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Power line connection automatic in Impedance network without transformer

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Abstract—The automotive industry is constantly looking for ways of improving vehicles fuel economy, reliability, and reducing cost of manufacturing and maintenance. As a result, vehicle manufacturers have looked into power line communication (PLC) technology as a possible solution. However the nature of a vehicles power lines such as extremely low impedances, time varying channel characteristics, and noise make it difficult for modems to provide reliable communication. Extensive research is being conducted to improve communication reliability over power line networks. One of the areas being studied is impedance matching. This paper examines previous impedance matching methods proposed for PLC and proposes a transformer less matching network. The transformer less topology allows for reduction in modem PCB size and for possible integration in a modem IC. Simulations are conducted on the proposed matching network to determine its ability to provide matches to impedances found on the vehicle power line. The noise characteristics of the matching network are also examined to determine the impact the circuit will have on the modem.

Key words—Transformer less, Power line communication (PLC), impedance, modem

I. INTRODUCTION

Power line communication (PLC) has attracted lots of attention in the automotive industry, due to the prospects of reduced weight, improved fuel efficiency, and ease of integration and maintenance (Benzi et al., 2008). Existing vehicle communication networks such as Controller Area Network (CAN) and Local Interconnect Network (LIN) require four wires to provide communication and power the modems. PLC utilizes the vehicles power lines for communication, eliminating the requirement for any extra wires except the power cable for communication. In order to achieve the benefits of PLC in vehicles, modem designers must contend with time-varying and location-varying impedances, impulsive noise sources, and significant attenuation due to transmission distance and low impedance loads (Sun and Amaratunga (2011). Typically modem designers have focused their efforts on developing robust modulation schemes such as orthogonal frequency division multiplexing (OFDM), frequency hop spread spectrum (FHSS) and quadrature phase shift keying (QPSK) (Maniati and Skipitaris, 2007; Fallows et al., 1998), along with improving the line drive ability of the transmitters. However, the varying nature of the power line channel impedance makes standard impedance matching networks ineffective. The lack of efficient impedance matching results in poor signal power transferred through the channel. This leads to higher power consumption, reduced transmission distance, and produces reflections resulting in poor communication performance of the PLC modem (Sun and Amaratunga, 2011; Araneo et al., 2009). There has been research to develop PLC impedance matching solutions. However most efforts are focused on AC power line networks (Antoniou, 1967; Li et al., 2004; Despande et al., 2013; Sun and Amaratunga, 2011; Choi et al., 2008; Sibanda et al., 2011). This paper will focus on automotive power line networks and propose a transformerless impedance matching solution for this application. The proposed matching networking is based on current matching network topologies and will focus on cost and IC integration and performance. In the remaining part of this paper, background of DC power line impedance characteristics and a review of available PLC impedance matching approaches was provided. Next is a presentation of the proposed impedance matching network. This is followed by simulation results of the impedance matching network. Thereafter, the results are summarized and the paper concluded.

II. REVIEW OF AUTOMOTIVE POWER LINE IMPEDANCE CHARACTERISTICS

While there are similarities between AC power line impedance characteristics and automotive power line impedance characteristics, there are key differences which prevent AC power line impedance characteristics from being used directly into DC power line. The primary difference is that most devices connected to the vehicle power line have bypass capacitors. This means the power line impedance may not be purely inductive as it would be in AC power line networks. Secondly, the loads inside a car are always connected and generally will not be removed under normal operation, as opposed to AC networks where devices can be removed from the network. Thirdly, the impedance of the automotive power line changes as motors, actuators and electronic devices are turned on and off inside the car (Mohammadi et al., 2009), leading to varying channel impedance. Due to these issues, standard fixed impedance matching networks do not function well. Therefore an adaptive impedance matching network must be designed.

Vehicle power line impedance characteristics

Like AC PLC networks, the impedance characteristics of DC PLC networks are time and location varying, resulting in poor signal power being transferred to the channel (Mohammadi et al., 2009). The cause of the impedance variations is due to the activation and deactivations of motors, actuators and electronics within the vehicle during the course of operation. The state changes generate impulsive noise and change the impedance of the line. Research has been conducted to analyze the impedance characteristics of vehicle power line systems during varying states of operation. Figure 1 shows the impedance vs. carrier frequency using a 2006 Pontiac Solsctice (Mohammadi et al., 2009) with ignition on and off. The measurements were taken from three points: front, cabin and rear of the vehicle. As can be seen from Figure 1, the impedance values change with respect to vehicle operating state along with different carrier frequencies. The magnitude of the channel impedance ranges from 10 to 600 Ω (Mohammadi et al.,2009). It is difficult to determine the complex impedance characteristics of the power line with only the magnitude shown in Figure 1. Nevertheless, from previous investigations on AC and high voltage automotive PLC, it can be assumed that the imaginary part is inductive (Choi et al., 2008).

Previous PLC impedance matching topologies

Currently, there are three popular methods for impedance matching and improving power transferring of a PLC transceiver. Several of these designs are specifically designed for AC PLC transceivers. However the principles can be applied to DC PLC transceivers. i) One popular method of improving power transferring is to utilize an equalizer such as proposed in Araneo et al. (2009). This technique boosts the power gain of high frequency and low impedance signals, improving power transferring for broadband PLC modems. However there is a trade off with increased power consumption and it is only ideal for broadband systems. ii) The second method is to utilize capacitor banks (Choi and Park, 2007) or tapped transformers and inductors (Li et al., 2004) which operate on the principle of electronically tuning the inductor or transformer values to match the transceiver output impedance to the power line channel impedance. The benefit of this design is that a true impedance match is established resulting in no reflections, improved power transferred to the channel and lower supply power consumption. However the downfall of this design is the large amount of board space and limited tuning range. iii) The last method improving on the tapped transformer and inductors is to replace the tapped inductor with an active inductor (Sun and Amaratunga, 2011; Leuciue and Goras, 1998), as shown in Figure 2. This circuit eliminates the need for a tapped inductor by replacing it with an active inductor based on Antoniou's general impedance converter shown in Figure 3. By using the active inductors, the impedance tuning range is improved, as well as a smaller PCB and reduced component count being achieved. While there are many benefits to this design, the downside is that a transformer is still required to aid in current carrying ability (Sun and Amaratunga, 2011). This prevents the matching network from being embedded in the modem IC. In the case of PLC in vehicles it can be expensive. PROPOSED IMPEDANCE MATCHING SOLUTION Previously in this study, several impedance matching schemes were introduced and their advantages and disadvantages were examined. It emphasized the benefits of active inductors over tapped transformer or tapped inductor solutions for PLC impedance matching. However the need for a transformer makes the active inductor matching network an expensive solution for automotive PLC systems. Therefore a transformerless impedance matching circuit combined with capacitor banks and active inductor topologies was proposed. The tuning range of the proposed matching networks can be improved while allowing for ease of integration in a modem IC. Figure 4 is the schematic of the proposed impedance matching network. This network construction allows for several different L-matching network configurations. The variable capacitors will be based on a small four capacitor network and the variable inductor will be based on Antoniou's general impedance converter (Antoniou, 1967)

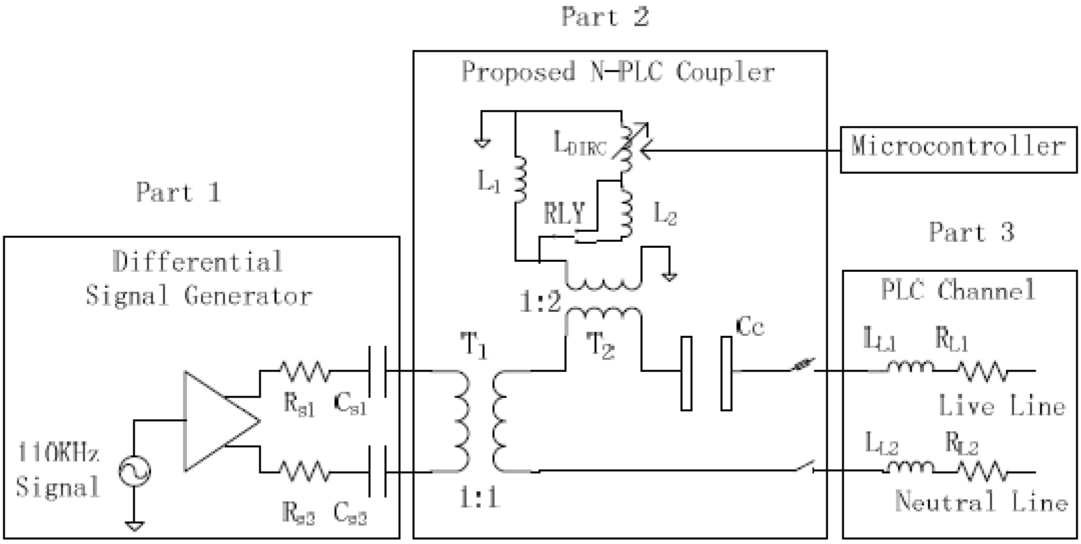

Figure 1. Adaptive impedance matching network designed in Sun and Amaratunga (2011).

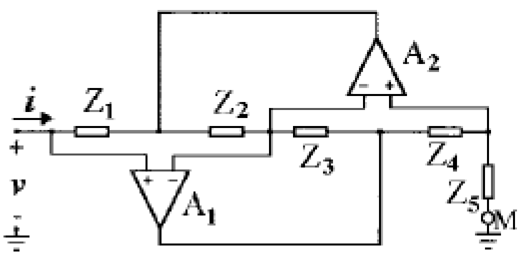

Figure 2. Antoniou's general impedance converter schematic (Leuciue and Goras, 1998).

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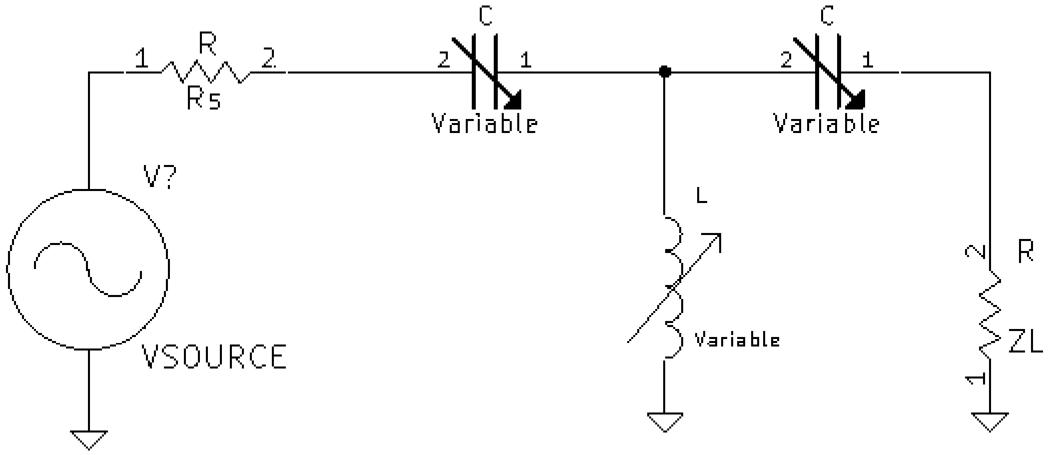

Figure 3. Schematic of the proposed impedance matching network

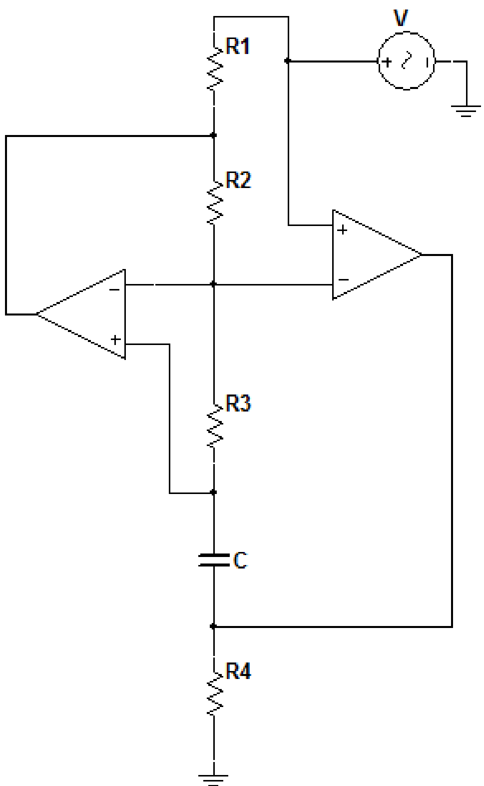

Figure 4. Active inductor schematic.

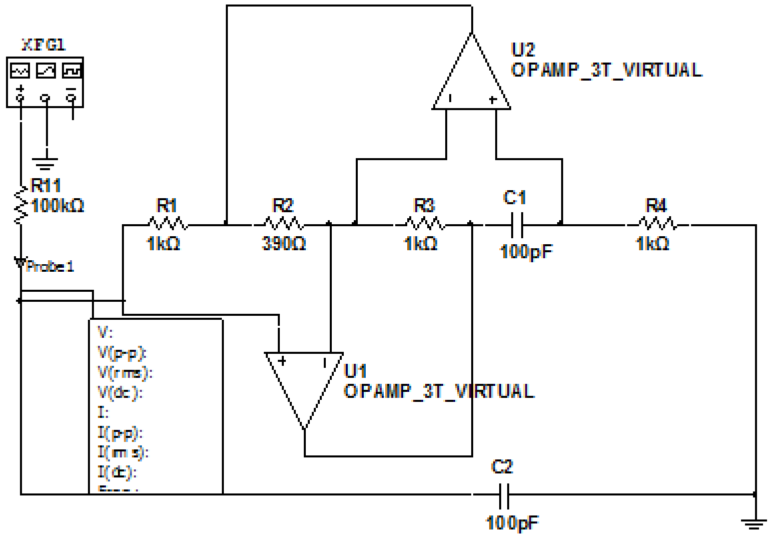

Figure 5 Test bench for the active inductor circuit.

Active inductor

Like the impedance matching network designed in Sun and Amaratunga (2011), the proposed design uses Antoniou's general impedance converter (Antoniou, 1967). Figure 5 shows the modified Antoniou's general impedance converter. The circuit replaces $Z4$ with a capacitor and $Z2$ and $Z3$ with digital potentiometers and the remaining impedances with resistors. The formula for determining the inductance value of the active inductor is as follows: (1) The tuning range of the active inductor will be limited to the digital potentiometer's resistance range. The selected digital potentiometer is Microchip MCP42100 which has a maximum resistance of 100 $k\Omega$ and 256 taps which means the minimum resistance value is 390 Ω. With $R1$, $R3$ and $R4$ set to 1 $k\Omega$ and C set to 100 pF and $R2$ as the digital potentiometer, the tuning range was calculated to be 1.13 to 253 μH. **Active inductor circuit operation** The active inductor was simulated using Multisim 11. Here the active inductor was connected as a parallel RLC tank bandpass filter with a known filtering capacitance as seen in Figure 6. By changing the resistance of $R2$ within the bounds of the MCP42100 digital potentiometer the inductance values is given as, $L = CR1R3R4\ R2$
(2) Substituting $\omega = 2\pi F$ and rearranging (2) for L provides the inductance value for the given $R2$ as, (3) By changing the value of $R2$, the centre frequency of the band pass filter changes as shown in Figures 7 and 8. An important note is that the quality factor of the active inductor as well as the bias point can be adjusted with $R1$. $\omega = 1/C\ L = 1\ 4\pi 2F2C$

III. SIMULATION RESULTS

Multisim 11 is used for the simulation. The results will be obtained by observing the output power waveforms to determine if a match is established. The carrier frequency used for the simulations will be 5.5 MHz and the output impedance of the signal source will be 150 Ω. The simulations consist of four scenarios as: 1) real to real match with load impedance lower than the source impedance; 2) real to inductive impedance match; 3) automotive load impedances; and 4) variable load impedances. These simulations will help to determine the matching networks viability for operation in automotive applications.

Real Source Impedance Real Load Impedance The first test is to match a 150 Ω source impedance to a 10 Ω load impedance. This impedance value represents an ideal case, as most impedances found on the power line will have a reactive component. However the circuits line drive capability and tuning range need to be examined to determine the matching networks viability. Figure 10 shows the power waveforms of RS and ZL before impedance matching. As expected most of the power is dissipated in the source resistor RS and very little is transferred to ZL. Figure 11 is the result after applying the proposed impedance matching network. As expected, both input and output waveforms are closely related in power, meaning a successful match was established.

Real Source Impedance Complex Load Impedance The second test was to match a 150 Ω source impedance to a complex load impedance of 700 Ω + j50 Ω. This scenario represents a realistic matching condition found on a PLC network, as the complex component of the channel impedance is usually inductive. Figure 12 shows the power waveforms of *RS* and *ZL* before impedance matching. As before, most of the power is dissipated in *ZL*. Figure 13 shows the power waveforms after applying the matching network. As expected, both *RS* and *ZL* share the power equally, meaning a successful match is established.

Automotive Load Impedances The third test is to examine the matching networks ability to operate with the impedances of automotive devices. The tests are to match the 150 Ω signal generator impedance to the impedances of a car battery and various lights of the vehicle. As the PLC modem may be connected close to t hese devices, the low power transferred after matching to the power transferred before matching. The impedance values of the components are determined through the measurements in Taherinejad et al. (2011) for a frequency of 5.5 MHz. Table 1 shows the results of the matching network when matched to various automotive devices. The results from Table 1 show the impedance matching network improves the power transferred of the PLC modem to the channel with multiple folds. A point to note would be that the improvement drops off as the impedance increases closer to the value of the source impedance. This is explained by noting that the real part of the impedance is closer in value to the source impedance, meaning the device is better matched compared to the devices with smaller impedances.

Variable Load Impedances The fourth test was to examine the matching networks ability to perform impedance matches over a range of impedances found on automotive power lines as the impedances observed on the automotive power line can vary from close to 0 Ω to 1 kΩ, with varying reactive components (Mohammadi et al., 2009; Reuter et al., 2011). Therefore the tuning range of the matching network must be examined to determine if this design is viable option for automotive PLC impedance matching. In these tests the proposed matching network will attempt to match a 150 Ω signal generator impedance to 1) variable real impedance and j50 Ω reactive component; 2) 300 Ω real impedance and variable reactive impedance; and 3) 20 Ω and variable reactive impedance. Figures 13, 14 and 15 will show the power delivered to the load before and after the matching network is applied. The results from Figures 13, 14 and 15 shows that the matching network improves the power transfer of the signal generator to the load over the expected range of automotive impedances. The results show the proposed matching network has the ability to provide matches over most expected impedance on automotive power lines. A point to note is that the matching network will have trouble matching large capacitive loads <-j100 Ω with small real values. This is due to the need for extremely large value capacitors in the capacitor banks which would make the size of the proposed design impractical. However since most impedance found in automotive power lines have inductive components (Taherinejad et al., 2011), this means the need to match large capacitive impedances will be very rare.

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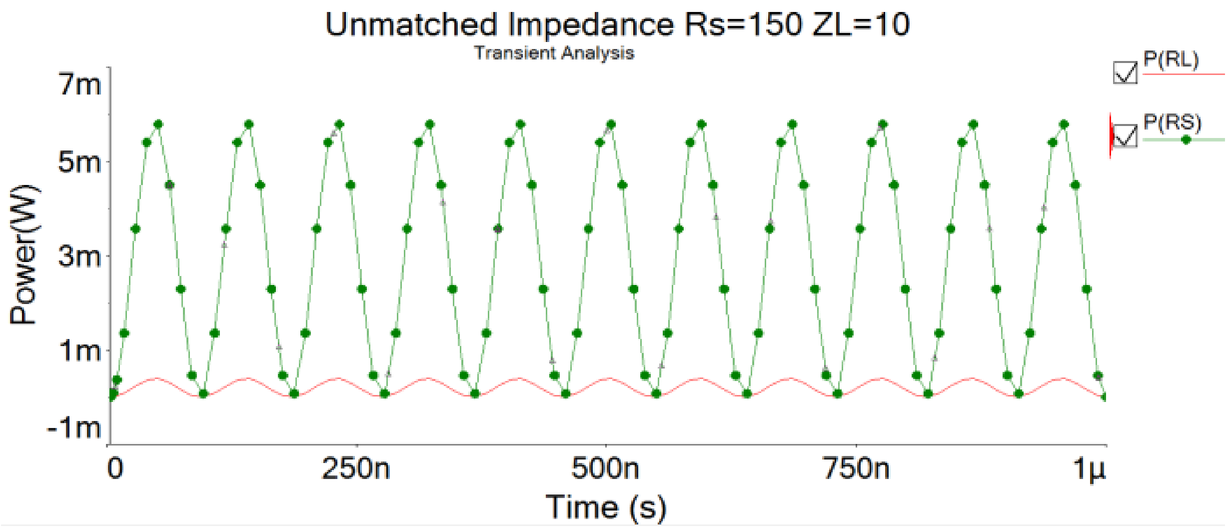

Figure 6. Input output power waveform for 150 Ω source impedance and 10 Ω load impedance before matching.

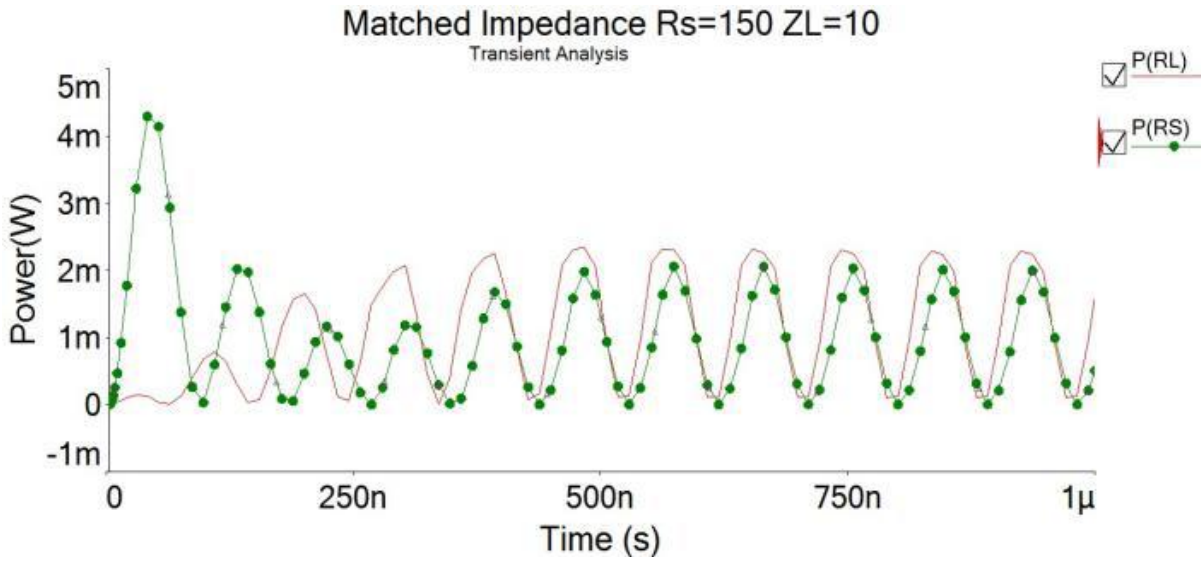

Figure 7. Input output power waveform for 150 Ω source impedance and 10 Ω load impedance after matching.

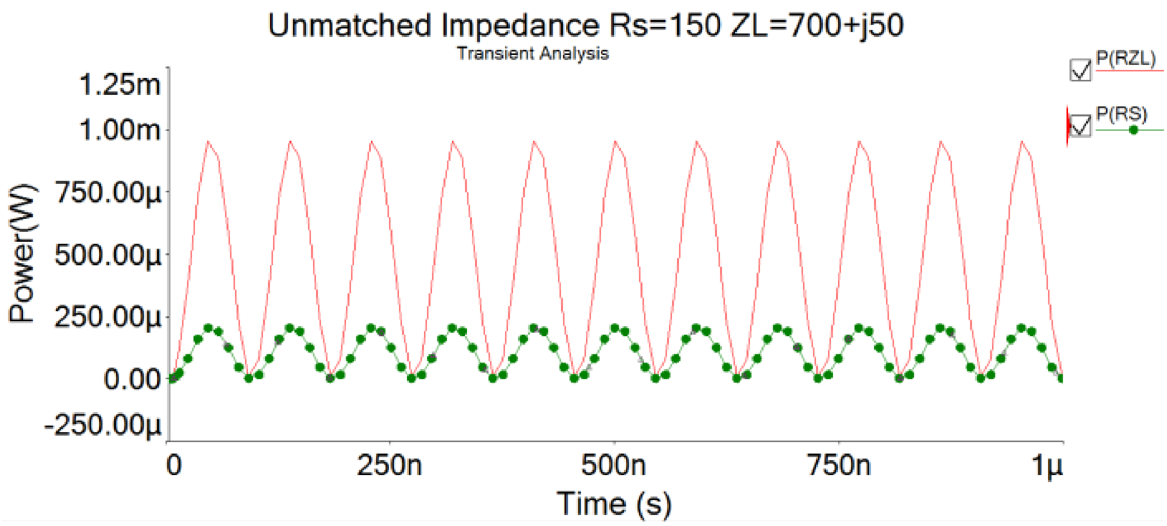

Figure 8. Input output power waveform for 150 Ω source impedance and 700 Ω + j50 Ω load impedance before matching.

IV. CONCLUSIONS

An adaptive impedance matching network for automotive PLC was proposed based on Antoniou's general impedance converter in this paper. It was shown that the

Table 1. Automotive impedance matching results.

Device	**State**	**Impedance (Ω)**	**Power transfer before (μW)**	**Power transfer after**	**Improvement factor**
Car Battery	N/A	1 + j6	42.93	302 µW	7.0
Headlights	Off	0.32 + j5.97	16.17	122.6 µW	7.6
Headlights	On	2.74 + j5.97	122.7	734 µW	5.98
Rear lights	Off	6.59 + j9.3	260	1.27 mW	4.88
Rear lights	On	25.2 + j9.3	805	1.68 mW	2.08

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