Multiple-Receiver Wireless Power Transfer with Efficient Power Control Strategy

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***Abstract*—Because the target power levels and impedance matching conditions are mostly not satisfied, it is difficult for Multiple-receiver wireless power transfer system (MRWPT) systems to provide target power and maximal efficiency simultaneously. Therefore, a power control strategy is developed in MRWPT system to balance supporting multiple target power levels and operating under high efficiency. As an example, a 100-kHz two-receiver wireless power transfer (WPT) system and establishes a control strategy for enabling the system to achieve target output power levels with high efficiency; At last, the proposed MRWPT system is proved to obtain an efficiency of more than 89.1% and provide the target output power.**

Keywords—power control; multiple receivers; impedance matching

I. Introduction (*Heading 1*)

Wireless power transfer (WPT) technology has attracted great attention for its safety and convenience in charging electrical devices and electronic products. The rapid economic development results in an increase demands for embedding multiple electrical devices in a WPT system simultaneously. However, devices embedded into a WPT system mostly with utterly different charging characteristics and power levels. Study on high efficiency control strategy and power control For multiple receiver WPT system should be further conducted.

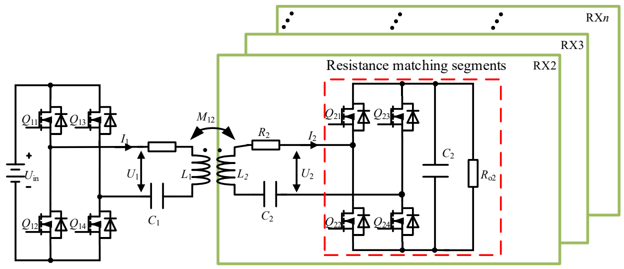
In WPT system, load resistances method [1] is introduced to achieve maximum system efficiency. However, it was difficult to balance the power control and high efficiency operating. Different topologies and control method is adopted in WPT system to improve system efficiency. Buck circuit [2] is introduced to MRWPT system for obtaining the optimal loads. The obtained maximum efficiency is 80% at 13.56 MHz and this method fails to regulate the output power because the optimal loads conditions have to be satisfied. Dual active bridges [3-4] is adopted to replace the uncontrolled rectifier. With this topology, system can manipulate the conduction angle of receiver coils and control the equivalent resistances. An efficiency of 85.4% is obtained in [3]. A buck-boost circuit[5] is introduced to the receiver coils to manipulate the load resistance, and reach a maximum efficiency of 78 %. A study [6] is proposed to ensure there is sufficient current in the transmit coil to make the receive coils able to deliver power, ensure that the total transfer power of the transmit coil was more than the summed transfer powers of the receive coils operating under rated load to avoid bifurcation. And in [7], a highly efficiency power control method is introduced to MRWPT system to control output power and provide high efficiency. However, the method is limited to two-receiver WPT system. In this study, power control method is extended to multiple-receiver WPT system and provide high efficiency.

The organization of this paper is arranged as follows: Section II analyzes the math model and equivalent circuit of MRWPT system, and analyzes the impedance matching method. Section III develops a power control strategy for MRWPT system to regulate output power, operate under high efficiency. Simulation and experiment results are presented in Section IV. Finally, the conclusion is shown in Section V.

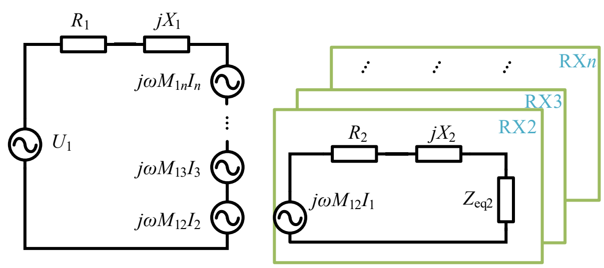
II. Design Principoles

A. Circuit Modeling of WRWPT system

The schematic and equivalent circuits of the proposed multiple-receiver WPT system are shown in Fig.1. The mutual coupling between receiver coils are neglected in this study because the receivers are placed so far apart. In Fig.1a, coil 1 is the transmitter coil and RX*i* (i = 2, 3, …, n) are the receiver coils. The solid and dotted arrows denote mutual inductances between coils, and the red dotted box denotes the impedance matching segments. R_i, L_i, and C_i (i = 1, 2, …, n) denote the resistance, inductance, and compensation capacitance of the coils, respectively. The equivalent circuit of the multiple-receiver WPT system are displayed in Fig.1b. Z_{eqi} (i = 2, 3, …, n) represent the equivalent impedance of the impedance matching segment.



(a)



(b)

Fig. 1. Schematic and equivalent circuits of MRWPT system: (**a**) schematic circuit of WRWPT system; (**b**) equivalent circuit of WRWPT system.

According to the Kirchhoff Voltage Laws (KVLs), the equivalent mathematical model of the MRWPT system is achieved as:

$$\begin{bmatrix} R_1 + j\omega L_1 + \frac{1}{jwC_1} & -j\omega M_{12} & \cdots & -j\omega M_{1n} \\ -j\omega M_{12} & R_2 + j\omega L_2 + \frac{1}{j\omega C_2} + Z_{eq2} & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots \\ -j\omega M_{1n} & 0 & \cdots & R_n + j\omega L_n + \frac{1}{j\omega C_n} + Z_{eqn} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ \cdots \\ I_n \end{bmatrix} = \begin{bmatrix} U_1 \\ 0 \\ \cdots \\ 0 \end{bmatrix} \quad (1)$$

The RMS value of the fundamental component U_1 is derived in (2):

$$U_1 = \frac{2\sqrt{2}}{\pi} U_{in} \sin\beta_1 \times e^{j\phi_1} \quad (2)$$

The RMS value of the fundamental component U_1 is derived in (3):

$$U_i = \frac{2\sqrt{2}}{\pi} U_{oi} \sin\beta_i \times e^{j\phi_i} \text{ , } (i = 2, 3, \ldots, n) \quad (3)$$

where U_i indicates the voltage of active bridge, $2\beta_i$ indicates the conduction angle of the active bridges, and ϕ_i indicates the phases of the fundamental component of the square waves.

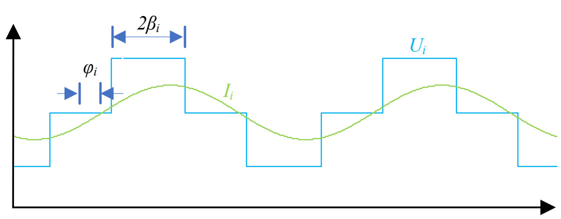


Fig. 2. Square-wave voltage and resonant current waveform in MRWPT system

To simplify the system, system operates under resonant frequency (3), and thus the imaginary part of Z_{eqi} are fully compensated, that is $Z_{eqi} = R_{eqi}$.

$$j\omega L_i + \frac{1}{j\omega C_i} = 0 \text{ , } (i = 1, 2, \ldots, n) \quad (4)$$

The efficiency of system is defined as :

$$\eta = \frac{\sum_{i=1}^{n}\left(\left|I_i\right|^2 R_{eqi}\right)}{\mathrm{Re}\left[U_1 I_1\right]} \text{ , } (i = 2, \ldots, n) \quad (5)$$

Based on the derivation in (5), U_{in}, L_1, C_1, β_1 are not related to the system efficiency, which means that U_{in} and β_1 can be controlled for output voltage regulation while not affecting system efficiency. Besides, efficiency η is related to operating frequency. coil parameters, mutual inductances and equivalent matching resistances R_{eqi}. However, it is impractical to control the mutual inductances and coils parameters to manipulate the power of each receiver coils when system is operating. Therefore, instead of mutual inductances, the equivalent impedance should be controlled to improve system efficiency.

B. Impedance Matching Control Method

To derive a maximum η, the optimal matching impedance R_{eqi} can be calculated by taking the first-order partial derivative of η, and then the optimal matching impedance R_{eqi} can be derived [8]:

$$R_{eqi,\,OPT} = R_i \sqrt{1 + \frac{1}{R_1} \sum_{i=2}^{n} \left(\frac{\omega^2 M_{1i}^{\ 2}}{R_i}\right)} \quad (6)$$

According to Fig.1b, the output power $P_{i,\ OPT}$ can be derived as follows:

$$P_{i,\,OPT} = \frac{U_1^{\ 2}}{\left[\left(R_1 + \sum_{i=2}^{n} \frac{\omega^2 M_{1i}^{\ 2}}{R_i + R_{eqi}}\right)^2\right]^2} \frac{\omega^2 M_{1i}^{\ 2}}{R_i + Z_{eqi}} \frac{R_{eqi}}{R_i + R_{eqi}} \quad (7)$$

Based on the strict resistance matching conditions displayed in (6), the output power of the multiple receivers may not satisfy the target output power because the mutual inductance M_{1i} and coils parameters hardly satisfy system design. In previous studies, the efficiency is controlled by active bridges at the receivers, which is difficult to provide both high efficiency and power control simultaneously. The following section further discusses the control strategy used for balancing the efficiency and target output power of the system.

III. Power Control Method

In this study, a control strategy is proposed that the active bridge at the transmitter coils control the efficiency and the active bridges at the receiver coils control the transfer power.

In previous study, the resistance matching segments are set as the best matching resistance to provide maximum efficiency. However, under such best matching resistance condition, the system seldom satisfies the power requirements of each receiver coils. For this problem, U_1 is regulated to obtain high system efficiency and the receiver coils are controlled to achieve the target output power.

In the proposed system, the receiver coils control the target output power and the transmitter coil ensures optimal system efficiency. Because the equivalent resistances must be controlled to produce the target power, the impedance matching segment cannot be set randomly. To solve this problem, U_1 can be regulated to achieve high system efficiency and the receiver coils can be controlled to reach the target output power.

For most cases, it is difficult to derive the exact R_{eqi} for providing different target power levels. Therefore, this study simplify the MRWPT system and derive the approximate R_{eqi} to provide target power levels. In general, for coils, the equivalent resistance R_{eqi} $(i = 2, 3, ..., n)$ is considerably higher than the parasitic resistance R_i $(i = 2, 3, ..., n)$. For simplicity, (7) can be simplified as follows:

$$P_{i,\,SIMP} = \frac{U_1^{\,2}}{\left(R_1 + \sum_{i=2}^{n} \frac{\omega^2 M_{1i}^{\,2}}{R_{i2} + R_{eqi}}\right)^2} \frac{\omega^2 M_{1i}^{\,2}}{R_i + R_{eqi}} \tag{8}$$

By solving (1)(8), the equivalent resistance under power control condition can be replaced by P_i and U_1 as follow:

$$R_{eqi,\,SIMP} = \frac{2\omega^2 M_{1i}^{\,2} S_n^{\,2}}{P_i(U_1^{\,2} - 2R_1 S_n + U_1\sqrt{U_1^{\,2} - 4R_1 S_n})} - R_i \tag{9}$$

where $S_n = P_2 + P_3 + ... + P_n$.

From the (5) (9), the equivalent resistance $R_{eqi,\,SIMP}$ is a function of P_i, the efficiency η becomes a function of U_1 and P_i, where P_i are the design output powers. According to (10), P_i are constants which depend on system requirement and the efficiency η becomes a function of U_1:

$$\eta=\eta\left(U_1, R_{eqi,\,SIMP}\left(P_i, U_1\right)\right) \tag{10}$$

Substituting (8) into (5) yields the approximate efficiency η_{SIMP} (11), By solving $\frac{\partial \eta_{SIMP}}{\partial U_1} = 0$, when the U_1 satisfies (12), the system derives the optimal efficiency.

$$\eta_{SIMP} = \frac{\omega^2 \sum_{i=2}^{n} \frac{M_{1i}^{\,2} Z_{eqi}}{\left(R_i + Z_{eqi}\right)^2}}{R_1 + \sum_{i=2}^{n} \frac{\omega^2 M_{1i}^{\,2}}{R_i + Z_{eqi}}} \tag{11}$$

$$U_1 = \sqrt{R_1 S_n + \frac{A R_1^{\,2}}{S_n \omega^2} + \frac{\sqrt{A R_1\left(A R_1 + S_n^{\,2}\omega^2\right)^3}}{A S_n \omega^2}} \tag{12}$$

where $A = \sum_{i=2}^{n} \frac{P_i^2 R_i}{M_{1i}^{\,2}}$.

As reported by a previous study [9], the imaginary component of the impedance matching segment should be zero due to the resonance condition presented in (4), and the equivalent impedance of the impedance matching segment can be expressed as follows:

$$R_{eqi} = \mathrm{Re}\left[\frac{8R_{oi}\sin^2\beta_i}{\pi^2} + j\frac{8R_{oi}\cos\varphi_i\sin^2\beta_i\sin\varphi_i}{\pi^2}\right] \tag{13}$$

Fig.3 shows the control strategy of MRWPT system. TX indicates the transmitter coil and RXi indicates the receiver coils. To achieve highly efficient design output power, β_1 and φ_1 are tuned to achieve optimal U_1 according to (2) and (12); β_i, φ_i $(i = 2, 3, …, n)$ control the receiver coils to regulate the target transfer power according to (9) and (13).

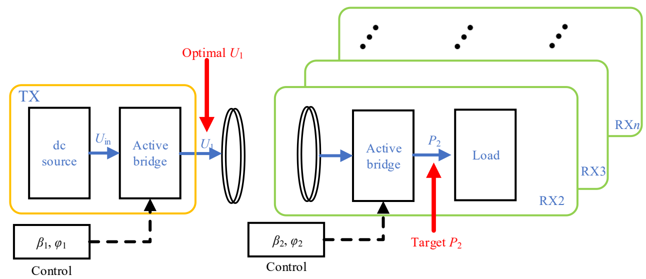


Fig. 3. MRWPT system configuration

IV. RESULT

To prove the validity of proposed WRWPT system, the mathematical model is derived using MATLAB and simulated using the MATLAB/Simulink platform. An experimental prototype is also constructed.

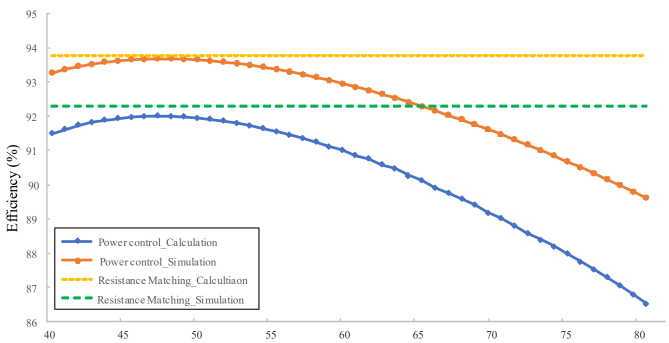
Firstly, a single-transmitter four-receiver WPT system is calculated and simulated to verify the practicability of proposed control strategy. System parameters are presented in Table 1.

TABLE I. KEY PARAMETERS OF FOUR-RECEIVER SYSTEM

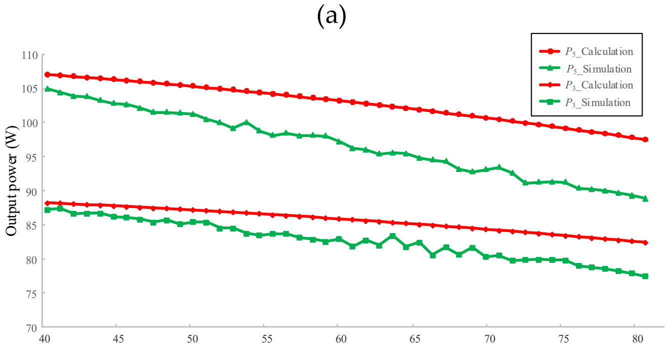
Symbol	*Quantity*	*Value*
L_1, L_2, L_3, L_4, L_5	Inductances of coils	22 μH
C_1, C_2, C_3, C_4, C_5	Compensation capacitor	115 nF
R_1, R_2, R_3, R_4, R_5	Parasitic resistances	12 mΩ, 11 mΩ, 12mΩ, 12 mΩ, 11 mΩ,
f	Operating frequency	100 kHz
$M_{12}, M_{13}, M_{14}, M_{15}$	Mutual inductance	5μH
$\varphi_1, \varphi_2, \varphi_3, \varphi_4, \varphi_5$	Phase	0
U_{in}	Input voltage	30 V

Symbol	*Quantity*	*Value*
P_2, P_3, P_4, P_5	Target power	80 W, 90 W, 100 W, 110W

R_i and P_i in receiver coils are set different values to ensure each receiver coil parameters are different. Proposed control strategy is compared to the resistance matching control strategy in Fig.4. Fig.4a displays the efficiencies of two control strategies. When $U_1 = 47$ V, maximum achieved efficiency of proposed power control strategy is 92.0%, which is extremely close to the efficiency (92.3%) of resistance matching control strategy. Fig.4b and Fig.4c displays the output powers of each receiver. Under optimal U_1 condition, output powers are $P_1 = 76.2$ W, $P_2 = 85.4$ W, $P_3 = 94.3$ W, $P_4 = 101.5$ W, which are close to the target powers 80, 90, 100 and 110 W respectively. It means that the using proposed power control strategy system achieves power control and operates with high efficiency



(a)



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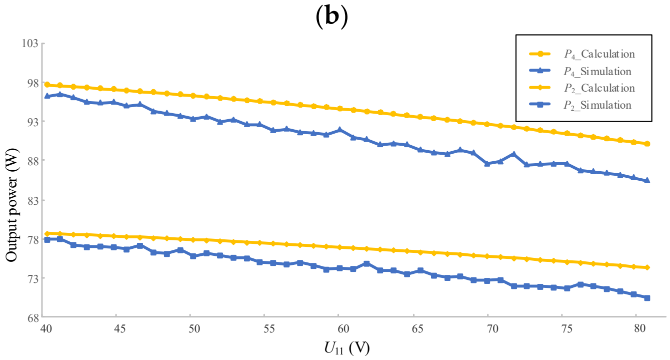


(c)

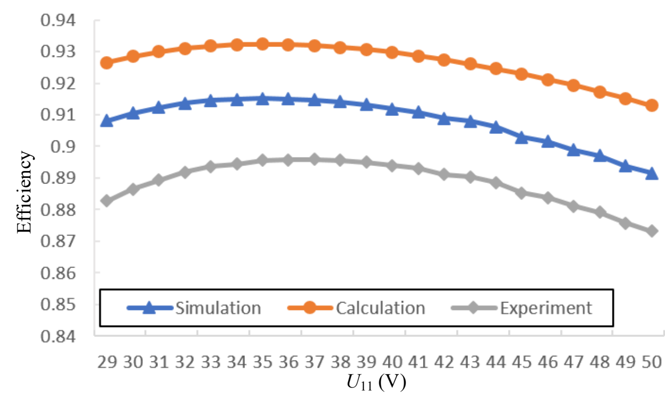
Fig. 4. Calculation results of four-receiver WPT system: (**a**) efficiency comparition of proposed control strategy and resistance matching strategy; (**b**) calculation and simulation result of output powre P_3 and P_5; (c) calculation and simulation result of output powre P_2 and P_4

TABLE II. KEY PARAMETERS OF TWO-RECEIVER SYSTEM

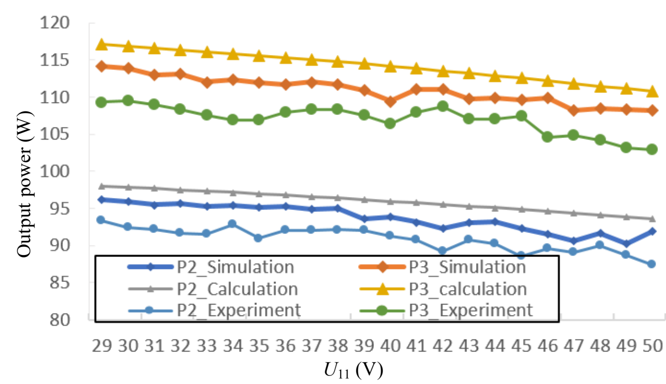
Symbol	*Quantity*	*Value*
L_1, L_2, L_3	inductances of coils	22.78 µH, 22.54 µH, 22.87µH
C_1, C_2, C_3	compensation capacitor	110 nF
R_1, R_2, R_3,	parasitic resistances	12.25 mΩ, 12.78 mΩ, 12.79 mΩ
f	operating frequency	100 kHz
M_1, M_2, M_3	mutual inductance	5µH
φ_1, φ_2, φ_3	Phase	0
P_2, P_3	Target power	70 W, 100 W,

Secondly, a two-transmitter two-receiver WPT system is experimented to further examine the practicability of proposed control strategy. The system parameters are shown in Table 2.

Fig.5a displays the observed efficiencies among the mathematical model, simulation model, and experiments. For each model, the efficiencies show analogous trends at the various output powers. Maximum efficiencies are achieved when U_1 is 31.4, 31.4 and 35.1 V respectively, and the efficiency levels of the mathematical model, simulation model, experimental prototype are 93.3%, 91.5%, and 89.1%. As illustrated in Fig.5b, output power levels of the simulation model and experimental prototype are extremely correlated with the design target power levels 70 W and 100 W. It means the proposed strategy could provide target power with high efficiency.



(a)



(b)

Fig. 5. Result comparation: (**a**) efficiency levels of mathematical model, simulation model, and experimental prototype; (**b**) output powers of mathematical model, simulation model and experimental prototype.

V. CONCLUTION

This paper proposes a power control strategy for a MRWPT system that enables the system to provide efficient target output power. In MRWPT systems, solving (7) and (11) to derive the analytic solution of R_{eqi} is difficult tasks. This research propose a solution by simplifying the mathematical model and deriving an approximate analytic solution of R_{eqi} in the form of P_i. A four-receiver WPT system is simulated and a two-receiver WPT system is experimented. Consequently, the two-receiver WPT system has a simulated efficiency of 91.5% and an experimental efficiency of 89.1% at a frequency of 100 kHz, as well as achieving target power levels of 70 and 100 W.

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