

Article

Coordinated Control of Constant Output Voltage and Maximum Efficiency in Wireless Power Transfer Systems

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Abstract: This article presents a coordinated control method used for wireless power transfer (WPT) systems. This method can improve WPT system transmission efficiency while maintaining the constant output voltage. First, the topology of the DC–DC converter is selected and the equivalent circuit model of the WPT system is established. Then, the WPT system characteristics are discussed and the mutual inductance estimation process is presented. Furthermore, the coordinated control method is proposed, where the constant voltage output is achieved by connecting the Buck–Boost converter after the diode rectifier. Meanwhile, the optimal phase shift angle is calculated and sent to the controller to achieve maximum transmission efficiency tracking control, according to the measured load voltage and current. Finally, simulations and experiments are adopted to verify the proposed coordinated control method. The experimental results indicate that the average system transmission efficiency is increased by 1.80% and the efficiency fluctuation is decreased by 2.67% when the system load resistance varies, while the average system transmission efficiency is increased by 1.80%, and the efficiency fluctuation is decreased by 3.14% when the mutual inductance changes. This means the proposed coordinated control method is effective under the conditions of the WPT load and mutual inductance variations.

Keywords: wireless power transfer; coordinated control; Buck–Boost converter; constant voltage output; maximum efficiency tracking



Citation: Wang, X.; Guo, Y.; Wang, R.; Zhang, Y. Coordinated Control of Constant Output Voltage and Maximum Efficiency in Wireless Power Transfer Systems. *Appl. Sci.* **2024**, *14*, 6546. <https://doi.org/10.3390/app14156546>

Academic Editor: Andreas Sumper

Received: 22 June 2024

Revised: 19 July 2024

Accepted: 24 July 2024

Published: 26 July 2024



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1. Introduction

With the continuous advancement of science and technology, the degree of electrification within human society continues to deepen, and the utilization of electric energy has infiltrated every aspect of daily life [1]. Consequently, the modes of electricity transmission are evolving rapidly. In recent years, wireless power transfer (WPT) has been increasingly applied in domains such as underwater operations, consumer electronics, and modern medicine [2–7], owing to its superior flexibility and convenience. Nonetheless, this technology encounters several challenges, particularly when system loads fluctuate or the mutual inductance between coils varies. These variations can negatively impact the system output voltage [8–10] and transmission efficiency [11,12]. Therefore, researchers have proposed various methods to improve the system efficiency under the conditions of load and mutual inductance variations.

To maintain the constant system output voltage, the method of cascading DC–DC converter at the input or output of the WPT system is usually adopted [13,14]. Sun et al., from Chongqing University in China, connected a DC–DC converter at the input of the WPT system, and a method was proposed to adjust the output voltage by varying the duty cycle of the Buck converter connected to the system input [15]. However, this method relies heavily on the accuracy of the identification algorithm and necessitates high sampling

precision. The authors of [16,17] describe an alternative approach where a DC–DC converter is connected to the output of the WPT system. The method adopts a Proportional–Integral (PI) controller to maintain constant current (CC) charging for the variable load.

In addition, some methods without DC–DC converters have been proposed. The authors of [18] introduce a battery charging control strategy that needs no bilateral communication and an additional DC–DC converter. This approach achieves constant current output or constant voltage (CV) output regardless of load and position changes through phase shift control. Moreover, a prototype is built to demonstrate the CC/CV output over a transmission distance of 10–25 cm. The authors of [19] propose a strategy for pre-control calibration, in which the system mutual inductance is detected during the calibration stage, and the system output voltage is estimated in real time based on this mutual inductance value. Then, the output voltage is adjusted through the phase shift control of the inverter. The authors of [20] introduce a phase shift control method for a half-bridge rectifier and derive the equivalent impedance related to the phase shift angle of the half-bridge rectifier. This method allows for the adjustment of the system output voltage without DC–DC converters.

At the same time, some methods have been proposed to improve the transmission efficiency of the WPT system during mutual inductance and load changes. Yang et al., from the University of Hong Kong, propose a discrete sliding mode control for a series–series-compensated WPT system, enabling rapid maximum efficiency tracking and output voltage regulation [21]. In [22,23], a control method by adjusting the phase shift angle of the active rectifier was proposed for real-time maximum efficiency tracking. The method can adjust the equivalent load impedance and output voltage to solve the efficiency reduction problem caused by load changes.

This article proposes a control method for the WPT system, focusing on improving transmission efficiency while maintaining a constant output voltage. First, a Buck–Boost converter is cascaded after the diode rectifier of the WPT system to achieve a constant voltage output. Then, the output voltage of the rectifier is measured to estimate the mutual inductance and calculate the optimal phase shift angle for maximum efficiency tracking. Finally, the value of the optimal phase shift angle is sent to the controller of the WPT primary side to improve the system transmission efficiency. A method for constant voltage charging of battery-type loads is proposed in this article, while simultaneously achieving maximum efficiency tracking control of the WPT system. It can significantly improve system transmission efficiency. Additionally, the short feedback control loop minimizes the delay time, thus enabling a quick and stable output for the WPT systems. This article is organized as follows. Section 2 presents a coordinated control method of constant voltage output and system transmission efficiency. Section 3 provides the simulation analysis of the proposed method. Section 4 gives the experimental verifications and discussions. Finally, Section 5 presents the conclusion.

2. Models and Methods

To address the impact of mutual inductance variation on the output voltage, a DC–DC converter is cascaded after the diode rectifier of the WPT system to achieve constant voltage output. The adjustment ranges of the input resistance and output voltage of DC–DC converters with different topologies are shown in Table 1, where R_L is the load resistance; U_{in} is the DC–DC converter input voltage; and D is the duty cycle.

Table 1. Input resistance and output voltage adjustment ranges of the typical DC–DC converters.

Topology	Output Voltage	Input Resistance
Buck	DU_{in}	R_L/D^2
Boost	$U_{in}/(1-D)$	$(1-D)^2 R_L$
Buck–Boost	$DU_{in}/(1-D)$	$(1-D)^2 R_L/D^2$

Table 1 indicates that the Buck–Boost converter has a wider range of output voltage regulation and input resistance regulation, compared to the Buck converter and Boost converter. A larger range of output voltage regulation means that constant voltage output can be achieved within a wider range of the mutual inductance variation. Therefore, a Buck–Boost DC–DC converter is adopted in this article.

Figure 1 illustrates the schematic diagram of the proposed WPT system with a cascaded Buck–Boost converter, where U_{dc} is the DC input voltage source; L_1 , L_2 , and M are the self-inductances and mutual inductance of the coupling coils; R_1 and R_2 are the resistances of the coils; the primary side LCC compensation network includes the inductance L_{p1} , the parallel capacitance C_{p1} , and the series capacitance C_{p2} ; C_{s1} is the secondary side compensation capacitance; L_f and C_o are the inductance and the output capacitance of the Buck–Boost converter; R_L is the system load resistance; G_1 – G_4 constitute the full-bridge inverter; D_1 – D_4 constitute the full-bridge rectifier; S and VD are the MOSFET and diode of the Buck–Boost converter, respectively; i_{Lp1} , i_{L1} and i_{L2} are the inverter output current, the current in the transmit coil and receive coil, respectively; u_{inv} is the equivalent output voltage of the inverter; U_f is the voltage across the rectifier output capacitance C_f ; U_{out} and I_{out} are the voltage and current of the system load; and φ_{opt} is the calculated optimal phase shift angle.

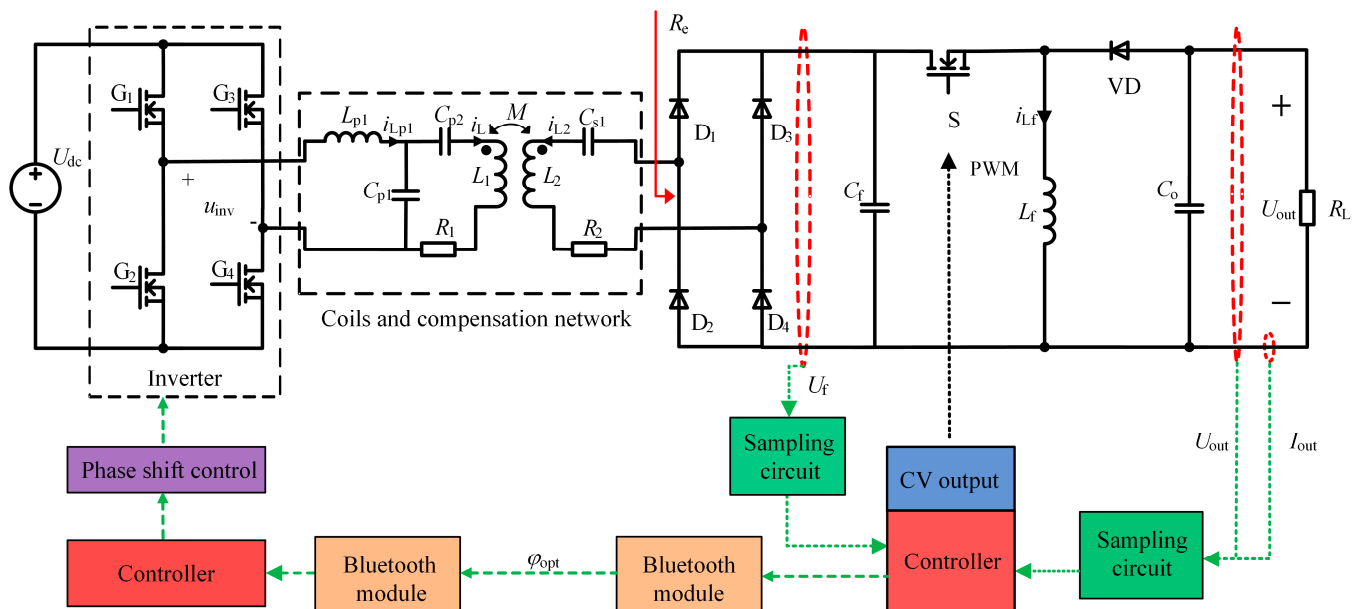


Figure 1. Schematic diagram of the WPT system with cascaded Buck–Boost converter and the presented coordinated control method.

First, the RMS value of the inverter equivalent output voltage U_{inv} can be given by (1), where φ is the phase shift angle of the inverter.

$$U_{inv} = \frac{2\sqrt{2}}{\pi} U_{dc} \cos\left(\frac{\varphi}{2}\right) \quad (1)$$

Then, the components after the secondary side compensation capacitance C_{s1} are equivalent to an equivalent resistance R_e . Therefore, the WPT equivalent circuit model with the LCC-S compensation network can be obtained and shown in Figure 2, where u_{rec} is the rectifier input voltage, and the expression of R_e is given by (2).

$$R_e = \frac{8}{\pi^2} \left(\frac{U_f}{U_{out}} \right)^2 R_L \quad (2)$$

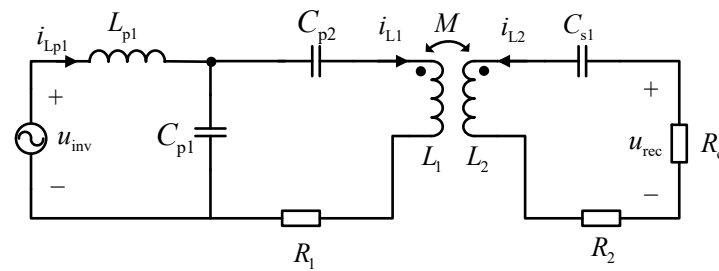


Figure 2. WPT equivalent circuit model with LCC-S compensation network.

According to the WPT equivalent circuit model in Figure 2, the KVL equation is given by (3), where ω is the system operation angular frequency.

$$\begin{cases} u_{\text{inv}} = j\omega L_{p1}i_{Lp1} + \left(j\omega L_{L1} + \frac{1}{j\omega C_{p2}} + R_1\right)i_{L1} + j\omega M i_{L2} \\ u_{\text{inv}} = j\omega L_{p1}i_{Lp1} + \frac{1}{j\omega C_{p1}}(i_{Lp1} - i_{L1}) \\ -j\omega M i_{L1} = \left(j\omega L_2 + \frac{1}{j\omega C_{s1}} + R_e + R_2\right)i_{L2} \end{cases} \quad (3)$$

In the LCC-S compensated topology of the WPT system, the primary side and secondary side are typically in the resonant states, which means $\omega L_{p1} = 1/\omega C_{p1} = \omega L_1 - 1/\omega C_{p2}$ and $\omega L_2 = 1/\omega C_s$. Under the resonant conditions, the inverter output current i_{Lp1} , the rectifier input voltage u_{rec} , and the current in the transmit coil i_{L1} can be calculated based on the KVL equation and given by (4).

$$\begin{cases} i_{Lp1} = \frac{(\omega^2 M^2 + R_1 R_2 + R_1 R_e)u_{\text{inv}}}{\omega^2 L_p^2 (R_2 + R_e)} \\ u_{\text{rec}} = \frac{\omega M u_{\text{inv}}}{\omega L_{p1} (R_2 + R_e)} \\ i_{L1} = \frac{u_{\text{inv}}}{j\omega L_{p1}} \end{cases} \quad (4)$$

Moreover, according to the above equations, the output power P_{out} and the input power P_{in} can be given by (5).

$$\begin{cases} P_{\text{in}} = \frac{(\omega^2 M^2 + R_1 R_2 + R_1 R_e)}{(R_2 + R_e)\omega^2 L_{p1}^2} U_{\text{inv}}^2 \\ P_{\text{out}} = \frac{R_e M^2}{L_{p1}^2 (R_e + R_2)^2} U_{\text{inv}}^2 \end{cases} \quad (5)$$

Therefore, the expression of the system transmission efficiency η can be derived as

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{\omega^2 M^2 R_e}{(R_e + R_2)(\omega^2 M^2 + R_1 R_2 + R_1 R_e)} \quad (6)$$

By solving the derivative of η over R_e , the optimal load condition can be obtained from (7) in order to achieve the maximum transmission efficiency.

$$\begin{cases} \frac{d\eta}{dR_e} = 0 \\ \frac{d^2\eta}{dR_e^2} < 0 \end{cases} \rightarrow R_{e_ \eta \text{max}} = \sqrt{\omega^2 M^2 \frac{R_2}{R_1} + R_2^2} \quad (7)$$

Furthermore, the transmission efficiency is related to the mutual inductance M as shown in (6) and (7). In practice, mutual inductance M will change due to factors such as the coil misalignment during the charging process. Therefore, real-time estimation of the mutual inductance is crucial for improving system efficiency. In order to estimate the

mutual inductance, the expression of the rectifier output voltage can be derived from (1) and (4) and given by (8).

$$U_f = \frac{U_{dc} \cos(\frac{\varphi}{2}) M R_e}{(R_e + R_2) L_{p1}} \quad (8)$$

According to (8), the expression for the mutual inductance M can be obtained as

$$M = \frac{U_f (R_e + R_2) L_{p1}}{U_{dc} \cos(\frac{\varphi}{2}) R_e} \quad (9)$$

Substituting (2) into (9), the relationship between the mutual inductance M and the system load resistance R_L can be given by

$$M = \frac{U_f L_{p1} (8U_f^2 R_L + \pi^2 U_{out}^2 R_2)}{8U_{dc} U_f^2 R_L \cos(\frac{\varphi}{2})} \quad (10)$$

Equation (10) indicates that the mutual inductance M is related to the DC input voltage U_{dc} , the rectifier output voltage U_f , the inverter phase shift angle φ , etc. In practical applications, the primary side compensation inductance L_{p1} and the receive coil resistance R_2 are usually constant. Meanwhile, the parameter values of the DC voltage U_{dc} , load resistance R_L , and the inverter phase shift angle φ are also known. Therefore, the mutual inductance can be estimated by measuring the rectifier output voltage U_f .

Based on the mutual inductance M estimation result, system transmission efficiency can be improved by adjusting the inverter phase shift angle. Considering the expression of R_e shown in (2) and the optimal load resistance shown in (7), and then setting $R_e = R_{e_{\eta\max}}$, the inverter optimal phase shift angle can be obtained from (11) to achieve maximum transmission efficiency.

$$\varphi_{opt} = 2\arccos \left(\sqrt{\frac{\pi^2 U_{out} R_{e_{\eta\max}} L_{p1}^2}{8M^2 U_{dc}^2}} \right) \quad (11)$$

Finally, on the basis of the above analysis, the proposed coordinated control method is presented step by step as follows:

Step 1: Measure the rectifier output voltage U_f , the Buck–Boost converter output voltage U_{out} , and the output current I_{out} .

Step 2: Calculate the load resistance R_L according to the measured output voltage U_{out} and output current I_{out} ; then get the equivalent resistance R_e based on (2).

Step 3: According to the obtained result of R_e , get the real-time estimated value of the mutual inductance M based on (10).

Step 4: Obtain the optimal phase shift angle φ_{opt} based on (11), and then the inverter phase shift angle is adjusted to achieve maximum transmission efficiency tracking.

Step 5: Adjust the duty cycle of the Buck–Boost converter to achieve the constant voltage output.

According to the above steps, the proposed WPT coordinated control method can be implemented, which can improve WPT system transmission efficiency while maintaining the constant output voltage.

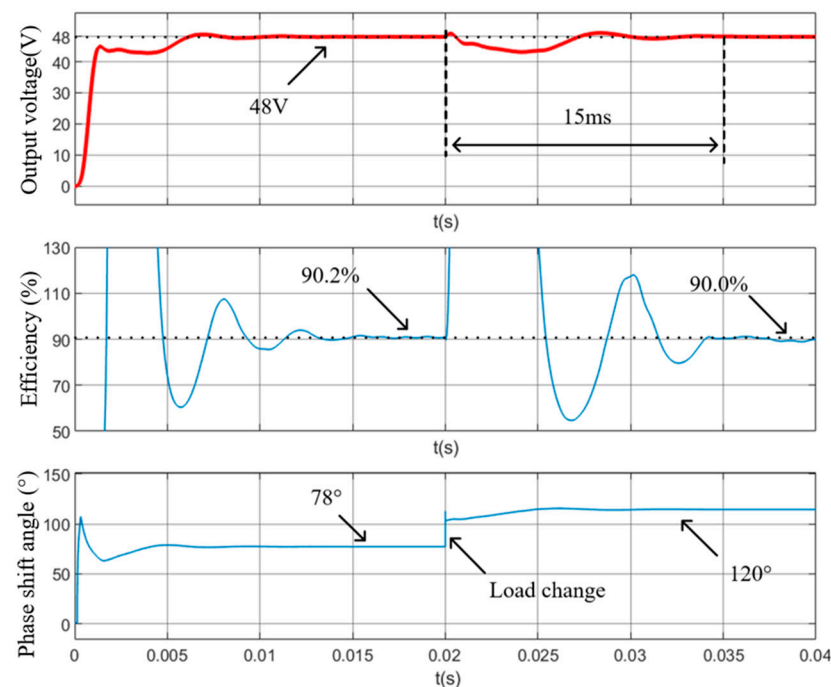
3. Simulation Verification and Analysis

In order to verify the effectiveness of the proposed method, a WPT simulation is conducted through MATLAB/Simulink. Consistent with the schematic shown in Figure 1, the simulation system consists of a DC power supply, LCC-S compensation network, transmit coil, receive coil, Buck–Boost converter, CV controller, and phase shift controller. In order to simulate the actual situation, the simulation parameter values are selected according to those of the experimental WPT prototype and shown in Table 2.

Table 2. Parameter values of the developed WPT prototype.

Parameters	Symbol	Values
System operating frequency	f	85 kHz
DC source voltage	U_{dc}	80 V
Primary side compensation inductance	L_{p1}	55.95 μ H
Primary side parallel compensation capacitance	C_{p1}	62.94 nF
Primary side series compensation capacitance	C_{p2}	28.18 nF
Self-inductance of the transmit coil	L_1	181 μ H
Self-inductance of the receive coil	L_2	179.24 μ H
Resistance of the transmit coil	R_{L1}	149 m Ω
Resistance of the receive coil	R_{L2}	128 m Ω
Secondary side series compensation capacitance	C_{s1}	19.5 nF
Switching frequency of the Buck–Boost converter	f_s	50 kHz
Inductance of the Buck–Boost converter	L_f	120 mH
Output filter capacitance	C_o	220 μ F

First, simulation results of the output voltage, transmission efficiency, and phase shift angle variations are shown in Figure 3 when the load resistance changes from 20 Ω to 40 Ω . It suggests that before the load resistance changes, the output voltage is stable at 48 V, the transmission efficiency is 90.20%, and the phase shift angle is 78°. At 0.02 s, the load resistance changes suddenly, and after a 15 ms adjustment period, the output voltage returns to 48 V, with a transmission efficiency of 90.00% and a phase shift angle of 120°. In addition, Figure 3 suggests that the system overshooting is 10.4% when the load resistance changes from 20 Ω to 40 Ω . Meanwhile, the system output voltage is finally stabilized at 48 V after an adjustment time of 15 ms, which indicates that the system has good stability under variable load conditions.

**Figure 3.** Simulation results of the output voltage, transmission efficiency, and phase shift angle, when the load resistance changes from 20 Ω to 40 Ω .

Simulation results of the output voltage, transmission efficiency, and phase shift angle variations are shown in Figure 4 when the mutual inductance changes from 45 μ H to 35 μ H. In Figure 4, when the mutual inductance is 45 μ H, the system transmission efficiency is 91.50%, and the phase shift angle is 122°. After the mutual inductance suddenly changes

to 35 μH , the system transmission efficiency is 90.10%, and the phase shift angle is 122° . In addition, before and after the mutual inductance variation, the voltage across the load can be maintained at 48 V and the system works stably. Figure 4 suggests that the overshooting is 6.25% during the mutual inductance variation. Meanwhile, the system output voltage is stabilized at 48 V after a 10 ms adjustment time, which shows that the system has good stability under the variable coupling conditions.

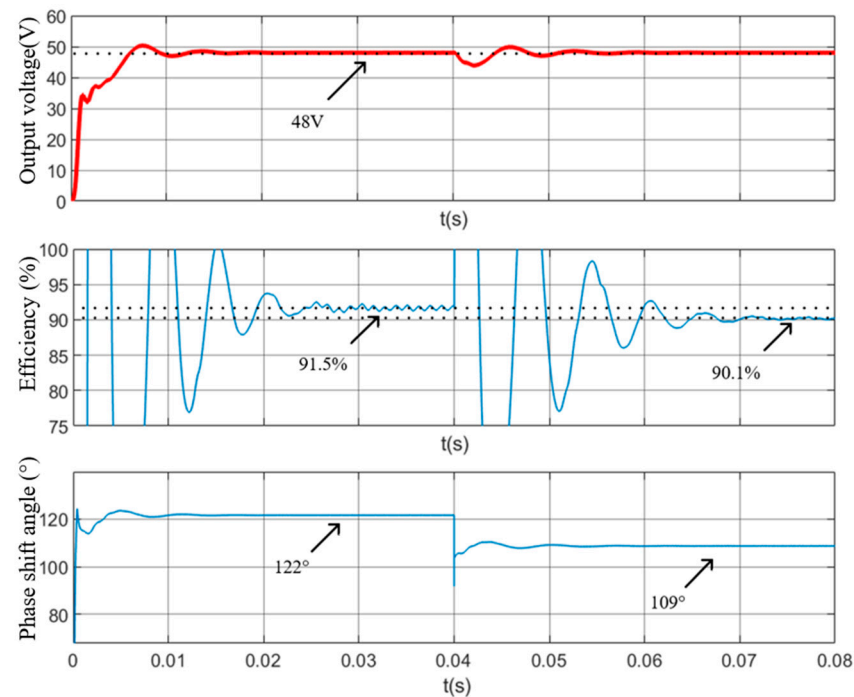


Figure 4. Simulation results of the output voltage, transmission efficiency, and phase-shift angle, when the mutual inductance changes from 45 μH to 35 μH .

In addition, Figure 5 shows the open-loop transfer baud plot of the system after adding a constant voltage PID controller, from which can be seen that the phase angle margin is 70.1 deg, indicating that the system has good stability after adding a constant current output PID controller.

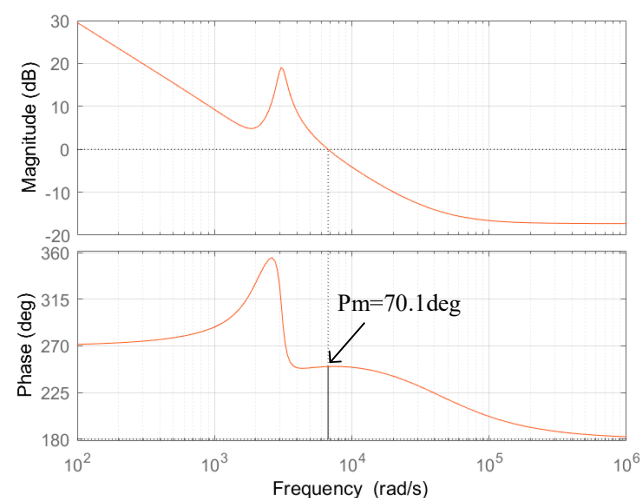


Figure 5. Bode diagram of open-loop transfer function for constant voltage control.

The THD analysis has been conducted considering the transmitting and receiving coil currents under variable coupling and variable load conditions. Figure 6 shows the waveform and THD of the current through the receiver coil under variable mutual inductance conditions. The results show that the current waveform is basically sinusoidal and the THD value is less than 5%.

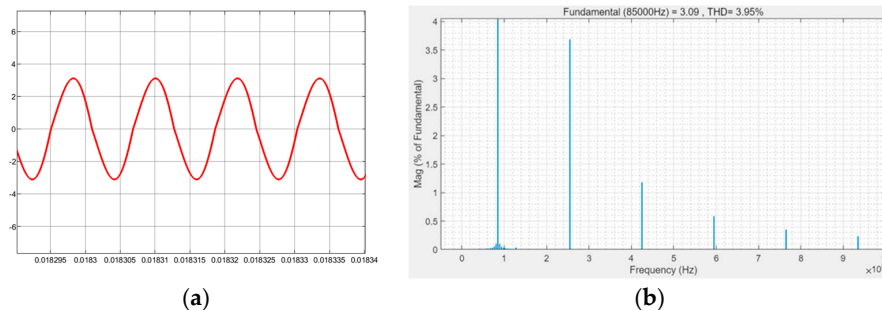


Figure 6. Waveform and THD of the current through receiver coil under variable mutual inductance conditions. (a) Waveform of the current through receiver coil. (b) THD of the current through the receiver coil.

Finally, the simulation results indicate that the proposed coordinated control method can ensure constant voltage output while maintaining high transmission efficiency under the conditions of WPT load resistance and mutual inductance variations. Therefore, the effectiveness of the proposed WPT coordinated control method of constant voltage output and maximum transmission efficiency has been preliminarily verified.

4. Experimental Verification and Discussion

4.1. Hardware Design

A WPT prototype is developed to verify the proposed control method, and its configuration is shown in Figure 7, which includes a DC power supply, inverter and its drive circuit, LCC-S compensation network, transmit coil, receive coil, Buck–Boost converter and its drive circuit, electronic load, etc. MOSFETs (IPW6R190C6) and diodes (MBR20200FCT) are adopted in the primary side inverter and the secondary side rectifier. Both the transmit and receive coils are spiral-shaped disc structures. An electronic load with a constant resistance mode is adopted as the system load.

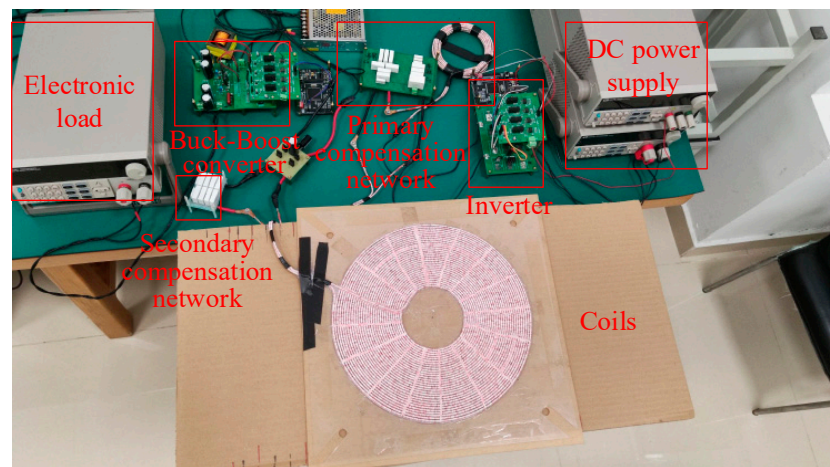


Figure 7. Photograph of the developed WPT prototype.

The vertical distance between the coils is 10 cm. The horizontal misalignment range of the coils is selected from 0 cm to 10 cm, which corresponds to the mutual inductance varying

from 45.30 μH to 28.27 μH . Other parameter values of the developed WPT prototype are shown in Table 2.

The constant voltage output and maximum efficiency coordinated control method rely on wireless communication between the WPT primary and secondary sides. The BT24 Bluetooth module is selected to achieve the communication between the primary and secondary side DSP controllers in the developed prototype. The Bluetooth module can automatically pair after power is on. After pairing is completed, the secondary side controller will continuously send the calculated optimal phase shift angle that makes the system work at the maximum efficiency point. When the primary side controller receives the optimal phase shift angle, it will generate two complementary pulse width modulation (PWM) signals with the optimal phase shift angle to control the inverter.

4.2. Software Design

The flow chart of the software control procedure of the proposed WPT constant voltage output and maximum efficiency tracking coordinated control algorithm is shown in Figure 8. The main control chips used in the WPT primary and secondary sides are TMS320F28335. First, the initialization of the controller needs to be completed, including the configuration of the system clock, analog-to-digital converter (ADC) interrupt, PWM, and other peripherals. In the DSP controller on the WPT secondary side, the ADC interrupt service function mainly completes the sampling of the load voltage U_{out} , the load current I_{out} , and the rectifier output voltage U_f . While completing the voltage closed-loop control, the inverter works at the optimal phase shift angle.

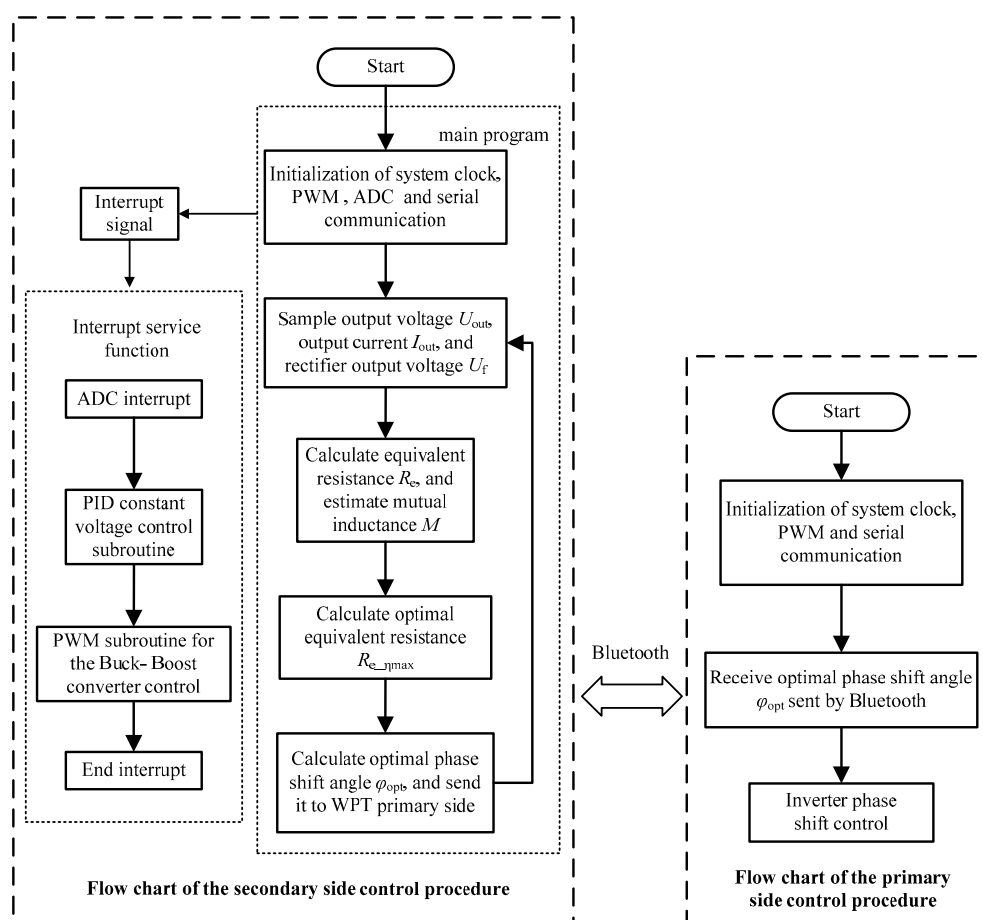


Figure 8. Flow chart of the software control procedure of the proposed WPT constant voltage output and maximum efficiency tracking coordinated control.

In the main program, the optimal phase shift angle φ_{opt} calculated by the ADC interrupt is sent to the Bluetooth module at the WPT secondary side via the serial port. The Bluetooth module at the WPT secondary side sends φ_{opt} to the Bluetooth module at the WPT primary side. In the DSP controller on the WPT primary side, the program is adopted to process the received optimal phase shift angle φ_{opt} , and output two PWM signals with complementary phase shift to control the inverter.

4.3. Experimental Verification

In the proposed method, the precondition of the maximum efficiency tracking control is that the mutual inductance can be accurately estimated. Therefore, the mutual inductance estimation method is experimentally verified first. Figure 9 shows the comparison between the estimated and measured mutual inductance values under the conditions of different coil misalignment distances. It suggests that the estimated mutual inductance values are close to the measured ones, and the maximum error is 3.50%. It can meet the requirements of the subsequent experiments within the allowable error range [24].

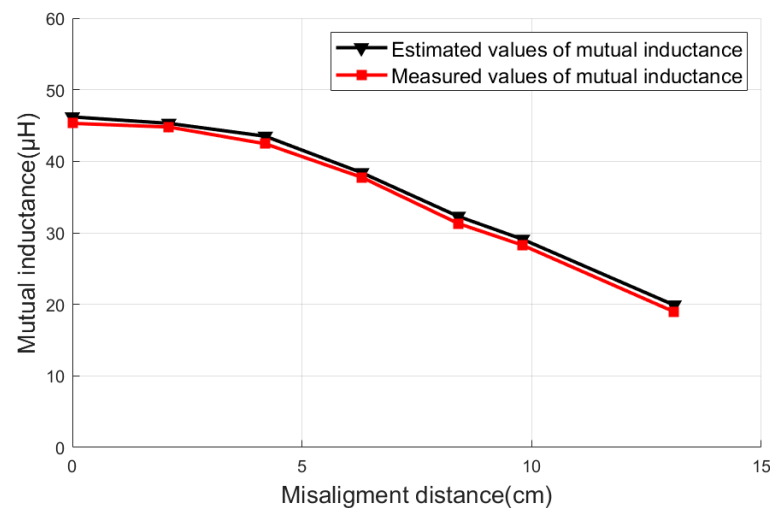


Figure 9. Comparison between the estimated and measured values of the mutual inductance at different coil misalignment distances.

Then, the waveforms of the inverter and system output voltages and currents are shown in Figure 10 under the conditions of different load resistances, where the mutual inductance is 45.30 μH and the load resistance is 15 Ω , 24 Ω , and 32 Ω , respectively. It indicates that the system consistently maintains an output voltage of 48 V when the load resistance changes. As the load resistance increases, the inverter phase shift angle continuously increases, which keeps the optimal phase shift angles to achieve the WPT system's maximum efficiencies.

Furthermore, the waveforms of the inverter and system output voltages and currents are shown in Figure 11 under the conditions of different mutual inductances, where the load resistance is 40 Ω and the mutual inductance is 45.30 μH , 37.75 μH , and 28.27 μH , respectively. It indicates that when the mutual inductance changes, the inverter phase shift angle is adjusted accordingly, while the load voltage remains constant.

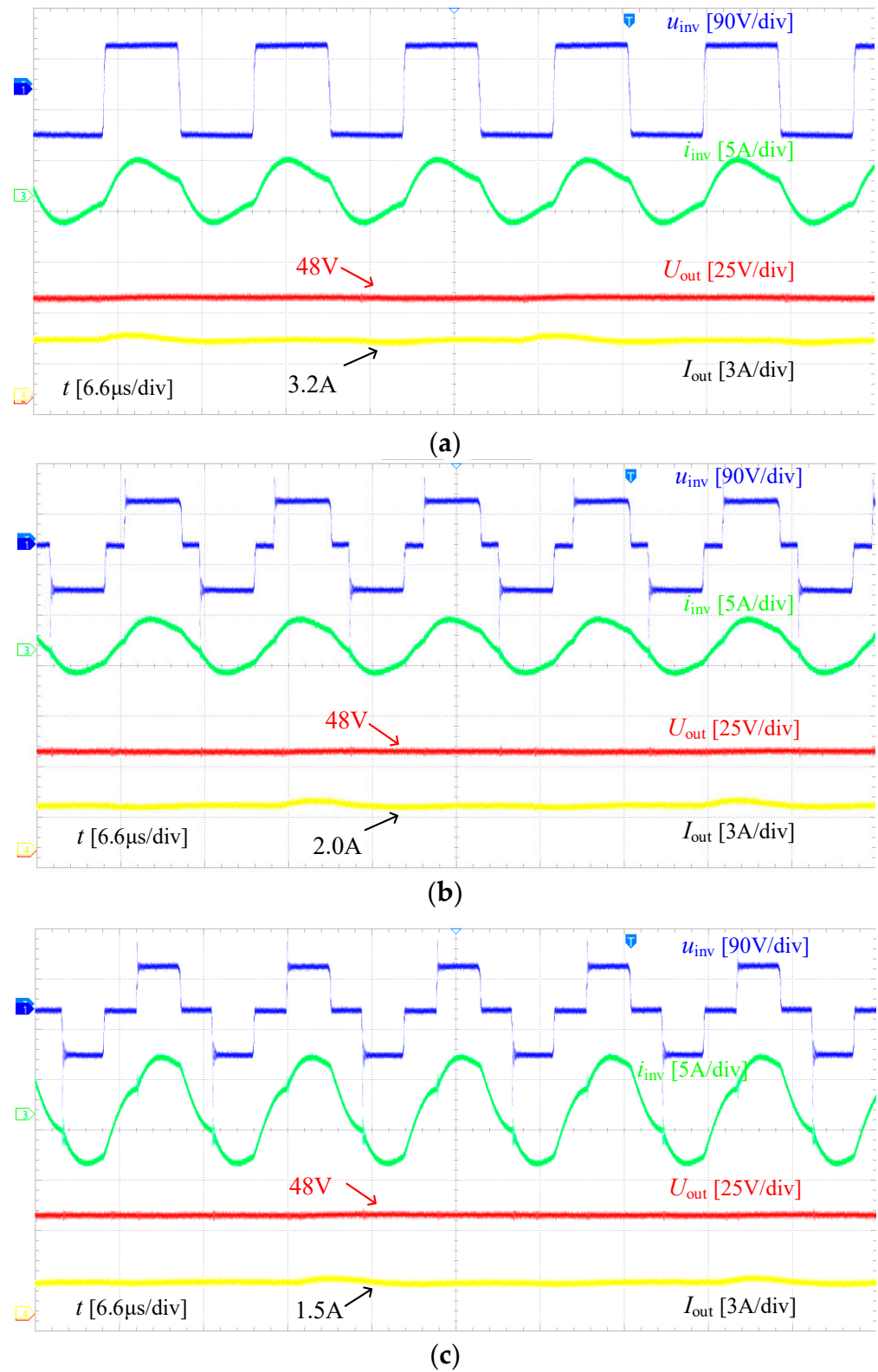


Figure 10. Experimental waveforms of the inverter and system output voltages and currents under the conditions of different load resistances. (a) $M = 45.30 \mu\text{H}$, $R_L = 15 \Omega$. (b) $M = 45.30 \mu\text{H}$, $R_L = 24 \Omega$. (c) $M = 45.30 \mu\text{H}$, $R_L = 32 \Omega$.

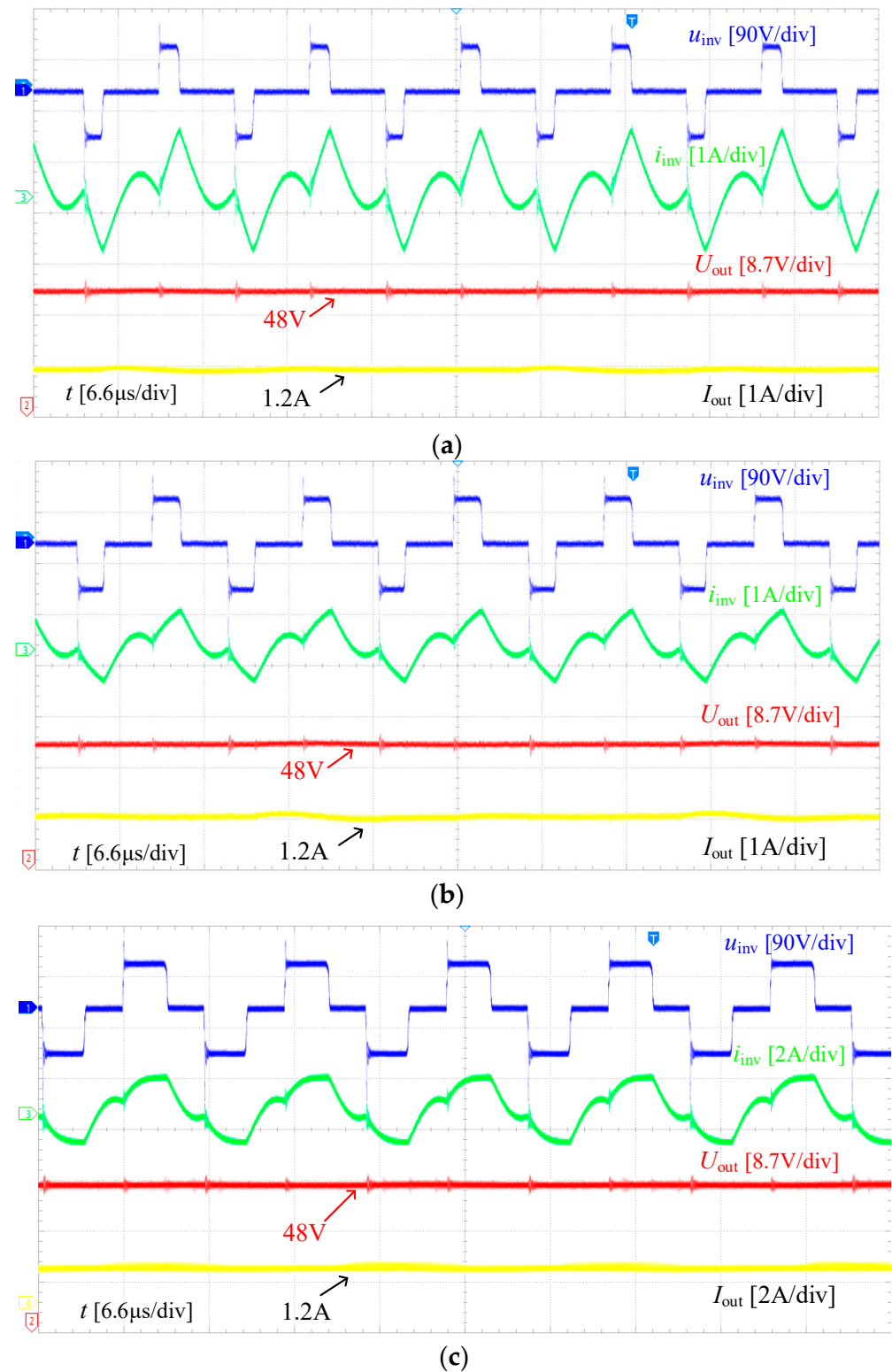


Figure 11. Experimental waveforms of the inverter and system output voltages and currents under the conditions of different mutual inductances. (a) $R_L = 40 \, \Omega$, $M = 45.30 \, \mu\text{H}$. (b) $R_L = 40 \, \Omega$, $M = 37.75 \, \mu\text{H}$. (c) $R_L = 40 \, \Omega$, $M = 28.27 \, \mu\text{H}$.

In addition, the inverter phase shift angle also changes with the load resistance or the mutual inductance. These values of the inverter phase shift angle are calculated based on (11) to maintain system transmission efficiency at the maximum points.

Finally, comparisons of experimental system transmission efficiencies with and without the maximum efficiency tracking control are shown in Figure 12 under the conditions of load resistance and mutual inductance variations.

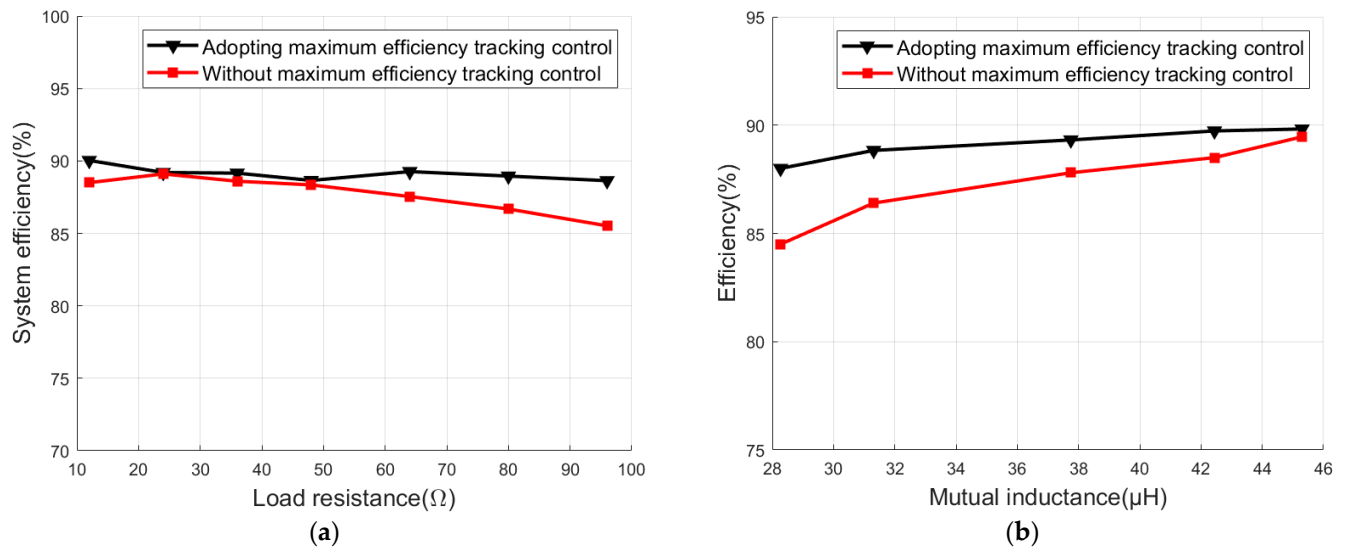


Figure 12. Comparisons of experimental system transmission efficiencies with and without the maximum efficiency tracking control. (a) The conditions of load resistance variation. (b) The conditions of mutual inductance variation.

As shown in Figure 12a, without the maximum efficiency tracking control method, the system transmission efficiency generally decreases with the load resistance, until reaching 85.52% at 96 Ω . When the maximum efficiency tracking control method is adopted, system transmission efficiency remains relatively stable despite changes in load resistance. When the load resistance is 96 Ω , system transmission efficiency is 88.63%, representing a 3.11% improvement, compared to the conditions that the method is not adopted. Further calculations suggest that the average system transmission efficiency is increased by 1.80%, and the efficiency fluctuation is decreased by 2.67%, in the load resistance range of 12 Ω to 96 Ω .

As shown in Figure 12b, the system transmission efficiencies have been improved with the maximum efficiency tracking control method. This improvement is evident under the conditions of different mutual inductances, and the maximum efficiency increase is 3.50%. Further calculations suggest that the average system transmission efficiency is increased by 1.80%, and efficiency fluctuation is decreased by 3.14%, over the range of the mutual inductance variation from 28.27 μH to 45.30 μH .

Therefore, the experimental results show that the proposed coordinated control method can achieve constant voltage outputs and improve system transmission efficiencies, under the conditions of different load resistances and mutual inductances.

5. Discussion

5.1. Comparison with Existing Methods

The comparison between the proposed method and the existing WPT control methods is summarized in Table 3. Here, five aspects are compared including the number of DC–DC converters, controller, number of samples, response time, and maximum efficiency [25,26].

Table 3. Comparison of the control methods.

Ref.	Number of DC–DC Converters	Controller	Number of Samples	Response Time	Maximum Efficiency
[13]	Two	FPGA controller	Two	Not provided	85%
[14]	One	STM32F429VIT6	Six	<100 ms	85.4%
[16]	One	Not provided	One	100 ms	88%
[17]	One	TMS320F28379D	Five	17 ms	Not provided
[20]	Zero	FPGA controller	Three	Not provided	94.4%
proposed	One	TMS320F28335	Three	<50 ms	88.6%

5.2. Limitations and Future Work

This article proposes a coordinated optimization control method for constant voltage output and transmission efficiency, but the addition of Bluetooth communication increases the complexity of the system. The future work will be adding a parameter identification algorithm that does not require communication between the WPT primary and secondary sides. Moreover, this article mainly focuses on the WPT system with LCC-S compensation. In addition to the LCC-S topology, there are many other topologies. Future work will apply the proposed control method to other compensation network topologies.

6. Conclusions

Regarding the problem that mutual inductance and load variations will affect WPT system performance, this article presents a coordinated control method to achieve constant voltage output and maximum efficiency tracking. In the proposed method, mutual inductance can be estimated in real-time within a certain range of WPT load and mutual inductance variations, and maximum system transmission efficiencies are reached while maintaining system constant voltage output. It can significantly improve system transmission efficiency. Additionally, the short feedback control loop minimizes the delay time, thus enabling a quick and stable output for WPT systems.

The proposed coordinated control method is verified through simulations and experiments. The results show that the maximum mutual inductance estimation error is less than 3.50% at different coil misalignment distances. Based on the proposed coordinated control method, the developed WPT prototype can achieve constant voltage output, and the system transmission efficiencies are maintained at high levels. Furthermore, the average system transmission efficiency is increased by 1.80% and the efficiency fluctuation is reduced by 2.67% in the load resistance range from 12 Ω to 96 Ω , while the average system transmission efficiency is increased by 1.80% and the efficiency fluctuation is reduced by 3.14% over the range that the mutual inductance varies from 28.27 μH to 45.30 μH . Therefore, the effectiveness of the proposed coordinated control method has been verified under the conditions of WPT load resistance and mutual inductance variations.

Author Contributions: Conceptualization, X.W. and Y.G.; methodology, X.W.; software, R.W.; validation, X.W. and R.W.; formal analysis, X.W.; investigation, R.W.; resources, Y.G.; data curation, X.W.; writing—original draft preparation, X.W.; writing—review and editing, X.W.; visualization, Y.G.; supervision, Y.Z.; project administration, Y.G.; funding acquisition, Y.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China under Grant No. 52107176 and No. 52237008.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

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

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