

Phase-Controlled Capacitor Circuit and Efficiency-Based Tuning Method for Wireless Power Transfer

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Abstract: In order to solve the detuning phenomenon caused by the influence of load variation, coupling state and other factors in the wireless power transfer system, the phase-controlled capacitor circuit and corresponding tuning strategy are proposed. The simulation and experimental results show that the resonant wireless power transfer system using the phase-controlled capacitor circuit and the tuning strategy can effectively solve the detuning problem and improve the output power and transfer efficiency.

1. Introduction

The magnetically coupled resonant wireless power transfer (WPT) system is susceptible to variations in transfer distance and system parameters and cannot operate in a resonant state, thereby reducing transfer efficiency and output power [1,2,3]. An adaptive impedance-matching network based on a novel capacitor matrix is proposed to solve the detuning problem [4]. As in [5], a method for phase-shift and amplitude control is proposed to improve transfer efficiency. A auto-frequency tuning method based on a PI approach is proposed to minimize the switching loss by the load variations. As in [7,8], DC-DC converter is used to provide impedance matching. The minimum reflection coefficient magnitude, meanwhile, has also been applied to provide high output power [9,10]. As in [11], an double side LCLC compensation and its tuning method are proposed to achieve high efficiency. In this paper, the method for phase-controlled capacitor circuit is proposed. Firstly, make an simply introduction of phase-controlled capacitor circuit and corresponding control algorithm. Then, the proposed method is validated through simulation and experiment.

2. Tuning Strategy Analysis

The phase-controlled capacitor circuit is shown in Fig. 1(a). The phase-controlled capacitor circuit is connected in parallel with the resonant compensation capacitor, and then connected in series with the transmitting coil to form an LC resonant circuit. Change the equivalent capacitance value by changing the time that and are connected to the resonant tank.

The voltage across the phase-controlled capacitor circuits A and C is a sinusoidal signal. Set θ as the conduction angle. According to Fig. 2, when the voltage waveforms across the phase-controlled capacitor circuits A and C are in the positive half cycle, at this time, the diode D_2 is always on, and the switch is short-circuited, so the capacitor C_2 is directly charged and discharged in the resonant circuit during this period. When the conduction angle is during $(\pi-\theta, 2\pi+\theta)$, C_1 is always connected to resonant circuit. When the conduction angle is during $(\theta, \pi-\theta)$, charging and discharging of C_1 are stopped. Similarly, when the voltage signals across the phase-controlled capacitor circuits A and C are in the negative half cycle, the operation is similar to the previous method.

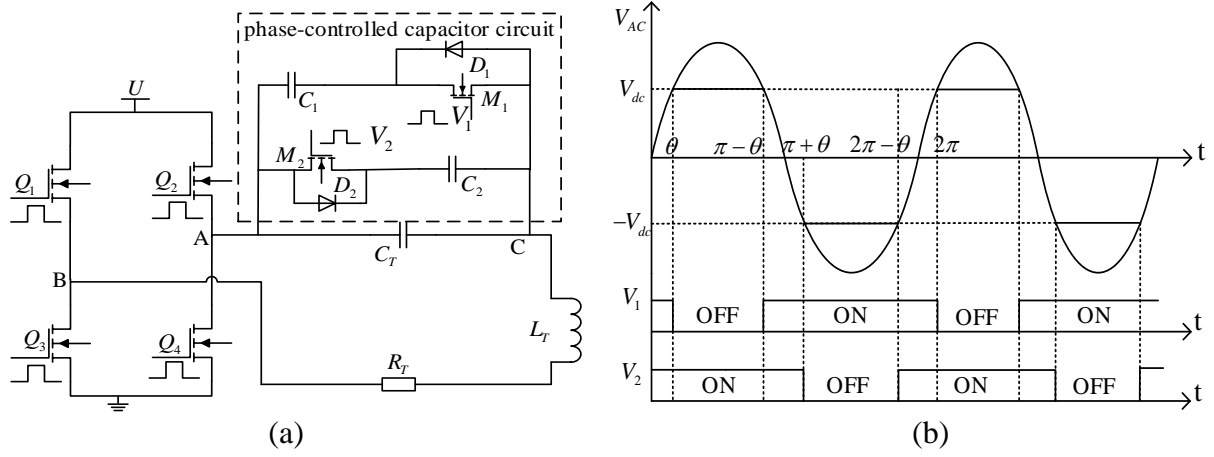


Fig. 1. (a) Phase-controlled capacitor circuit. (b) Control signal conform.

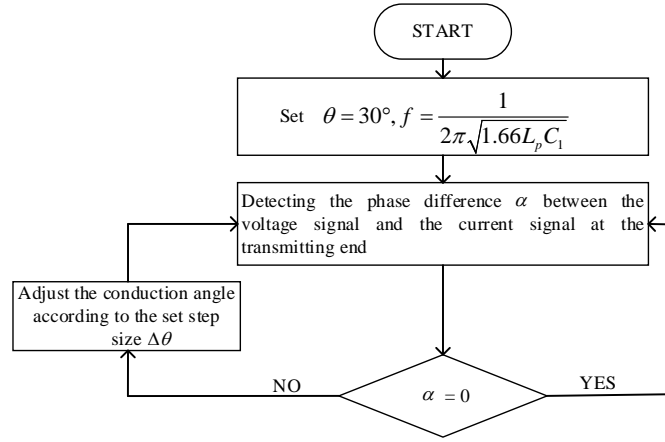


Fig. 2. The flow chart of control strategy.

According to Fig. 1(b), the following relationship is satisfied between the conduction angle θ , V_{dc} and V_{AC} .

$$\theta = \arcsin\left(\frac{V_{dc}}{V_{AC}}\right)$$

Let the equivalent capacitance generated by the phase-controlled capacitor circuit be C_t , according to the fact that the absolute value of the charge and discharge charge is equal in one duty cycle. Let $C_1 = C_2 = C$.

$$\begin{aligned} & \int_0^{2\pi} C_t V_{AC} |\sin(\omega t)| d(\omega t) \\ &= \int_0^{2\pi} C_1 V_{AC} |\sin(\omega t)| d(\omega t) + \int_0^{2\pi} C_2 V_{AC} |\sin(\omega t)| d(\omega t) \end{aligned}$$

$$C_t = \frac{[4 - 2\cos(\theta) + \sin(\theta)(\pi - 2\theta)]}{2} C$$

First, set the conduction angle to 30° . When it is detected that there is a phase difference α between the current signal of the transmitting end and the voltage signal, the conduction angle is adjusted according to the step size $\Delta\theta$. In this paper, the step size of the conduction angle is set to 1° , so that the variation of the equivalent capacitance value at the transmitting end is small.

When the current signal of the transmitting end lags behind the voltage signal, it indicates that the WPT system is in an inductive state, and it is necessary to reduce the equivalent capacitance value, that is, reduce the conduction angle. When the voltage signal of the transmitting end lags behind the current signal, it indicates that the WPT system is in a capacitive state, and it is necessary to increase the equivalent capacitance value, that is, increase the conduction angle. The control strategy

is shown in Figure 2.

3. Simulation and Experiment Verification

3.1. Simulation Verification

The feasibility of the proposed method is verified by using Simulink to construct the model shown in Figure 3.

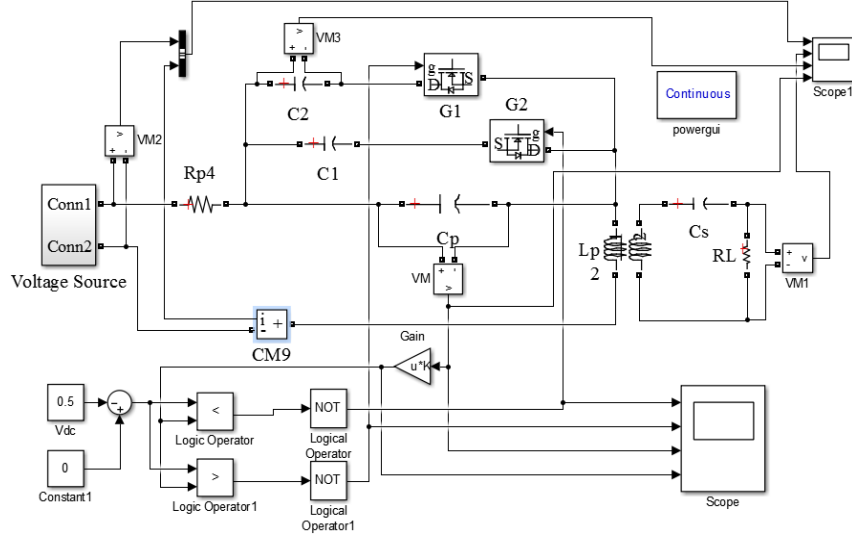


Fig. 3. WPT system simulation model.

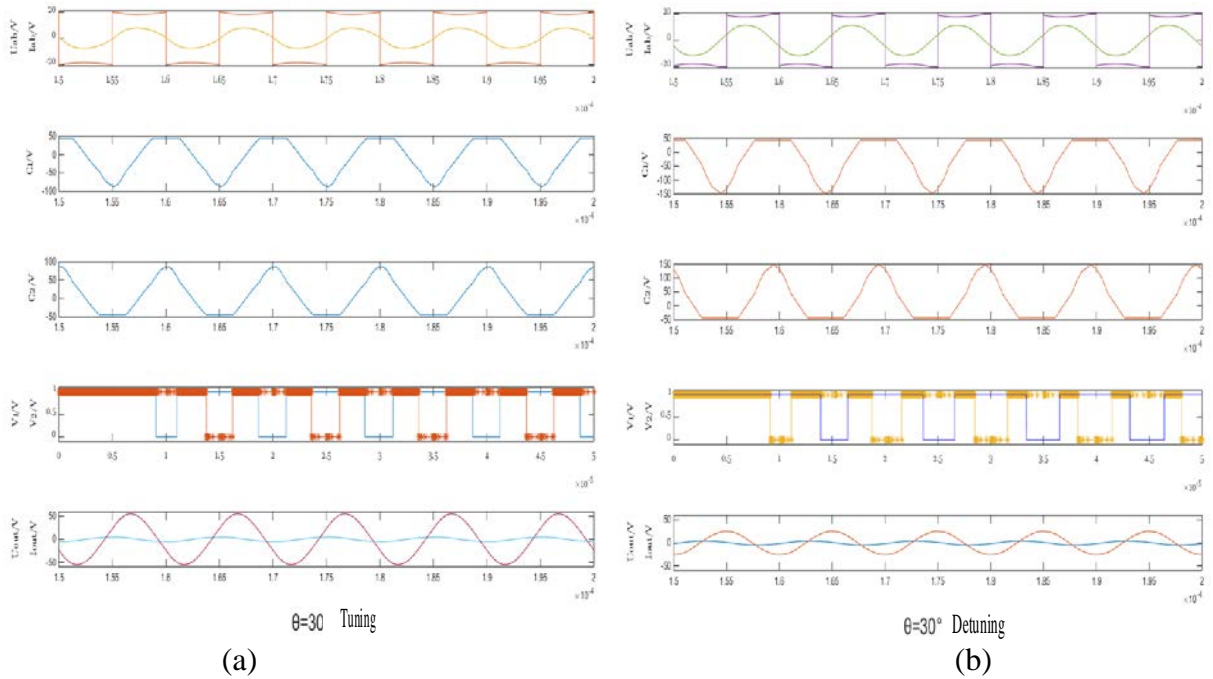


Fig. 4. (a) Resonant state.

(b) Nonresonant state.

Set the input voltage U to 20V, the resonant frequency of the transmitting end, the resonant frequency of the receiving end, and the excitation frequency of the power supply are all 100kHz.

Fig. 4 is a comparison of the system in a resonant state and a non-resonant state in the case of $\theta=30^\circ$. From the waveform of the receiving end, the voltage and current waveforms in the non-resonant state are smaller than the voltage and current amplitudes under resonance, indicating that the transfer power of the system is low in the nonresonant state.

3.2. Experiment Verification

The hardware platform built is shown in Fig. 5. The power inverter frequency is set to 80kHz, the transmitter and receiver inductances are all about 67 μ H, the compensation resonant capacitor is 58nF, the phase-controlled tuning capacitor is 10nF, and the coil distance is 10cm. The load is connected by 10W LED bulb group. When a capacitor at the receiving end is removed, the phase-controlled capacitor circuit is not added at this time, the WPT system is detuned, and the phase difference between the voltage and current at the transmitting end is as shown in Fig. 6(a).

A phase-controlled capacitor circuit is added to the transmitting end, and the voltage and current waveforms of the transmitting end on the oscilloscope substantially coincide, as shown in Fig. 6(b).

In fact, the phase difference between voltage and current cannot be absolutely zero, so it is assumed that the system is now back to the resonant state. Experiments have shown that a tuning algorithm based on a phase-controlled capacitor device can return the system to a resonant state.



Fig. 5. Hardware platform.

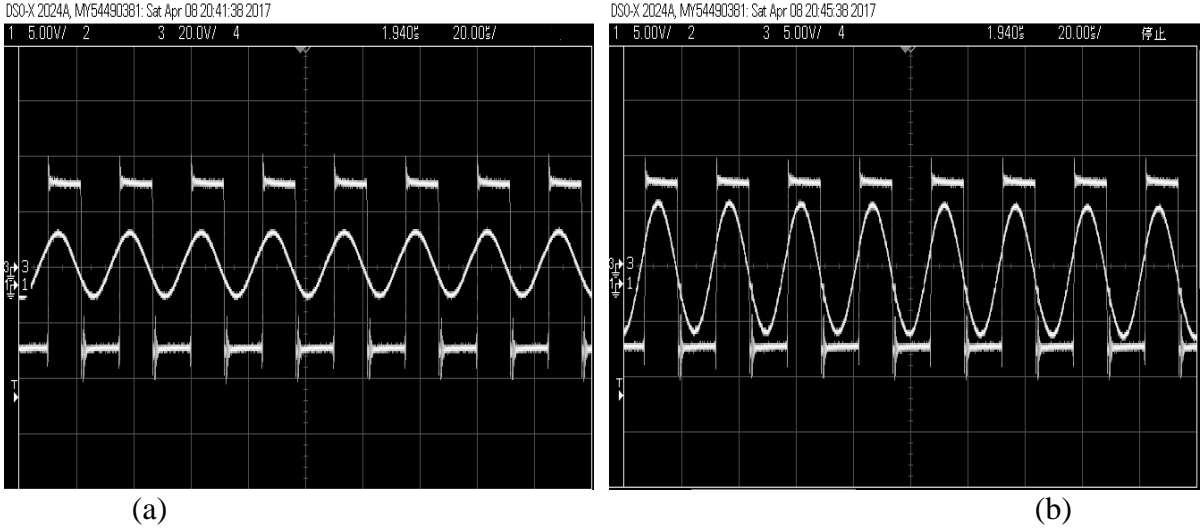


Fig. 6. (a) Without phase-controlled capacitor circuit. (b) Use phase-controlled capacitor circuit.

When the phase-controlled capacitor circuit is not added to transmitting end, the input power is 5.6W and the output power is 2.1W.

$$\eta = \frac{P_{out}}{P_{in}} \times 100\% = \frac{2.1}{5.6} \times 100\% = 37.5\%$$

When the phase-controlled capacitor circuit is added to transmitting end, and the voltage and current waveforms of the transmitting end on the oscilloscope substantially coincide, as shown in Fig. 7. At this time, the input power is 9.6W and the output power is 5.7W.

$$\eta = \frac{P_{out}}{P_{in}} \times 100\% = \frac{5.7}{9.6} \times 100\% = 59.4\%$$

4. Summary

Simulation and experiment results show that the proposed method can make the transmitting end work in the resonant state and improve the WPT system output power and transfer efficiency. And the method is feasible and has important significance for the practical application of magnetically coupled resonant wireless energy transfer technology.

Acknowledgment

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