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Time-Sharing Control Strategy for Multiple-Receiver Wireless Power Transfer Systems

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Received: 31 December 2019; Accepted: 24 January 2020; Published: 29 January 2020

Abstract: The cross-coupling effect between the induction coils of a multiple-receiver wireless power transfer (MRWPT) system severely weakens its overall performance. In this paper, a time-sharing control strategy for MRWPT systems is proposed to reduce the cross-coupling between receiver coils. An active-bridge rectifier is introduced to the receivers to replace the uncontrollable rectifier to achieve synchronization of the time-sharing control. The synchronization signal generated by an active-bridge rectifier can be directly used to realize the synchronization of time-sharing control and hence saved the traditional zero-crossing point detection circuits for time-sharing circuits. Moreover, the proposed time-sharing system has the advantages of both operating under a resistance-matching condition and providing target output voltage for each receiver. Furthermore, a voltage control strategy was developed to provide both high efficiency and a target output voltage for each receiver. Finally, the simulation and experimental results show that the time-sharing MRWPT system reduced the cross-coupling effect between the receiver coils, and the voltage control strategy provided both a high efficiency and a target output voltage for each receiver.

Keywords: wireless power transfer; multiple receiver; cross-coupling

1. Introduction

Wireless power transfer (WPT) is a promising technology that eliminates the need for transmission cables leading to electrical devices and makes power transfer more convenient. WPT technology has recently attracted increased attention in industry and academia where it has been widely applied to areas like underwater systems [1,2], biomedical implants [3–6], mining devices [7,8], smart robots [9], and electronic equipment [7]. With the increasing demands for embedding multiple electrical devices in a WPT system, the technologies in a multiple-receiver wireless power transfer (MRWPT) system are becoming advanced. Multiple types of equipment embedded into a WPT system mostly operates with different loading characters and different output voltages. Further research may be conducted to simultaneously achieve both high efficiency and target output voltages. Furthermore, the cross-coupling between the receiver coils severely weakens the system's efficiency and decreases the output voltages when the receiver coils are in proximity. More research is needed to improve the compensation for the cross-coupling effect between receivers.

Some studies have focused on improving the system efficiency and providing voltage control on MRWPT systems, as discussed in References [10–15]. A MRWPT system [10] is proposed for portable devices with simplified receiver design. In Cannon et al. [11], multiple receiver systems with resonant coupling are constructed with a low complexity circuit and a resonant frequency splitting effect is

observed in MRWPT systems. To increase the system's efficiency, impedance matching theory [12] is analyzed within an MRWPT system. Moreover, metamaterials are introduced to the MRWPT system to improve the system's efficiency, and as a result, the efficiency is improved by approximately 20% [13]. To provide a high efficiency and a transfer target output power in a two-receiver WPT system, a control method based on a simplified math model was developed to meet the demands of different load characteristic [14]. To meet the constant output voltage commands, a load-independent voltage method was analyzed in Sun et al. [15].

WPT systems achieve maximum power transfer efficiency when the load resistances comply with the impedance matching methods [12]. To increase the system's efficiency, multiple topologies and control strategies have been proposed for WPT systems. The optimal impedances for the MRWPT systems have been investigated and buck circuits are employed in receivers to manipulate the equivalent load resistances [16]. The system achieves an efficiency of 80% at the frequency 13.56 MHz. However, the output voltage cannot be controlled because the buck circuit must meet the optimal load demand. To manipulate the load resistance for the impedance matching method, a buck-boost topology [17] is introduced to the rectifier for optimizing the load resistances. The system achieves maximum efficiency of 78% when transferring 16 W of power. An amplitude control strategy with a phase-shifting method [18] is introduced to control the equivalent load resistance for impedance matching. The maximum efficiency is about 36% with a factor $k = 0.6$ and can reach 83% with a factor $k = 0.3$. A buck converter [19] is introduced to the transmitter to regulate the input power and a boost converter is constructed at the receiver to manipulate the load resistance. The system transfers 100 W with an efficiency of about 79%. Dual-active bridge circuits [20,21] are introduced to the WPT systems to displace the uncontrolled rectifier. Compared to the uncontrolled rectifier, a dual-active bridge has a smaller conduction resistance and can manipulate the load resistance. The system achieved an improved efficiency of 85.4% in Li et al. [20], while Liu et al. [21] achieved an efficiency of 80.4%. However, the performances of these circuits are weakened by cross-coupling between coils; when these circuits are applied to MRWPT systems, the circuits should be improved to reduce the cross-coupling effect.

The cross-coupling effect between multiple receivers in MRWPT systems is surveyed in Ahn and Hong [22]. This study indicates that the resonant frequency varies for the cross-coupling effect and the compensation networks need to be readjusted correspondingly. To reduce and eliminate the cross-coupling effect, various approaches are proposed. Coupling effects are considered during an impedance matching procedure in Kim et al. [23] to improve the system efficiency. The design of the source coil and optimal load impedance are achieved based on circuit analysis. Some studies have reduced the cross-coupling effect by compensating the cross-coupling with resonance capacitors. The cross-coupling effect in the two-receiver WPT systems are analyzed and compensated to achieve a higher system efficiency [24]. Furthermore, the cross-coupling effect compensations are extended to the multiple-receiver WPT systems to reduce the cross-coupling influence on multiple receivers in Fu et al. [25]. However, the compensation methods regarding cross-coupling are based on a fixed cross-coupling value and fail to be effective for the MRWPT systems where the distances between coils are constantly changing. Further studies on cancelling the constantly changing cross-coupling effect should be investigated to improve MRWPT system efficiencies.

Other methods to cancel the cross-coupling effect are proposed for each receiver to operate on different frequencies or set each receiver to turn on in different time sequences. Due to the different resonant frequencies of each receiver, the transmitter is manipulated to transfer the specified resonant frequency to activate specified receiver in Jiang et al. [26]. Three different resonant frequencies, namely 60 kHz, 100 kHz, and 140 kHz, are chosen to deliver power to three DC motors with an efficiency of about 60%. Moreover, the cross-coupling effect between coils is isolated by separating the resonant frequencies in Kim et al. [27] and the separated resonant frequencies are achieved using a special compensation network. The system has an efficiency of 24%–29% at the resonant frequencies of 20 MHz, 22.5 MHz, and 25 MHz. A dual-frequency mode for 3-D stacked multiple receivers is developed

in Yanagawa et al. [28] to increase the system efficiency. The dual-frequency mode is formulated using an optimization methodology involving tuning capacitor values to achieve an efficiency of 58.7% at 6.78 MHz and 13.56 MHz. Moreover, an uncontrollable rectifier bridge is introduced to the MRWPT system to manipulate the time-division of each receiver in Yin et al. [29] and time-sharing WPT systems are developed in Jiang et al. [30] to eliminate the cross-coupling effect in DC motor drives. By introducing a time-sharing method in manipulating the compensation capacitors at the transmitter, the transmitter transfers a specific frequency in different time intervals to activate a specific receiver. Another method used to cancel cross-coupling effect is proposed in Juliet et al. [31] by compensating cross-coupling with an additional relay coil and independent resonance frequency tuning. The system operates under 1 MHz, 1.5 MHz, and 3 MHz, eliminating the frequency splitting effect and reducing the cross-coupling effect in the MRWPT systems. However, these methods are based on operating at different resonant frequency and are not applicable for single-band applications.

In this paper, the topology of a time-sharing multiple-receiver wireless power transfer (TS-MRWPT) system with an active-bridge rectifier is developed to reduce the effect of cross-coupling between receiver coils, and a synchronization strategy is developed to control the time-sharing sequence of each receiver. Moreover, a voltage control strategy is proposed to achieve both a high system efficiency and to satisfy the output voltage demands for each receiver.

The organization of this paper is as follows: Section 2 analyzes the mathematical model and cyclic control strategy of TS-MRWPT systems with uncontrollable rectifiers. Section 3 develops a topology of TS-MRWPT systems with active-bridge rectifiers, proposes a synchronization strategy for the time-sharing sequence of each receiver, and analyzes the drive signal generation and influences brought about by RC absorbing circuits. The output voltage control strategy is developed for the proposed topology to achieve both a high efficiency and satisfying the output voltage demands of each receiver. Section 4 presents the simulation and experiment results, and finally, the conclusion is given in Section 5.

2. TS-MRWPT System with Uncontrollable Rectifiers

2.1. Modeling of a TS-MRWPT System with Uncontrolled Rectifiers

Figure 1 displays the schematic and equivalent circuits of the time-sharing MRWPT system with uncontrolled rectifiers. R_i , L_i , and C_i represent the resistance, inductance, and compensation capacitance of the i th coil, respectively. R_{oi} denotes the load resistance of coil i , C_{oi} denotes the filter capacitance of coil i , and U_{in} denotes the input DC voltage. U_{oi} denotes the DC output voltage of the load resistance R_{oi} in coil i . Q_{11} – Q_{14} are the gate drive signals of the converters of coil 1. D_i indicates the duty cycle of S_{i5} and T_{rec} indicates the switching cycle of the S_{i5} . Frequency f_1 indicates the frequency of the inverter at the primary side. Frequency f_2 indicates the frequency of Q_{i5} . N_f indicates the ratio f_1/f_2 .

Compared to the dual-series compensation MRPWT system in Liu et al. [21], based on the Kirchhoff voltage laws (KVLs), the equivalent mathematical model of the TS-MRWPT system can be derived as:

$$\begin{bmatrix} j\omega L_{f1} + \frac{1}{j\omega C_{f1}} & -\frac{1}{j\omega C_{f1}} & 0 & \cdots & 0 \\ -\frac{1}{j\omega C_{f1}} & R_1 + j\omega L_{s1} + \frac{1}{j\omega C_{f1}} + j\omega L_1 + \frac{1}{j\omega C_1} & -j\omega M_{12} & \cdots & -j\omega M_{1n} \\ 0 & -j\omega M_{12} & R_2 + j\omega L_2 + \frac{1}{j\omega C_2} + Z_{eq2} & \cdots & j\omega M_{2n} \\ 0 & -j\omega M_{13} & j\omega M_{23} & \cdots & j\omega M_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & -j\omega M_{1n} & j\omega M_{2n} & \cdots & R_n + j\omega L_n + \frac{1}{j\omega C_n} + Z_{eqn} \end{bmatrix} \begin{bmatrix} I_1 \\ I_{p1} \\ I_2 \\ I_3 \\ \vdots \\ I_n \end{bmatrix} = \begin{bmatrix} U_1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad (1)$$

Figure 1. Schematic and equivalent circuits of a time-sharing multiple-receiver wireless power transfer (WPT) system with uncontrollable rectifiers: (a) schematic circuit and (b) equivalent circuit.

In the TS-MRWPT system, at any time, only one Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) S_{i5} is turned on and the other S_{i5} ($j \neq i, j = 1, 2, \dots, n$) are turned off. Therefore, the currents satisfy $I_i \neq 0$ and $I_j = 0$ and Equation (1) can be simplified to (2):

$$\begin{bmatrix} j\omega L_{f1} + \frac{1}{j\omega C_{f1}} & -\frac{1}{j\omega C_{f1}} & 0 \\ -\frac{1}{j\omega C_{f1}} & R_1 + j\omega L_{s1} + \frac{1}{j\omega C_{f1}} + j\omega L_1 + \frac{1}{j\omega C_1} & -j\omega M_{1i} \\ 0 & -j\omega M_{1i} & R_i + j\omega L_i + \frac{1}{j\omega C_i} + Z_{eqi} \end{bmatrix} \begin{bmatrix} I_1 \\ I_{p1} \\ I_i \end{bmatrix} = \begin{bmatrix} U_1 \\ 0 \\ 0 \end{bmatrix} \quad (2)$$

In order to turn off the currents at the receiver side, the compensation network at the receiver side has to have voltage-source characteristics instead of current-source characteristics. The compensation network of the receiver side are in a series compensation circuit instead of a parallel compensation circuit or LCC compensation circuit. The compensation networks satisfy Equation (3):

$$\omega L_i = \frac{1}{\omega C_i}, \quad (i = 1, 2, \dots, n) \quad (3)$$

According to the characteristics of an LCL circuit, the L_{f1} , L_{s1} , and C_{f1} satisfy Equation (4):

$$\omega L_{f1} = \omega L_{s1} = \frac{1}{\omega C_{f1}} \quad (4)$$

The ratio α of current I_{p1} and voltage U_1 satisfies Equation (5) based on Equations (1) and (4):

$$\alpha = \frac{I_{p1}}{U_1} = \frac{1}{j\omega L_{f1}} \quad (5)$$

When the filter capacitors C_{oi} ($i = 2, 3, \dots, n$) are large enough, the output voltages U_{oi} are supposed to remain unchanged. U_i ($i = 2, 3, \dots, n$) indicates the fundamental component of the converter voltage at receiver side, which are derived as:

$$U_i = \frac{2\sqrt{2}}{\pi} U_{oi} \quad (6)$$

Supposing no extra power losses occur at the converters, the power switches S_{i5} , and at the receiver side, based on the law of energy conservation, the power of the load resistances satisfies Equation (7):

$$\int_0^{T_{rec}} \frac{U_{oi}^2}{R_{oi}} dt = \int_0^{D_i T_{rec}} \frac{U_i^2}{R_{eqi}} dt \quad (7)$$

By deriving Equation (7), the equivalent resistance R_{eqi} of load resistance R_{oi} satisfies Equation (8):

$$R_{eqi} = \frac{8D_i}{\pi^2} R_{oi} \quad (8)$$

Based on Equations (1) and (6), the output voltage of the i th receiver coil satisfies Equation (9):

$$U_{oi} = \frac{8M_{1i}R_{oi}U_{in} \sin \beta_{1i}}{L_{f1}(\pi^2 R_i + 8R_{oi})} \quad (9)$$

2.2. Cyclic Control of a TS-MRWPT System with Uncontrollable Rectifiers

This section proposes a cyclic control strategy for a TS-MRWPT system. This cyclic control strategy enables multiple receivers to be turned on in different time sequences, which can reduce the effect of cross-coupling between receiver coils. Meanwhile, a cyclic control strategy is a periodic control strategy that manipulates the power index of each load resistance by manipulating the amount of the full-wave of the rectifier at a switch cycle T_{rec} .

Figure 2 displays the cyclic control method of a time-sharing, single-transmitter, three-receiver WPT system. The figure includes the drive signal Q_{i5} of S_{i5} and the output currents i_{oi} of each load resistance.

Figure 2. Cyclic control method of the single-transmitter, three-receiver, time-sharing WPT system with an uncontrollable rectifier.

There are self-inductances L_i ($i = 2, 3, \dots, n$) at the receiver coils. The sudden turn-off of S_{i5} will cause a large $L_i \frac{di_i}{dt}$ at the receiver coils, which may lead to the breakdown of receiver coils. Therefore, the S_{i5} are turned off when the currents I_i are at the zero-crossing condition.

However, the cyclic control of a TS-MRWPT system must introduce a zero-crossing current detection of I_i to avoid a large voltage U_i in the receiver coils. Furthermore, the tuning range of the equivalent resistances are restricted by the duty cycle D_i , and the tuning range of the output power of each load resistance R_{oi} . New topologies and a control strategy should be proposed to improve the performance of the time-sharing MRWPT system.

3. Time-Sharing, Multiple-Receiver, Wireless Power Transfer System with Active-Bridge Rectifiers

To improve the performance of the TS-MRWPT system, an active-bridge rectifier is introduced to the TS-MRWPT system. An active-bridge rectifier has the advantage of lower power loss in the converters and a controllable equivalent resistance. Moreover, an active-bridge rectifier enables the MRWPT system to achieve the phases of the receiver currents I_i .

3.1. Modeling of the TS-MRWPT with Active-Bridge Rectifiers

Figure 3 shows the schematic of a TS-MRWPT system with active-bridge rectifiers. The uncontrollable rectifiers in Figure 1a are replaced by an active bridge in Figure 3. The active bridge is driven by drive signal Q_{i1} – Q_{i5} . Q_{i1} – Q_{i4} ($i = 1, 2, \dots, n$) are the gate drive signals of the converters of the coil i .

Compared to the equivalent resistance R_{eqi} of a TS-MRWPT system with uncontrollable rectifiers in Equation (6), the equivalent resistance R_{eqi} of a TS-MRWPT system with an active bridge can be derived to give Equation (10), where $2\beta_i$ denotes the conduction angle of the converters:

$$R_{eqi} = \frac{8D_i}{\pi^2} R_{oi} \sin^2 \beta_i \quad (10)$$

Based on Deng et al. [32], the best matching resistances $R_{eqi, \text{BEST}}$, ($i = 2, 3, \dots, n$) of an MRWPT system satisfies Equation (11):

$$R_{eqi, \text{BEST}} = R_i \sqrt{1 + \frac{1}{R_1} \left(\frac{\omega^2 M_{1i}^2}{R_i} \right)} \quad (11)$$

Figure 3. Schematic of a time-sharing, multiple-receiver WPT system with active-bridge rectifiers.

In Figure 3, U_1 denotes the fundamental component of the inverter voltage. By performing a Fourier decomposition, U_{i1} is derived as:

$$U_1 = \frac{2\sqrt{2}}{\pi} U_{in} \sin \beta_1 \quad (12)$$

Based on Liu et al. [21], the fundamental component of the converter voltage U_i ($i = 2, 3, \dots, n$) at the receiver is derived as:

$$U_i = \frac{2\sqrt{2}}{\pi} U_{oi} \sin \beta_i \quad (13)$$

By solving Equations (1) and (9)–(13), the output voltage of the i th load resistance U_{oi} can be derived to give Equation (14).

$$U_{oi} = \frac{8D_i M_{1i} R_{oi} U_{in} \sin \beta_1 \sin \beta_i}{L_{f1} (\pi^2 R_i + 8D_i R_{oi} \sin^2 \beta_i)} \quad (14)$$

In practical applications, the R_i satisfy $R_i \ll \frac{8D_i R_{oi} \sin^2 \beta_i}{\pi^2}$, and Equation (14) can be simplified to give Equation (15):

$$U_{oi} \approx U_{in} \frac{M_{1i} \sin \beta_1}{L_{f1} \sin \beta_i}, \text{ when } R_i \ll \frac{8D_i R_{oi} \sin^2 \beta_i}{\pi^2} \quad (15)$$

From Equation (15), the output voltage remains unchanged despite the variation of D_i . Moreover, the output voltage is controlled by β_1 , and the equivalent resistances of the load resistances are controlled by β_1 and D_i cooperatively. Therefore, the proposed topology has the advantage of a constant output voltage despite the variation of D_i and the output voltages are consistently controlled by β_1 and β_i ($i = 2, 3, \dots, n$). Furthermore, in practical applications, it is difficult to achieve accurate values for D_i due to the full-wave control strategy. The full-wave control strategy must assure that the number of the turn-on waveforms of the voltage is an integer. The proposed topology can reduce the output voltage error caused by the D_i error.

3.2. Cyclic Control for a Time-Sharing, Multiple-Receiver, Wireless Power Transfer System with Active-Bridge Rectifiers

This section proposes a cyclic control strategy for a TS-MRWPT system with active-bridge rectifiers. A cyclic control strategy focuses on turning off the power switches S_{i5} when S_{i5} reach their zero-crossing current conditions. The zero-crossing detection signal is generated by the synchronization signals, which are driven by the synchronization control of the active-bridge rectifiers.

This paragraph illustrates the synchronization procedure of the TS-MRWPT system. According to Liu et al. [21], the synchronization signal can be achieved by detecting the voltage u_{Ci} . After the synchronization control of the active-bridge rectifiers, the phases of the voltage u_i at the receiver side are the same phases as the phases of the current i_i , and the zero-crossing point can be represented by the synchronization signal PWM3 (Pulse Width Modulation). Figure 4 shows the identical wave of the synchronization control. In Figure 4, the triangle wave indicates the time-base counter register (TBCTR) of the digital signal processor (DSP). S_d denotes the phase detection signal. The signal S_d is generated by achieving the AND-operation of PWM3 and $u_{C2\text{square}}$. The signal $u_{C2\text{square}}$ is achieved by detecting the voltage u_{C2} of the capacitor C_2 and then modulating the u_{C2} with a comparator to generate $u_{C2\text{square}}$. The voltage u_2 is modulated by the four compared registers 1CMPA, 1CMPB, 2CMPA, and 2CMPB in the DSP. When the four compared registers 1CMPA, 1CMPB, 2CMPA, and 2CMPB subtract or add a phase value, the voltage u_2 is modulated to shift left or right, respectively, and finally be the same phase as the resonant current i_2 . The PWM3 generated by the DSP is the same phase as the voltage u_2 . When each active-bridge rectifier in the MRWPT system reaches its synchronization state, that is the voltage u_2 is the same phase as the resonant current i_2 , the PWM3 is the same phase as the currents i_i . In this synchronization state, the 1-state of PWM3 indicates that the i_i is higher than zero, and the 0-state of PWM3 indicates that the i_i is lower than zero. Based on the method given in Liu et al. [21], when the voltage u_2 and i_2 are at the same phase in Figure 4, the value satisfies $\theta = 0^\circ$ and the $d = 90^\circ$, and the phase of PWM3 represents the phase of the zero-crossing current point. When the d is not equal to 90° , the system manipulates the phase of U_i by tuning the turn-on sequences of Q_{i1} – Q_{i4} until $\theta = 0$.

Figure 5 shows the overall block diagram of the TS-MRWPT system. The control block in Figure 5 shows the information processing and drive signal generation. The “LPF” in Figure 5 denotes the low-pass filter block and modulates the S_d signal into a smooth DC voltage. The signal PWM3 produced by the controllers at the receivers represents the phase signal of the voltage u_i at the receiver side. After the synchronization control of the active-bridge rectifier, the currents i_i of the rectifiers are in phase with the voltage u_i and the PWM3 can represent the phase of the current i_i . Using an AND operation on both the signal PWM3 and the Q'_{i5} signal, the cyclic control of the TS-MRWPT system can turn off the S_{i5} when the current i_i reaches its zero-crossing condition.

Figure 4. Generation of the synchronization control signal. CMP: compare register; PWM: Pulse Width Modulation; TBCTR: time-base counter register; TBPRD: time-base period register.

Figure 5. Overall block diagram of a time-sharing, multiple-receiver, wireless power transfer system. LPF: low-pass filter.

In Figure 6, the drive signal $Q_{i1} \sim Q_{i4}$ must be set to a low level when the D_i is at a low level. This is because the current i_i still follows if the drive signal $Q_{i1} \sim Q_{i4}$ are not set to a low level. Figure 6 shows the drive signals of the active-bridge rectifiers and S_{i5} . $Q_{i1} \sim Q_{i4}$ represent the drive signals of the phase-shifting control signals, and Q_{i5} represents the drive signal of S_{i5} . During the range $t_1 \sim t_2$, though the Q_{i5} is set to a low level, the Q_{i1} and Q_{i3} are set to a high level, and the current still follows from S_{i1} to S_{i3} and the current i_i still follows. For the same reason, during the range $t_3 \sim t_4$ the Q_{i2} and Q_{i4} are set to a high level, the current i_i still follows from S_{i2} to S_{i4} . Therefore, the system achieves the AND-operation of both the synchronization signal and the $Q_{i1} \sim Q_{i4}$ signal to avoid the current freewheeling.

Figure 6. Drive signals of active rectifier bridges and power switch S_5 .

Figure 7 displays the drive signals Q_{i5} of the time-sharing, three-receiver WPT systems. Since the D-flip-flop in Figure 5 operates when the rising edge of PWM3 arrives, there are phase-shifts in the actual Q_{i5} . In Figure 7, all the actual Q_{i5} turns on in different time intervals. To reduce the complexity of the drive signals, the drive signal modulation block is also generated through the digital signal processor (DSP).

Figure 7. The actual drive signals Q_{i5} of the time-sharing, three-receiver, wireless power transfer system before and after the D-flip-flop with a rising edge trigger.

Figure 8 indicates the operating modes of the proposed TS-MRWPT system and Figure 9 shows the typical waveforms of a single-transmitter, three-receiver, time-sharing WPT system using the cyclic control method. The electrical circuits at the secondary side respectively undergo two kinds of turn-on modes and two kinds of turn-off modes within a period, as showed in Figure 8. In Figure 9, the receivers stagger their turn-on time intervals and there are direct current offsets in the voltages u_{iAB} because the S_{i5} turn-off and the voltage u_{Ci} remain the voltage before the S_{i5} turn-off. The detailed analysis of the different modes is given in the following text.

- (1) Mode 1: Figure 8a displays the operating mode when $i_i > 0$ ($i = 2, 3, \dots, n$) and Q_{i5} are set to a high level. The S_{i5} are turned on and the potential difference u_{AC} is the turn-on voltage drop of the S_{i5} . The current flow is $L_i-C_i-D_{i1}-S_{i5}-R_{oi}$ (C_{oi})- $D_{i4}-R_i$. The filter capacitance C_{oi} are charging and the output voltage U_{oi} of the filter capacitance C_{oi} are increasing. The voltage $u_{Ci}(t)$

satisfies Equation (16). $i_i(t)$ and $u_{Ci}(t)$ denote the instantaneous values of the resonant currents and voltages of the capacitances C_i in Figure 8.

$$u_{Ci}(t) = \frac{i_i(t)}{j\omega C_i} \quad (16)$$

- (2) Mode 2: Figure 8b displays the operating mode when $i_i = 0$ ($i = 2, 3, \dots, n$) and Q_{i5} is set to a low level. The S_{i5} are turned off and the circuit of the receiver coils are open circuits. The potential difference is $u_{AC} = u_{AB} - u_{oi}$, the current i_{oi} is supported by the filter capacitance C_{oi} , and the filter capacitance C_{oi} is discharging. The current flow is $C_{oi}-R_{oi}$. For the currents $i_i = 0$, the potential difference u_{AB} is no longer equal to the resonant voltage and the capacitance voltage u_{Ci} remain at the voltage $u_{Ci}(t_{\text{mode1}}^-)$. Therefore, the u_{Ci} in mode 2 in Equation (17) remains unchanged and is equal to the value of $u_{Ci}(t_{\text{mode1}}^-)$, which is the voltage of the C_i at the end of mode 1. Moreover, the $u_{Ci}(t_{\text{mode1}}^-)$ can be derived to give Equation (17) and the ω is the resonant angle frequency of the system, which is constant. The voltage u_{AB} satisfies Equation (18). $i_{p1}(t)$ and $u_{AB}(t)$ denote the instantaneous current of the current i_{p1} in Figure 3 and the instantaneous potential difference of points A and B in Figure 8. Furthermore, $t_{\text{mode}i}^-$ denotes the time when mode i ends.

$$u_{Ci}(t) = u_{Ci}(t_{\text{mode1}}^-) = \frac{i_i(t_{\text{mode1}}^-)}{j\omega C_i} \quad (17)$$

$$u_{AB}(t) = j\omega M_{1i} i_{p1}(t) + u_{Ci}(t) = j\omega M_{1i} i_{p1}(t) + \frac{i_i(t_{\text{mode1}}^-)}{j\omega C_i} \quad (18)$$

- (3) Mode 3: Figure 8c displays the operating mode when $i_i < 0$ ($i = 2, 3, \dots, n$) and Q_{i5} are set to a high level. The S_{i5} are turned on and the potential difference u_{AC} is the turn-on voltage drop of S_{i5} . The current flow is $L_i-C_i-D_{i3}-S_{i5}-R_{oi}$ (C_{oi})- $D_{i3}-R_i$. The filter capacitance C_{oi} are charging and the voltage u_{oi} of the filter capacity C_{oi} are increasing. The voltage u_{Ci} satisfies Equation (16).
- (4) Mode 4: Figure 8d displays the operating mode when $i_i = 0$ ($i = 2, 3, \dots, n$) and Q_{i5} are set to a low level. The S_{i5} are turned off and the circuit of the receiver coils are open circuits. The potential difference is $u_{AC} = u_{AB} - u_{oi}$, the current i_{oi} are supported by the filter capacity C_{oi} , and the filter capacity C_{oi} are discharging. The current flow is $C_{oi}-R_{oi}$. For the currents $i_i = 0$, the voltage u_{Ci} satisfies Equations (19) and (20):

$$u_{Ci}(t) = u_{Ci}(t_{\text{mode3}}^-) = \frac{i_i(t_{\text{mode3}}^-)}{j\omega C_i} \quad (19)$$

$$u_{AB}(t) = j\omega M_{1i} i_{p1}(t) + u_{Ci}(t) = j\omega M_{1i} i_{p1}(t) + \frac{i_i(t_{\text{mode3}}^-)}{j\omega C_i} \quad (20)$$

Figure 10 shows the general flowchart of the system control program of a TS-MRWPT system. Before the system is launched, an MRWPT system should be tuned to be under the resonant condition, and the suitable L_i and C_i must be designed for the resonant condition. Furthermore, the L_{f1} , L_{s1} , and C_{f1} must be designed based on Equation (5) for an appropriate ratio α . The β_i and D_i must be appropriately designed based on Equations (10) and (14) to satisfy both the best matching resistances and constant output voltages of each receiver before the system is launched. After the system is launched, the S_{i5} turn on and system is under synchronization control. Lastly, after the synchronization, the synchronization signal PWM3 is provided to the DSP for time-sharing control.

Figure 8. Operating modes of the proposed time-sharing, multiple-receiver, wireless power transfer system, where the red lines show the current loop and the blue lines show the voltage loop of u_{AB} : (a) mode 1, (b) mode 2, (c) mode 3, and (d) mode 4.

Figure 9. Typical waveforms of the proposed single-transmitter, three-receiver, time-sharing WPT system with a cyclic control method.

Figure 10. Flowchart of system control program.

3.3. RC Absorbing Circuits for Time-Sharing, Multiple-Receiver Systems

For applications, power switches are paralleled with RC absorbing circuits to absorb the peak voltage of the power switches. Therefore, as shown in Figure 11, when Q_{i5} and Q_{i1} – Q_{i4} turn off, the current i_i is not totally shut off, which follows through the RC absorbing circuits and brings a ringing voltage effect on u_i and i_i . However, the capacitors of the RC absorbing circuit are small enough and the current i_i are negligible.

Figure 11. Current flow figure when S_{i5} turns off.

3.4. Output Voltage Control for Time-Sharing, Multiple-Receiver, Wireless Power Transfer Systems

In this section, this paper presents verifications that the proposed TS-MRWPT system has the advantage of both controlling the output voltages and operating under a resistance-matching condition simultaneously.

To control each receiver such that they provide different voltage levels, there are two methods used to manipulate the TS-MRWPT system. One is to control the inverter voltage U_1 for each receiver when the S_{i5} turns on, while the other is to keep the inverter voltage U_1 unchanged and tune the receiver circuit to control the output voltages of each receiver circuit. For the first method, when the power switch S_{i5} of the i th receiver turns on, the inverter voltage U_1 is controlled to tune the output

voltage. However, in the TS-MRWPT system, the method of controlling the inverter voltage U_1 to provide the target output voltage for each receiver requires building the effective synchronization between the transmitter and receivers. This adds extra complexity to the system control procedures.

Another method of controlling the receiver circuit in the proposed the TS-MRWPT system has the advantage of both controlling the output voltages and operating under a resistance-matching condition simultaneously. As seen in Equation (8), different from the buck circuits, the power switches S_{i5} have the advantages of manipulating the equivalent resistances of load resistances and hardly influencing the output voltages, and the active rectifiers are able to manipulate both the equivalent resistances of the load resistances and the output voltages. By controlling the active rectifiers and the power switch S_{i5} cooperatively, the TS-MRWPT system can both control the output voltages and operate under a resistance-matching condition simultaneously. The principal problem in a TS-MRWPT system regarding operating under a resistance-matching condition is that under the periodic control method, the duty cycle D_i has to ensure that the number of the turn-on waveforms of each active rectifier bridge in each receiver is an integer. To operate the systems under a resistance-matching condition, the duty cycle D_i are updated to D_i' to ensure the number of the turn-on waveforms is a integer.

When the TS-MRWPT system satisfies $R_i \ll \frac{8D_i R_{oi} \sin^2 \beta_i}{\pi^2}$, by solving Equation (15), β_i ($i = 2, 3, \dots, n$) can be replaced by the output voltage U_{oi} :

$$\beta_i = \arcsin \frac{U_{in} M_{1i} \sin \beta_1}{U_{oi} L_{f1}} \quad (21)$$

For the TS-MRWPT system, the equivalent resistance of R_{eqi} in each receiver satisfies $R_{eqi} = R_{eqi, \text{BEST}}$ in Equation (11). By solving Equation (10), the duty cycle D_i satisfies Equation (22):

$$D_i = \frac{\pi^2 R_{eqi}}{8 R_{oi} \sin^2 \beta_i} \quad (22)$$

To improve the efficiency of a TS-MRWPT system, the sum of D_i should satisfy Equation (23). When the sum of the D_i is less than 1, the current I_1 still follows, even though all the S_{i5} are turned off and it introduces extra power loss to the systems.

$$\sum_2^n D_i = 1 \quad (23)$$

By solving the Equations (21)–(23), the β_1 of the inverter at the transmitter side can be derived to give Equation (24):

$$\beta_1 = \arcsin \sum_2^n \left(\frac{\pi U_{oi} L_{f1}}{4 U_{in} M_{1i}} \sqrt{\frac{2 R_{eqi}}{R_{oi}}} \right) \quad (24)$$

By substituting the β_1 into Equations (21) and (22), the duty cycle D_i of the power switch S_{i5} is able to control the output voltage. Moreover, the duty cycle D_i is updated to D_i' to ensure the number of the turn-on waveforms is a integer in Equation (25). The $[x]$ in Equation (25) is the rounding operator.

$$D_i' = \frac{[D_i N_f]}{N_f} \quad (25)$$

Furthermore, the duty cycle D_i' is updated to D_i'' in Equation (26) to ensure that the updated duty cycle satisfies Equation (23). The function $g(x)$ is defined such that when the sum of the D_i is less than 1, the D_i' that satisfies $\max\{D_i' N_f - [D_i' N_f]\}$ is previously compensated with Equation (23) until the sum of D_i'' satisfies Equation (23).

$$D_i'' = g(D_i') = \begin{cases} D_i', & D_i' \text{ no need to compensated} \\ \frac{D_i' N_f + 1}{N_f}, & D_i' \text{ needed to compensated} \end{cases} \quad (26)$$

The detailed flowchart of the output voltage control for the TS-MRWPT system is shown in Figure 12.

Figure 12. Flowchart of the output voltage control program for the time-sharing wireless power transfer systems.

4. Results

4.1. Simulation Result of the Cross-Coupling Effect

To verify the impact of cross-coupling between receiver coils, coil models were simulated using software COMSOL (version 5.3, COMSOL Inc., Sweden) to illustrate the cross-coupling effect in an MRWPT system. Figure 13 shows the coil models of the transmitter and receiver coils built in COMSOL. The round coil models cost a lot of computer resources in COMSOL software and will often fail to achieve convergence during simulations. Therefore, these coil models are usually constructed as near-circular coil models with a fillet as shown in Figure 13. Table 1 shows the parameters of transmitter coil and receiver coil.

Table 1. Key parameters of the coil models.

Coil	Turns	Length of Outer Square (mm)	Gap between Adjacent Lines (mm)	Width of Coil (mm)	Equivalent Conductivity of Wire (m·Ω)	Equivalent Resistance (mΩ)	Self-Inductance (μH)
Transmitter coil	5	420	2	2	1.5×10^6	17.439	17.535
Receiver coil	8	200	2	2	1.5×10^6	15.433	18.103

Figure 13. Simulation models of coils with a square model: (a) transmitter coil and (b) receiver coil.

The distance d_{TR} between the two receiver coils and the transmitter coil was 100 mm. The distance d_R between the centers of the receivers was 180 mm. Figure 14a shows the magnetic field simulation of the transmitter coil, which was activated with a 1 A, 100 kHz current. Figure 14b shows the magnetic field simulation of the receiver coil 3 (Rx3), which was activated with a 1 A, 100 kHz current. Figure 14c shows the magnetic field simulation of both transmitter and receiver coil 3, which were both activated with a 1 A, 100 kHz current. According to the simulation results, the magnetic flux densities of the center point of coil 2 (Rx2) were 10.184 μT , 2.9245 μT , and 13.024 μT , respectively, when the system was activated using Tx1, Rx3, and both Tx1 and Rx3. Comparing the results in Figure 14, the received magnetic field of receiver coil 2 was improved by the cross-coupling from receiver coil 3. However, when the systems were activated by both Tx1 and Rx3, the magnetic flux densities were improved, and the resonant conditions were weakened by the cross-coupling of the receivers. Furthermore, the induced voltage on Rx2, which was generated by I_3 , varied when I_3 varied. Therefore, the cross-coupling problems are great challenges for an MRWPT system.

Figure 14. Simulations of the magnetic field distribution: (a) transmitter coil was activated, (b) receiver coil 3 was activated, and (c) both transmitter coil and receiver coil 3 were activated.

4.2. Simulation and Experimental Results of Time-Sharing, Multiple-Receiver WPT Systems

To verify the validity of the proposed TS-MRWPT system, the mathematical model was constructed and simulated using the PLECS platform (version 4.12, Plexim GmbH Inc., Switzerland). An experimental prototype was constructed as displayed in Figure 15. Table 2 presents parameters of a time-sharing, two-receiver WPT system. The transmitter coil and receiver coils were constructed based on the COMSOL simulation model.

Figure 15. Experimental platform of the TS-MRWPT system.

Table 2. Key parameters of the time-sharing, two-receiver, wireless power transfer models.

Symbol	Quantity	Value
L_1, L_2, L_3	Self-inductances of coils	22.78 μ H, 24.53 μ H, 24.62 μ H
L_{f1}, L_{s1}	Inductances	25.12 μ H, 25.20 μ H
C_1, C_2, C_3, C_{f1}	Compensation capacitors	110 nF, 100 nF, 100 nF, 100 nF
C_{02}, C_{03}	Filter capacitors	2200 μ F, 2200 μ F
R_1, R_2, R_3	Parasitic resistances of coils	21.74 m Ω , 17.03 m Ω , 17.53 m Ω
N_1, N_2, N_3	Turns of coils	5, 8, 8
r_1, r_2, r_3	Radius of coils	420 mm, 200 mm, 200 mm
R_{02}, R_{03}	Load resistances	5 Ω , 5 Ω
f_1	Operating frequency	100 kHz
f_2	Operating frequency	5 kHz
M_{23}	Mutual inductance	0.9660 μ H

In Figure 15, Tx1 indicates the transmitter coils, Rx2 and Rx3 indicates the receiver coils. The experimental coils in Figure 15 were constructed with a round model and the measured parameters are listed in Table 2. C_i indicates the compensation capacitances. The active bridge at each coil was constructed with two half-bridge circuit modules KIT8020CRD8FF1217P-1 (Cree Inc.). The MOSFET in the half-bridge circuit modules was SCT3030KL (Rohm Inc.), the turn-on resistance of which was about

30 m Ω . Systems were respectively controlled by controller 1 and controller 2, which each consisted of a digital signal processor (DSP) TMS320F28335 (Texas Instruments Ins.).

Figure 16 shows the experiment waveforms of the TS-WPT system with active-bridge rectifiers. The voltages in Figure 16a show the drive signals of the TS-MRWPT system, where the Q_{21} and Q_{24} agreed with the drive signal modulation block in Figure 5. Figure 16b shows the waveforms of the receiver coil Rx2, where the ringing in U_2 was caused by the RC absorbing circuit, which was parallel to the power switch. When the S_{i5} turned off, the circuit at the secondary side was cut off, but currents I_2 still followed the RC absorbing circuit. The current I_2 in Figure 16b shows that the current I_2 was generally cut off when the Q_{25} turned off. Figure 16c shows the capacitor voltages of the TS-MRWPT system. The U_{C2} held the voltage value when S_{25} turned off, and C_2 was the resonant condition when S_{25} turned on.

Figure 16. Experimental waveform: (a) drive signals waveform, (b) waveforms of coil 2, and (c) voltage waveforms of the capacitors.

Figure 17 shows the simulation waveform comparison of the TS-MRCT system without the RC absorbing circuits and with the RC absorbing circuits. In Figure 17a, the TS-MRWPT system without

the RC absorbing circuits nearly removed the ringing effect, while the TS-MRWPT system with the RC absorbing circuits had a ringing effect. Figure 17c,d shows the enlarged view of the voltage U_2 and current I_2 in the TS-MRWPT system with RC absorbing circuits and the ringing effect was weakened by improving the resistances of the RC absorbing circuit from $10\ \Omega$ to $100\ \Omega$.

Figure 17. Simulation waveform: (a) system without RC absorbing circuits; (b) system with RC absorbing circuit, where the resistance was $10\ \Omega$; (c) enlarged view of the voltages and currents of the system with RC absorbing circuits, where the resistances were $10\ \Omega$; and (d) enlarged view of the voltages and currents of system with two RC absorbing circuits, where the resistances were $100\ \Omega$.

To verify the validity of the TS-MRWPT system, the TS-MRWPT system was compared to a MRWPT system that had the same parameters and under a best-matching resistance condition based on Equation (11). The parameters of the TS-MRWPT system and the MRWPT system follow Table 2, and the power switches S_{i5} in the MRWPT system were removed to avoid the extra power loss from S_{i5} . Figure 18a shows the efficiency comparisons of different topologies and control strategies. Figure 18a shows that the simulation efficiencies of the MRWPT system without cross-coupling were slightly

higher than the simulation efficiencies of the TS-MRWPT system, and the simulation efficiencies of the MRWPT system with cross-coupling was severely weakened by the cross-coupling effect and the transfer efficiencies were lower than 30%. The experimental results of the proposed TS-MRWPT system achieved a maximum efficiency of about 82.4% at the distance of 50 mm, and decreased due to the increasing distances between the transmitter and receivers. Figure 18c shows the same tendency with Figure 18a, where the voltage U_{o2} was improved in the TS-MRWPT system. This shows that the proposed TS-MRWPT reduced the cross-coupling effect between receivers and increased the efficiencies of the MRWPT systems.

Figure 18. Simulation and experiment results: “Sim” and “Exp” indicates simulation and experiment, respectively. “Cr” and “NCr” indicates the simulation setup with cross-coupling and without cross-coupling, respectively. “TS” and “NTS” indicates the system having time-sharing control and without time-sharing control, respectively. “NRC” and “RC” indicates the system introducing an RC absorbing circuit and without an RC absorbing circuit, respectively. “10 Ω ” and “100 Ω ” indicates the absorbing resistances. (a) Efficiency comparisons. (b) Efficiency comparisons between systems with RC absorbing resistances and without RC resistances. (c) Output voltage U_{o2} comparisons. (d) Output voltage U_{o2} comparisons between systems with RC absorbing resistances and without RC absorbing resistances.

In Figure 18a,c, the simulation efficiencies and output voltages of the MRWPT system without a cross-coupling effect was higher than the ones of the TS-MRWPT. This was because the MRWPT system without a cross-coupling effect was built without power switches S_{i5} , and hence without the power loss. However, in a practical application, the MRWPT system without a cross-coupling effect is an ideal model and cannot be achieved if the receiver coil gets close. Furthermore, the experimental efficiency of the TS-MRWPT was about 10% lower than the simulation efficiency of the TS-MRWPT. This was because the resistance of the inductances and capacitances of the LCL compensation topologies were not considered in the simulation, and the parameter errors of the components in the compensation network also introduced an extra efficiency decrease to the TS-MRWPT systems. Both the simulation efficiencies and experimental efficiencies of the TS-MRWPT system decreased when the distance between the transmitter coil and the receiver coil got larger (Figure 18a).

Figure 18b,d shows that the simulation comparisons of the efficiencies and output voltage U_{o2} for systems with RC absorbing circuits and without RC absorbing circuits. The efficiencies and voltage U_{o2} of the circuits with RC absorbing circuits and without absorbing were nearly the same. The simulation results showed that the efficiencies of the TS-MRWPT system with an RC absorbing circuit were a little higher than the circuit without RC absorbing circuits, and the efficiencies of an RC absorbing circuit with an absorbing resistance $100\ \Omega$ was a bit higher than the efficiencies with absorbing resistance of $10\ \Omega$. This verifies that a higher absorbing resistance helped to reduce the ringing effect of the TS-MRWPT systems and improve the system efficiency.

4.3. Simulation Comparison between the Time-Sharing Method and Compensation Method

To verify the validity of the time-sharing voltage control for the TS-MRWPT system, the system was compared with the efficiency of the compensation method in Fu et al. [25]. Table 3 lists the comparison result of the two different approaches. The comparisons were constructed under the parameters listed in Table 2. Based on Fu et al. [25], the compensation capacitances C_2 and C_3 in the compensation method were set to $110\ \text{nF}$ and $100\ \text{nF}$, respectively, to compensate for the cross-coupling inductances between receivers when $d_{TR} = 50\ \text{mm}$. The maximum simulation efficiency of the cross-coupling method was about 94.3%, which was slightly higher than the maximum simulation efficiency of the time-sharing method, which was about 93.2%. In Figure 19, the distance d_{TR} between the transmission coil and receiving coil was swept from $50\ \text{mm}$ to $300\ \text{mm}$ and the efficiencies of the system using the compensation method, which are marked “Sim-Com-NTS”, were similar to the efficiencies of the system without cross-coupling in Figure 19. The compensation method had a better performance than the time-sharing method when the relative distance between the receiver coils were unchanged. However, the compensation method must operate under fixed currents and the efficiencies dropped rapidly when the load resistances and cross-coupling changed. The simulation comparisons regarding the efficiency are discussed in later sections.

Comparisons were made to compare the performances of the compensation method and time-sharing method under different distances between the receiver coils in a two-receiver WPT system. Table 3 displays the parameters of the coil models. The receivers were placed as displayed in Figure 20: receiver coil 2 was placed at position “A” and receiver coil 3 was placed at position “B” or “C,” transmitter coil 1 was placed under the receiver coils, and $d_{TR} = 100\ \text{mm}$ where the mutual inductance M_{TR} between the transmitter coil and receiver coil satisfied $M_{TR} = 0.43343\ \mu\text{H}$. The position “B” and “C” were reached by rotating the receiver coil at place “A” by 90° and 180° , respectively. The mutual inductance M_{23} between the two receiver coils satisfied $M_{23} = 0.072997\ \mu\text{H}$ when the receivers were placed at positions “A” and “B,” and satisfied $M_{23} = 0.033368\ \mu\text{H}$ when the receivers were placed at positions “A” and “C”. Both the compensation and time-sharing methods were simulated under best-matching resistance conditions based on Equation (11), where the $R_{eq2, \text{BEST}} = 21.74\ \text{m}\Omega$ and $R_{eq3, \text{BEST}} = 21.74\ \text{m}\Omega$. In the compensation system, the derived compensation capacitance $C_2 = C_3 = 0.507821\ \mu\text{F}$ when receiver coil 2 was placed at position “A” and receiver coil 3 was placed at “B” were directly applied to systems where receiver coil 2 was placed at “A” and receiver coil 3 was

placed at “C.” Table 4 displays the simulation result. In Table 4, the compensation method had a higher system efficiency than the time-sharing method when the cross-coupling was compensated. However, when receiver coil 3 moved to the position “C,” the efficiency rapidly dropped due to the variation of the mutual inductances of the cross-coupling effect. However, the time-sharing method had a more flexible choice for the placement of the receiver coil and achieved a high efficiency at position “C.” The efficiency of the time-sharing method was generally unchanged despite the variation of the distance between receivers.

Table 3. Key parameters of the coil models.

Coil	Turns	Length of Outer Square (mm)	Gap between Adjacent Lines (mm)	Width of Coil (mm)	Equivalent Conductivity of Wire ($m\Omega$)	Equivalent Resistance ($m\Omega$)	Self-Inductance (μH)
Receiver coil	7	130	2	2	1.5×10^6	7.4915	5.0214
Transmitter coil	5	420	2	2	1.5×10^6	15.433	18.103

Figure 19. Simulation results of the time-sharing, three-receiver, wireless power transfer system with an output voltage control strategy.

Figure 20. Simulation results of a time-sharing, three-receiver, wireless power transfer system with an output voltage control strategy.

Table 4. Simulation results of the comparison between the time-sharing and compensation methods.

Method	Efficiency	
	Position “B”	Position “C”
Cross-coupling compensation method	88.33%	77.66%
Time-sharing method	85.41%	85.40%

4.4. Simulation Result of the Voltage Control of a Time-Sharing, Multiple-Receiver WPT System

To verify the validity of the output voltage control for the TS-MRWPT systems, a three-receiver WPT system with a time-sharing method was simulated in PLECS software. The parameters of the proposed system are shown in Table 5. The active-bridge rectifiers of the TS-MRWPT system were constructed without RC absorbing circuits. The calculated D_2 , D_3 , and D_4 were $D_2 = 0.373$, $D_3 = 0.291$, and $D_4 = 0.336$, and the updated D_2'' , D_3'' , and D_4'' were $D_2'' = 0.35$, $D_3'' = 0.3$, and $D_4'' = 0.35$. Figure 21 shows the voltage U_i and current i_i of each receiver and the output voltage U_{o2} , U_{o3} , and U_{o4} achieved 7.29 V, 8.98V, and 11.03 V, respectively with target powers of 8 V, 10 V, and 12 V, respectively. The simulation results achieved a simulation efficiency of 89.66%, and in comparison, the simulation results of the traditional MRWPT system, which compensated for the cross-coupling with resonant capacitor in Fu et al. [25] under the same system parameters achieved a simulation efficiency of 94.66%. It verifies that though the efficiency was lower than the efficiency of the system that compensated the cross-coupling, the TS-MRWPT system still achieved a high efficiency. Moreover, the TS-MRPWT had the advantages that TS-MRWPT was applicable for a time-variant cross-coupling MRWPT system.

Table 5. Key parameters of the time-sharing, three-receiver, wireless power transfer models.

Symbol	Quantity	Value
L_1, L_2, L_3, L_4	Self-inductances of coils	22.78 μ H, 24,53 μ H, 24,53 μ H, 24,53 μ H
L_{f1}, L_{s1}	Inductances	25 μ H, 25 μ H
$C_1, C_2, C_3, C_4, C_{f1}$	Compensation capacitors	110 nF, 100 nF, 100 nF, 100 nF, 100 nF
C_{o2}, C_{o3}, C_{o4}	Filter capacitors	2200 μ F, 2200 μ F, 2200 μ F
R_1, R_2, R_3, R_4	Parasitic resistances of coils	12.25 m Ω , 17.03 m Ω , 17.03 m Ω , 17.03 m Ω
R_{o2}, R_{o3}, R_{o4}	Load resistances	4 Ω , 8 Ω , 10 Ω
f_1	Operating frequency	100 kHz
f_2	Operating frequency	5 kHz
U_{o2}, U_{o3}, U_{o4}	Target voltage	8 V, 10 V, 12 V
M_{23}, M_{24}, M_{34}	Mutual inductance	0.9660 μ H

Figure 21. Simulation results of the time-sharing, three-receiver, wireless power transfer system with an output voltage control strategy.

5. Conclusions

This study developed a TS-MRWPT system to reduce the cross-coupling effect between receivers. First, a multiple-receiver system was simulated to illustrate that the cross-coupling between the receivers changed the magnetic field distribution. Second, the proposed time-sharing method in the TS-MRWPT was compared to the compensation method to verify that the time-sharing method had a high efficiency of about 93.2% for the simulation and about 82.4% for the experiment, which was close to the simulation efficiency of the compensation method of about 94.3%. Moreover, further simulation comparisons between the time-sharing method and compensation method showed that the efficiency of the time-sharing method generally remained an 85.41%, despite the variation of the distance between receivers, while the efficiency of the compensation method dropped rapidly from 88.33% to 77.66%. The time-sharing method had a more flexible choice for the placement of the receiver coil. Finally, based on the proposed voltage control method, the TS-MRWPT system achieved output voltages of 7.29 V, 8.98 V, and 11.03 V, respectively, with target power voltages of 8 V, 10 V, and 12 V, respectively, and the efficiency was about 89.66% according to the simulation results.

Author Contributions: W.C. proposed the main idea, designed and performed the experiments, and wrote the manuscript. K.H. and J.X. double-checked and discussed the results and the whole manuscript. X.L., D.M., and H.T. contributed to the discussion of this study. All authors have approved the final version of this manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

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