

Article

Multi-Level Power Output for Wireless Power Transfer System Based on Hardware Reuse and Inverter Mode Selection at Primary Side

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Abstract

To satisfy the requirements of multi-level power output in wireless power transfer (WPT) systems, this paper proposes a multi-level power regulation strategy based on primary-side hardware reuse and inverter mode selection. The proposed approach reduces hardware complexity and control difficulty under diverse power demands, while eliminating the performance degradation of inverters induced by wide-range duty-cycle modulation. In this study, the configuration of the established system is first presented. Maintaining the inherent output connection of the full-bridge inverter, two operational modes realized via power device gating control are analyzed and deduced. On this basis, an analytical circuit model is constructed for the multi-level power output system incorporating primary-side hardware reuse, and the corresponding static characteristics of the system are investigated. Combined with the application of receiving coils with different specifications, a refined multi-level power output scheme relying on inverter mode selection is further formulated. Finally, experimental validation demonstrates that the prototype system achieves four discrete power levels simply through primary-side hardware reuse and mode switching, without modifying circuit connections or adjusting duty ratios. The maximum received power under each level reaches 405 W, 212 W, 101 W and 51 W, respectively; meanwhile, the corresponding DC–DC efficiency is maintained at 92.6%, 91.5%, 92.3% and 90.92%.

Keywords: multi-level power output; hardware reuse; inverter mode selection; wireless power transfer; circuit model



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1. Introduction

Wireless power transfer (WPT) is a novel power transmission method that enables energy delivery without cables. It can avoid risks such as plug wear and contact sparks commonly encountered in wired power transmission [1–4]. Featuring high safety, convenience, and strong environmental adaptability, WPT has been widely applied in electric vehicles, medical devices, unmanned aerial vehicles, and other fields [5,6].

Compensation circuits are usually adopted in WPT systems to achieve efficient and controllable energy transmission. The commonly used topologies include S-S, LCC-S, and LCC-LCC. Among them, the WPT system with LCC-S compensation topology is more widely used due to its constant primary-side current and constant secondary-side voltage output characteristics [7,8].

In recent years, with the development of WPT systems, to meet the demand for different output power levels, reduce hardware complexity, control difficulty under various power requirements, and realize stable and efficient multi-level power transmission, research on multi-level power output methods for WPT systems has gained great significance [9–12].

At present, most studies on WPT technology focus on single-load applications, mainly including inverter control, magnetic coupling mechanism design, compensation circuit design, and system performance optimization. A negative polarity partial power conversion method is presented in [13], which reverses the voltage polarity of the DC-DC converter, allowing a larger proportion of power to be unregulated and thus greatly improving overall system efficiency. An IPT system based on a clamp circuit and a reconfigurable rectifier is introduced in [14]. An optimal control strategy based on four full variables is demonstrated in [15], which achieves peak efficiency by satisfying multiple optimality conditions. A self-compensating planar coil scheme integrated with a single-switch voltage regulator is described in [16]. The impact of primary-side compensation inductance misalignment on the power, efficiency, and input phase characteristics of an LCC-S wireless charging system is examined in [17]. Dual-side phase-shift control for a strongly coupled series-compensated WPT system is explored in [18]. A variable-frequency pulse-width modulation circuit for the input control of a 6.78 MHz resonant WPT system is constructed in [19].

For output power regulation of a single load, common approaches include inserting a DC voltage conversion stage on the primary side, adding a DC voltage conversion circuit on the secondary side, adjusting the control angle of the primary-side inverter, or employing an advanced primary-side inverter topology. A bidirectional DC-DC WPT system with LCC-C resonant compensation is reported in [20]. A DC-DC converter capable of three operating modes is proposed in [21]. A frequency design method for mitigating low-frequency oscillations caused by a post-rectifier DC-DC converter in wireless charging systems is established in [22]. A hybrid control scheme combining phase-shift modulation and switched-capacitor regulation is outlined in [23]. A WPT converter that merges a series half-bridge and an active rectifier is detailed in [24] to reduce switching losses under light and medium loads. A mode-switching phase-shift control method for WPT systems is formulated in [25]. An extended hybrid modulation strategy is proposed in [26]. By expanding the regulation range of phase-shift modulation and applying it synchronously in both inverters and active rectifiers, up to 16 operating modes are enabled to support multi-level constant-current output. A dual-side capacitor-tuning and cooperative control strategy for wireless electric vehicle charging is presented in [27].

Although the above methods can regulate output power within a limited range, system efficiency and soft-switching performance are often compromised. In addition, the power supply demands of loads with different power levels are rarely addressed. Despite extensive research on WPT systems for various loads, most studies focus on simultaneous power supply to multiple loads. These works typically involve multi-transmitter coil arrays, sophisticated primary-side control algorithms, and coordinated operation of multiple inverters.

A WPT system is proposed in [28], which passively reshapes the magnetic field into multiple beams precisely directed toward receivers, allowing a single transmitter coil to power two receivers independently. A novel single-transmitter multi-frequency multi-power WPT system is implemented in [29]. A multi-frequency multi-load magnetically coupled resonant WPT system using a hybrid sinusoidal pulse-width modulation strategy is investigated in [30]. A novel independently regulated multi-output WPT system is introduced in [31], consisting mainly of a single main transmission channel, band-pass filters for each output, and a digital control unit. Each output voltage is regulated by

adjusting the frequency and amplitude of the corresponding frequency component in the digital controller.

In reference [32], a one-to-multiple WPT system with a single-transistor P-type LCC-S compensation network was studied to address the issues of difficult system decoupling and limited effective power reception area caused by uncertain load positions and cross-coupling during the simultaneous charging of multiple loads. Hardware reuse at the transmitter side has been achieved in this study; however, most of the proposed schemes still rely on complex control methods. A novel isolated bidirectional single-input multi-output converter is developed in [33], which supports bidirectional power conversion between one DC port and multiple AC ports. It features electrical isolation between input and output stages and inherent bidirectional power flow capability. An innovative WPT system equipped with a new H6-bridge inverter for multi-output operation is presented in [34], which enables flexible multi-mode functioning of the WPT system. A bridgeless single-inductor multi-output AC-AC converter is proposed in [35], which uses only one inductor in the power stage to generate multiple independent AC output voltages. A multi-output WPT system that integrates a reconfigurable resonant topology and an interactive power transfer mechanism is described in [36], supporting both uniform and relay-assisted power delivery modes to extend the voltage gain range for multi-vehicle charging. A multi-frequency multi-load magnetically coupled resonant WPT system based on cascaded H-bridge multilevel inverters is established in [37]. Using phase-modulated multi-frequency excitation, the system supports arbitrary frequency and quantity combinations by configuring the number, frequency, and amplitude of modulation waves. The WPT system based on a reconfigurable magnetic coupler for AUVs replenishing underwater energy is proposed in [38,39]. A variable-structure dual-frequency dual-load WPT system is designed in [40] for multi-frequency multi-load applications, aiming to overcome unstable voltage, poor load independence, and excessive complexity in conventional constant-current control schemes.

The non-simultaneous demand of loads with different power levels is rarely involved in existing studies. In fact, using the same set of transmitting hardware to achieve compatibility with different receivers and output different power levels can significantly reduce system costs and enhance compatibility across different receivers. The different operating modes of full-bridge inverters and the reuse of primary-side hardware are considered rarely. Further combination with the design of different magnetic coupling mechanisms at receiving side will help expand the multi-power-level output capability of WPT systems.

To solve these problems, a WPT system and a multi-level power output method based on hardware reuse and inverter mode selection at primary side are proposed in this paper. For the WPT system with LCC-S compensation topology, without changing the output connection circuit of inverter, two different output voltage values can be realized only by adjusting the control mode of the full-bridge inverter to operate in full-bridge and half-bridge modes. Combined with two different coils at the receiving end, four different output levels are formed.

Compared with existing methods, the proposed method does not require additional voltage regulation stages to adjust the input or output DC voltage, nor does it need to adjust the duty cycle of the inverter, which helps to ensure that the inverter always operates in a soft-switching state. The main contributions of this paper are as follows. Firstly, the structure of the proposed multi-level power output WPT system is introduced in this paper. Secondly, two inverter control modes, full-bridge output and half-bridge output, for the commonly used full-bridge inverter are studied. Through Fourier decomposition, the expressions of the fundamental output voltage of the inverter and the system output power are derived. Then, a system circuit analysis model of the LCC-S compensation topology is

established, through which the expressions of the final output power and efficiency of the system under the two operating modes of the inverter are derived. Furthermore, combined with two receiving coils of different sizes, a four-level output method of the WPT system is formed. Finally, relevant experiments are designed to achieve four power levels of 405 W, 212 W, 101 W and 51 W, with corresponding efficiencies of 92.6%, 91.5%, 92.3%, and 90.92%, respectively. The correctness and feasibility of the proposed method are verified.

2. Materials and Methods

This chapter begins with an introduction to the circuit structure of the proposed multi-level power output wireless power transfer system. Theoretical derivations are then carried out to establish the relationship between the output voltage of the transmitter-side inverter circuit and the DC input voltage for both full-bridge and half-bridge operating modes. A general compensation circuit model for multi-level power transfer is subsequently developed. Finally, based on the output characteristics of the inverter, the relationships among system output power, efficiency, DC input voltage, mutual inductance between the transmitting and receiving coils, and load resistance are derived for the two inverter operating modes.

2.1. Structure of WPT System with Multi-Level Power Output

The circuit structure of the multi-level power output WPT system proposed in this paper is shown in Figure 1. U_{DC} represents the DC bus voltage. The inverter circuit supports both full-bridge and half-bridge operating modes. U_{in} is the output voltage of the inverter. I_f is the output current of the inverter. The LCC-type compensation circuit on the transmitter side consists of the inductor L_f , capacitor C_p , and capacitor C_f . L_p is the self-inductance of the transmitting coil, with its parasitic resistance denoted as R_p . The self-inductance of the receiving coil is denoted as L_s and its parasitic resistance as R_s , while the mutual inductance between the transmitting coil and the receiving coil is M . To realize the reuse of primary-side hardware for the proposed system with different receiving coils, the secondary side can selectively adopt a larger square coil or a smaller circular coil according to the actual load conditions. Among them, the self-inductances of the square coil and the circular coil are L_{s1} and L_{s2} , respectively, and their parasitic resistances are R_{s1} and R_{s2} , respectively. The mutual inductance between the transmitting coil and the square coil is marked as M_{ps1} , and that between the transmitting coil and the circular coil is M_{ps2} . Diodes D_1 – D_4 constitute an uncontrolled rectifier circuit. C is the filter capacitor. and R_L is the system load.

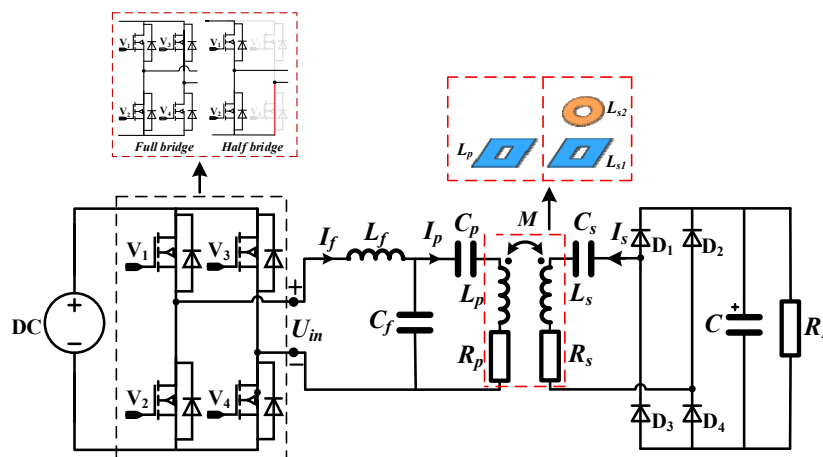


Figure 1. Topology of LCC-S WPT system based on primary-side hardware reuse and inverter mode selection.

The two inverter control modes can be freely combined with the two receiving coils in pairs according to actual conditions. In this way, four different system combinations are formed without changing the circuit connection structure, realizing the reuse of primary-side hardware. The following text will conduct an in-depth study on the two operating modes of the full-bridge inverter circuit and the magnetic coupling mechanisms composed of different receiving coils.

2.2. Analysis of the Operating Modes of Full-Bridge Inverter Circuits

2.2.1. Full-Bridge Mode

Two control modes are designed for the full-bridge inverter circuit in this paper: the full-bridge control mode and the half-bridge control mode. The inverter circuit topology operating in full-bridge mode, along with the inverter's excitation control signals and output voltage waveform, are presented in Figure 2.

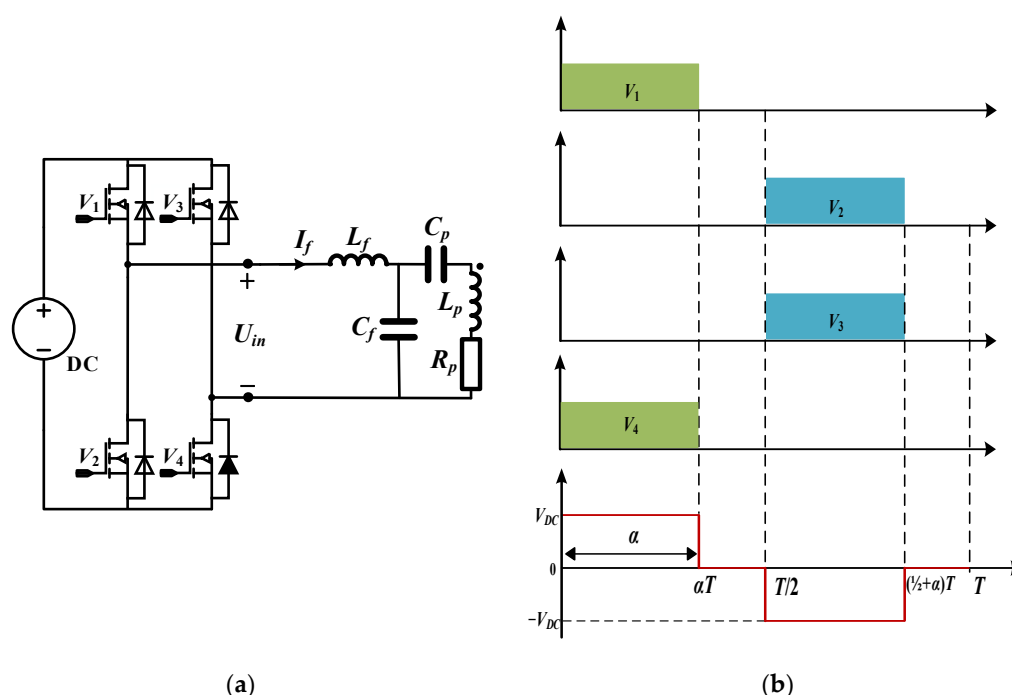


Figure 2. (a) Full-bridge controlled mode; (b) excitation signal and output voltage waveform of full-bridge controlled inverter.

Let the frequency be f and the period be T . When the duty cycle is α , within one period T , during $0 \leq t \leq \alpha T$, thyristors V_1 and V_4 are in the conducting state while thyristors V_2 and V_3 are in the off state; during $T/2 \leq t \leq (1+2\alpha)T/2$, thyristors V_2 and V_3 are in the conducting state while thyristors V_1 and V_4 are in the off state. The magnitude of the output voltage over one period is

$$V_0(t) = \begin{cases} V_{DC} & 0 \leq t \leq \alpha T \\ -V_{DC} & T/2 \leq t \leq (1+2\alpha)T/2 \\ 0 & \text{else} \end{cases} \quad (1)$$

This waveform is a periodic function, and the Fourier series expansion of this waveform is as follows:

$$V_0(t) = a_0 + \sum_{n=1}^{\infty} [a_n \cos(n\omega t) + b_n \sin(n\omega t)] \quad (2)$$

The DC component a_0 is

$$a_0 = \frac{1}{T} \int_0^T V_0(t) dt = 0 \quad (3)$$

The cosine coefficient a_n is

$$a_n = \frac{2}{T} \int_0^T V_0(t) \cos(n\omega t) dt = [1 + (-1)^{n+1}] \cdot \frac{V_{DC}}{\pi n} \sin(2\pi n\alpha) \quad (4)$$

The sine coefficient b_n is

$$b_n = \frac{2}{T} \int_0^T V_0(t) \sin(n\omega t) dt = [1 + (-1)^{n+1}] \cdot \frac{V_{DC}}{\pi n} [1 - \cos(2\pi n\alpha)] \quad (5)$$

Substituting Equations (3)–(5) into Equation (2), we can obtain the result

$$V_0(t) = [1 + (-1)^{n+1}] \cdot \sum_{n=1}^{\infty} \frac{V_{DC}}{\pi n} [\sin(2\pi n\alpha) \cos(n\omega t) + (1 - \cos(2\pi n\alpha)) \sin(n\omega t)] \quad (6)$$

Let $n = 1$, and take the fundamental component only; then, the amplitude of the output voltage is

$$V_p = \frac{2V_{DC}}{\pi} \sqrt{\sin^2(2\pi\alpha) + [1 - \cos(2\pi\alpha)]^2} = \frac{4V_{DC}}{\pi} |\sin(\pi\alpha)| \quad (7)$$

The phase angle of the output voltage is

$$\Phi = \arctan\left(\frac{1 - \cos(2\pi\alpha)}{\sin(2\pi\alpha)}\right) = \pi\alpha \quad (8)$$

Ultimately, the fundamental wave relationship between the inverter output voltage and the grid-side DC voltage under the full-bridge control mode is derived as follows:

$$V_0(t) = \frac{4V_{DC}}{\pi} |\sin(\pi\alpha)| \cdot \cos(\omega t - \pi\alpha) \quad (9)$$

With a duty cycle of 50%, the effective value of the inverter output voltage under the full-bridge control mode is obtained:

$$U_{in} = \frac{2\sqrt{2}V_{DC}}{\pi} \quad (10)$$

2.2.2. Half-Bridge Mode

Figure 3 shows the topology of the inverter circuit operating in half-bridge mode, the excitation control signal of the inverter, and the output voltage waveform of the inverter. When the duty cycle is α , within one cycle T , V_4 remains in the on state and V_3 remains in the off state. In the interval of $0 \leq t \leq \alpha T$, the thyristor V_1 is on and the thyristor V_2 is off; in the interval of $\alpha T \leq t \leq T$, the thyristor V_2 is on and the thyristor V_1 is off. The voltage amplitude of the output voltage within one cycle is as follows.

$$V'_0(t) = \begin{cases} V_{DC} & 0 \leq t \leq \alpha T \\ 0 & \alpha T \leq t \leq T \end{cases} \quad (11)$$

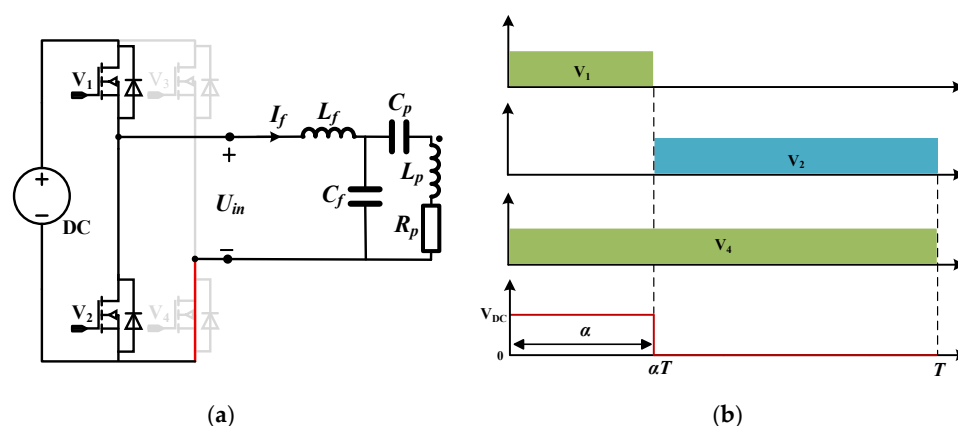


Figure 3. (a) Half-bridge controlled mode; (b) excitation signal and output voltage waveform of half-bridge controlled inverter.

In the same strategy, Fourier decomposition is performed on the waveform, and the final output voltage of the inverter under the half-bridge mode can be obtained as

$$V'_0(t) = \alpha V_{DC} + \sum_{n=1}^{\infty} \frac{V_{DC}}{\pi n} [\sin(2\pi n\alpha) \cos(n\omega t) + (1 - \cos(2\pi n\alpha)) \sin(n\omega t)] \quad (12)$$

Let $n = 1$, and take the fundamental component only; then, the amplitude of the output voltage is

$$V'_p = \frac{V_{DC}}{n} \sqrt{\sin^2(2\pi\alpha) + [1 - \cos(2\pi\alpha)]^2} = \frac{2V_{DC}}{\pi} |\sin(\pi\alpha)| \quad (13)$$

The phase angle of the output voltage is

$$\Phi' = \arctan\left(\frac{1 - \cos(2\pi\alpha)}{\sin(2\pi\alpha)}\right) = \pi\alpha \quad (14)$$

Ultimately, the fundamental wave relationship between the inverter output voltage and the grid-side DC voltage under the half-bridge control mode is derived as follows:

$$V'_0(t) = \frac{2V_{DC}}{\pi} |\sin(\pi\alpha)| \bullet \cos[\omega t - \pi\alpha] \quad (15)$$

With a duty cycle of 50%, the effective value of the inverter output voltage under the full-bridge control mode is obtained:

$$U'_{in} = \frac{\sqrt{2}V_{DC}}{\pi} \quad (16)$$

These equations indicate that the output voltage of the inverter circuit adopting the half-bridge control mode contains both an alternating current (AC) component and a direct current (DC) component. Moreover, the amplitude of the AC component is half of that in the full-bridge control mode, with the phase angles of the two being consistent.

2.3. General Circuit Model for Multi-Level Power Output WPT System

To obtain the electrical characteristic expressions of the multi-level power output WPT system, this section establishes a general circuit model for the multi-level power output WPT system. Based on this model, the general relationships between the inverter output voltage and the parameters of the magnetic coupling mechanism can be derived. Combined with the output voltages under the two operating modes of the inverter and the combination of the two magnetic coupling mechanisms, the relationships between the

electrical characteristics and system parameters under the four output power levels can be finally deduced.

Figure 4 shows the general circuit model of the multi-level power output WPT system constructed in this paper, in which the DC input power supply and the inverter circuit of the WPT system are equivalent to an AC voltage source U_{in} . The influences of the transmitting and receiving coils on each other's circuits can be equivalently represented by a voltage source; the connected load and the rectifier circuit are equivalent to an AC resistance value R_0 , which has the following relationship with the DC equivalent resistance of the battery: $R_L:R_0 = 8R_L/\pi^2$.

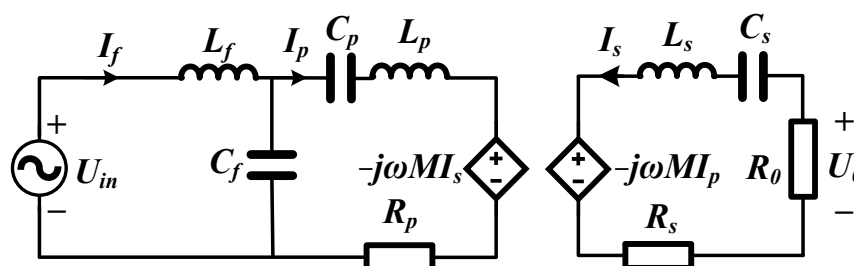


Figure 4. Simplified Diagram 1 of multi-level power output WPT system.

When the system is tuned, it shall satisfy the following relational expressions:

$$\begin{cases} j\omega L_f + \frac{1}{j\omega C_f} = 0 \\ j\omega L_p + \frac{1}{j\omega C_p} + \frac{1}{j\omega C_f} = 0 \\ j\omega L_s + \frac{1}{j\omega C_s} = 0 \end{cases} \quad (17)$$

Using the loop current method, the KVL equations for the equivalent circuit are listed as follows:

$$\begin{cases} U_{in} = \left(j\omega L_f + \frac{1}{j\omega C_f}\right) \cdot I_f - \frac{1}{j\omega C_f} \cdot I_p \\ \left(R_p + \frac{1}{j\omega C_f} + \frac{1}{j\omega C_p} + j\omega L_p\right) \cdot I_p - j\omega M I_s - \frac{1}{j\omega C_f} \cdot I_f = 0 \\ j\omega M I_p - \left(R_s + \frac{1}{j\omega C_s} + j\omega L_s + R_0\right) \cdot I_s = 0 \end{cases} \quad (18)$$

It can be deduced from the relational expressions contained in Equations (17) and (18) that

$$j\omega M I_s = -\frac{(\omega M)^2}{R_s + R_0} I_p \quad (19)$$

According to Equation (19), let $Z_{eq} = \frac{(\omega M)^2}{R_s + R_0}$. The equivalent circuit of the WPT system can be further simplified to that shown in Figure 5.

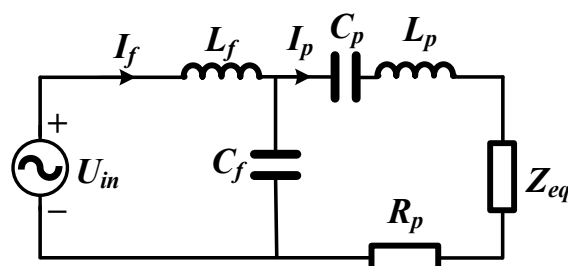


Figure 5. Simplified Diagram 2 of multi-level power output WPT system.

Combined with the respective expressions in Equations (17) and (18), the respective current values of the system can be derived as follows:

$$I_p = \frac{U_{in}}{j\omega L_f}, I_f = \frac{U_{in}(R_p + Z_{eq})}{\omega^2 L_f^2}, I_s = \frac{j\omega M I_p}{R_s + R_0} = \frac{M U_{in}}{(R_s + R_0) L_f} \quad (20)$$

Thus, the equivalent impedance of the system is obtained:

$$Z_{in} = \frac{U_{in}}{I_f} = \frac{\omega^2 L_f^2}{R_p + Z_{eq}} \quad (21)$$

Input power P_{in} and output power P_{out} as well as the transmission efficiency of the system η_{LCC-S} :

$$\begin{cases} P_{in} = \frac{U_{in}^2}{Z_{in}} = \frac{U_{in}^2 (R_p + Z_{eq})}{\omega^2 L_f^2} \\ P_{out} = I_s^2 R_0 = \frac{M^2 U_{in}^2 R_0}{(R_s + R_0)^2 L_f^2} \\ \eta_{LCC-S} = \frac{P_{out}}{P_{in}} = \frac{\omega^2 M^2 R_0}{[R_p (R_s + R_0) + \omega^2 M^2] \cdot (R_s + R_0)} \end{cases} \quad (22)$$

The voltage U_0 across the equivalent AC resistance R_0 and the voltage gain G are

$$U_0 = I_s R_0 = \frac{M R_0 U_{in}}{(R_s + R_0) L_f}, G = \frac{U_0}{U_{in}} = \frac{M R_0}{(R_s + R_0) L_f} \quad (23)$$

When the inverter adopts the full-bridge control mode, the primary and secondary coil currents and the output voltage at this time can be derived from Equations (10), (20) and (23):

$$\begin{cases} I_p = \frac{2\sqrt{2}V_{DC} |\sin(\pi\alpha)|}{j\pi\omega L_f} \\ I_s = \frac{2\sqrt{2}\pi M V_{DC} |\sin(\pi\alpha)|}{(\pi^2 R_s + 8R_L) L_f} \\ U_0(t) = \frac{16\sqrt{2}M R_L V_{DC} |\sin(\pi\alpha)|}{(\pi^3 R_s + 8\pi R_L) L_f} \end{cases} \quad (24)$$

Substituting Equation (10) into Equation (22) and combining the relational expressions between R_0 and R_L , the following relationships can finally be derived between the input power, output power and efficiency of the system under the full-bridge control mode, and the DC input voltage and system load:

$$\begin{cases} P_{in} = \frac{8V_{DC}^2 \cdot [R_p(\pi^2 R_s + 8R_L) + (\pi\omega M)^2]}{(\pi\omega L_f)^2 \cdot (\pi^2 R_s + 8R_L)} \cdot \sin^2(\pi\alpha) \\ P_{out} = \frac{64V_{DC}^2 M^2 R_L}{(\pi^2 R_s + 8R_L)^2 L_f^2} \cdot \sin^2(\pi\alpha) \\ \eta_{LCC-S} = \frac{8(\pi\omega M)^2 R_L}{[R_p(\pi^2 R_s + 8R_L) + (\pi\omega M)^2] \cdot (\pi^2 R_s + 8R_L)} \end{cases} \quad (25)$$

Since the output voltage of the system's inverter circuit in the half-bridge control mode is half of that in the full-bridge mode, the primary and secondary coil currents and the output voltage of the system shall be 0.5 times those in the full-bridge mode, the input and output power shall be 0.25 times that in the full-bridge mode, and the efficiency will be the same as that in the full-bridge mode. The relational expressions are as follows:

$$\begin{cases} I'_p = \frac{1}{2} I_p, I'_s = \frac{1}{2} I_s, U'_0(t) = \frac{1}{2} U_0(t) \\ P'_{in} = \frac{1}{4} P_{in}, P'_{out} = \frac{1}{4} P_{out}, \eta'_{LCC-S} = \eta_{LCC-S} \end{cases} \quad (26)$$

In this way, through the modeling and theoretical calculation of the multi-level power output WPT system, the relational expressions between the relevant parameters (such as output voltage, output power, and efficiency) of the inverter operating in the full-bridge mode and half-bridge mode, respectively, and the input DC voltage, primary and secondary coil parameters, as well as the load, are successfully derived. Then, by substituting the parameters of the two different types of magnetic coupling mechanisms proposed in this section (i.e., the two coil combinations shown in Figure 6), the derivation of the four output power levels is successfully realized.

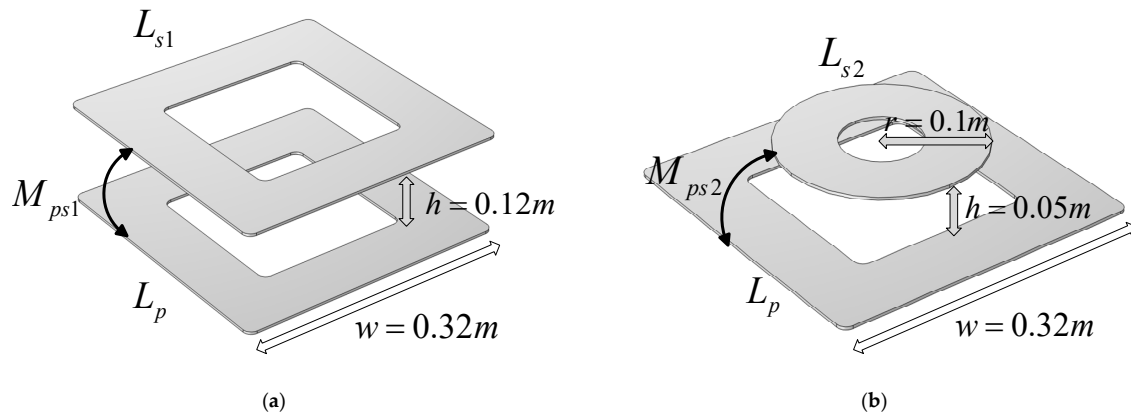


Figure 6. Design of magnetic coupling mechanisms under two combination modes: (a) primary square planar spiral coil and secondary square planar spiral coil; (b) primary square planar spiral coil and secondary circular three-dimensional spiral coil.

3. Results

This chapter begins with an introduction to the magnetic coupling mechanisms of the two combination modes, followed by simulations to determine the mutual inductance for each mode. The system parameters are subsequently substituted into Equations (25) and (26) to obtain the theoretical output characteristics of the four modes. Next, the variations in system output power and efficiency are calculated under lateral offset of the receiving coil and load variation. Finally, the proposed method is validated through experiments.

3.1. Simulation of Multi-Level Power Output Mode

3.1.1. Implementation of the Four Operating Modes

To realize the multi-level power output method proposed in this paper, a three-dimensional simulation model of the WPT system is first established, as shown in Figure 6. Figure 6a shows the combination of a primary square planar spiral coil L_p and a secondary square planar spiral coil L_{s1} , where the two coils have the same parameters: the maximum side length is 32 cm, the number of turns is 23, the turn-to-turn distance is 3 mm, and the transmission distance is 12 cm. Figure 6b shows the combination of a primary square planar spiral coil L_p and a secondary circular three-dimensional spiral coil L_{s2} . The parameters of the primary coil are the same as those in Figure 6a, while the secondary circular coil has 20 turns, a radius of 10 cm, and a turn-to-turn distance of 3 mm. Other parameters of the system are listed in Table 1.

When a combination of a square transmitting coil and a square receiving coil is adopted, with the distance between the transmitting and receiving coils set to 11 cm, the mutual inductance M_{ps1} between the coils is found to be 39.814 μH and the internal resistance R_p 0.367 Ω via simulation. When a combination of a square transmitting coil and a circular receiving coil is adopted, with the distance between the transmitting and receiving coils set to 5 cm, the mutual inductance M_{ps2} between the coils is obtained as 27.162 μH and the internal resistance R_p 0.147 Ω through simulation.

Table 1. System parameter.

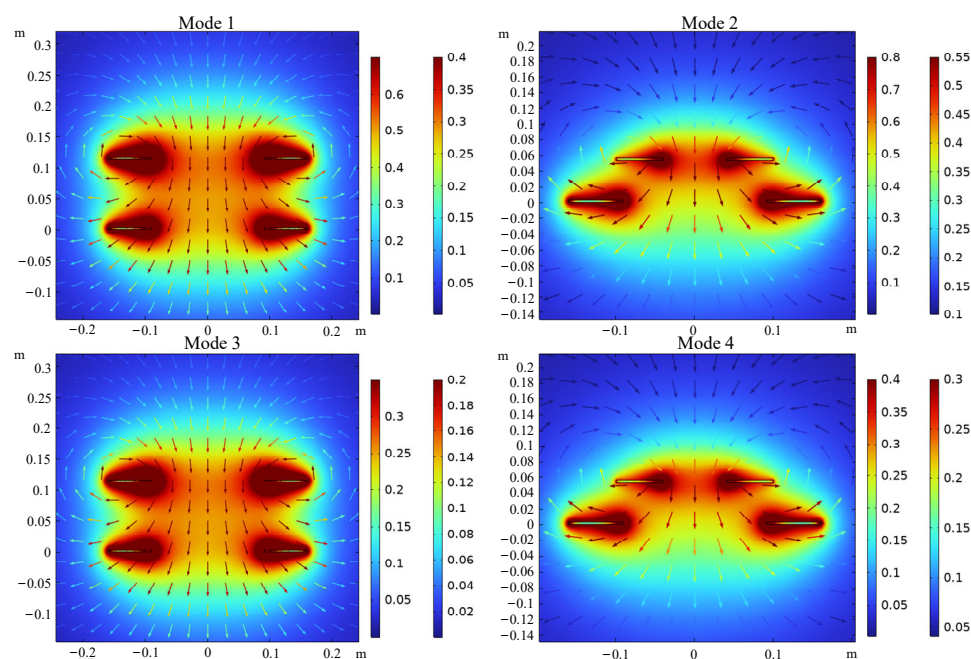
System Parameters	Parameter Values
DC-side Voltage	80 V
System Operating Frequency	100 kHz
Inductance of Square Coil	209.35 μ H
Resistance of Square Coil	0.367 Ω
Inductance of Circular Coil	60.702 μ H
Resistance of Circular Coil	0.147 Ω
Load Resistance	30 Ω
Inductance L_f	27.75 μ H

The four operating modes of the WPT system are defined as follows. Mode 1: the inverter circuit operates in the full-bridge control mode with a square receiving coil. Mode 2: the inverter circuit operates in the full-bridge control mode with a circular receiving coil. Mode 3: the inverter circuit operates in the half-bridge control mode with a square receiving coil. Mode 4: the inverter circuit operates in the half-bridge control mode with a circular receiving coil. With the duty cycle α set to 50%, the simulation-derived data are substituted into Equations (24)–(26). The input–output power, primary and secondary coil currents and system efficiency of the system under each combination can be obtained through calculations, as shown in Table 2.

Table 2. System current, power and efficiency under four operating modes.

Operating Mode	I_p (A)	I_s (A)	P_{in} (W)	P_{out} (W)	$\eta/\%$
Mode 1	4.131	4.187	439.00	426.17	97.078
Mode 2	4.131	2.882	209.43	201.95	96.426
Mode 3	2.066	2.093	109.75	106.54	97.075
Mode 4	2.066	1.441	52.36	50.49	96.423

The magnetic field distribution nephograms of the four modes are shown in Figure 7, where the left color legend represents the magnetic flux density magnitude on the surface and the right color legend represents the magnetic flux density of the arrows on the surface.

**Figure 7.** Magnetic field distribution nephograms under four modes.

3.1.2. Analysis of Output Power and Efficiency Characteristics of the System

The following analysis investigates the changes in the output characteristics of the system under the four modes when the receiving coil undergoes lateral offset. By subjecting the receiving coil to lateral offset, the variation curves of the system's output power and efficiency with the coil offset degree under the four modes are obtained as shown in Figures 8 and 9.

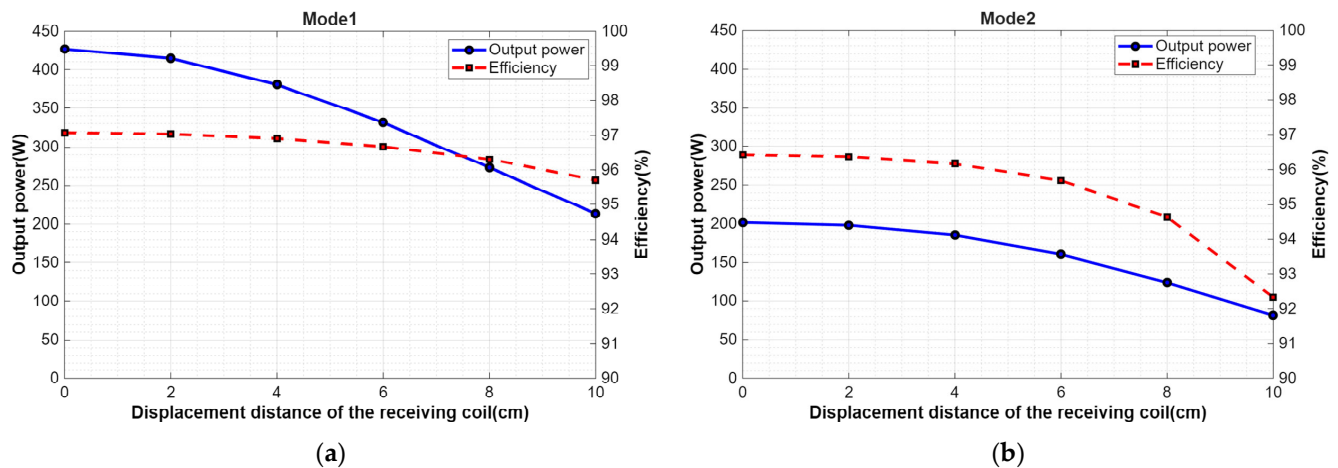


Figure 8. Receiving power and efficiency of the system versus horizontal displacement of the square receiving coil: (a) inverter operating in full-bridge mode; (b) inverter operating in half-bridge mode.

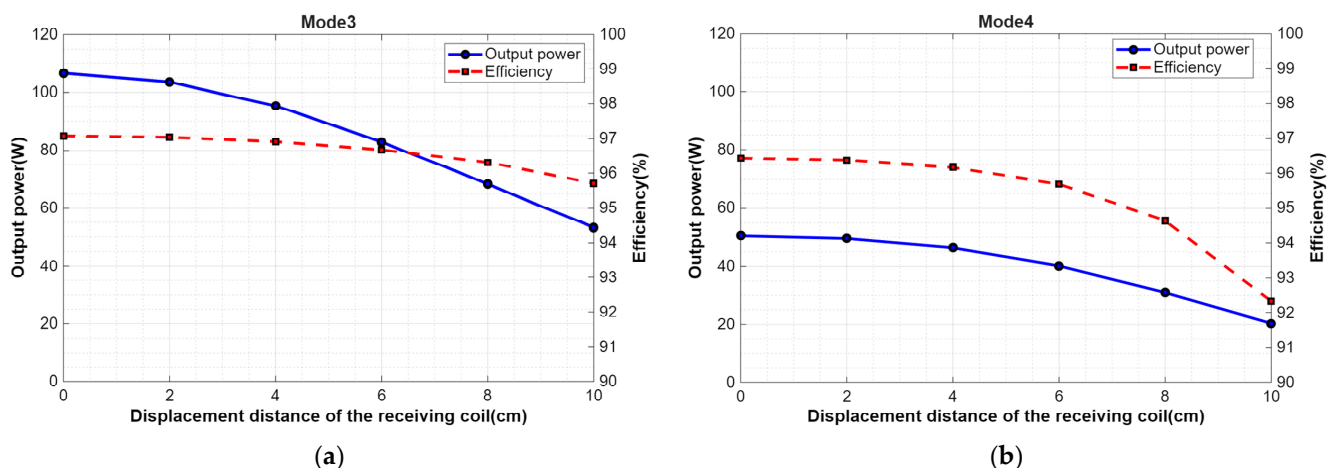


Figure 9. Receiving power and efficiency of the system versus horizontal displacement of the circular receiving coil: (a) inverter operating in full-bridge mode; (b) inverter operating in half-bridge mode.

The following presents the variation curves of the output power and efficiency of the system under four modes with respect to the coil offset distance when the load resistance changes. The load resistance is varied from $20\ \Omega$ to $40\ \Omega$ with a step of $5\ \Omega$. The variation curves of the output power and efficiency of the system under four modes with respect to the load change are shown in Figures 10 and 11.

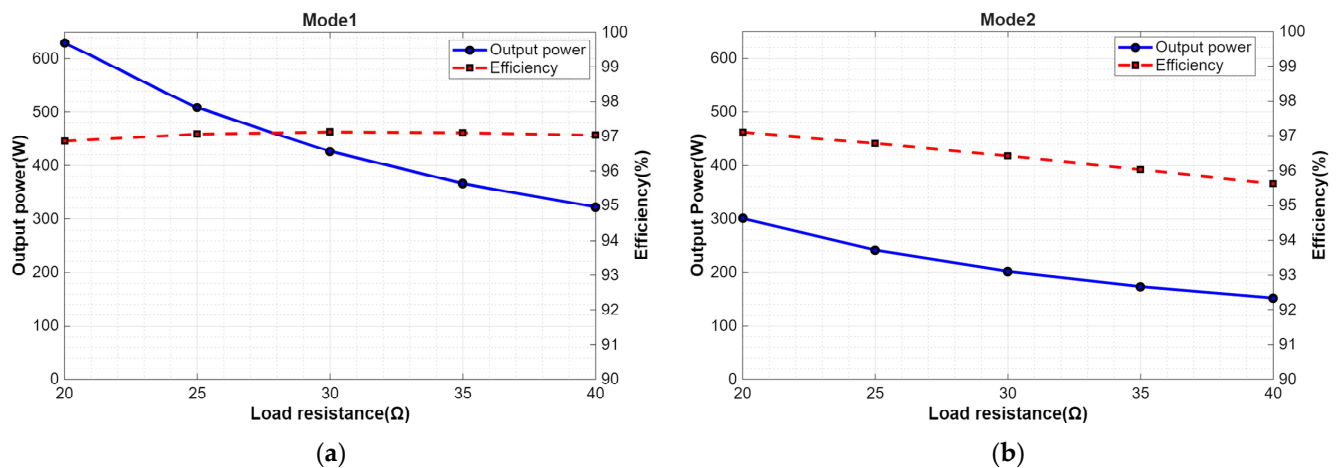


Figure 10. Receiving power and efficiency of the system versus load variation when the receiving end is a square coil: (a) inverter operating in full-bridge mode; (b) inverter operating in half-bridge mode.

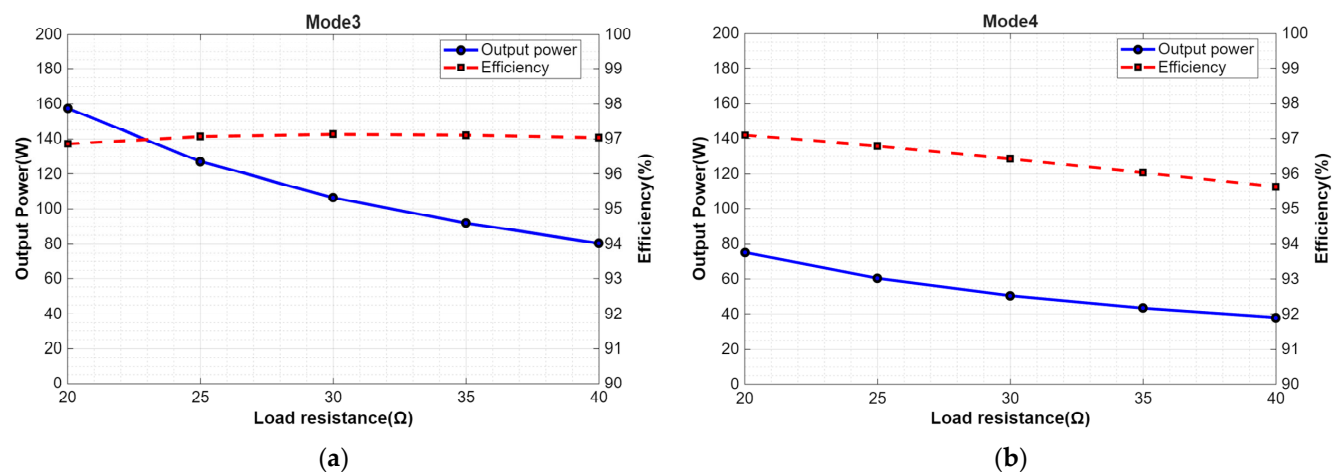


Figure 11. Receiving power and efficiency of the system versus load variation when the receiving end is a circular coil: (a) inverter operating in full-bridge mode; (b) inverter operating in half-bridge mode.

3.2. Experimental Verification

To validate the aforementioned theoretical investigations, an experimental prototype of a multi-output mode wireless power transfer (WPT) system based on transmitter hardware multiplexing and inverter mode selection is established in this paper, as illustrated in Figure 12. The hardware-multiplexed transmitter is configured with a DC power supply, a dual-mode full-bridge inverter, an LCC compensation network, and a transmitting coil. Specifically, the full-bridge inverter is constructed using four MOSFETs (IRFP4227PBF, Infineon Technologies AG, Munich, Germany) (IRFP4227PBF), while a digital signal processor (TMS320F28335, Texas Instruments, Dallas, TX, USA) is employed as the core controller to generate four-channel driving signals. The WPT system is operated at a fixed resonant frequency of 100 kHz, with the DC input voltage of the inverter set to 80 V. For the receiver side, two types of receiving coils (i.e., square coil and circular coil, as depicted in Figure 13) are designed, each matched with a dedicated compensation circuit. Furthermore, the receiver subsystem is integrated with a full-bridge rectifier consisting of four diodes (DSEP15-06A, IXYS, Lampoldshausen, Germany) and a programmable DC electronic load for load characteristic simulation and output performance testing.

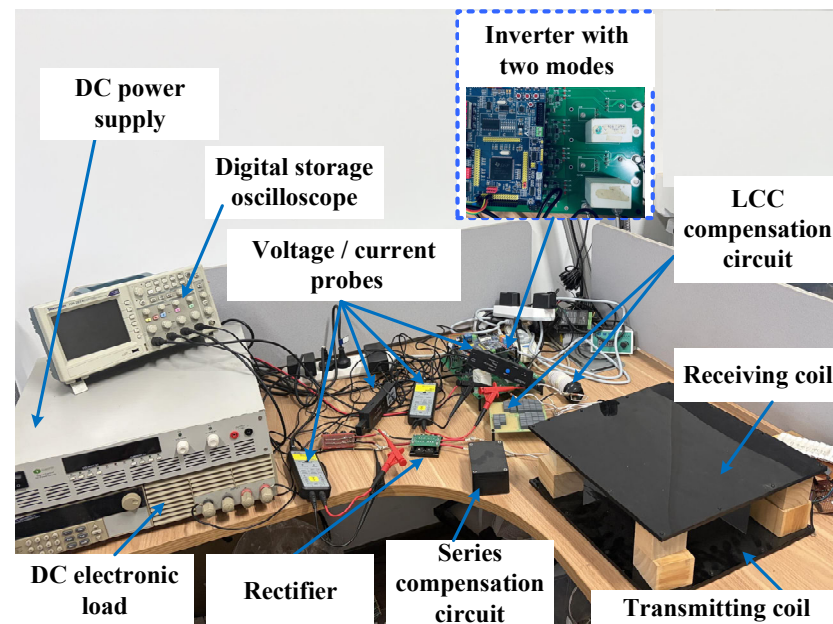


Figure 12. Experimental prototype of multi-output mode wireless power transfer system.

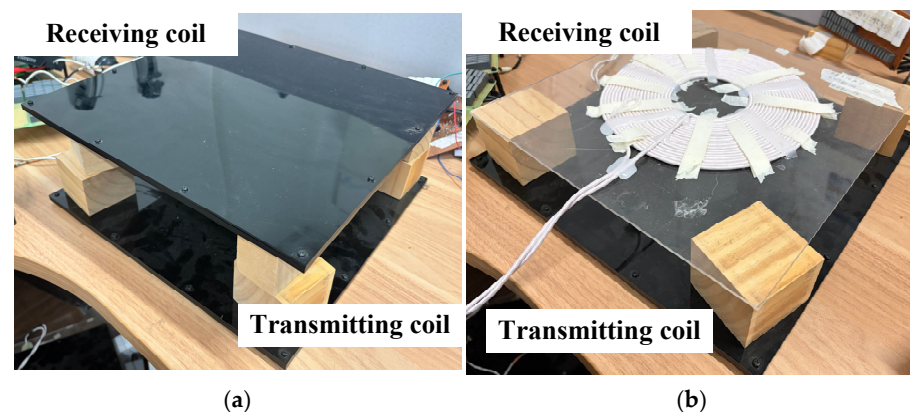


Figure 13. Magnetically coupled mechanism: (a) square receiving coil; (b) circular receiving coil.

After the magnetically coupled mechanism was wound according to the parameters listed in Table 1, the inductance of each coil was measured. The inductance of the transmitting coil is $203.18 \mu\text{H}$, with an internal resistance of 0.18Ω . The inductance of the square receiving coil is $201.31 \mu\text{H}$, with an internal resistance of 0.18Ω . The inductance of the circular receiving coil is $58.52 \mu\text{H}$, with an internal resistance of 0.074Ω .

In the LCC compensation circuit adopted by the multiplexed transmitter, the parameters are $L_f = 27.75 \mu\text{H}$, $C_f = 91.3 \text{ nF}$, and $C_p = 14.5 \text{ nF}$. Both optional receiving coils employ a series capacitor compensation topology. The compensation capacitor for the square receiving coil is 12.5 nF , and that for the circular receiving coil is 43.2 nF .

Based on the aforementioned theoretical analysis, the transmitter-side inverter can operate in either full-bridge or half-bridge inversion mode by controlling the operating states of the four switching devices. The switching between full-bridge and half-bridge modes of the inverter is realized only through control of the switching devices, without altering the connection of the actual hardware circuit. Combined with differently designed receiving terminals, multi-level power output based on transmitter-side hardware multiplexing and inverter mode switching is thus achieved.

For the larger receiving coil, different operating modes of the transmitter-side inverter are adopted. Under the condition that the load resistance is 30Ω , the position of the

receiving coil is varied, and the DC voltage and current at the input side of the inverter as well as the rectified DC voltage and current at the load side are measured. The characteristic curves of the received power and the system DC-DC efficiency varying with the receiver position for the system with the larger receiving coil are obtained, as shown in Figure 14.

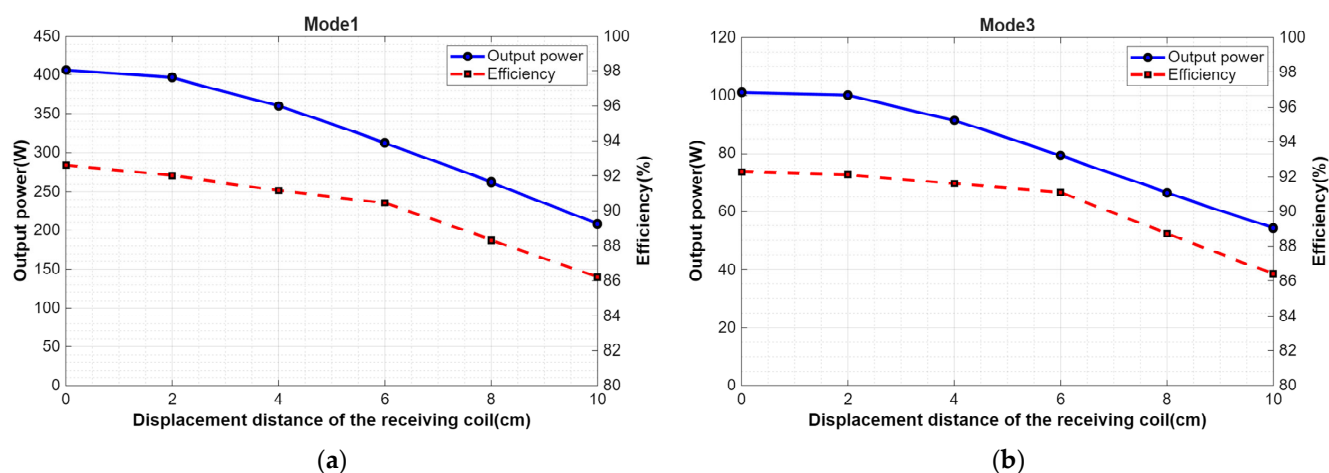


Figure 14. Characteristic curves of the received power and system DC-DC efficiency varying with the receiver position for the system with the larger receiving coil: (a) transmitter-side inverter operating in full-bridge mode; (b) transmitter-side inverter operating in half-bridge mode.

The waveforms of the output voltage U_{in} and output current I_f of the transmitter-side inverter, together with the load voltage U_{out-DC} and current I_{out-DC} at the receiving end, under the aligned position for the two operating modes corresponding to the larger receiving coil, are illustrated in Figure 15.

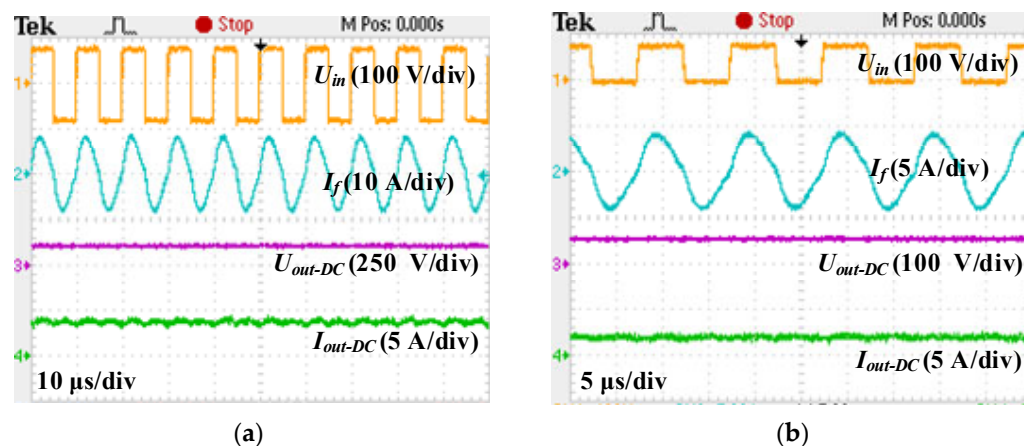


Figure 15. Waveforms of the transmitter-side inverter output voltage U_{in} , output current I_f , and the receiver-side load voltage U_{out-DC} and current I_{out-DC} at the aligned position with the large receiving coil: (a) transmitter-side inverter operating in full-bridge mode; (b) transmitter-side inverter operating in half-bridge mode.

For the smaller receiving coil, different operating modes of the transmitter-side inverter are also adopted. Under a load resistance of 30 Ω , the position of the receiving coil is varied, and the DC voltage and current at the input side of the inverter as well as the rectified DC voltage and current at the load side are measured. The characteristic curves of the received power and the system DC-DC efficiency varying with the receiver position for the system with the smaller receiving coil are obtained, as shown in Figure 16. Figure 17 shows the waveforms of the transmitter-side inverter output voltage U_{in} , output current I_f , and

the receiver-side load voltage U_{out-DC} and current I_{out-DC} at the aligned position for the two operating modes corresponding to the small receiving coil.

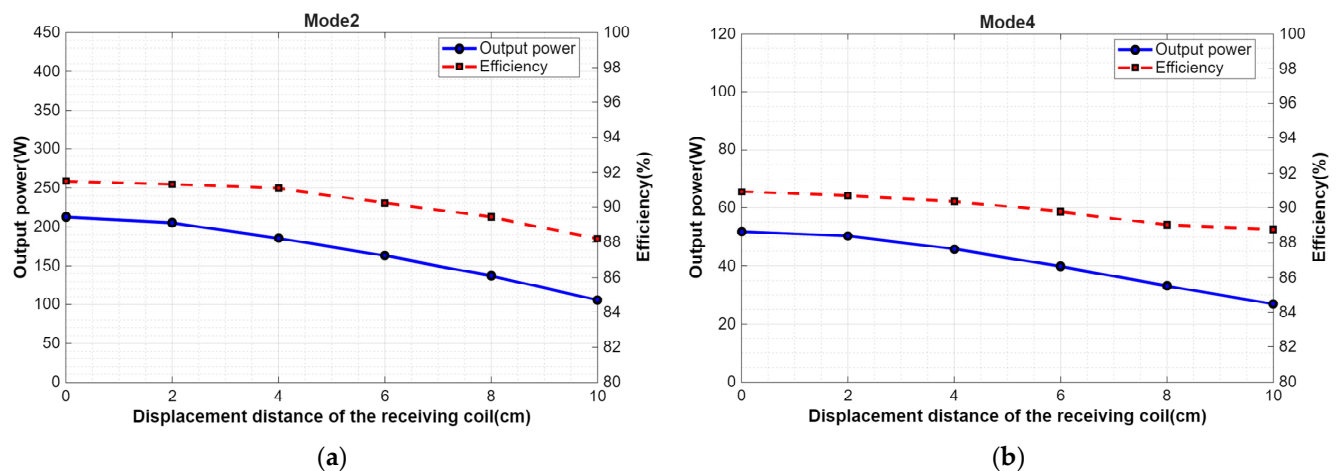


Figure 16. Characteristic curves of system-received power and system DC-DC efficiency versus receiver position for a smaller receiving coil: (a) transmitter inverter operating in full-bridge mode; (b) transmitter inverter operating in half-bridge mode.

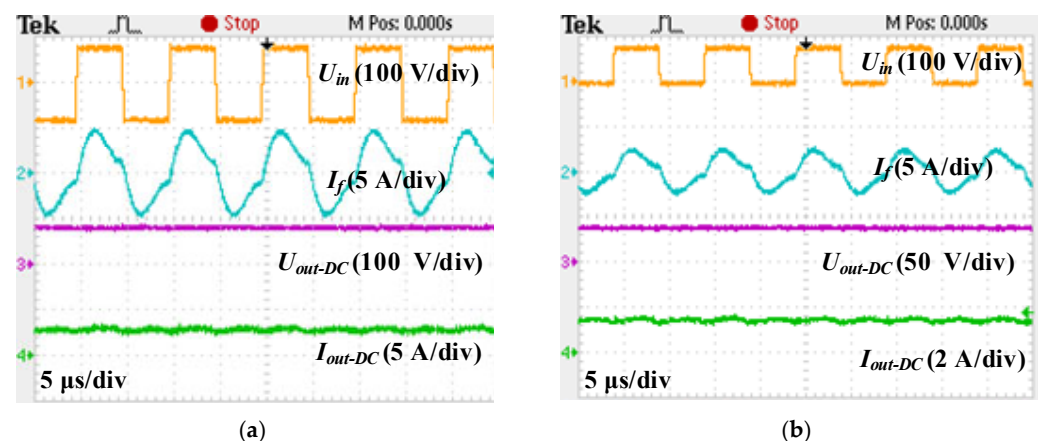


Figure 17. Waveforms of the transmitter inverter output voltage U_{in} and output current I_f , as well as the receiver load voltage U_{out-DC} and current I_{out-DC} at the position where the small receiving coil is aligned face-to-face: (a) transmitter inverter operating in full-bridge mode; (b) transmitter inverter operating in half-bridge mode.

4. Discussion

Through simulation of the output characteristics of the multi-level power magnetic coupling mechanism, it can be seen from Table 2 that the output powers of the system under the four modes are defined as the first, second, third and fourth power levels, respectively. That is, the WPT system under the four combinations can achieve the above four levels of power output separately, with no overload of the primary and secondary currents and a relatively high system efficiency.

As can be observed from Figures 8 and 9, both the output power and efficiency of the system under all four modes decrease with the increase in the lateral offset of the receiving coil. Among them, for Mode 1 and Mode 3, the system efficiency is less affected by the coil offset degree, and remains high when the lateral offset of the receiving coil is less than or equal to 10 cm. For Mode 2 and Mode 4, the system's output power is significantly affected by the coil offset degree, and the influence of coil offset degree on system efficiency

is greater than that on Mode 1 and Mode 3. The system efficiency can be maintained stably when the lateral offset of the receiving coil is less than or equal to 10 cm.

A similar trend is depicted in Figures 10 and 11, where the output power of the system under the four modes decreases with the increase in the lateral misalignment of the receiving coil. For Mode 1 and Mode 3, the system efficiency varies slightly with the resistance, and shows a slight downward trend with the increase in resistance. For Mode 2 and Mode 4, the system efficiency decreases with the increase in resistance when the load reaches 40 Ω , and the output efficiency under the four modes can be maintained at a high level when the load varies in the range of 20 Ω to 40 Ω .

As is shown in Figures 14–17, the experiments verify the effectiveness of the multi-level power output method for the wireless power transfer system proposed in this paper, which is based on transmitter hardware reuse and inverter mode switching. Without changing the hardware circuit connections at the transmitter, four different levels of power output are achieved only by controlling the switching devices of the transmitter inverter. The maximum received powers under different modes are 405 W, 212 W, 101 W and 51 W, respectively. The corresponding system DC-DC efficiencies are 92.6%, 91.5%, 92.3%, and 90.92%, respectively.

By comparing theoretical calculations with experimental results, Table 3 presents a comparison of the theoretical and experimental output power variations with the receiver coil offset under four modes. It can be observed that, for all four modes and at each offset position, the actual output power values are consistent with the theoretical calculations, with the discrepancies within a controllable range. Table 4 presents a comparison of the efficiency variations with the receiver coil offset under four modes between theoretical and experimental results. It can be seen that, for all four modes and at each offset position, the actual efficiencies are slightly lower than the theoretical calculations. This is because, under the conditions of theoretical calculations, the additional impedances of the components in the resonant circuit are simplified, and the switching losses of controllable elements in the inverter and rectifier are neglected. Additionally, there are minor differences between the actual component parameters used in the experiment and the simulation parameters. Nevertheless, the experimentally measured system efficiency can still be maintained above 90% under aligned conditions, demonstrating the feasibility of the proposed method.

Table 3. Comparison between experimental and theoretical output power of the system under different misalignment degrees of the receiving coil (the horizontal axis represents the offset distance of the receiving coil relative to the center position).

Mode 1	0 cm	2 cm	4 cm	6 cm	8 cm	10 cm
Theoretical	426.17 W	414.31 W	380.84 W	331.38 W	273.12 W	213.00 W
Experimental	405.83 W	396.37 W	360.24 W	312.53 W	262.17 W	208.20 W
Mode 2	0 cm	2 cm	4 cm	6 cm	8 cm	10 cm
Theoretical	201.95 W	198.24 W	185.39 W	160.43 W	123.70 W	81.34 W
Experimental	212.02 W	205.12 W	185.24 W	162.53 W	137.17 W	105.60 W
Mode 3	0 cm	2 cm	4 cm	6 cm	8 cm	10 cm
Theoretical	106.54 W	103.58 W	95.21 W	82.85 W	68.28 W	53.25 W
Experimental	101.02 W	100.15 W	91.41 W	79.33 W	66.46 W	54.21 W
Mode 4	0 cm	2 cm	4 cm	6 cm	8 cm	10 cm
Theoretical	50.49 W	49.56 W	46.35 W	40.11 W	30.93 W	20.33 W
Experimental	51.98 W	50.38 W	45.74 W	39.78 W	33.25 W	26.76 W

Table 4. Comparison between experimental and theoretical efficiency of the system under different misalignment degrees of the receiving coil (the horizontal axis represents the offset distance of the receiving coil relative to the center position).

Mode 1	0 cm	2 cm	4 cm	6 cm	8 cm	10 cm
Theoretical	97.08%	97.04%	96.91%	96.69%	96.31%	95.71%
Experimental	92.60%	92.02%	91.19%	90.46%	88.35%	86.21%
Mode 2	0 cm	2 cm	4 cm	6 cm	8 cm	10 cm
Theoretical	96.43%	96.37%	96.17%	95.69%	94.64%	92.33%
Experimental	91.50%	91.32%	91.09%	90.23%	89.43%	88.21%
Mode 3	0 cm	2 cm	4 cm	6 cm	8 cm	10 cm
Theoretical	97.08%	97.04%	96.91%	96.69%	96.31%	95.71%
Experimental	92.30%	92.12%	91.59%	91.10%	88.72%	86.42%
Mode 4	0 cm	2 cm	4 cm	6 cm	8 cm	10 cm
Theoretical	96.43%	96.37%	96.17%	95.69%	94.64%	92.33%
Experimental	90.92%	90.68%	90.37%	89.78%	89.02%	88.78%

5. Conclusions

A multi-level power output method for wireless power transfer systems based on transmitter hardware reuse and inverter mode switching is proposed in this paper, aiming to address the problems of complex hardware structure and high control difficulty in traditional multi-power systems. Based on the LCC-S compensation topology, the same set of transmitter hardware is reused in the proposed method, and the full-bridge inverter is only switched between full-bridge and half-bridge control modes. Combined with two receiving coils of different sizes, four different system operating combinations are flexibly formed. The expressions for the output voltage, primary and secondary coil currents, input–output power and efficiency under full-bridge and half-bridge control modes are derived through modeling and calculation of the WPT system. Under constant DC input voltage and fixed duty cycle, four-level power output is achieved. In addition, high efficiencies are still retained when lateral offset occurs in the receiving coil. The experimental prototype of the wireless charging system with the multi-level power output based on hardware reuse and inverter mode selection at primary side is designed and built. Four different levels of power output are achieved. The maximum receiving power values of each output power are 405 W, 212 W, 101 W and 51 W, respectively, while the efficiencies are 92.6%, 91.5%, 92.3%, and 90.92%, respectively.

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