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Development of a transformerless impedance matching model for automatic power line communication

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ABSTRACT

Power Line Communication (PLC) is a technology that uses existing power cables as the transmission medium for information and data exchange. In automatic PLC systems, such as vehicle assembling and automatic meter reading, effective impedance matching circuits are essential as a way of improving vehicles fuel economy, reliability, and reducing cost of manufacturing and maintenance. However, due to the harsh channel environments, location and time-varying nature of network access impedance, finding appropriate impedance matching solution is considerably challenging especially in low-voltage power line communication. This study therefore developed a transformerless impedance matching model using capacitor banks and active inductor for automatic power line communication applications. The development used RLC band pass filter and microcontroller for efficient impedance matching. The simulation was carried out on 150Ω signal generator impedance before and after applying the matching network under three different scenarios using MATLAB. The results from the scenarios showed that the power transfer of the signal generator to the load improved with the matching network over the expected range of automotive impedance. The results also indicated that the developed transformerless impedance matching network has the ability to provide matching over most expected impedance on automatic power lines. Thus, the transformerless impedance matching has proved effective for impedance matching and maximum power transfer.

Keywords: Power Line Communication, RLC Band-pass Filter, Automatic PLC, Transformerless, Impedance matching, Low-Voltage.

1. INTRODUCTION

Power Line Communication (PLC) is one of the technologies using existing power cables as transmission medium for information and data exchange [3, 5]. This technology is used in high voltage and low voltage network, as it is the only wired communication technology that is comparable with wireless communication network. Power line communication works by injecting a modulated carrier wave into the electric cables from one transceiver to another [1, 6, 10].

In the past, most of the application of the PLC technology such as smart meter and grid are AC PLC types. However, modern power grids are comprised of new alternative energy sources, which include solar and wind power as well as new types of electric appliances [2]. The technology has also been applied in the automotive industry, due to the prospects of improved fuel efficiency, ease of integration and maintenance. The technology utilizes the vehicles power lines for communication, eliminating the requirement for any extra wires except the power cable for communication [7].

In addition, the number of electronic devices connected to Direct Current (DC)PLC type power supplies has significantly increased and has dominating the engineering applications since they do not involve any wiring to perform connection between hardware. Most of the hardware such as industrial machineries, electrical appliances, automatic gate and security system among others requires electric cable as the power supply in order to operate in correct mode [3, 9]. Therefore, PLC can be used as option to perform monitoring and control the hardware. But, there is signal attenuation along the power line caused by the impedance mismatch in the power line communication network. This impedance mismatch reduce transmission, caused low power gain and low reliability in PLC system. Thus, the impedance mismatch is one of main concern of PLC technology, particularly in the low voltage network in residential area [8, 10-11].

The purpose of impedance matching is to achieve maximum power transfer through the channel [11]. However, the impedances in the power line are time and location variant and it is rather complex to design a circuit that allows maximum power transfer in the system all the time, also the varying nature of the power line channel impedance makes standard impedance matching networks ineffective. Therefore, improper impedance matching results in poor signal power transferred through the channel and may leads to reduction in transmission distance, higher power consumption and produces poor communication performance in the PLC system [10-11].

Power Line Communication Technology

The Power Line Communication (Power Line Carrier) (PLC), which is also called Broadband over Power Lines (BPL), Power line Digital Subscriber Line (PDSL) or Mains Communication (MC) is a communication media carrying data or information between the transmitter and the receiver. Power Line Communication technology uses the residential electrical power wiring as a transmission medium to control the lighting and appliances without installation of additional new wiring [1, 10-11].

Typically, a carrier wave with digital signals generated from the PLC transmitter are normally modulated by home control devices and sending it to the receiver between 3 kHz to 148.5 kHz in the household wiring. However, in each receiver there is an address which is used to command individual transmitted signal over a household wiring with demodulation signal at the receiver. These devices may be plugged into regular or permanently power outlets [3, 9, 11].

The PLC technology offer several benefits when compared to regular cable connections, in which the extensive available infrastructure help people in remote areas to connect to internet with little utility equipment [1, 3-4]. However, the PLC application still has problems that need to be improved. For instance, PLC comprises of additive non-white noise which is extremely harsh environment for communication. Particularly in low voltage network, the source of the noise comes from the household machinery and devices and office equipment. Therefore, it is crucial to implement suitable electronic device to filter out the noise in power line [5, 7, 10].

Impedance mismatch is a major concern of PLC application apart from high noise level. The impedance mismatch leads to data reflection, and cause signal attenuation in the power line system [1]. In addition, in the automatic power line impedance, most devices connected to the vehicle power line have bypass capacitors. Also, impedance of the automatic power line changes as motors, actuators and electronic devices are turned on and off inside the vehicle leading to varying channel impedance. Therefore, it is necessary to perform impedance matching in the PLC systems in order to achieve ideal maximum power transfer in the systems [8, 10-11].

The Impedance Matching

Impedance matching is the practice of designing the input or output impedance of an electrical load with corresponding signal source in order to maximize the power transfer or minimize reflections from the load and is the one of the major areas of improving power line communication [7, 10]. In addition, for conventional communication, depending on the characteristic impedance of the transmission channel impedance matching is usually satisfied by means of 50 or 75 ohm transceivers. The characteristics of DC PLC system with impedance matching like AC PLC system are also varying with time and location, and this caused poor power signal transferred to the channel as a result of the activation and deactivations of motors, electronics and actuators within the vehicle during the course of operation [2, 5, 10].

There are various ways of matching the transceiver and access impedance either by making a change in existing circuit or using an external circuit to bring impedance change. A PLC coupler designed for impedance matching between PLC modems and PLC channel are usually comprises of an impedance matching circuit and a coupling circuit [3, 7, 9]. This is usually placed between the transmitting or receiving power line communication modem and the port of the power line network as shown in Figure 1 while the change which needs to be made to improve the PLC system is shown in Figure 2 [1, 2, 6].

Figure 1: Basic layout of Impedance Matching

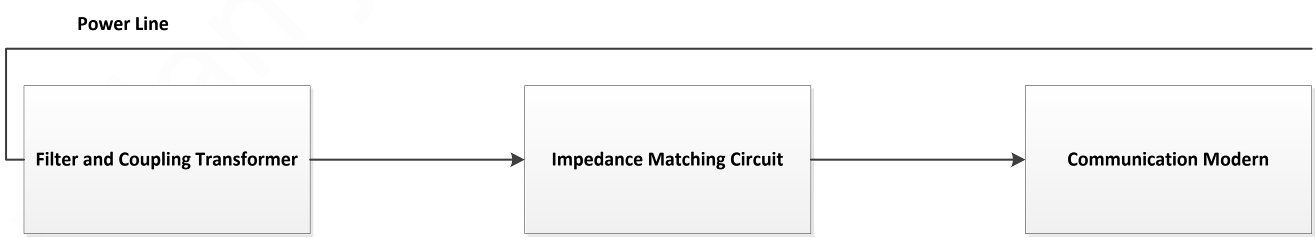

Figure 2: Scheme of Power Line Communication with Impedance Matching Circuit

2. RELATED WORKS

Many techniques have been proposed to achieve impedance matching solution in PLC. Despande *et al.* (2013) presented an adaptive impedance matching circuit which automatically matches to the varying impedance and helps in providing better perceptive of power line communication in real applications. The study concludes that an adaptive variable coupling transformer for the transceiver circuit establish good convergence for impedance matching and maximum power transfer.

Rui *et al.* (2014) presented an adaptive impedance matching circuits for narrowband PLC based on the RLC band-pass filter circuit. This concept was designed to achieve simpler configuration and higher matching resolution. The method has relatively simple and clear mathematic algorithm to match the PLC source and channel impedances continuously. The method has advantage in higher matching resolution and easier control compare with other existing adaptive impedance matching method.

Nejad *et al.* (2016) analyses the improvement of communication-signal transfer via transmitter and the receiving device using an adaptive impedance matching. The study evaluates the PLC system by simulate a wide range of impedance test points and S-parameters of Vehicular Power Line Communication (VPLC) networks. Simulation results demonstrated that under a wide range of conditions, the technique achieved signal power transfer close to that of optimal matching and also improved the performance for broadband transmission around the nominal matching frequency.

Sridhar et al. (2017) designed an efficient and simpler transmitter filter for appropriate voltage supply according to changing loads using RLC-band pass filter and microcontroller for impedance matching. The study considered insertion loss issue in narrow band power line communication. The result indicated that the design is simple and easily adaptive to the varying load impedances ensuring the maximum power transfer to the load at all times. Thus the design provided reliable adaptive impedance matching for narrow band power line communication application.

However most efforts were focused on AC power line networks and also the techniques were complex which rendered them ineffective for impedance matching solution. Therefore, effective PLC impedance matching design is a challenging goal. Thus, this study presented a transformerless impedance matching model for automatic power line communication. The technique is simple and reliable in achieving proper match between source and channel impedances. This concept was designed to achieve simpler configuration and higher matching resolution.

3. MATERIALS AND METHOD

This study combined capacitor banks and active inductor to develop a transformerless impedance matching circuit which is a more accurate method of impedance matching in automatic PLC technology. The design used RLC band pass filter and microcontroller for efficient impedance matching. The variable capacitors were based on a small four capacitor network and the variable inductor was based on general impedance converter employed by Nisbet *et al.* (2014), and simulation was done using MATLAB. The simulation was performed to determine the matching networks viability for operation in automatic PLC network.

The simulation scheme consists of transmitter circuit of a 130 kHz signal generator having a source impedance of 50 ohms was connected to a 230Volt AC line through a coupling capacitor. The carrier frequency used for the simulations was 5.5 MHz. The circuit diagram of the developed transformerless impedance matching network is shown in Figure 3.

Some of the issues considered for designing the impedance matching circuit are: gain and insertion loss, bandwidth and attenuation, as well as matching region and structure.

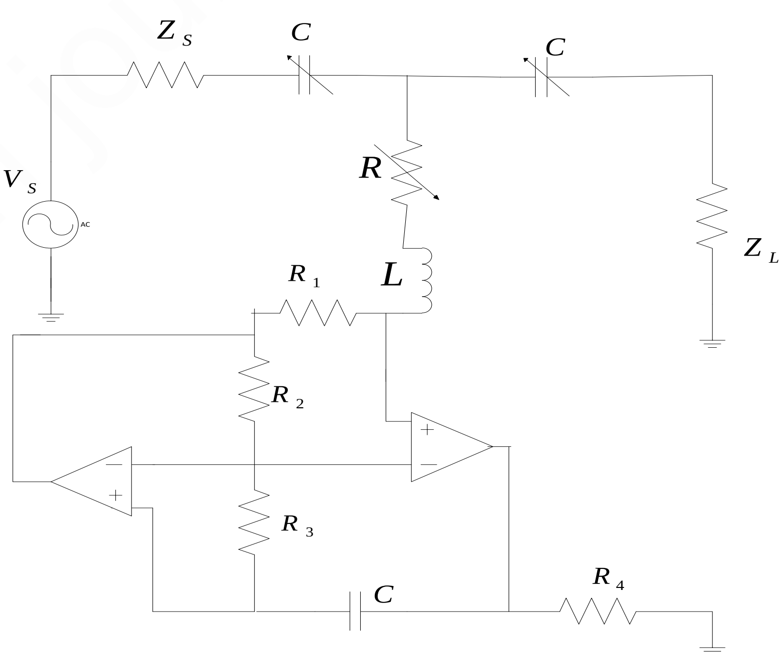

Figure 3: The schematic diagram of transformerless impedance matching networks

Applying Thévenin theorem, the source impedance is given as:

$$Z_S = jX + \left(R \times \frac{Z_L}{(R + Z_L)} \right) \quad 1$$

$$Z_L = (Z_S + jX) \times \frac{R}{(R + Z_S + jX)} \quad 2$$

Simplifying equations (1) and (2) for *R* and *X*

$$X = Z_S \times \frac{Z_L}{jR} \quad 3$$

$$R = Z_S \times Z_L \times \frac{Z_L}{(Z_L - Z_S)} \quad 4$$

but

$$X = X_C - X_L \quad 5$$

$$\omega = \sqrt{\frac{1}{C}} = 2\pi \times f \quad 6$$

$$C = \frac{1}{(4\pi^2 \times f^2 \times X_C)} \quad 7$$

Therefore, the relationship between the resistance and capacitor of the band-filter with the load and source impedance from the circuit is given as:

$$L = \frac{CR_1R_3R_4}{R_2} \quad 8$$

Substituting equation (7) into equation (8) and rearranging to provide the inductance value for the given R_2 as:

$$L = \frac{1}{4\pi^2 f^2 C} \quad 9$$

Changing the value of R_2, the centre frequency of the band pass filter also changes. Note that the quality factor of the active inductor as well as the bias point can be adjusted with R_1.

The power transfer function of the band pass filter is given as:

$$P(j\omega)=\frac{R}{R+j\left(\omega L-\frac{1}{\omega C}\right)} \qquad 10$$

where;

C is the desired capacitance for given Z_S and Z_L

Z_S is the source impedance

Z_L is the load impedance

R is the desired resistance for given Z_S and Z_L

X_C is the capacitive reactance

X_L is the load reactance

X is the entire reactance of the circuit

f is the frequency

4. THE SIMULATION

The tuning range of inductor was restricted to the resistance range (R_2) and connected as a parallel RLC tank bandpass filter with a known filtering capacitance. The digital potentiometer has a maximum resistance of 10 kΩ and minimum resistance value of 50 Ω with R_1, R_3, and R_4 set to 1.0 kΩ and *C* set to 100 µf. The load impedance was varied according to the load connected to it and the output impedance of the signal source was 150 Ω. The appropriate value for the maximum power transfer was determined through the existing relationship between the components of filter and the load impedance and was used to determine if an impedance match was established.

The simulation was done using MATLAB to examine the matching networks ability to operate with the impedances of automatic PLC devices as the impedances that needed to be observed on the automatic power line which can be vary from 0 Ω to 1 kΩ, with varying reactive components.

In order to determine the effectiveness of the developed transformerless impedance matching for automatic PLC, simulation was carried out on 150Ω signal generator impedance before and after applying the matching network under three (3) different scenarios:

i. By adjusting variable real impedance with 50 Ω reactive component
ii. By adjusting variable reactive impedance with 250 Ω real impedance
iii. By adjusting variable reactive impedance with 20 Ω real impedance.

5. RESULTS AND DISCUSSION

The results of the impedance matching for automatic PLC under the three (3) different scenarios are presented in Figures 4 to 12. Figure 4 showed the power delivered to the load before applying the matching network for scenario one. The result showed that the value of power transfer function for impedance value of100 Ω, 200 Ω, 300 Ω, 400 Ω, 500 Ω, 600 Ω, 700 Ω, 800 Ω, 900 Ω and 1000 Ω were1.0 mW, 1.3 mW, 0.7 mW, 0.5 mW, 0.3 MW, 0.22 mW, 0.21 mW, 0.21 mW, 0.20 mW, and 0.1 mW respectively. While Figure 5 showed the power delivered to the load after applying the matching network for scenario one. The value of power transfer function for impedance value of 100 Ω, 200 Ω, 300 Ω, 400 Ω, 500 Ω, 600 Ω, 700 Ω, 800 Ω, 900 Ω and 1000 Ω were 1.7 mW, 1.6 mW, 1.6 mW, 1.6 mW, 1.6 mW, 1.6 mW, 1.6 mW, 1.6 mW, 1.6 mW, and 1.6 mW respectively. The comparison of the power delivered to the load before and after applying the matching network for scenario one is shown in Figure 6. The results showed that the matching network improved the power transfer of the signal generator to the load over the expected range of automotive impedances.

Figure 7 illustrated the power delivered to the load before applying the matching network for second scenario. The result showed that the value of power transfer function for impedance value of 100 Ω, 200 Ω, 300 Ω, 400 Ω, 500 Ω, 600 Ω, 700 Ω, 800 Ω, 900 Ω and 1000 Ω were1.4 mW, 1.2 mW, 1.0 mW, 0.8 mW, 0.7 MW, 1.25 mW, 1.15 mW, 0.95 mW, 0.85 mW, and 0.7 mW respectively. Figure 8 indicated the relationship between the power delivered to the load after applied the matching network for second scenario. The value of power transfer function for impedance value of 100 Ω, 200 Ω, 300 Ω, 400 Ω, 500 Ω, 600 Ω, 700 Ω, 800 Ω, 900 Ω and 1000 Ω were 1.6 mW, 1.6 mW, 1.6 mW, 1.6 mW, 1.6 mW, 1.78 mW, 1.76 mW, 1.75 mW, 1.75 mW, and 1.7 mW respectively. The comparison of the power delivered to the load before and after applied the matching network for second scenario is shown in Figure 9.

Figure 10 indicated the power delivered to the load before applying the matching network for third scenario. The result showed that the value of power transfer function for impedance value of 100 Ω, 200 Ω, 300 Ω, 400 Ω, 500 Ω, 600 Ω, 700 Ω, 800 Ω, 900 Ω and 1000 Ω were1.3 mW, 1.15 mW, 1.0 mW, 0.8 mW, 0.7 MW, 1.3 mW, 1.2 mW, 1.0 mW, 0.8 mW, and 0.71 mW respectively. Figure 11illustratedthe power delivered to the load after applying the matching network for third scenario. The value of power transfer function for impedance value of 100 Ω, 200 Ω, 300 Ω, 400 Ω, 500 Ω, 600 Ω, 700 Ω, 800 Ω, 900 Ω and 1000 Ω were 1.62 mW, 1.6 mW, 1.6 mW, 1.6 mW, 1.6 mW, 1.75 mW, 1.73 mW, 1.72 mW, 1.72 mW, and 1.7 mW respectively. The comparison of the power delivered to the load before and after applied the matching network for third scenario is shown in Figure 12.

The results from Figures 4 to 12 showed that the power transfer of the signal generator to the load improved with the matching network over the expected range of automotive impedances. The results also indicated that the developed transformerless impedance matching network had the ability to provide matching over most expected impedance on automatic power lines.

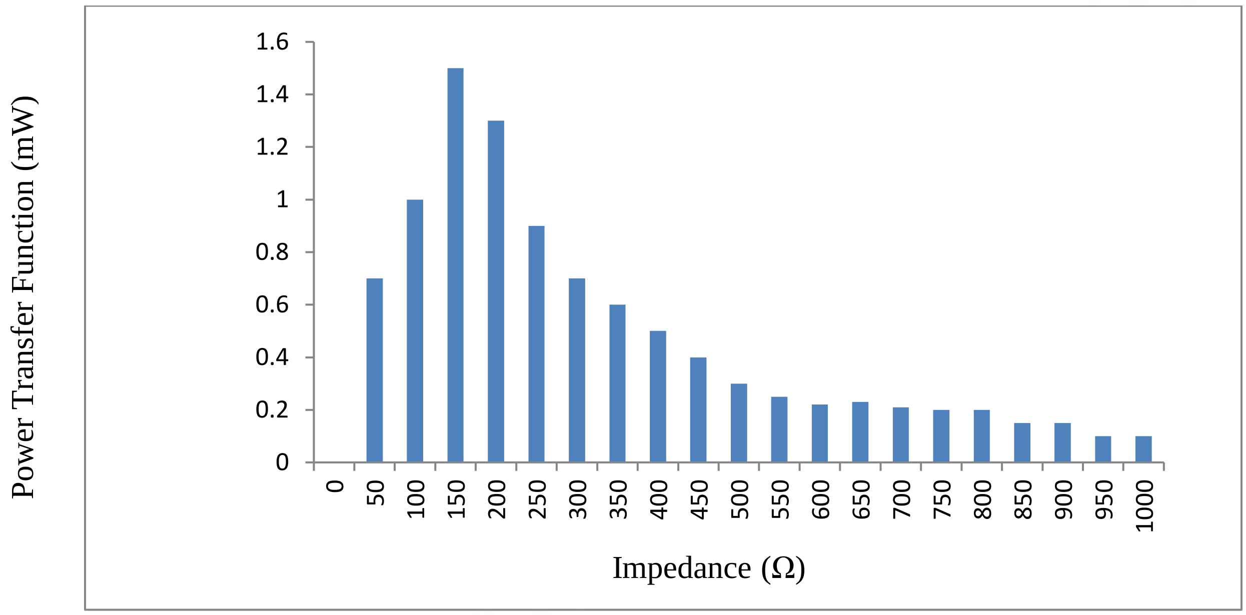

Figure 4: Power delivered to load before impedance matching network for variable real impedance with 50 Ω reactive component

Figure 5: Power delivered to load after impedance matching network for variable real impedance with 50 Ω reactive component

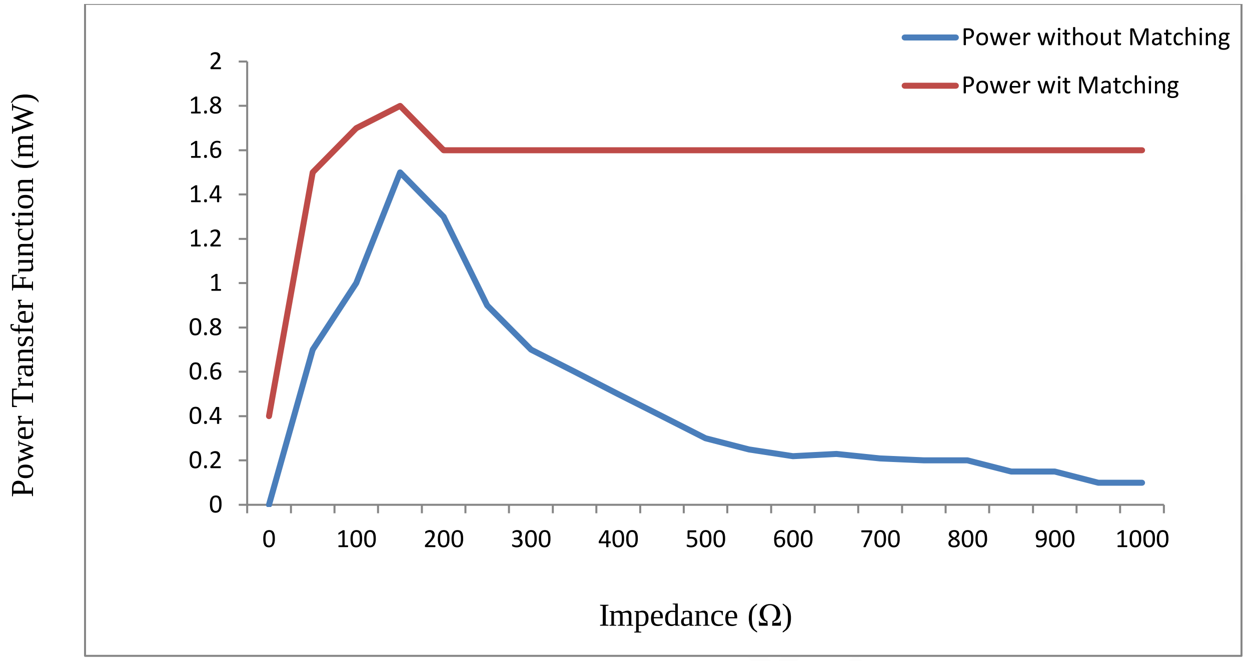

Figure 6: Comparison of power delivered to load before and after impedance matching for variable real impedance with 50 Ω reactive component

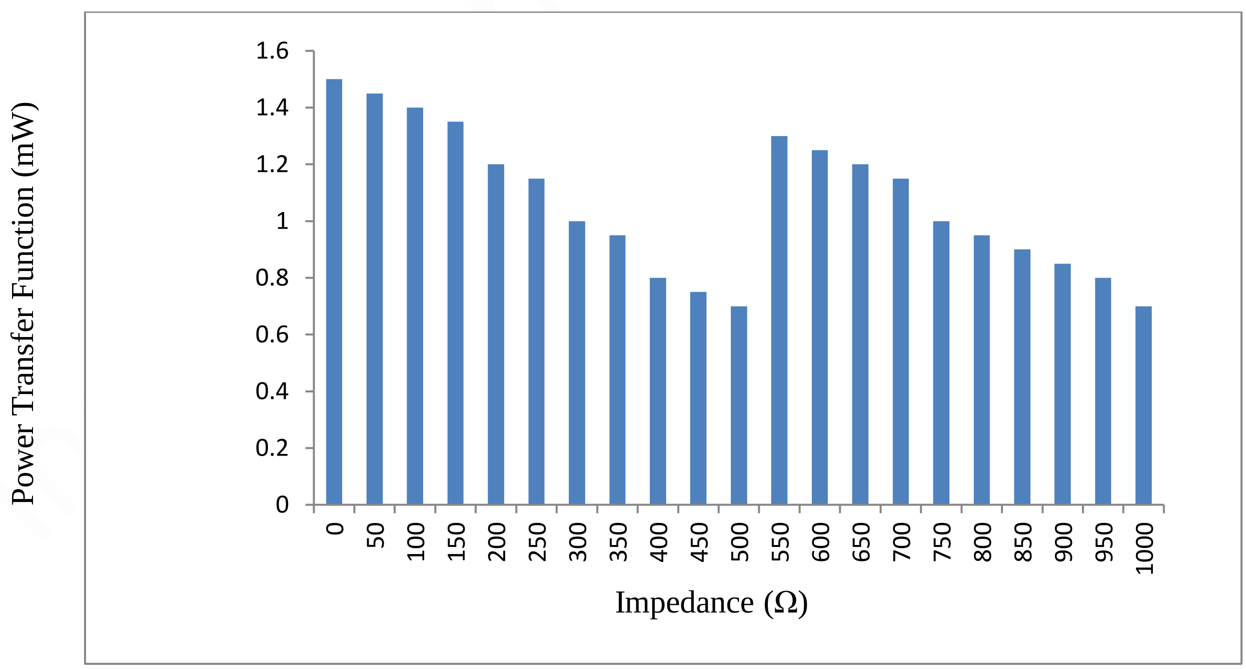

Figure 7: Power delivered to load before impedance matching network for variable reactive impedance with 250 Ω real impedance

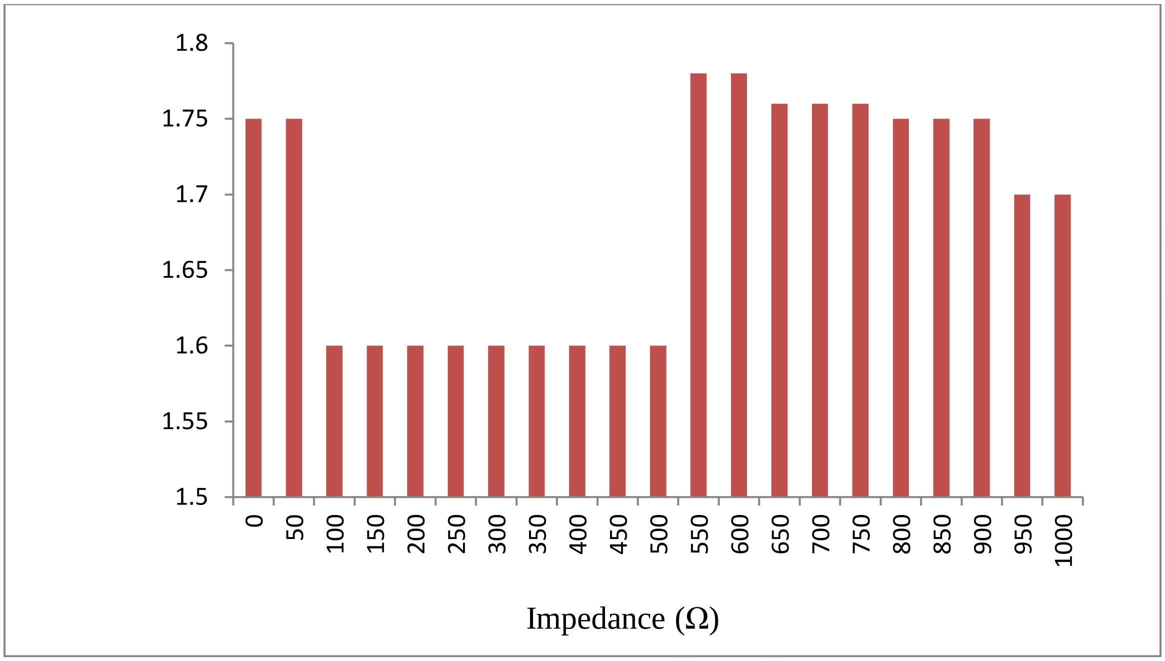

Figure 8: Power delivered to load after impedance matching network for variable reactive impedance with 250 Ω real impedance

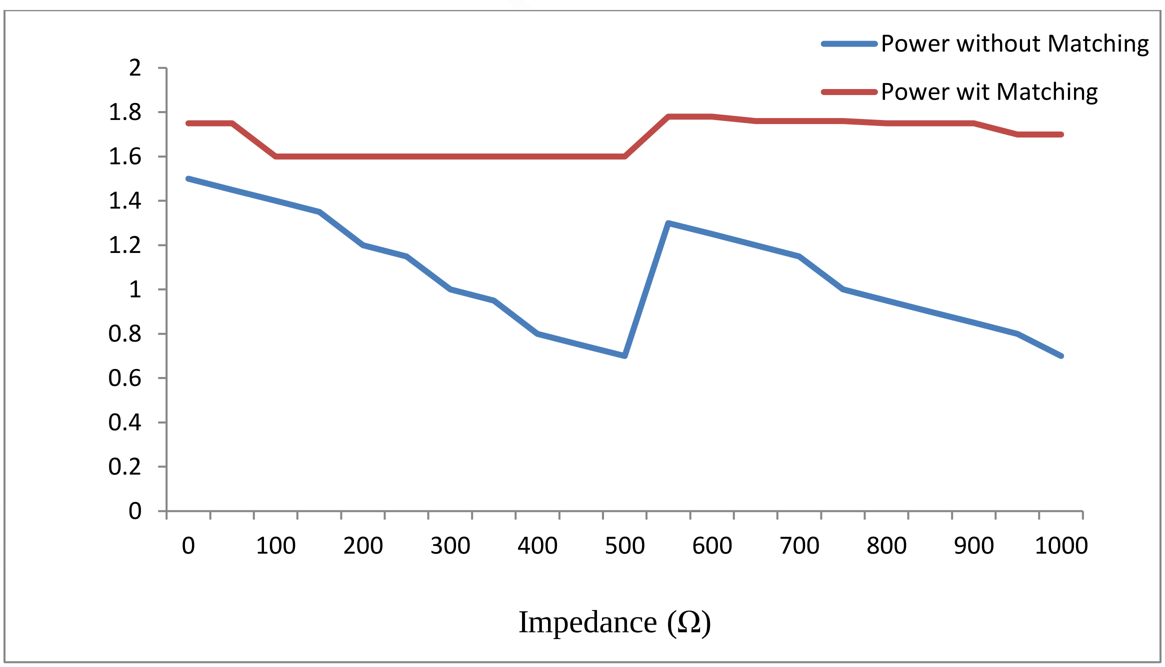

Figure 9: Comparison of power delivered to load before and after impedance matching for variable reactive impedance with 250 Ω real impedance

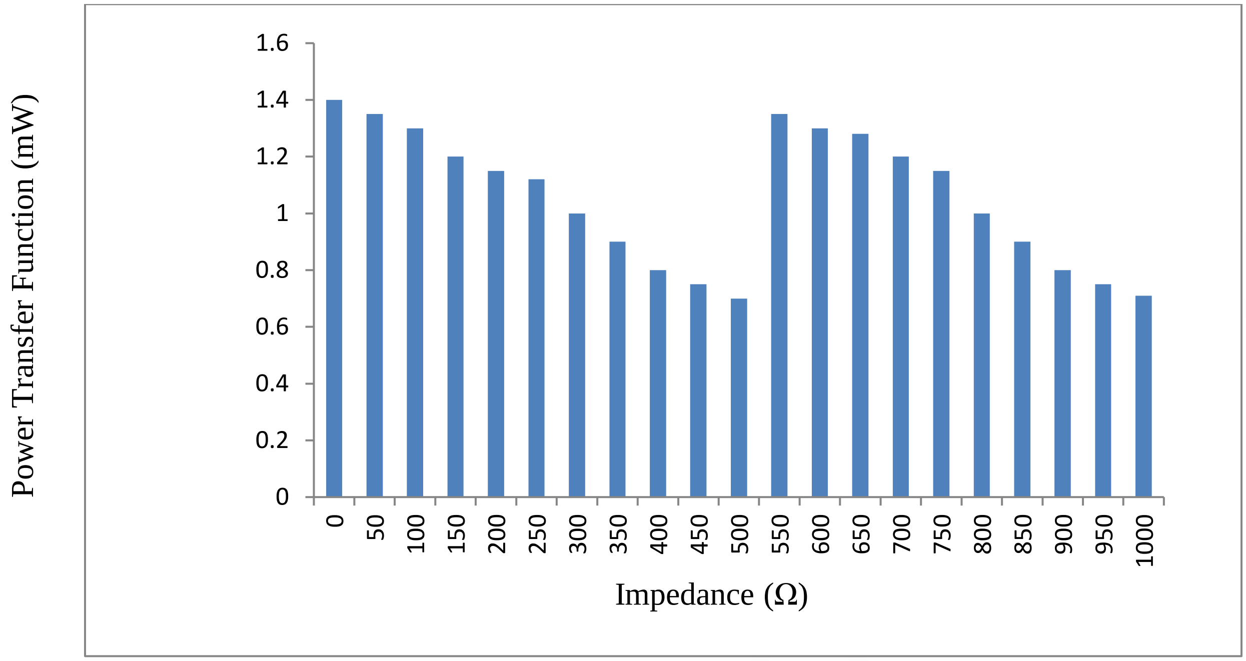

Figure 10: Power delivered to load before impedance matching network for variable reactive impedance with 20 Ω real impedance.

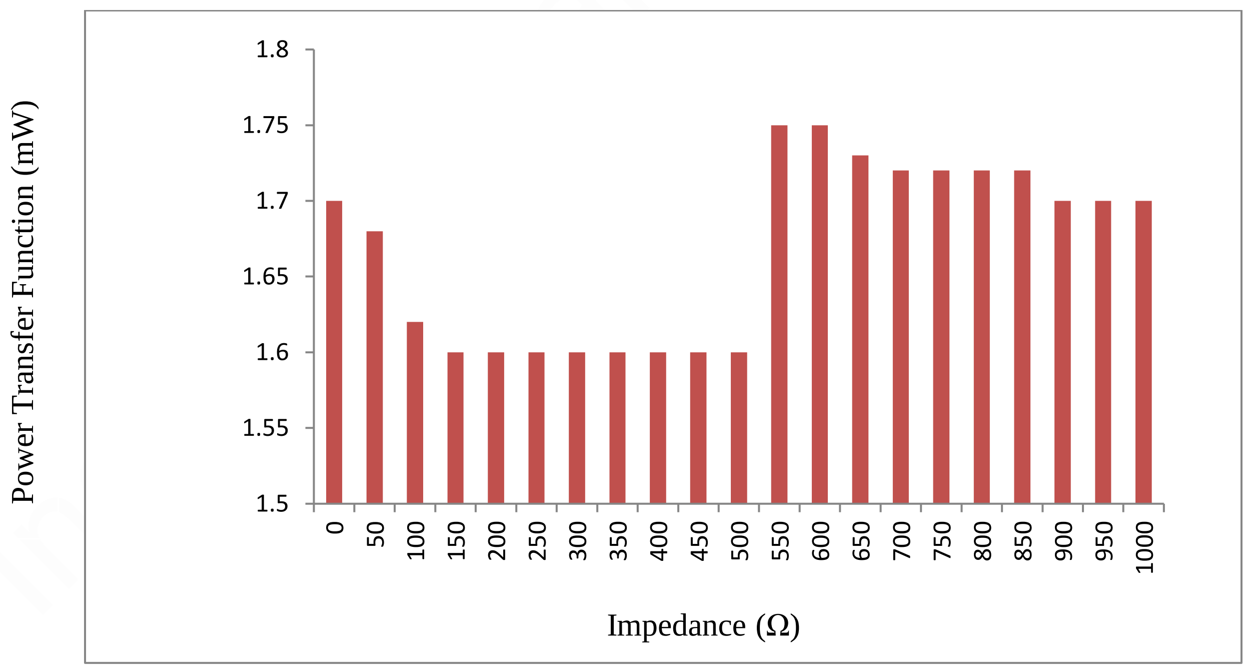

Figure 11: Power delivered to load after impedance matching network for variable reactive impedance with 20 Ω real impedance.

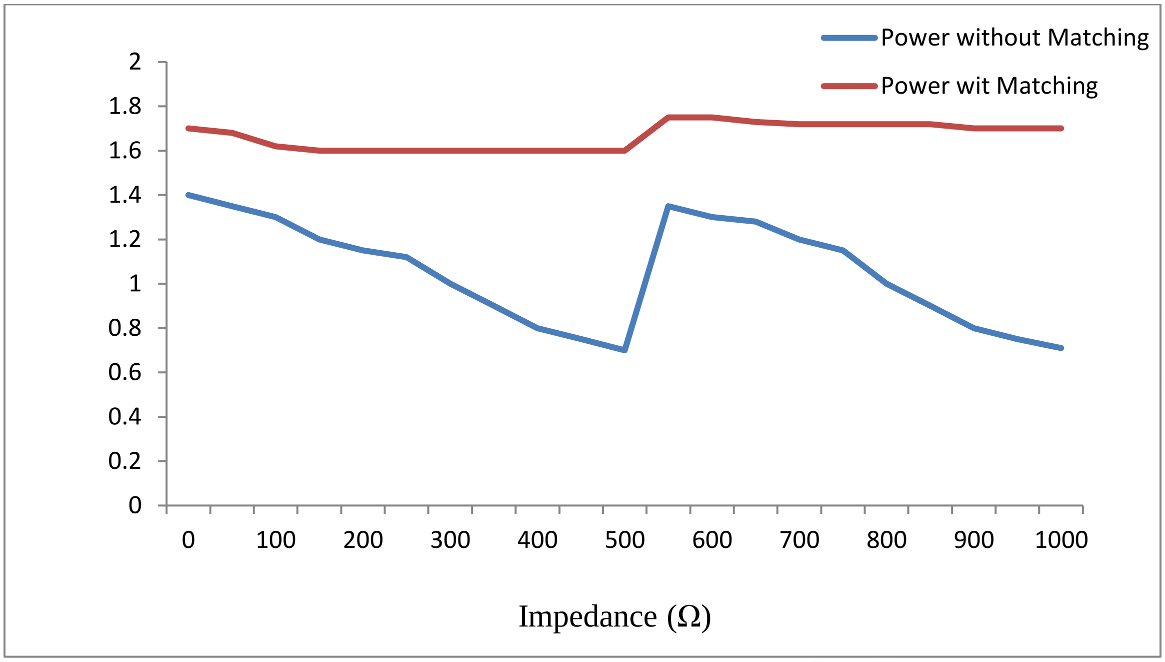

Figure 12: Comparison of power delivered to load before and after impedance matching for variable reactive impedance with 20 Ω real impedance.

6. CONCLUSION

The study has developed a simple and effective transformerless impedance matching for automatic Power Line Communication for impedance load variation in order to ensure maximum power transfer to the load at all times. The design was simple and provided reliable impedance matching for automatic power line communication application as the components were accurately tuned to produce desired output and did not use any costly components. From the results, the transformerless impedance matching has proved really effective for impedance matching and maximum power transfer.

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Conflicts of Interest

The author declares no conflict of interest.

Data and materials availability

All data associated with this study are present in the paper.

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