Broadband Impedance Matching Circuit Design for PLC Coupler Using Tchebycheff Equalizer

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Abstract**—**This paper is about design broadband impedance matching circuit for Coupler to improve power transfer efficiency in the power line communication (PLC) system. The Tchebycheff gain function algorithm is represented to design broadband matching circuit. A practical PLC Coupler impedance matching circuit is designed, and the characteristics for S11 and S21 of PLC coupler are enhanced comparing with unmatched one. This is done by maximizing the power transfer gain from modem to the load.

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

I. INTRODUCTION

Power Line communication (PLC) has undergone a rapid development during recent years due to its promise of significant cost savings and versatility both in control and in general purpose data communication applications. BPL (Broadband Power Line) communication 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, protection and control, but also for home internet access. In the areas where consumers already have cable modem or asymmetric digital subscriber line modem for internet access, BPL could provides another broadband medium alternative. Due to the concern of radio frequency emission and interference, the permissible BPL modem's power injection into power line networks is very limited. If the impedance of a BPL modem mismatches the load impedance at a power line connection port, the BPL modem signal power injection into the power line connection port will further be reduced. This will not only limit the BPL modem signal delivery distance to next BPL modem hence more repeaters needed, but also will cause the BPL modem signal reflection (or radio frequency emission) from the power line connection port. The problem could be solved by using a suitable Broadband Impedance Matching (BIM) circuit.

BIM circuit design methods can mainly be classified into two categories: (i) analytical approach and (ii) numerical approach. The first theory for formulating a BIM circuit made of a ladder Inductance and Capacitors (LCs) circuit was derived by Youla [1]. The first explicit formula for implementing Youla's theory was developed by W.-K. Chen [2]. However Chen's explicit formula is very difficult to be used to implement a LCs ladder circuit design order higher than the 5th. Numerical methods using different techniques, such as 'Real frequency technique' [3, 4,5], 'Parametric Representation of Brune Functions' [6,7] and 'Stochastic Gauss-Newton algorithm' [8] have been proposed.

In this paper, we use a Tchebycheff gain functions algorithm to achieve broadband impedance matching for power line communication (PLC) networks. 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 functions 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.

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II. BROADBAND IMPEDANCE MATCHING THEORY

The general configuration of PLC system is represented in figure 1. In figure 1, BPL 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.

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

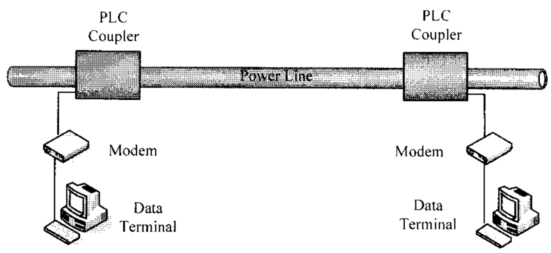


Fig. 1 PLC communication system

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 the PLC Coupler. The broadband impedance matching (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.

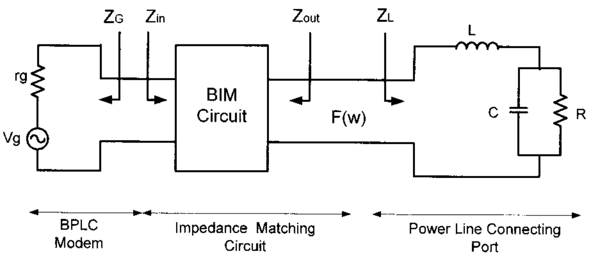


Fig.2 Schematic of Impedance Matching

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.

$$Z_G = Z_L^* \qquad (1)$$

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).

$$P_g = P_t + P_r \qquad (2)$$

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).

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

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 constr aints have to be satisfied. Let us define $[F_1>0, F_2]$ the fr equency band suitable for the wideband impedance mat ching. Achieving wideband impedance matching in the $[F_1, F_2]$ band is possible if and only if $F(\omega^2)$ is maximize d within the $[F_1, F_2]$ band and minimize outside from thi s frequency band. Note that for the majority of PLC syst ems, F_1 and F_2 can be around 0.1MHz and 30MHz, resp ectively. Knowing the characteristics of the impedance of the load and the source, the impedance matching algo rithm has to optimize the gain function to satisfy the tw o previous constraints. Different shapes can be chosen f or the gain functions, among these, are Tchebycheff and Butterworth gain functions. We only focus in the follo wing on Tchebycheff gain functions. We use Tchebyche ff gain function in equation (4).

$$F\left(\omega^2\right)=\frac{K}{1+\varepsilon^2 C_n^2\left(\frac{\omega}{\omega_c}\right)} \tag{4}$$

where K is a scale factor ($0< K \le 1$), ε is an oscillation factor strictly positive, ω_c is the cutoff frequency corr esponding to the greatest frequency, C_n is the n order Tc he-bycheff polynomial defined by equation (5) and (6).

$$C_n\left(\frac{\omega}{\omega_c}\right)=\cos\left(n\ arc\cos\left(\frac{\omega}{\omega_c}\right)\right) \quad \text{if} \quad \left|\frac{\omega}{\omega_c}\right|\le 1 \tag{5}$$

$$C_n\left(\frac{\omega}{\omega_c}\right)=\cosh\left(n\ arc\cosh\left(\frac{\omega}{\omega_c}\right)\right) \quad \text{if} \quad \left|\frac{\omega}{\omega_c}\right|> 1 \tag{6}$$

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. We define some basic quantities used in the algorithms.

r_g is the resistance of the PLC modem and R is the resistance of PLC Coupler. [7]

$$\frac{R}{r_g}=\left(\frac{1+\sqrt{1-K}}{1-\sqrt{1-K}}\right)^{\pm 1} \quad \text{when } n \text{ is odd} \tag{7}$$

$$\frac{R}{r_g}=\left(\frac{\sqrt{1+\varepsilon^2}+\sqrt{1+\varepsilon^2-K}}{\sqrt{1+\varepsilon^2}-\sqrt{1+\varepsilon^2-K}}\right)^{\pm 1} \quad \text{when } n \text{ is even} \tag{8}$$

$$a=\frac{1}{n}\operatorname{arcsin h}\left(\frac{1}{\varepsilon}\right) \tag{9}$$

$$b=\frac{1}{n}\operatorname{arcsin h}\left(\frac{1}{\mu}\right) \tag{10}$$

$$\mu=\frac{\varepsilon}{\sqrt{(1-K)}} \tag{11}$$

$$f_m(\sinh a,\sinh b)=\sinh^2 a+\sinh^2 b+\sinh^2\gamma_m -2\sinh a\sinh b\cos\gamma_m \tag{12}$$

$$\gamma_m=\frac{m\pi}{2n} \tag{13}$$

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

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

$$\text{when } RC\omega_c\sinh a\ge 2\sin\gamma_1 \tag{14}$$

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

$$\text{when } RC\omega_c\sinh a< 2\sin\gamma_1 \tag{15}$$

$$L=L_1 \tag{16}$$

$$C_{2m}L_{2m-1}=\frac{4\sin\gamma_{4m-1}\sin\gamma_{4m+1}}{\omega_c^2 f_{2m}(\sinh a,\sinh b)} \tag{17}$$

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

$$C_{2m}L_{2m+1} = \frac{4\sin\gamma_{4m+1}\sin\gamma_{4m+3}}{\omega_c^2 f_{2m+1}\left(\sinh a, \sinh b\right)} \quad (18)$$

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

Now we can get the relationship between the load and source. In the next section, we will use these theories to design the circuit.

III. THE DESIGN OF IMPEDANCE MATCHING CIRCUIT

In this section, we design a broadband impedance matching (BIM) circuit for PLC Coupler using previous Tchebycheff gain functions. The developed PLC coupler without impedance matching circuit is shown in Figure 3, and In figure4, S11 characteristics of unmatched coupler is represented on the Smith chart using the vector network analyzer in 10Hz to 30MHz frequencies, and impedance characteristics are represented in Figure 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 figure 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 figure 6. We choose the L-C low pass filter type as structure of equalizer, and applying to Weinberg relations of equation 14 to 18, 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. The figure 7 is the simulation result for S21 of equalizer using the Advanced Design System (ADS) of Agilent. 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.

We developed PLC coupler including the broadband impedance matching circuit as following figure 8. PLC Coupler contains three main parts: noise filter, magnetic core and impedance matching circuit.

Fig. 3 PLC Coupler without matching circuit

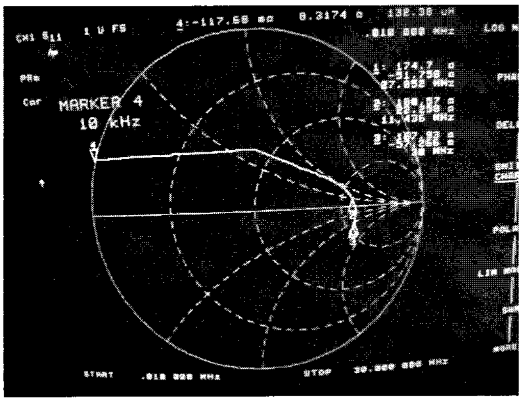


Fig.4. Test results of S-parameter (S11) of unmatched Coupler

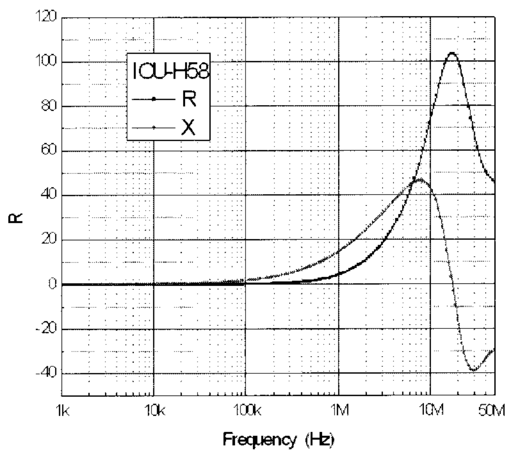
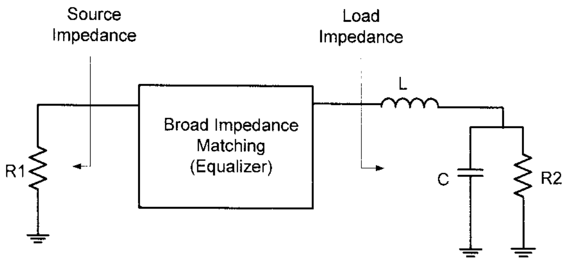
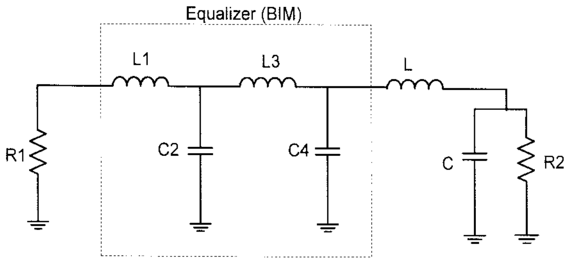


Fig. 5 Impedance(R+jX) of unmatched PLC Coupler



(a)



(b)

Figure 6. (a) equivalent circuit (b) the circuit of Equalizer(BIM)

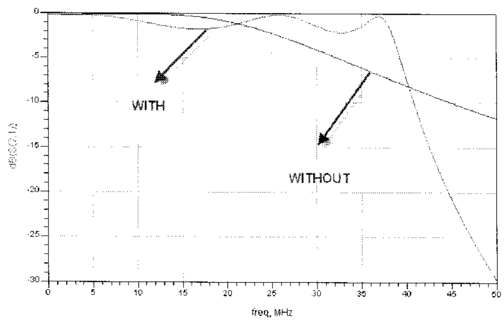
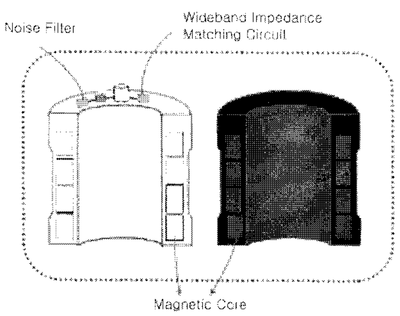
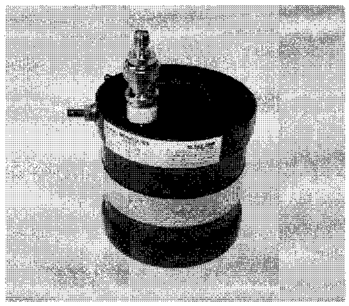


Fig. 7 S21 characteristics of the circuit with and without Equalizer (BIM)



(a) Configuration



(b) photo of developed coupler

Fig.8 PLC Coupler with broadband impedance matching circuit

IV. RESULTS AND CONCLUSIONS

We tested to get the characteristics of broadband ma tching circuit of PLC coupler using the vector network analyzer. Figure 9 is shown S11 characteristic of dev eloped Coupler with broadband impedance matching c ircuit comparing with characteristic of unmatched cou pler, and figure 10 is result for Smith chart of S11 char acteristic for it. Figure 11 is shown the comparing re sults for S21 characteristic with and without impedanc e matching circuit in PLC coupler.

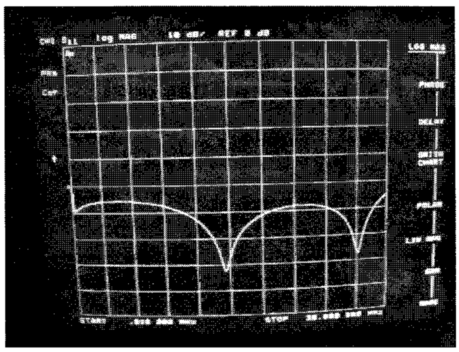


Fig. 9 S11 Characteristic of developed Coupler

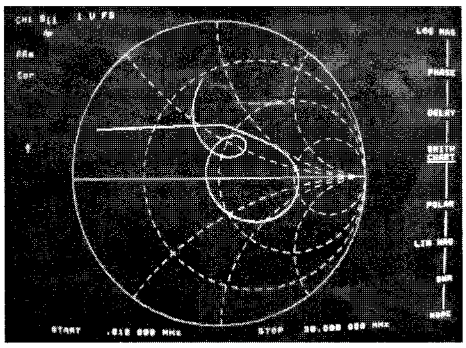


Fig. 10 Smith chart for S11

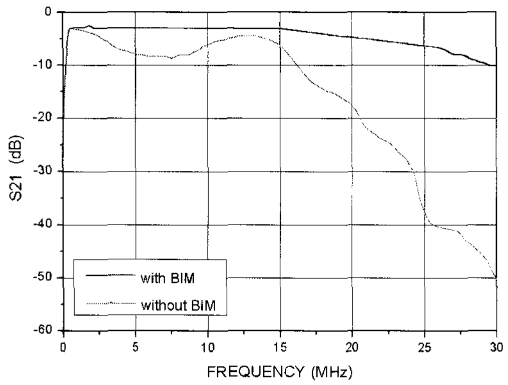


Fig. 11 S21 Characteristic of developed Coupler

In the 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.

In this paper, we have presented a general design fo r a wideband impedance matching in power line comm unication. We use the theory to analyze the coupling ci rcuit we want to get. Then we make the circuit in pract ical. It is important to modify in practical conditions.

REFERENCES

[1] D. C. Youla, "A new theory of broad-band matching," IEEE Trans, Circuit Theory, vol. CT, pp.30-50, Mar.1964.

[2]. WAI-KAI CHEN, "Explicit Formulas for the Synthesis of Optimum Broad-Band Impedance-Matching Networks," IEEE TRANSACTION ON CIRCUITS AND SYSTEMS, VOL. CAS-24, NO.4, APRIAL, 1997.

[3] Fawzi Issa, Michel Goldberg, Haiyu Li and Simon Rowland, "Wideband impedance matching using Tchebycheff gain functions", submitted to International Symposium on PLC and its Application, Vancouver, Canada, 2005.

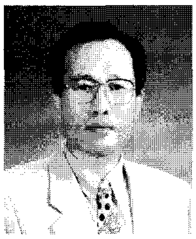
[4] H.J.Carlin, "A new approach to gain-bandwidth problems,' IEEE Trans, Circuit Syst, Vol. CAS-24, pp. 170-175, Apr. 1997.

[5] H.J.Carlin and J.J. Komiak, "A new method of broad-band equalization applied to microwave amplifiers," IEEE Trans, Microwave Theory Tech, vol, MTT-24, pp. 93-99, Feb.1979.

[6] H.Takahasi," On the ladder-type filter network with Tchebysheff response," J. Inst. Elec. Commoum. Engrs. Japan, vol. 34, pp. 65-74, Feb, 1951.

[7] W.K. Chen, Theory and Design of Broadband Matching Networks. New York: Pergamon Press, Apr.1976.

[8] W.K. Chen,"Explicit formulas for the synthesis of Chebyshev impedance matching networks," Electronics Letters, vol. 12, pp. 412-413, Aug. 1976.



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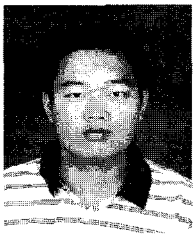

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