Multiple receivers wireless power transfer systems using decoupling coils to eliminate cross-coupling and achieve selective target power distribution

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Abstract Current research in selectively supplying power to multi-receiving coil by each means has advantages and disadvantages. In response, the authors designed a more efficient selective power transmission and power allocation method. Multiple different specifications coaxial decoupling coils as the receiving coils. And the transmitting coils of the same specification as the receiving coils are integrally arranged on the same axis. Since the cross-coupling between the receiver coils can be eliminated. Therefore, excite the transmit coil can selectively supply power to the same specification receiver coil. And the load power can be designed by the impedance inverter of the receiving coil.

Keywords: wireless power transfer, multi-receiver, cross-coupling, selective power distribution, decoupling coil, impedance inverter

Classification: Microwave and millimeter-wave devices, circuits, and modules

1. Introduction

Compared with the cable power transmission, the wireless power transmission (WPT) technology has aroused wide attention for its high efficiency, safety and reliability [1, 2]. Nowadays, wireless power transmission technology has been broadly used in electric vehicles, consumer electronics as well as implantable medical devices [3, 4, 5, 6].

As the conventional single-transmitting (Tx) and single-receiving (Rx) circuits cannot fulfill the requirement of simultaneously providing power for multiple electrical devices in practical applications, the study on multi-Rx coils has made great progress in recent years [7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21]. For multi-Rx coil systems, the cross-coupling between the coils cannot be ignored when Rx coils are very close to each other. The cross-coupling will reduce the transmission efficiency and transmission power of the system at the resonant frequency [11, 12, 13, 14]. In [14], the author adopted the method of reactance compensation to eliminate the impact of cross-coupling on the WPT system. But the reactance compensation has low application flexibility. When the load or cross inductance changes, the appropriate reactance should be reselected for compensation. Another way to eliminate the impact of cross-coupling between receivers is to exploit multiple frequencies [15, 16, 17].

Some studies utilized decoupling coils to eliminate the mutual inductance between coils, and the major decoupling methods include: i) insert a metal insulator between the coils [22]; ii) adjust the coils position (e.g., overlap and orthogonal) and make the net magnetic flux between the coils to be zero [23, 24, 25]; iii) use different structures of coils (e.g., unipolar coil and bipolar coil) to eliminate the magnetic flux between the coils [26, 27, 28, 29, 30, 31]. The existing studies have not used the decoupling coil as a separate Rx in the WPT system. It is noteworthy that in practical multi-Rx WPT systems, if these methods served as decoupling of the Rx coils, metal insulators will obstruct the magnetic field between the Tx coil and the Rx coil and overlap and orthogonally limit the placement of the coils. In this study, unipolar coils and bipolar coils separated from each other served as Rx coils, and a decoupling coil set consisting of a series of decoupling coils was proposed and then used in the WPT system.

In a multi-Rx system, in addition to ensuring high efficiency of energy transmission, the controllability of power distribution is also very important in practical applications, which includes two aspects: the one is to selectively supply power to the target Rx; the other is that the power of the target Rx can be adjusted. Some researchers used the different frequencies to distinguish the Rxs [15, 16, 17], which makes the power distribution at the receiving Rx side selective. In [18], the author analysed the energy transmission direction of multiple coils on the same axis, of which each coil gets the same power by adjusting the distance between the coils. To control the load power of the Rx coil at a fixed distance, K. Ean et al. explored the power distribution method of using impedance inverter on the Rx side of single-Tx and multi-Rx system [19]. However, the parameters of impedance inverter were affected by other Rxs. Unlike most multi-Rx WPT systems [7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21], this study proposed WPT system that eliminates the energy multipath effect and distinguishes the multiple Rxs to realize one-to-one transmission energy in single-frequency, which helps to achieve selective target power distribution. The proposed system can be used in battery charging applications to increase system efficiency, because it can prevent the power supply to fully charged devices by selectively not transmitting power to the target receiver [16]. Also, impe-
dance inverter was used at the Rx side to adjust the load power, compared with [19] the parameters that were not affected by other Rx s. By adjusting the parameters of the impedance inverter, multiple loads can get the same power. Therefore, the system can also be applied to practical applications such as chain wireless sensor networks that need to supply the same power to multiple loads at different distances [18].

This paper is organized as follows. Section 2 proposes a series of new structure decoupling coil and schematic diagram of the proposed multi-Rx WPT system. Section 3 analyzes the power ratio of the multi-Rx system load and inserts an impedance inverter between the load and the Rx in the system proposed here, as a result, the desired load power can be achieved within a certain range. In Section 4, the analysis results are verified by experiments. Section 5 draws a brief conclusion.

2. Decoupling coils structure and WPT system model

![](image)

(a) Unipolar coil (b) Vertical bipolar coil (c) Horizontal bipolar coil
(d) Quadrupole coil (e) Vertical quadrupole coil (f) Octapole coil

Fig. 1. The decoupling coils set.

2.1 The proposed decoupling coils set

The unipolar coils and bipolar coils are show in Fig. 1(a), (b) and (c). The magnetic fields generated by the unipolar coil have the same direction. The bipolar coil can be seen as a reverse connection of two unipolar coils, therefore, the bipolar coil can generate two opposite magnetic fields, which are symmetric along the axis. In accordance with the design principle of the bipolar coil, more coils can be designed according to the principle, such as: quadrupole coil, vertical quadrupole coil, octapole coil and so on, the simplified model of the coils are show in Fig. 1(d)–(f) (double arrows indicate that two wires overlap). As same as the bipolar coil, these coils are symmetrical and connected in reverse. The coils in Fig. 1 can form a decoupling coils set.

2.2 Coupling analysis of the decoupling coils set

For coils in the decoupling coils set, since the coil is bilateral symmetry, and the magnetic fields generated on both sides are opposite in direction (except unipolar coil). Therefore, for any two different structure coils, when the coils are coaxial, the magnetic field generated by one coil flowing into the other coil equals to that flowing out. So, the total magnetic flux is zero, the coils are decoupled.

![Simulation model of the decoupling coils set](image)

Table 1. Simulation results of the coupling coefficient between the coils

|   | \(k_{ij}\) | \(L_1\) | \(L_2\) | \(L_3\) | \(L_4\) | \(L_5\) | \(L_6\) |
|---|---|---|---|---|---|---|---|
| \(L_1\) | 0.176 | 0.00023 | 0.00013 | 0.000002 | 0.000003 | 0.000001 |
| \(L_2\) | \(\backslash\) | 0.122 | 0.0002 | 0.0003 | 0.0027 | 0.000001 |
| \(L_3\) | \(\backslash\) | \(\backslash\) | 0.122 | 0.0016 | 0.000005 | 0.000006 |
| \(L_4\) | \(\backslash\) | \(\backslash\) | \(\backslash\) | 0.089 | 0.00002 | 0.0028 |
| \(L_5\) | \(\backslash\) | \(\backslash\) | \(\backslash\) | \(\backslash\) | 0.04 | 0.000002 |
| \(L_6\) | \(\backslash\) | \(\backslash\) | \(\backslash\) | \(\backslash\) | \(\backslash\) | 0.032 |

The decoupling coils set were simulated by the finite-element analysis (FEA) tool Maxwell3D. The size of the coil is “20 cm x 20 cm”, and the distance between the coils is 50 mm. When the coils are aligned, simulation model of the decoupling coils set is shown in Fig. 2. Simulation results of the coupling coefficient between the coils is shown in Table 1, in which \(k_{ij}\) represent the coupling coefficient between the \(L_i\) and \(L_j\). The coupling coefficient between any two different structure coils is less than 0.0028, in an actual WPT system, the coils are considered to be decoupled. When the distance changes, the coupling coefficient between the different structure coils is still small, this indicates that the coupling coefficient between the different coils is independent of the distance.

2.3 The proposed multi-Rx WPT system model

These decoupled coils in Fig. 1 can be used in Multi-Rx system as the Rx to eliminate the cross coupling between the Rxs. In order to simplify the analysis, this study takes a three-Rx WPT system as a representative example. Schematic diagram of the proposed multi-Rx WPT system is shown in the Fig. 3. For the proposed WPT system, the coils are only coupled with same coils. In order to transfer power to each Rx, The Tx coils should be the same as the Rx coils, therefore, the quadrupole coil (Fig. 1(d)) are employed as the transmitter \(L_{11}\) and receiver \(L_{21}\), vertical bipolar coil (Fig. 1(b)) are selected as transmitter \(L_{22}\) and receiver \(L_{22}\), unipolar coil (Fig. 1(a)) are choose as transmitter \(L_{31}\) and receiver \(L_{31}\), and all coils are in same size. The Tx coils \(L_{11}\), \(L_{22}\), and \(L_{31}\) are integrated on the same
plane, \( L_{r1} \) is tightly embedded inside the \( L_{q2} \), \( L_{q2} \) is tightly embedded inside the \( L_{r3} \). And the three Rx coils, namely \( L_{r1} \), \( L_{r2} \), and \( L_{r3} \) are at different distances from the Tx coils.

For the proposed system, in order to maintain the decoupling effect between the coils, the following conditions and usage restrictions should be met:

1) Multiple Rx coils should be aligned on the same axis as the Tx coils and face each other.

2) The plurality of Rx coils are air core coils.

When the above conditions are met, the Rx coils can be placed in front or back the Tx coil, and the distance between the Rx coil and the Tx coil should not be larger than the size of the coil to obtain a large coupling coefficient. The spacing between the Rx coils is free, and the position and order of the plurality of Rx coils are also free. And the number of Rx coils can be added or subtracted according to the actual application.

3. Theoretical analysis of system circuits

According to the section 2, when coils of different structures are decoupled, the WPT system proposed in this study can be considered as three independent single-Tx single-Rx systems. The WPT system circuit is show in Fig. 4. Three Tx parallel connections on one voltage source. Where \( V_s \) is the peak value of the AC voltage source, \( L_0 \) (\( L_{r1} \)) refers to the inductance parameter of Tx (Rxi), \( C_0 \) (\( C_{r1} \)) is the resonant capacitor, and \( R_0 \) (\( R_{r1} \)) is the impedance of the inductor, and \( R_{L1} \) is the load impedance, \( M_{di} \) is the mutual inductance between the Tx coil and the Rx coil, \( I_{r1} \) (\( I_{r2} \)) is the peak current of the Tx (Rx) coil.

To achieve a controllable load power of \( R_{x1} \), this system inserts the impedance inverter at the Rx. The Tx switch (S1, S2, S3) can be used to achieve selective target power distribution, and the Tx only supplies power to the corresponding Rx, which makes the design of multi-Rx systems more flexible and controllable. And the power can be supplied to multiple Rx coils at the same time.

The equivalent load impedance after adding the impedance inverter is shown in the Fig. 5. The parameters of the three Rx impedance inverters are different. To simplify the calculation, \( L_{r1} \), \( C_{r1} \) (i = 1, 2, 3) was used to represent the parameters of the impedance inverter at Rx. According to \([19, 20, 21]\), impedance inverter can be implemented with one inductor and two capacitors, and \( K_{r1} \) is the characteristic impedance of the inverter, where \( K_{r1} = \omega L_{r1} = 1/(\omega C_{r1}) \) (i = 1, 2, 3). The equivalent impedance \( R_{L1} \) can be expressed as

\[
R_{L1} = \frac{U_1}{I_1} = \frac{K_{r1}^2}{R_{r1}} \tag{1}
\]

Thus, we can use the equivalent impedance \( R_{L1} \) to calculate the load power. The system is resonant, it yields \( \omega = 2\pi f = 1/\sqrt{L_0C_0} = 1/\sqrt{L_{r1}C_{r1}} \) (i = 1, 2, 3). According to Kirchhoff’s laws, the loop current of Rx1 can be calculated as

\[
I_{r1} = \frac{j\omega M_{r1} V_s}{R_0 (R_{r1} + R_{L1}) + \omega^2 M_{r1}^2} \tag{2}
\]

Load power can be calculated based on load current \( I_{r1} \), and coil resistance and source resistance are generally small. So, the load power is approximately expressed as

\[
P_{RL1} = P_{RL} = \frac{1}{2} \times |V_s|^2 \times R_{L1} \approx \frac{V_s^2 R_{L1}}{2\omega^2 M_{r1}^2} = \frac{V_s^2 K_{r1}^2}{2\omega^2 M_{r1}^2 R_{L1}} \tag{3}
\]

The power division ratio between the Rx1, Rx2, Rx3 is

\[
P_{RL1}:P_{RL2}:P_{RL3} = K_{r1}^2 : M_{r1}^2 R_{L1} : M_{r1}^2 R_{L2} : M_{r1}^2 R_{L3} \tag{4}
\]

Total transmission efficiency can be expressed as

\[
\eta = \frac{\sum_{i=1}^{3} P_{RLi}}{\sum_{i=1}^{3} \text{Re}(V_s I_{r1})} \tag{5}
\]

As suggested from Eq. (1) and Eq. (3), the load power can be changed by adjusting the parameters of the impedance inverter, and the impedance inverter has little energy loss.
4. Simulation and experiment

To verify that the proposed theory (section 2 and section 3), three sets of coils were made in accordance with the principle of Fig. 1. Litz wire was used to construct the coils. All coils are 10 turns, and “20 cm x 20 cm” in size, as shown in Fig. 6. The Tx coils $L_{1T}$, $L_{2T}$, and $L_{3T}$ are integrated on the same plane as shown in Fig. 6(d). The experimental prototype parameters are shown in the Table II. An experimental device of the propose multi-Rx WPT system is built, as shown in Fig. 7. Full-bridge inverter was connected to DC voltage source. At frequencies under a few hundred kHz it is easier to manufacture inverters, so, the operating frequency was set to 85 kHz. The input power can be calculated by the DC source’s voltage and current, and the probe of the oscilloscope was connected to the $R_{Li}$ to measure the voltage and then calculate the load power. Three switches were inserted between the full bridge inverter and the three Tx coils to selectively control the power of the Rx side from the Tx side. Switches can be also controlled by microcontrollers to meet different requirements.

![Fig. 6. Experimental prototype of coils](image)

A 1 W LED bulb was used to visually represent the selective target power distribution, as shown in Fig. 8. When the switch is closed, the corresponding Rx’s bulb is on. And the Rx’s bulbs can be illuminated at the same time. This shows that the power can be easily transmitted to a specific receiver through the WPT system proposed in this study.

In order to verify that the proposed system can adjust the load power through the impedance inverter, we let the power division ratio is given as $P_{RL1}:P_{RL2}:P_{RL3} = 1:1:1$, in the Rx side load impedance $R_{Li}$ ($i = 1, 2, 3$) is 10 Ω. The parameters of the impedance inverter are calculated by Eq. (1) and Eq. (3) and listed in the Table IV.

![Fig. 7. A prototype of the WPT system](image)

![Fig. 8. Selective target load power distribution](image)

A 1 W LED bulb was used to visually represent the selective target power distribution, as shown in Fig. 8. When the switch is closed, the corresponding Rx’s bulb is on. And the Rx’s bulbs can be illuminated at the same time. This shows that the power can be easily transmitted to a specific receiver through the WPT system proposed in this study.

In order to verify that the proposed system can adjust the load power through the impedance inverter, we let the power division ratio is given as $P_{RL1}:P_{RL2}:P_{RL3} = 1:1:1$, in the Rx side load impedance $R_{Li}$ ($i = 1, 2, 3$) is 10 Ω. The parameters of the impedance inverter are calculated by Eq. (1) and Eq. (3) and listed in the Table IV.

![Fig. 9(a)–(c) show the load power of the different distance RxS, and frequency splitting occurs as an impedance inverter is added to the Rx side [21]. For most electrical equipment, it is necessary to get the appropriate power rather than maximum power. When the resonant frequency is at 85 kHz, the load powers $P_{RL1}$, $P_{RL2}$, and $P_{RL3}$ is 1.01 W, 1.05 W and 0.98 W respectively. This shows that the load of different distances successfully obtained the same power through the impedance inverter.](image)
As shown in the Fig. 10, at operating frequency, the transmission efficiencies of Rx1, Rx2 and Rx3 are 88.1%, 82.9% and 79.8% respectively, and the total efficiency is 83.7%. Thus, although the power of the load at different distances can be regulated by the impedance inverter, with the increases of the distance, the mutual inductance and coupling coefficient decrease and the efficiency also decreases.

**5. Conclusion**

To eliminate cross-coupling between multiple Rxs, and selective supply power to multiple independent loads, this study proposed the use of decoupling coils in multiple Rxs WPT system. This method can eliminate the energy multi-path effect and achieve one-to-one transmission energy of multiple Rxs. Also, a series of new structures of decoupling coils was proposed. In the WPT system, an impedance inverter was inserted between the Rx and the load to regulate the load power at different distances. Finally, experiments showed that the method can eliminate the cross-coupling at multiple Rxs WPT system and achieve the adjustable power allocation.

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**References**

[1] N. Shinohara: “Current research and development status of wireless power transfer,” J. IEICE 99 (2016) 143.

[2] H. Sekiya: “Wireless power transfer system and its trends,” J. IEICE 101 (2018) 382.

[3] H. Abe, et al.: “A noncontact charger using a resonant converter with parallel capacitor of the secondary coil,” IEEE Trans. Ind. Appl. 36 (2000) 444 (DOI: 10.1109/28.833760).

[4] S. Li and C. C. Mi: “Wireless power transfer for electric vehicle applications,” IEEE J. Emerg. Sel. Topics Power Electron. 3 (2015) 4 (DOI: 10.1109/JESTPE.2014.2319453).

[5] A. Zaheer, et al.: “A dynamic EV charging system for slow moving traffic applications,” IEEE Trans. Transport. Electrific. 3 (2016) 354 (DOI: 10.1109/TTE.2016.2628796).

[6] S. Y. R. Hui, et al.: “A critical review of recent progress in mid-range wireless power transfer,” IEEE Trans. Power Electron. 29 (2014) 4500 (DOI: 10.1109/TPEL.2013.2249670).

[7] J. Kim, et al.: “Analysis of capacitive impedance matching networks for simultaneous wireless power transfer to multiple devices,” IEEE Trans. Ind. Electron. 62 (2015) 2807 (DOI: 10.1109/TIE.2014.2365751).

[8] J. J. Casanova, et al.: “A loosely coupled planar wireless power system for multiple receivers,” IEEE Trans. Ind. Electron. 56 (2009) 3060 (DOI: 10.1109/TIE.2009.2023633).

[9] X. Liu, et al.: “Efficient circuit modelling of wireless power transfer to multiple devices,” IET Power Electron. 7 (2014) 3017 (DOI: 10.1049/iet-pel.2013.0969).

[10] M. Fu, et al.: “Efficiency and optimal loads analysis for multiple-receiver wireless power transfer systems,” IEEE Trans. Microw. Theory Techn. 63 (2015) 801 (DOI: 10.1109/JSTDR.2015.2398422).

[11] D. Ahn and S. Hong: “Effect of coupling between multiple transmitters or multiple receivers on wireless power transfer,” IEEE Trans. Ind. Electron. 60 (2013) 2602 (DOI: 10.1109/TIE.2012.2196902).

[12] J. Kim, et al.: “Impedance matching considering cross coupling for wireless power transfer to multiple receivers,” 2013 IEEE Wireless Power Transfer (WPT) (2013) 226 (DOI: 10.1109/WPT.2013.6556924).

[13] C. K. Lee, et al.: “Effects of magnetic coupling of nonadjacent resonators on wireless domino-resonator systems,” IEEE Trans. Power Electron. 27 (2012) 1905 (DOI: 10.1109/TPEL.2011.2169460).

[14] M. Fu, et al.: “Compensation of cross coupling in multiple-receiver wireless power transfer systems,” IEEE Trans. Ind. Informat. 12 (2016) 474 (DOI: 10.1109/TI.2016.2516906).

[15] F. Liu, et al.: “Eliminating cross interference between multiple
receivers to achieve targeted power distribution for a multi-frequency multi-load MCR WPT system,” IET Power Electron. 11 (2018) 1321 (DOI: 10.1049/iet-pel.2017.0770).

[16] Y. Kim, et al.: “Selective wireless power transfer for smart power distribution in a miniature-sized multiple-receiver system,” IEEE Trans. Ind. Electron. 63 (2016) 1853 (DOI: 10.1109/TIE.2015.2493142).

[17] Y. Zhang, et al.: “Selective wireless power transfer to multiple loads using receivers of different resonant frequencies,” IEEE Trans. Power Electron. 30 (2015) 6001 (DOI: 10.1109/TPEL.2014.2347966).

[18] Y. Zhang, et al.: “Wireless power transfer to multiple loads over various distances using relay resonators,” IEEE Microw. Compon. Lett. 25 (2015) 337 (DOI: 10.1109/LMWC.2015.2409776).

[19] K. E. Koh, et al.: “Impedance matching and power division using impedance inverter for wireless power transfer via magnetic resonant coupling,” IEEE Trans. Ind. Appl. 50 (2014) 2061 (DOI: 10.1109/TIA.2013.2287310).

[20] J. Kuang, et al.: “Load-isolation wireless power transfer with K-inverter for multiple-receiver applications,” IEEE Access 6 (2018) 31996 (DOI: 10.1109/ACCESS.2018.2824334).

[21] J. Zhou, et al.: “Extendible load-isolation wireless charging platform for multiple-receiver applications,” IET Power Electron. 10 (2017) 134 (DOI: 10.1049/iet-pel.2016.0432).

[22] W. Chen, et al.: “Decoupling design of multi-coil wireless power transfer system with metal insulator,” 2017 IEEE PELS Workshop on Emerging Technologies: Wireless Power Transfer (WoW) (2017) 30 (DOI: 10.1109/WoW.2017.7959360).

[23] B. J. Varghese, et al.: “Design and optimization of decoupled concentric and coplanar coils for WPT systems,” 2017 IEEE Wireless Power Transfer Conference (WPTC) (2017) 1 (DOI: 10.1109/WPTC.2017.7953838).

[24] Z. Dai, et al.: “Selective omnidirectional magnetic resonant coupling wireless power transfer with multiple-receiver system,” IEEE Access 6 (2018) 19287 (DOI: 10.1109/ACCESS.2018.2809797).

[25] C. Zhang, et al.: “Basic control principles of omnidirectional wireless power transfer,” IEEE Trans. Power Electron. 31 (2016) 5215 (DOI: 10.1109/TPEL.2015.2479246).

[26] S. Y. Choi, et al.: “Generalized models on self-decoupled dual pick-up coils for large lateral tolerance,” IEEE Trans. Power Electron. 30 (2015) 6434 (DOI: 10.1109/TPEL.2015.2399938).

[27] S. Kim, et al.: “Analysis of mutually decoupled primary coils for IPT systems for EV charging,” 2016 IEEE Energy Conversion Congress and Exposition (ECCE) (2016) 1 (DOI: 10.1109/ECCE.2016.7854877).

[28] J. Deng, et al.: “Compact and efficient bipolar coupler for wireless power chargers: Design and analysis,” IEEE Trans. Power Electron. 30 (2015) 6130 (DOI: 10.1109/TPEL.2015.2417115).

[29] Y. Li, et al.: “Compact double-sided decoupled coils-based WPT systems for high-power applications: Analysis, design, and experimental verification,” IEEE Trans. Transport. Electrific. 4 (2018) 64 (DOI: 10.1109/TTE.2017.2745681).

[30] T. Kan, et al.: “A new integration method for an electric vehicle wireless charging system using LCC compensation topology: Analysis and design,” IEEE Trans. Power Electron. 32 (2017) 1638 (DOI: 10.1109/TPEL.2016.2552060).

[31] Y. Li, et al.: “A new-variable-coil-structure-based IPT system with load-independent constant output current or voltage for charging electric bicycles,” IEEE Trans. Power Electron. 33 (2018) 8226 (DOI: 10.1109/TPEL.2018.2812716).