goal of the equalizer since the design of this system has to be done in order to maximize P_t. A passive equalizer is built using passive components only like inductors and capacitors. In this paper, we focus on passive equalizer only.

It is convenient to use the gain function for the eval uation of the performance. The gain function is shown in equation (3).

$$F\left(\omega^2\right) = 1 - |\rho|^2 \tag{3}$$

where, $\rho = \dfrac{Z_G(j\omega) - Z_{in}(j\omega)}{Z_G(j\omega) + Z_{in}(j\omega)}$

The performances of the equalizer can therefore be evaluated using the gain function. Based on equation (3), we can see that the second part of $F(\omega^2)$ is the square of the magnitude of the reflection coefficient calculated at the emission port. The values taken by $F(\omega^2)$ are between 0 and 1 thus corresponding to a very poor equalizer and a powerful one, respectively. Basically, the main goal of the equalizer is to maximize the transmitted power (or to minimize the reflected power) at the emission port. Considering $F(\omega^2)$ =1 in a chosen frequency band is equivalent to a total cancellation of the reflection located at the emission port. On the other hand, $F(\omega^2)$=0 means that the designed equalizer is totally usefulness since there is a complete reflection at the emission port.

To properly design an equalizer, two technical constraints have to be satisfied. Let us define [F1>0, F2] the frequency band suitable for the wideband impedance matching. Achieving wideband impedance matching in the [F1, F2] band is possible if and only if F(ω2) is maximized within the [F1, F2] band and minimize outside from this frequency band. Note that for the majority of PLC systems, F1 and F2 can be around 0.1MHz and 30MHz, respectively. Knowing the characteristics of the impedance of the load and the source, the impedance matching algorithm has to optimize the gain function to satisfy the two previous constraints. Different shapes can be chosen for the gain functions, among these, are Tchebycheff and Butterworth gain functions. Tchebycheff gain function is refers in [1], and the following on Butterworth gain functions in equation (4).

$$F\left(\omega^2\right) = \frac{K}{1+(\omega/\omega_c)^{2n}} \qquad (4)$$

with maximum attainable DC gain K, where ω_c is the 3-dB bandwidth or the radian cutoff frequency.

Now we propose some algorithms to design the impedance matching circuit with references shown on the PLC Coupler in order to calculate the components of the matching circuit [3, 5, 6, 7].

According to the appendix equations, we can get the relationship between the load and source. In the next section, we will use these theories to design circuits and discuss the performances.

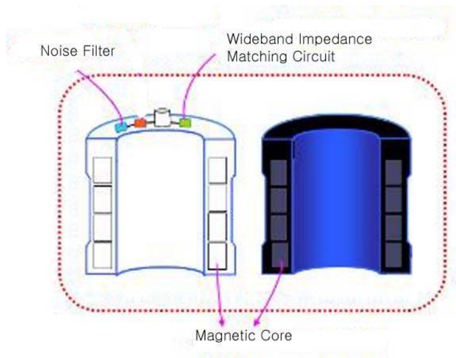
III. THE DESIGN OF IMPEDANCE MATCHING CIRCUIT

In this section, we design two BIM circuit for PLC Coupler using previous Tchebysheff and Butterworth gain functions. The PLC Coupler is shown in Fig. 3. PLC Coupler contains three main parts: noise filter, magnetic core and impedance matching circuit. In Fig. 4, S11 characteristics of the unmatched Coupler developed PLC Coupler is represented on the Smith chart using the vector network analyzer in 0.1MHz to 30MHz frequencies, and impedance characteristics are represented in Fig. 5.

We propose to design a broadband equalizer for a cutoff frequency of 30MHz since many PLC modems use some carriers between 1MHz and 30MHz. We can take a load equivalent circuit from the tested results of Fig. 4 and 5 as series inductance is 637.8nH, shunt resistance 76.29 ohm, shunt capacitance 100pF and source impedance is 50 ohm as shown in Fig. 5.

We choose the L-C low pass filter type as structure of equalizer, and applying to Weinberg relations of appendix equations, the elements values of equalizer are selected as L_1=61.424nH, C_2=27.187pF, L_3=381.16nH, and C_4=120.36nH in Butterworth gain function. And in Tchebycheff the elements values of equalizer are selected as L_1=711.64nH, L_3=691.51nH, C_2=130.54pF and C_4=86.04pF. Fig. 7 is the simulation result for S21 of equalizer using the Advanced Design System (ADS) of Agilent [8]. The simulation results show that the characteristic of filter with impedance matching circuit has more broadband comparing with without, and its cutoff frequency is about 30MHz.

(a) Photo of PLC Coupler



(b) Configuration

Fig. 3 Photo of PLC Coupler

Fig. 4 Test Test results of S-parameter (S11) of unmatched Coupler

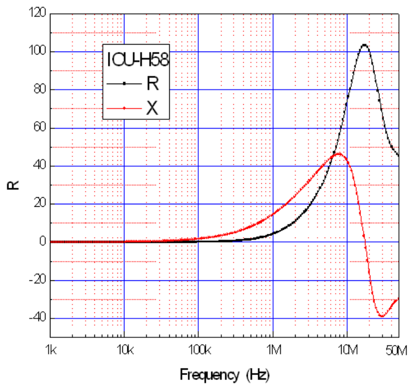


Fig. 5 Impedance(R+jX) of unmatched PLC Coupler

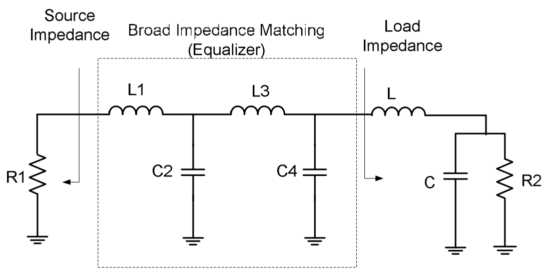


Fig. 6 the circuit of Equalizer (BIM)

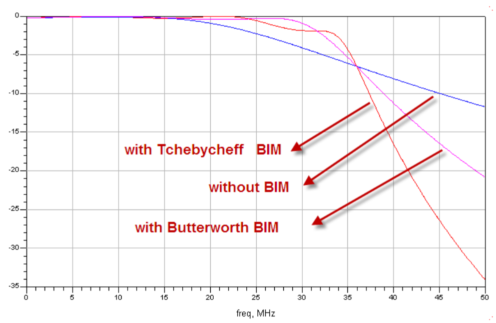


Fig. 7 S21 characteristics of the circuit with and without Equalizer (BIM)

IV. CONCLUSIONS

We tested to get the characteristics of broadband matching circuit of PLC Coupler using the vector network analyzer. Fig. 8 is shown S11 characteristic of developed Coupler with broadband impedance matching circuit comparing with characteristic of unmatched Coupler depending on Tchebycheff gain function, and Fig. 9 is result for Smith chart of S11 characteristic for it. Fig. 10 is shown S11 Characteristic of developed Coupler depending on Butterworth gain function. Fig. 11 is result for Smith chart of S11 characteristic for it.

In the broadband power line communication system, a lossless impedance matching circuit is a basic problem. The design of wideband impedance matching need more practice besides the theory.

Compare with results of two gain functions, we can see that the performance of Butterworth gain function is better that Tchebycheff gain function. But the calculated values of Butterworth gain function are so small that it's difficult to make practice.

In this paper, we have presented two general designs for a wideband impedance matching in power line communication. We use the theory to analyze the coupling circuit we want to get. Then we make the circuit in practical. It is important to modify in practical conditions.

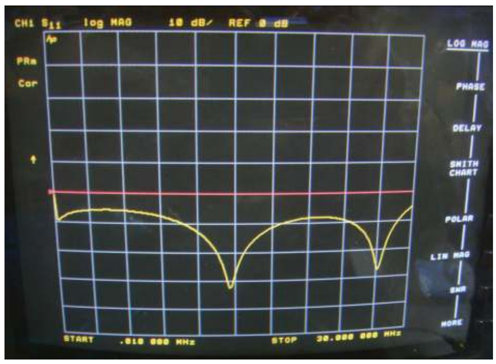


Fig. 8 S11 Characteristic of developed Coupler depending on Tchebycheff gain function

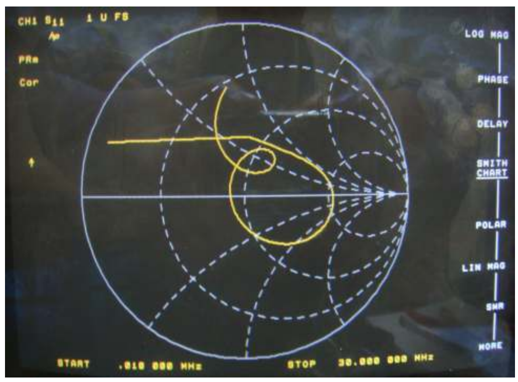


Fig. 9 Smith Chart for S11 depending on Tchebycheff gain function

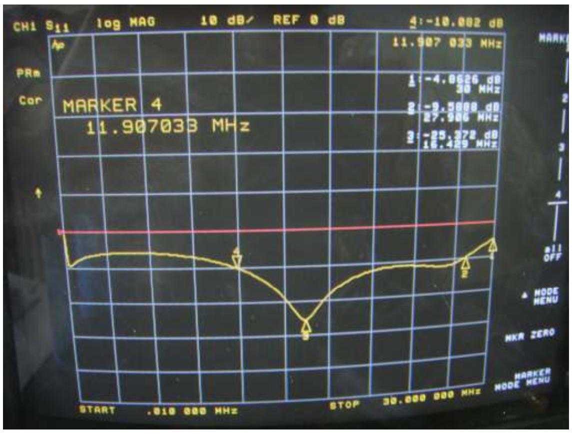


Fig. 10 S11 Characteristic of developed Coupler depending on Butterworth gain function

Fig. 11 Smith Chart for S11 depending on Butterworth function

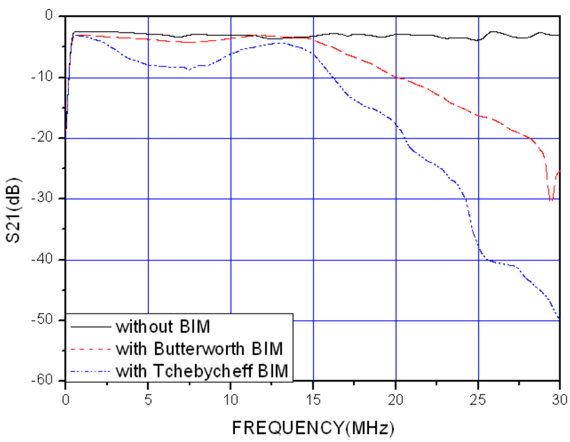


Fig. 12 S21 Characteristic of developed Coupler

APPENDIX

r_g is the resistance of the PLC modem and R is the resistance of PLC Coupler.

Butterworth:

$$x = RC\omega_c$$

$$\gamma_m = m\pi/2n \qquad m = 1, 2, \cdots, \left[\frac{1}{2}(n-1)\right], n > 1$$

$$r_g = R\frac{1-\delta^n}{1+\delta^n} \quad \Rightarrow \delta$$

When $x \geq 2\sin\gamma_1$,

$$L_{\alpha 1} = \frac{xR\sin\gamma_3}{\sin\gamma_1\left[(x-\sin\gamma_1)^2 + \cos^2\gamma_1\omega_c\right]}$$

When $x < 2\sin\gamma_1$,

$$L_{\alpha 2} = \frac{8R\sin^2\gamma_1\sin\gamma_3}{\left[(x-\sin\gamma_3)^2 + (1+4\sin^2\gamma_1)\sin\gamma_1\sin\gamma_3\right]\omega_c}$$

$$L_{\alpha 1}\,(\text{or } L_{\alpha 2}) = L_1$$

$$C_{2m}L_{2m-1} = \frac{4\sin\gamma_{4m-1}\sin\gamma_{4m+1}}{\omega_c^2(1-2\delta\cos\gamma_{4m}+\delta^2)} \qquad m \leq \frac{1}{2}(n-1)$$

$$C_{2m}L_{2m+1} = \frac{4\sin\gamma_{4m-1}\sin\gamma_{4m+3}}{\omega_c^2(1-2\delta\cos\gamma_{4m+2}+\delta^2)} \qquad m < \frac{1}{2}(n-1)$$

Tchebycheff:

$$\frac{R}{r_g} = \left(\frac{1+\sqrt{1-K}}{1-\sqrt{1-K}}\right)^{\pm 1} \qquad \text{when } n \text{ is odd}$$

$$\frac{R}{r_g} = \left(\frac{\sqrt{1+\varepsilon^2}+\sqrt{1+\varepsilon^2-K}}{\sqrt{1+\varepsilon^2}-\sqrt{1+\varepsilon^2-K}}\right)^{\pm 1} \qquad \text{when } n \text{ is even}$$

$$a = \frac{1}{n}\operatorname{arcsin\,h}\left(\frac{1}{\varepsilon}\right)$$

$$b = \frac{1}{n}\operatorname{arcsin\,h}\left(\frac{1}{\mu}\right)$$

$$\mu = \frac{\varepsilon}{\sqrt{(1-K)}}$$

$$f_m(\sinh a, \sinh b) = \sinh^2 a + \sinh^2 b + \sinh^2\gamma_m - 2\sinh a\sinh b\cos\gamma_m$$

$$\gamma_m = \frac{m\pi}{2n}$$

$$m = 1,2,\ldots,\left[\frac{1}{2}(n-1)\right], n > 1$$

$$L\sin\gamma_1 = \frac{R^2 C\sin\gamma_3}{\left(1 - RC\omega_c \sinh a \sin\gamma_1\right)^2 + R^2C^2\omega_c^2\cosh^2 a\cos^2\gamma_1}$$

when $RC\omega_c \sinh a \ge 2\sin\gamma_1$

$$L\omega_c \sinh a = \frac{8R\sin^2\gamma_1\sin\gamma_3}{\left(x\sinh a - \sin\gamma_3\right)^2 + \left(1 + 4\sin^2\gamma_1\right)\sin\gamma_1\sin\gamma_3 + x^2\sin^2\gamma_2}$$

when $RC\omega_c \sinh a < 2\sin\gamma_1$

$$L = L_1$$

$$C_{2m}L_{2m-1} = \frac{4\sin\gamma_{4m-1}\sin\gamma_{4m+1}}{\omega_c^2 f_{2m}\left(\sinh a, \sinh b\right)}$$

$$m \le \frac{1}{2}(n-1)$$

$$C_{2m}L_{2m+1} = \frac{4\sin\gamma_{4m+1}\sin\gamma_{4m+3}}{\omega_c^2 f_{2m+1}\left(\sinh a, \sinh b\right)}$$

$$m < \frac{1}{2}(n-1)$$

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Girae Kim received the B.S., M.S. in Electronic Engineering from the Sogang University, Seoul, Korea, in 1986, 1988, respectively. He also received Ph.D. from Kyungnam University, Korea in 1999. From 1988 to 1993 he was a researcher in Communication Research Center of Samsung Electronics Co. Ltd. Since 1999, he has been on the faculty of Electronics Engineering Department at the Silla University, Busan, Korea.