The Parallel Transmission of Power and Data With the Shared Channel for an Inductive Power Transfer System

Yue Sun, *Member, IEEE*, Peng-Xu Yan, Zhi-Hui Wang, *Member, IEEE*, and Ying-Ying Luan

***Abstract*—A shared physical communications channel is designed and implemented in this paper for inductive (contactless) power transfer (IPT) applications, wherein data are transferred without interfering power transfer, and, thus, maintained the efficiency of the IPT system. The channel is made of coupling coils, which are used to control the system and to transfer data bidirectionally at the rate of 19.2 Kb/s. To make the system work in two relatively independent modes, the wave trappers (passive bandpass and band-reject filters) are added into the system, and an integrated mathematical model is established based on separate models of data and power transfer. The proposed method was tested on a laboratory scale prototype, and was proved to be reliable for the parallel transmission of power and data. Therefore, the proposed method can be used to improve performance of the IPT system by precise control due to communication between the primary side and the pickup side.**

***Index Terms*—Inductive (contactless) power transfer (IPT), shared channel, wave trapper parallel transmission of power and data.**

Nomenclature

$E_{\mathrm{dc}}, V_{\mathrm{in}}$	Voltage of dc link and output voltage of the inverter, respectively.
L_p, L_s	Resonant inductor of primary and secondary sides, respectively.
R_p, R_s	Inherent resistor of primary and secondary resonant inductor, respectively.
C_p	Compensating capacitor of primary side.
C_{r1}, C_{r2}	Tuned capacitor of wave trappers of primary and secondary sides, respectively.
C_1, C_2	Tuned capacitor for data injection of primary and secondary sides, respectively.
C_3, C_4	Tuned capacitor for data detection of primary and secondary sides, respectively.
L_{r1}, L_{r2}	Tuned inductor of wave trappers of primary and secondary sides, respectively.
$L_{T1} - L_{T4}$	Self-inductance of transformer to send and receive data, respectively.
$M_1 - M_4$	Mutual inductance of transformer to send and receive data, respectively.
M	Mutual inductance between the primary and secondary coils.
R_e	Equivalent load resistance.
ω	Resonant frequency of power transfer.
ω_2	Frequency of the data carrier.

Manuscript received April 24, 2015; revised July 1, 2015 and September 6, 2015; accepted October 21, 2015. Date of publication November 6, 2015; date of current version March 2, 2016. This work was supported by the National Natural Science Foundation of China under Grants 51277192 and 51207173, and also by the the National High Technology Research and Development Program of China (863 Program) under Grant 2015AA016201. Recommended for publication by Associate Editor J. M. Rivas Davila.

Y. Sun is with the State Key Laboratory of Power Transmission Equipment & System Security and New Technology and College of Automation, Chongqing University, Chongqing 400044, China (e-mail: syue06@cqu.edu.cn).

P.-X. Yan, Z.-H. Wang, and Y.-Y. Luan are with the College of Automation, Chongqing University, Chongqing 400044, China (e-mail: 1119391366@qq.com; wzhcqu@hotmail.com; 1066454341@qq.com).

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Digital Object Identifier 10.1109/TPEL.2015.2497739

I. Introduction

INDUCTIVE power transfer (IPT) technology allows for electrical power transfer between systems without physical contact [1]. Due to its residue-free operation and tolerance to harsh environment, IPT has been widely used in electric vehicles, household appliances, and implantable biomedical devices [2]–[7], which play an increasingly vital part in future industrial applications. However, these systems often involve multiple receivers [8], [9], and, thus, require inherent communication on power control.

The power line communication (PLC) technology is widely used in traditional cable power supply systems, such as home intelligent applications [10], but the communication cannot be achieved when transformers are presented in the link. As coupling coils in IPT system are regarded as loosely coupled transformer so this PLC technology is not suitable for use in IPT systems. Alternatively, the multiband telemetry system and RF technology are often adopted to realize communication in the IPT system [11], [12]. Nonetheless, for some applications, such as the drilling system, communication is needed for controlling three rotary steerable motors and for power transfer [13]. However, the air gap is always within 1 cm and filled with mud and seawater, and the surrounding temperature can even reach 125 °C or higher, the RF technology is not suitable for alignment problems. Moreover, the power link and data link interact with each other, complicating the operation of both power and data transmission [11]. To achieve communication between IPT systems, coupling coils for power transfer is an option.

A few researches on the communication using the power transfer coupling coils have been reported. Literature [13], [14] realize data transfer by controlling injection of the energy into the inverter network, but data transfer will be affected when power supply is disturbed, and the reverse transfer is not achieved. Literature [15] realizes data transfer by changing the operating frequency of the inverter network, but the efficiency and capacity of power transfer will be affected by variation of

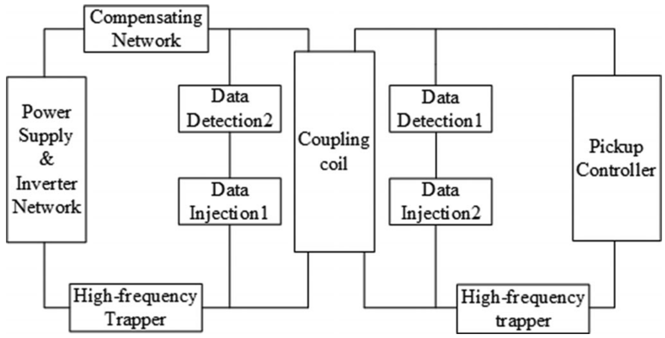


Fig. 1. Power transfer and communication system topology.

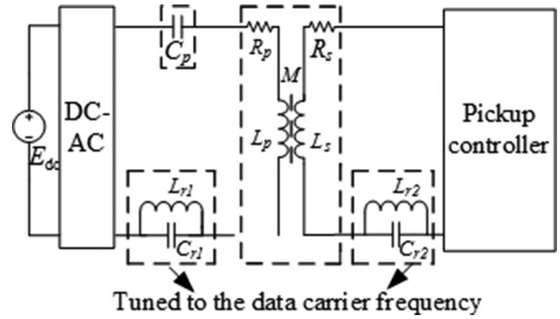


Fig. 2. Power transfer circuits.

the frequency. Literature [16], [17] adds transformers that are connected with the primary and secondary coupling coils in series, and data carrier is injected into the system through the transformers and then transferred bidirectionally, but the data carrier will be weaken by the compensation circuits of the power transfer and the power transfer will be affected by the harmonic. Literature [18] uses pairs of inductors and capacitors acting as passive bandpass and band-reject filters to realize the communication, but the data pickup coil is connected with the power transfer coils in series, so the carrier will be weaken by the compensation circuits of the power transfer.

This paper proposes a data transfer method using power transfer coils for IPT systems, whereby power transfer coils are used as a shared channel for power and data transfer. Pairs of inductors and capacitors acting as passive bandpass and band-reject filters (in order to describe vividly, they are represented by wave trappers in subsequent sections of this paper) are used to separate the power and data transfer, and the circuits to send and receive the data are connected with the shared channel in parallel, then the power and data can be transferred relatively independently. Finally, the experiment results verified the feasibility of the proposed method.

II. System Topology

Fig. 1 shows the system topology, to use the power transfer coil to form a communication channel; two new modules have been added. These are a circuit to send and receive data to and from the shared channel and a high-frequency trapper allowing the power transfer channel to be terminated in its characteristic impedance at the frequency used for communication, while maintaining a short-circuit at the frequency of power transfer.

A. Wave Trapper

As both power and data are transferred through the shared channel, the system needs to have different characteristics for the two frequencies. The impedance of the power transfer channel shall be high for data carrier transfer while low for power transfer, and the communication channel is the same.

Pairs of inductors and capacitors acting as passive bandpass and band-reject filters (wave trappers) can be used to separate and filter the two frequencies within the IPT system. The parallel inductor and capacitor forms a band-reject filter, while the series forms a bandpass filter. The center frequency of the two filter types is given by (1). Using the combinations of these two circuits, the whole system can be electrically divided into power and communication sections

$$f = \frac{1}{2\pi\sqrt{LC}}. \tag{1}$$

B. Power Transfer Circuit

There is no compensation capacitor in the pickup side of power transfer for the IPT platform, whereby the air gap is within 1 cm. The soft-switching frequency is sensitive to the loads for the high-Q resonant power transfer when there are compensation capacitors in both sides [19], because the switching stress is high once the frequency is deviate from the expected frequency, especially for the high surrounding temperature and the power transfer efficiency can reach 85% when there is no compensation capacitor in the pickup side, so the compensation topology is selected. To realize the communication, the high-frequency trappers (parallel inductor and capacitor ($Lr_1, C_{r1}; L_{r2}C_{r2}$) are connected with the shared channel in series as shown in Fig. 2.

The center frequency of the high-frequency trapper is tuned to the data carrier frequency which is far from the power transfer frequency so that the carrier cannot pass through the trappers for the high impedance, while the power transfer would not be affected, then the interference from the data transfer to the power transfer can be limited.

C. Communication Circuits

The circuits used to send and receive data are connected with the shared channel in parallel as shown in Fig. 3. The data are injected to and received from the shared channel by transformer $T_1(T_4)$, and transformer $T_2(T_3)$ in the forward (reverse) communication, respectively.

The capacitor C_1 and C_2 are connected with the secondary of the transformers in series which acts as the bandpass filter. Tuning the center frequency of the filter to the carrier frequency, the carrier can pass through easily but the power cannot pass for the high impedance, then the interference from the power transfer can be limited.

III. System Performance

In this section, the model of the system is established based on the reflected impedance analysis [20]. Because both the tuned

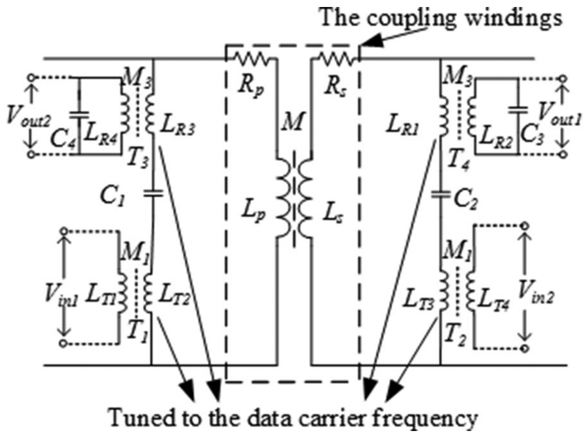


Fig. 3. Communication circuits.

inductors (inductors in the trappers and transformers to send and receive data) and the shared channel are wound around the magnetic core, and placed in slots made of steel, so that the mutual inductance between the tuned inductors and the shared channel is neglected.

A. Interference From the Communication Channel to the Power Transfer

The impedance of power transfer channel shall remain unchanged to ensure the stability of the power transfer frequency and capacity after the communication channel is added. For the original system, the impedance in the pickup side is given by

$$z_{p2} = j\omega L_s + R_s + R_e \tag{2}$$

where R_e is the equivalent load impedance, R_s is the equivalent series impedance of the pickup coils, then the impedance of the primary side is given by

$$z_{p1} = j\omega L_p + R_p + \frac{1}{j\omega C_p} + z_{p21} \tag{3}$$

where z_{p21} is the reflected impedance of the pickup side, then the output voltage is given by

$$V_{\text{out}} = \frac{j\omega M i_{p1}}{z_{p2}} R_e \tag{4}$$

where i_{p1} is the current in the power supply side. As mentioned in Section II, the trappers can be neglected when analyzing power transfer, so the impedance of the pickup side and the reflected impedance to the primary side after the communication channel is added and are given by

$$z_{d2} = j\omega L_s + R_s + \frac{R_e z_{ds}}{R_e + z_{ds}} \tag{5}$$

$$z_{d21} = \frac{\omega^2 M^2}{z_{d2}} \tag{6}$$

where z_{ds} is the impedance of the parallel communication channel, which is given by

$$z_{ds} = j\omega L_{R1} + j\omega L_{T3} + \frac{1}{j\omega C_2} + z_{42} \tag{7}$$

where z_{42} is the reflect impedance of the data receive circuits, then the impedance of the primary side after the communication channel is added into the system is given by

$$z_{d1} = \frac{1}{j\omega C_p} + \frac{z_{ds}(j\omega L_p + R_p + z_{d21})}{z_{ds} + j\omega L_p + R_p + z_{d21}}. \tag{8}$$

Then, the voltage in the primary side of the shared channel is given by

$$V_t = i_{dp} \frac{z_{ds}(j\omega L_p + R_p + z_{d21})}{z_{ds} + j\omega L_p + R_p + z_{d21}} \tag{9}$$

where i_{dp} is the current in the power supply side, then the voltage of the pickup side is given by

$$v_{d2} = j\omega M \frac{V_t}{j\omega L_p + R_p + z_{d21}}. \tag{10}$$

Then, the output voltage is given by

$$V_{\text{out}} = \frac{v_{d2}}{z_{d2}} \frac{R_e z_{ds}}{R_e + z_{ds}}. \tag{11}$$

The interference from the added communication channel to power transfer can be analyzed based on the attenuation from the output voltage of inverter (V_{in}) to the output voltage (V_{out}) whether the communication channel is added to the system or not.

B. Interference From Power Transfer When Forward Transmission Attenuation

Generally, the data extracted by the transformer will contain the interference from power transfer inevitably, in order to improve the signal to noise ratio (SNR), the attenuation of the interference has to be analyzed. The current in the communication channel in the pickup side is given by

$$i_s = \frac{V_{\text{out}}}{z_{ds}}. \tag{12}$$

Then, the voltage on the tuned capacitor C_3 is given by

$$V_{\text{out1}} = j\omega M_3 i_s. \tag{13}$$

The interference from power transfer when forward communication can be analyzed based on the attenuation from the output of inverter (V_{in}) to the output of data extraction (V_{out1}).

C. Interference From the Power Transfer When Reverse Transmission

Similarly, the interference from power transfer when reverse transmission can be analyzed based on the attenuation from the output of inverter (V_{in}) to the data extraction output (V_{out2}). The interference voltage from power transfer to the data extraction circuit is given by

$$V_{\text{out2}} = j\omega M_3 i_t \tag{14}$$

where i_t is the current in the communication channel in the pickup side.

D. Data Transfer Mission

The data carrier cannot pass through the trappers for the high impedance; thus, the carrier would not be weakened by the compensation circuits of power transfer. Meanwhile, the power would not pass through the circuits to inject and receive the data carrier for the high impedance, so that the data transfer can be insulated from the power transfer. Because the parameters of the communication channel in power supply side and pickup side are the same, so herein only the forward transmission is discussed. The reflected impedance of the communication channel in the pickup side is given by

$$z_r = \frac{\omega_2^2 M^2}{z_{ds} + j\omega_2 L_s + R_s}. \tag{15}$$

The impedance of the communication channel in the power supply side is given by

$$z_{dp} = j\omega_2 L_p + R_p + z_r + z_{ds}. \tag{16}$$

The current in the primary coupling coils is given by

$$i_{dp} = \frac{j\omega_2 M_1 v_{\rm in}}{(z_f + j\omega_2 L_{T2})\, z_{dp}} \tag{17}$$

where $v_{\rm in}$ is the input data voltage, z_f is the reflected impedance of the communication channel, then the voltage of extracted carrier can be given by

$$v_{\rm out1} = j\omega_2 M_3 \frac{v_1}{j\omega_2 L_s + R_s + z_{ds}} \tag{18}$$

where v_1 is the voltage in the secondary side of the shared channel, then data transmission can be analyzed based on the attenuation from the rejection data $(v_{\rm in})$ to the received data $(v_{\rm out1})$.

IV. Operating Principle and Verification

As mentioned in Section III, the interference between the power and data transfer can be analyzed based on the attenuation of the interference, so the results are discussed in this section. The power transfer is preferred not to be affected by the additional communication circuits, that is to say the attenuation (or the impedance) from the power supply to the output should keep unchanged, therefore it should be satisfied

$$\begin{cases} z_{p1} \cong z_{d1} \\ z_{p2} \cong z_{d2} \end{cases} \tag{19}$$

where z_{p1}, z_{p2} are the impedance of the power supply and pickup side of the original system respectively, while z_{d1}, z_{d2} are the impedance after the circuits to realize the communication are added. The SNR has to be high enough so the following condition has to be satisfied:

$$v_{\rm out} \gg V_{\rm out} \tag{20}$$

where $v_{\rm out}$ is the extracted data, while $V_{\rm out}$ is the interference from power transfer. In order to verify the feasibility of the proposed method, a simulation model with reference to Fig. 1 is set up and the main parameters are shown in Table I.

TABLE I
Parameters of the IPT Power and Data Transfer System

Parameters	Values
Primary compensation capacitor C_p	0.3 μF
Tuned capacitor C_1, C_2	0.1 nF
Tuned capacitor C_3, C_4	2.1 nH
Primary resonant inductance L_p	456 μH
Secondary resonant inductance L_s	457 μH
The inductance L_{T1}, L_{T3}	0.76 μH
The inductance L_{T2}, L_{T4}	76.7 μH
The inductance $L_{R1} - L_{R4}$	5 μH
Mutual inductance M	431 μH
Mutual inductance M_1, M_4	8.8 μH
Mutual inductance M_2, M_3	4 μH
The equivalent load R_e	8.9 Ω
$V_{\rm in}$	48 V

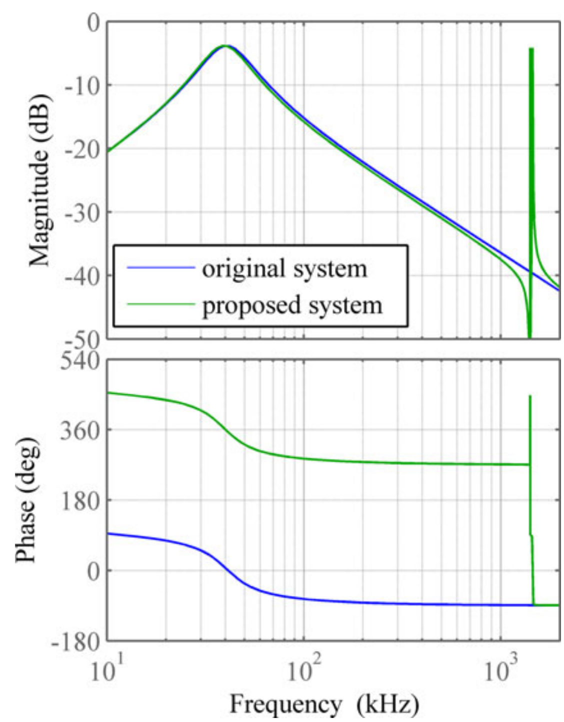


Fig. 4. Bode figure of the power transfer channel with and without the communication circuits.

As mentioned above, attenuation of the power transfer channel cannot be changed drastically around the power transfer frequency after related circuits (such as high-frequency trappers and the circuits used to send and receive the data carriers) are added into IPT systems. Then, the attenuation from inverter output $(V_{\rm in})$ to terminal voltage of the equivalent load $(V_{\rm out})$ with and without the related circuits are analyzed, respectively, and the results are shown in Fig. 4.

The blue line is the result of the original IPT system without the related circuits, while the green line is the result after the related circuits are added into the system. As shown in Fig. 4, after related circuits are added, two attenuation peaks appear, but the attenuation keeps almost unchanged in the low frequency range (below 100 KHz) after the related circuits are added. Because the operating frequency of power transfer is in the low frequency range so power transfer would not be affected too much. Though there is an additional peak around 1.46 MHz, it is far from the power transfer frequency, thus power transfer would not be affected either. On the other hand, as the data carrier cannot pass through the high-frequency trapper, the carrier can only be transferred within the communication channel, so the power and data can be transferred independently. In order to ensure that the SNR is high enough, the interference from power transfer should be small enough, so the interference from power transfer needs to be analyzed, herein attenuation from the inverter output $(V_{\rm in})$ to the data extraction ($V_{\rm out1}$ and $V_{\rm out2}$) is analyzed and the results are shown in Fig. 5.

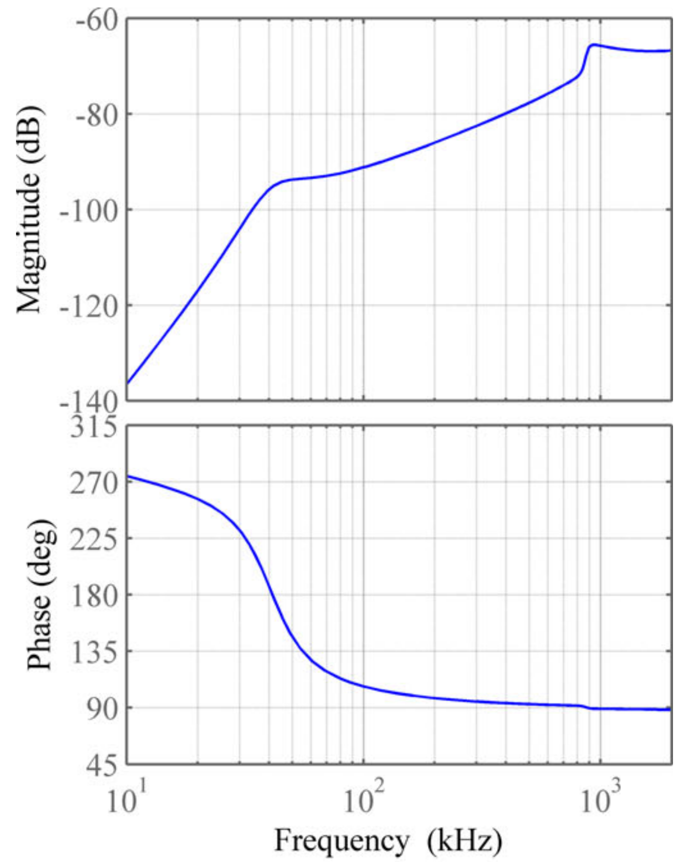
As shown in Fig. 5, attenuation from inverter output to the data extraction capacitor is -95.9 dB at 40 KHz and -66.9 dB at 1.49 MHz for forward transmission, while it is -85.9 and -27.2 dB at the same frequency for reverse transmission. Attenuation of the power within the communication channel is high for the high impedance, so the analysis in Section II proved to be correct. Attenuation of the communication channel needs to be analyzed to ensure that the data can be transferred stably. Because the channel is symmetry, there only needs to analyze either forward or reverse transmission, here the forward transmission is analyzed and the result is shown in Fig. 6.

As shown in Fig. 6, attenuation from the injected data to the extracted data is around 5.74 dB at 1.47 MHz and it is relatively flat around this frequency. In practical applications, a certain bandwidth is desired for communication so the carrier frequency can be around 1.5 MHz.

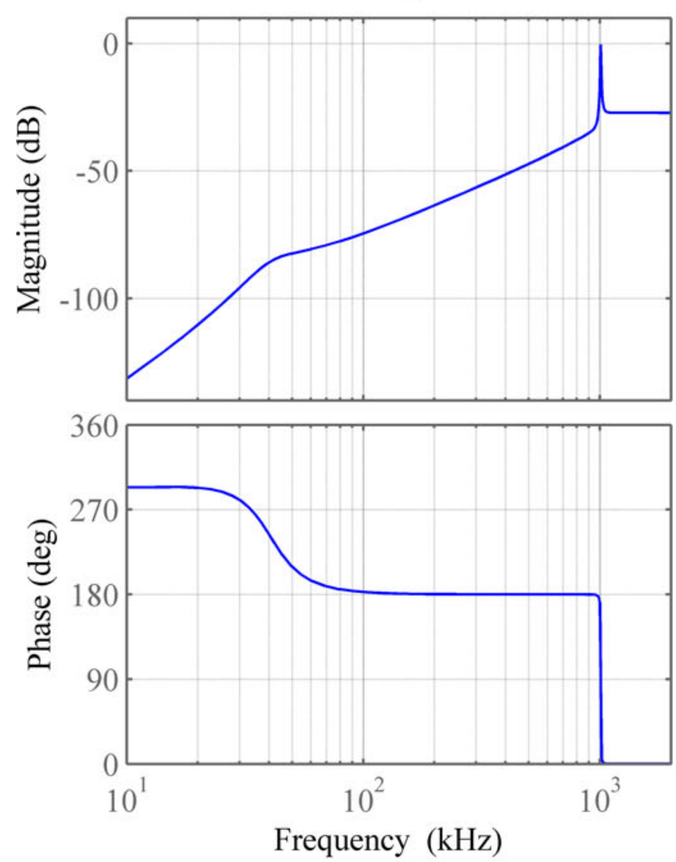
Based on the constructed system, the impedance reflected back in series with the shared channel is, therefore, just about j2 Ω, which is equivalent to an extra 1-μH inductor, and can cause a relatively small reflection factor of 0.1%. In the reverse direction, the calculation is the same.

V. Experimental Results

In order to verify the validity of the proposed topology and method, a prototype IPT system whose air gap is 2–7 mm was built, as shown in Fig. 7. This system aims to realize the parallel transmission of power and data via the shared channel. Parameters of the prototype are shown in Table I. The power supply side, fed by a 48-V source, was controlled by the full-bridge inverter to obtain a high-frequency ac voltage that goes through the series compensation circuits, while the pickup coil was connected to a full-bridge rectifier directly, and then a boost chopper was connected to the rectifier to maintain regulated output of 48 V. The circuits used to inject and receive data are connected with the channel in parallel. The data are modulated by on–off keying, then transferred bidirectional and half-duplex through the shared channel. The extracted data are shaped by a comparator with an appropriate threshold, so the interference from power transfer is eliminated. To meet requirements of actual applications, the data rates is chosen to be 19.2 kb/s [17]. The tuned inductors of high-frequency trappers cannot be too large because of the high-Q resonant power transfer, otherwise the frequency and capability of power transfer will be affected, so the inductors are chosen as shown in Table I, then the tuned capacitors are chosen taking account of the bandwidth of the



(a)



(b)

Fig. 5. Bode figure of the interference from power to the data transfer:

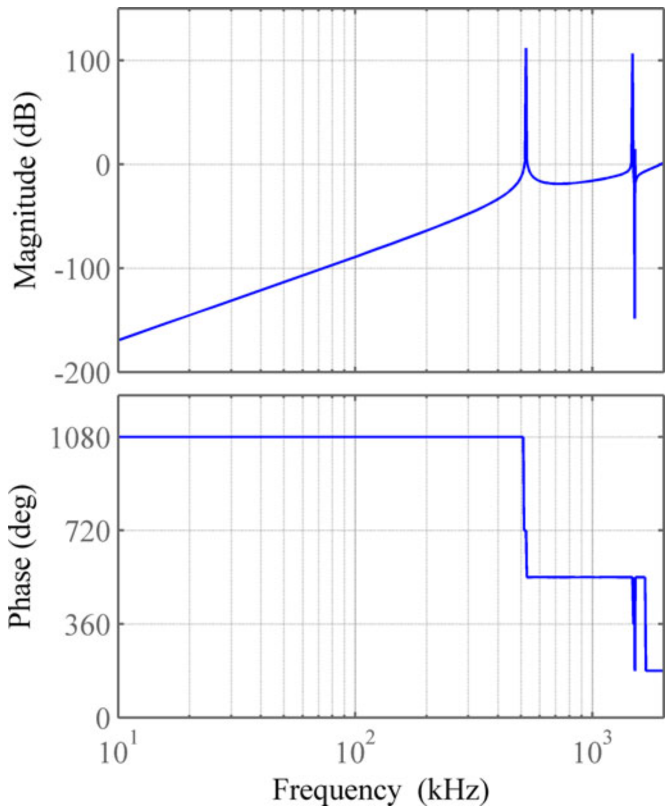


Fig. 6. Bode figure of the data forward transmission.

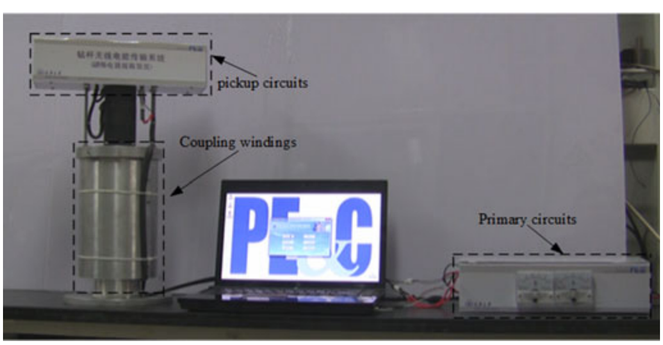


Fig. 7. Proposed IPT system.

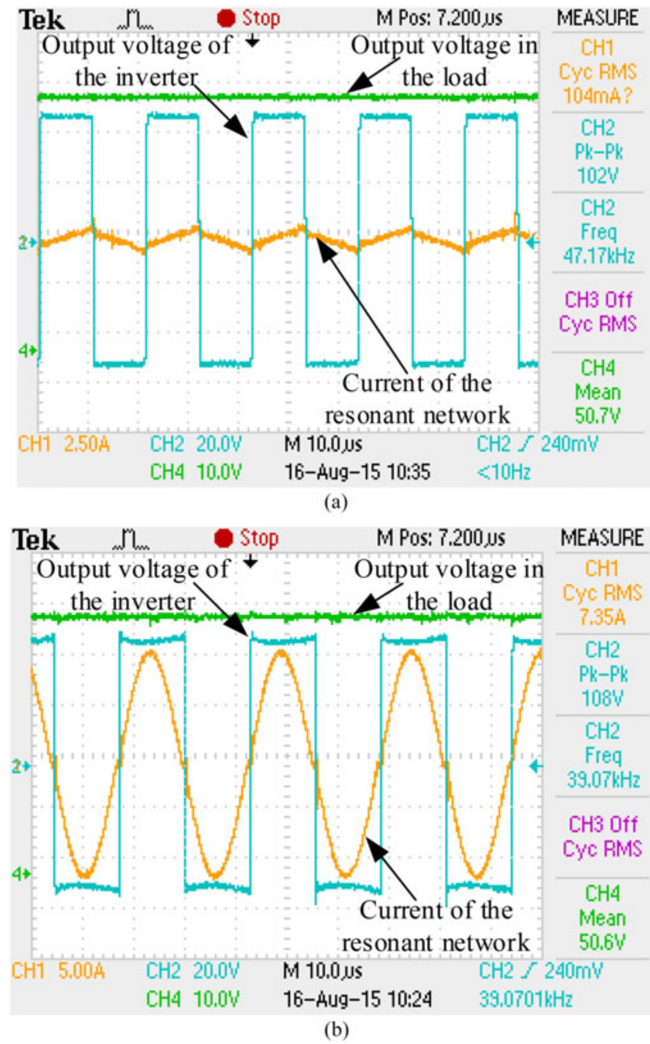


Fig. 8. Results of the original IPT system without the related circuits: (a) No load and (b) $R_e = 8.9\ \Omega$.

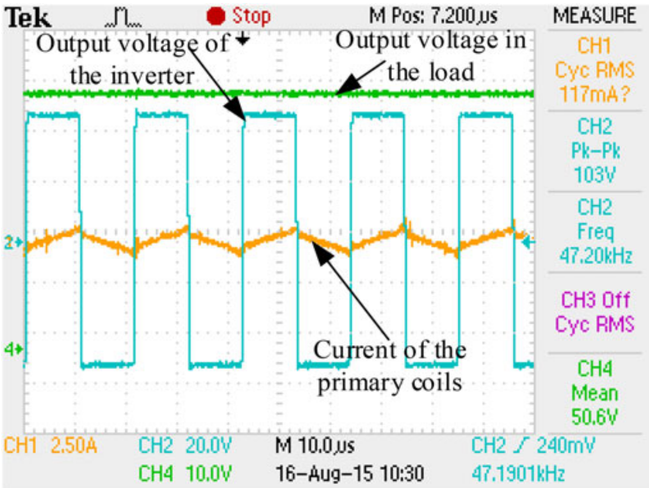
more attempts have been made to improve the data rates which requires new modulation and demodulation method.

In order to verify the performance of the proposed method, some indicators are tested, including the output voltage, the current in the coupling coils of primary side, the inverter output voltage, the working frequency of power transmission, the received data, and the demodulated data.

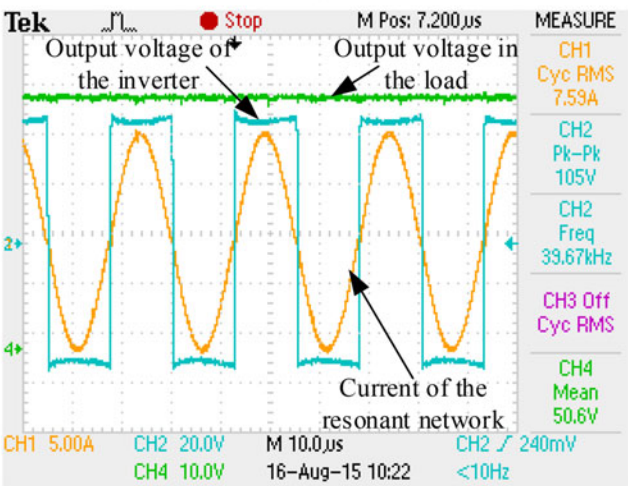
Fig. 8 shows the results of power transfer of the original IPT system without the communication channel in which (a) is the condition when there is no load, and (b) is the condition when R_e is 8.9 Ω, and the results after the additional communication channel are added into the system are given in Fig. 9.

After the related circuits are added, the output voltage changes from 50.7 to 50.6 V, drops by 0.2%, the power transfer frequency changes from 47.17 to 47.2 KHz when there is no load and changes from 39.06 to 39.67 KHz when R_e is 8.9 Ω, and the input current changes from 6.36 to 6.40 A where the transmission efficiency drops by 0.6%. The reason is that the impedance of the trappers and the communication channel is not theoretically infinite at the IPT power frequency so the performance is affected especially in the case that the quality factor of the power transfer channel is high as mentioned, so some measures such as the parameter optimization can be taken to improve the system performance. The results of the data transfer when the output power is 258 W are shown in Fig. 10 in which (a) is the forward transmission, and (b) is the reverse transmission.

As shown in Fig. 10, the output voltage drops by 1 V when the data are transferred; on one hand, the performance is changed as mentioned, and on the other hand, the boost regulator circuit in the pickup side is not that good. So some measures such as the further parameter optimization and a better control regulator circuit can be taken to improve the performance. As for the data transfer, the received data reaches 5.28 V while the noise is lower than 1 V, so the SNR is high enough. As expected, the data can be transferred simultaneously with the power. Despite the changes

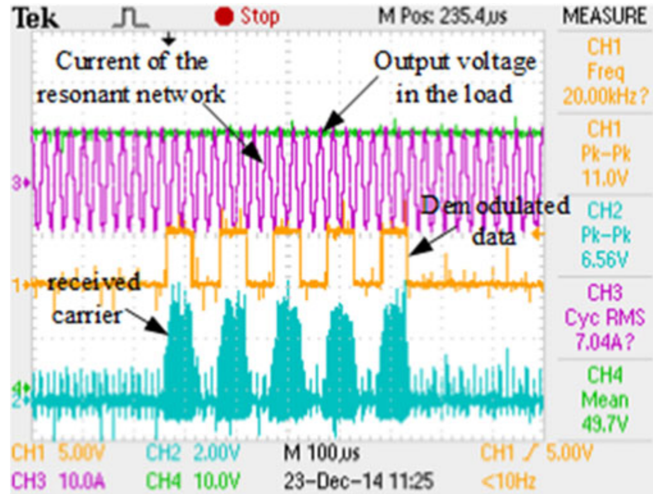


(a)

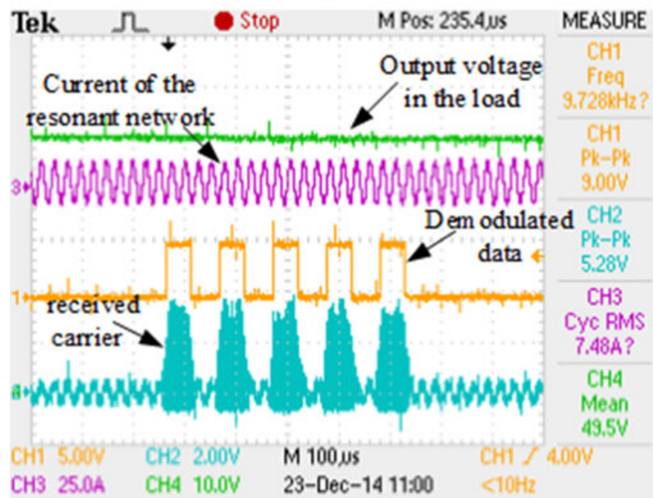


(b)

Fig. 9. Results of the proposed system with the related circuits: (a) No load and (b) $R_e = 8.9\ \Omega$.



(a)



(b)

Fig. 10. Results of the data demodulation: (a) Forward transmission and (b) reverse transmission.

TABLE II
RESULTS OF CONTINUOUS EXPERIMENTS

Load/output power	Input current	Input voltage	Data rates	Power transfer efficiency
No-load	–	48 V	19.2 kb/s	–
50 W	1.21 A	48 V	19.2 kb/s	86.08%
250 W	6.26 A	48 V	19.2 kb/s	83.2%

in power transfer, the proposed method is certainly feasible to realize the data transmission with the shared channel, and the reliability and stability of the proposed method is verified by working 6 h continuously, and the results are shown in Table II.

In addition, it should be noted that theoretically the proposed method in this paper is suitable for systems with the coupling coefficient from 0.1–0.5 as long as the trappers can prevent data carriers from entering the compensation circuits of power transfer. Besides, to obtain the same data rates, the carrier frequency do not need to be the same as in this paper, because the quality factor may not be that high, and, thus, parameters would not be that sensitive to the additional circuits. However, the parameter optimization may be needed and the power consumption of data transmission increases as the attenuation of the communication channel is much higher. Here, no more attempt has been made to discuss the condition where the coupling coefficient is very low, which requires further study.

VI. CONCLUSION

A novel topology and method for data and power transmission by one coupling coil for IPT systems has been described in this paper. A prototype IPT system is built to verify the feasibility of the proposed method. The mathematical model has been presented to shown the feasibility of the method by analyzing attenuation of interference between power and data transfer, and attenuation of the communication channel. Experimental results suggest that the data can be transferred bidirectionally when the data rate is 19.2 kb/s. Furthermore, the data can be transferred stably and reliably even if the transferred power is changed within a certain range. The condition where the mutual inductance is changed is not analyzed in this paper, because the air gap is just 2–7 mm so that the mutual inductance would not be changed too much. Despite of power loss and changes of performance parameters to realize the communication, the proposed method is feasible for the IPT systems in a certain sense, and the method has the potential on other systems which have the coupling coefficient from 0.1–0.5, but some more in-depth research and analysis on the interference between power and data transfer and improved means of data modulation is needed.

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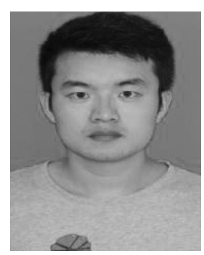
Yue Sun (M'07) received the B.E. degree in electrical engineering, the M.E. degree in industry automation, and the Ph.D. degree in mechanical electrical integrated manufacturing from Chongqing University, Chongqing, China, in 1982, 1988, and 1995, respectively.

In 1997, he was a Senior Visiting Scholar in France for one year. From 2008 to 2009, he was a Visiting Scholar with the University of Queensland, Brisbane, Australia. He is currently a Professor at the State Key Laboratory of Power Transmission Equipment & System Security and New Technology and College of Automation, Chongqing University. His research interests include automatic control, wireless power transfer, and power electronics applications



Peng-Xu Yan received the B.E. degree in automation from Chongqing University, Chongqing, China, in 2013, where he is currently working toward the M.E. degree in control science and engineering.

In 2013, he joined the Power Electronics and Control Laboratory, Chongqing University, as a Student. His research interests include automatic control and practical engineering applications in wireless power transfer.

Zhi-Hui Wang (M'09) received the B.E. and M.E. degrees in automation and the Ph.D. degree in control theory and control engineering from Chongqing University, Chongqing, China, in 2003, 2006, and 2009, respectively.

He is currently an Associate Professor at the College of Automation, Chongqing University. His research interests include fundamental investigations and practical engineering applications in efficient high-power converters and wireless power transfer.

Ying-Ying Luan received the B.E. degree from the College of Electronic Information and Automation, Qufu Normal University, Rizhao, China, in 2013, where she is currently working toward the M.E. degree in control engineering.

In 2013, she joined the Power Electronics and Control Laboratory, Chongqing University, Chongqing, China, as a Student. Her research interests include automatic control and efficiency analysis in wireless power supply.