A Flexible Load-Independent Multi-Output Wireless Power Transfer System Based on Double-T Resonant Circuit Technique

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***Abstract*—Wireless Power Transfer (WPT) technology has been increasingly applied in power supply for portable devices such as mobile phones and electric vehicles (EVs). Conventional WPT systems are usually designed to supply specified loads with only single voltage/current output. In many practical applications, however, electric appliances usually require different voltage and current levels. In this work, a load-independent multi-output WPT system with only one primary coil (transmitting coil) and one secondary coil (receiving coil) is proposed. By connecting parallel double-T resonant circuits to the common ac terminal of the receiving coil, multiple constant dc outputs can be achieved. Furthermore, by adjusting the parameters of the individual resonant circuit, each output channel can generate different voltage level flexibly. Theoretical analysis and experiment results of a laboratory prototype confirm the effectiveness of the proposed WPT system.**

Keywords—Wireless Power Transfer (WPT), load-independent multi-output, double-T resonant circuits

I. Introduction

Wireless power transfer (WPT), a technology that can transfer the energy from a source to a load without any mechanical contact by using magnetic coupling, has attracted much attention worldwide in the last decade [1]-[4]. Recently, to increase the safety and convenience, WPT technologies have been widely applied in portable devices such as mobile phones and electric vehicles for power supply and charging. Fig. 1 illustrates a typical inductive WPT configuration, which includes a transmitter and a receiver. In the transmitter, the inverter is used to generate high-frequency current to energize the primary coil. On the other side, the rectifier aims to convert the high-frequency voltage induced at the secondary coil into dc voltage.

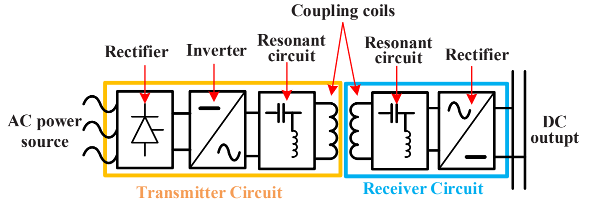

Fig. 1. A typical WPT topology.

By using the above WPT structure, there is no doubt that energy can be transferred in a wireless manner. Nevertheless, it presents a major limitation, that is, only one single dc voltage output can be obtained. In real applications, the portable devices usually require constant voltage input or constant current input. Moreover, different appliances have various voltage or current levels. In this sense, it is highly desired to develop a WPT system with load-independent multiple outputs, i.e., multiple constant outputs. In previous research, most of the WPTs use various resonant circuits such as SS, PS, LCL-S, or LCL-P to achieve constant current output or constant voltage output characteristics [2]-[5]. However, these structures commonly have only one transmitter side and a single receiving part. It means that to realize multiple charging electrical appliance at the same time, a large number of transmitting and receiving equipment are needed. This would significantly increase the total weight, costs and size. Another solution is to include additional dc-dc converters to generate different output voltages [6]. Once again, it will lead to increased system cost and overall system size. Recently, some other papers investigated another topology with one transmitter coil but multiple receiver coils [7]. This decreases the amount of the wingdings and the passive element in the transmitter side. Unfortunately, different output voltage and current levels are still not achieved.

In this work, a flexible load-independent multi-output WPT system with only one primary coil and one secondary coil is developed. By connecting parallel double-T resonant circuits to the common ac terminal of the receiving coil, multiple constant dc outputs can be achieved. Furthermore, by adjusting the parameters of the individual resonant circuit, each output channel can generate different voltage level. The experimental results of a laboratory prototype verify the effectiveness of the proposed WPT system.

II. Theoretical Analysis

A. Double-T Resonant Circuit

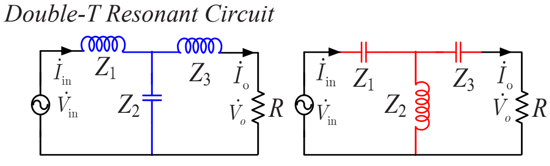

Fig. 2. T resonant circuits.

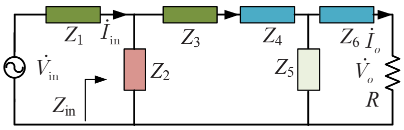

Fig. 3. A double T resonant circuit.

Fig.2 shows two typical T resonant circuits, i.e., inductor/capacitor/inductor (LCL) and capacitor/inductor/capacitor (CLC) resonant circuits. According to the Kirchhoff's Voltage Law (KVL), one can obtain

$$\begin{bmatrix}\dot{V}_{\text{in}}\\0\end{bmatrix}=\begin{bmatrix}Z_1+Z_2 & -Z_2\\R+Z_2+Z_3 & -Z_2\end{bmatrix}\begin{bmatrix}\dot{I}_{\text{in}}\\\dot{I}_{\text{o}}\end{bmatrix}\tag{1}$$

The currents and voltage can be derived by solving equation (1) as

$$\begin{bmatrix}\dot{I}_{\text{in}}\\\dot{I}_{\text{o}}\\\dot{V}_{\text{o}}\end{bmatrix}=\begin{bmatrix}\dfrac{R+Z_2+Z_3}{(Z_1+Z_2)R+Z_1Z_3+Z_2Z_3+Z_1Z_2}\\\dfrac{Z_2}{(Z_1+Z_2)R+Z_1Z_3+Z_2Z_3+Z_1Z_2}\\\dfrac{Z_2R}{(Z_1+Z_2)R+Z_1Z_3+Z_2Z_3+Z_1Z_2}\end{bmatrix}\dot{V}_{\text{in}}\tag{2}$$

If $Z_1=Z_3=-Z_2$ for resonance, the following equations can be derived

$$\begin{cases}\dot{I}_{\text{o}}=-\dfrac{1}{Z_2}\dot{V}_{\text{in}} \qquad \dot{V}_{\text{o}}=Z_2\dot{I}_{\text{in}}\\Z_{\text{in}}=\dfrac{\dot{V}_{\text{in}}}{\dot{I}_{\text{in}}}=-\dfrac{Z_2^{\,2}}{R}\end{cases}\tag{3}$$

According to (3), it is seen that the input impedance, Z_{in}, is purely resistive. This means that it can achieve zero phase angle (ZPA) operation. More importantly, another conclusion can be drawn from (3): A load-independent output current can be achieved by using a constant voltage as input, while a load-independent output voltage can be obtained with a constant current as input. In light of these, by connecting the output of the LCL circuit to the input of the CLC circuit to form a double-T resonant circuit, the load-independent constant output voltage can be obtained with a constant voltage as input. This new double-T resonant circuit is illustrated in Fig. 3. Based on its characteristic, the output voltage and the input impedance can be expressed as

$$\dot{V}_{\text{o}}=-\frac{Z_5}{Z_2}\dot{V}_{\text{in}} \qquad Z_{\text{in}}=\frac{\dot{V}_{\text{in}}}{\dot{I}_{\text{in}}}=\frac{Z_2^{\,2}}{Z_5^{\,2}}R\tag{4}$$

B. Receiver Circuit Design

According to (4), it now clearly demonstrates that this double-T circuit can achieve a load-independent voltage with a constant voltage as input. Also, the output voltage can be regulated by configuring the values of the resonant components. Based on this interesting feature, the double-T circuit can be inserted between the receiving coil and the rectifier to obtain a load-independent constant output voltage of the WPT system. Now if one step is taken further, by connecting multiple double-T circuits with different resonant components in parallel to the same receiving coil, different load-independent constant output voltages can be achieved.

Fig. 4 shows the circuit of the proposed WPT system with multiple output channels. Multiple double-T resonant rectifiers, e.g., LCL-CLC rectifiers will be connected in parallel to a common ac bus to form multiple channels with constant current outputs.

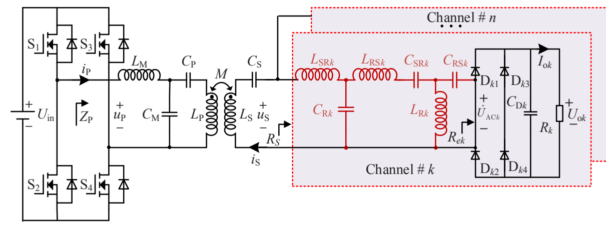

Fig. 4. The circuit of proposed WPT system.

So far, the receiver of the WPT system has been studied and developed. As long as an ac voltage is induced at the common receiving coil through magnetic coupling, multiple output ac voltages can be obtained at the terminal of multiple double-T circuits. Hence, multiple output dc voltages will be established at the rectifiers. In order to induce the ac voltage at the receiving coil, the coupling coils and the compensation network at the transmitter side should be designed properly, which will be discussed in the next section.

To facilitate the analysis, the fundamental voltage phasor of the inverter can be expressed as

$$\dot{U}_{\text{P}}=\frac{2\sqrt{2}U_{\text{in}}}{\pi}\sin\frac{\delta}{2}\angle 0^{\circ}\tag{5}$$

where δ represents the conduction angle of the voltage.

C. Transmitter Circuit Design

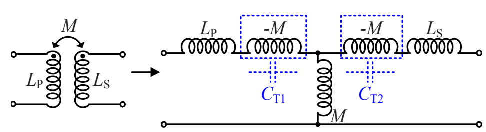

Fig. 5. The equivalent circuits of coupling coils.

In general, there are two useful methods to model the coupling coils, i.e., M model and T mode. By applying the T model, the equivalent circuit of the coupling coils can be obtained, as shown in Fig. 5. By substituting the T model (Fig. 5) into the WPT system (Fig. 4), the overall equivalent circuit of proposed WPT system can therefore be obtained, as shown in Fig. 6. It can be seen that, by performing in-depth circuit analysis, the compensation network and the transmitting coil also form a double-T resonant circuit (LCL-CLC). Consequently, the characteristics of the double-T circuit on the receiver side can all be applied on the transmitter side here. Therefore, the entire proposed WPT system is essentially a quadruple T-resonant circuit, specifically, with a high-frequency inverter supplying power as input and multiple rectifiers receiving power as outputs. Due to the two series-connected double-T resonant circuit structure, the load-independent multi-output WPT system can eventually obtained.

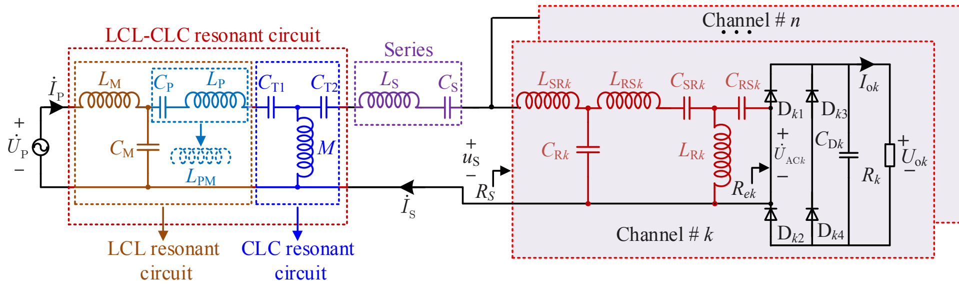

Fig. 6. The equivalent circuit of proposed WPT system.

D. Parameter Design and Tuning

For the proposed WPT system, the system parameters such as the dc input voltage U_{in}, the number of output channel n, the output dc voltage U_{Ok} of each channel, and the operating frequency ω, are determined according to the power level of the practical application and the specified National and International Standards, respectively. After that, the resonant components such as the L_M, C_M, L_{SRk}, C_{Rk}, etc., will be tuned carefully, and the turns of the coupling coils will be designed, according to the input and outputs requirement. One thing we should bear in mind is the rating currents of the inductors and the rating voltages of the capacitors.

To tune the resonant networks, the following equations should be satisfied

$$\begin{cases} L_M = L_{PM} = L_P - \dfrac{1}{\omega^2 C_p} & L_M \cdot C_M = \dfrac{1}{\omega^2} \\ L_S \cdot C_S = \dfrac{1}{\omega^2} & C_{T1} = C_{T2} = \dfrac{1}{\omega^2 M} \end{cases} \tag{6}$$

Therefore, after foregoing simplification, the output voltage $\dot{U}_S$ is easily deduced as

$$\dot{U}_S = \frac{\dot{U}_P}{\omega^2 L_M C_{T1}} \tag{7}$$

Combing (5), we can get

$$\dot{U}_S = \frac{2\sqrt{2} U_{in} M}{\pi L_M} \sin\frac{\delta}{2} \angle 0° \tag{8}$$

Then, the output dc voltage of the k^{th} channel can be given as

$$U_{ok} = \frac{U_{in} M}{\omega^2 L_M L_{SRk} C_{SRk}} \sin\frac{\delta}{2} \tag{9}$$

III. Experimental Verification

To verify the presented approach, the proposed wireless power transfer system with two constant output voltage channels is built in laboratory, as shown in Fig. 7. The distance between the coupling coils is 15cm. The voltage references of two output channels are set to 100V and 50V respectively for supplying two dc loads at the receiver side. The detailed system parameters are listed in Table I. In the experiment, ADUM3223 chips are employed as the power MOSFETs drivers to realize the high-frequency switch.

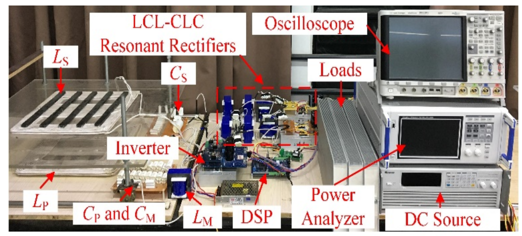

Fig. 7. The experimental prototype.

Two significant results are selected here to validate the effectiveness of the proposed WPT system. Fig. 8(a) shows the system performance at steady state. It is seen that the output voltage and output current of inverter are in phase, which indicates that the proposed WPT system can realize input ZPA. Also, the output voltages reach the reference and they are very stable. Fig. 8(b) demonstrates the load-independent output capability of the proposed WPT. In this test, the load of channel#2 is changed from 50Ω to 30Ω, then changed back to 50Ω. During this load variation, it is observed that the output voltages, u_{o1} and u_{o2}, are well maintained at the referenced levels. Meanwhile, the channel#2 is able to automatically increase its output current to meet the load demand.

TABLE I Circuit Parameters of the WPT System

Symbol	Value	Symbol	Value	Symbol	Value
L_M	34.25μH	C_M	102.4nF	M_{MIN}	30.02μH
L_p	242.83μH	C_p	16.69nF	M_{MAX}	40.33μH
L_S	248.37μH	C_S	14.04nF	R_{O1MIN}	8Ω
L_{SR1}	161.1μH	C_{SR1}	23nF	R_{O1MAX}	60Ω
L_{RS1}	161.1μH	C_{RS1}	23nF	R_{O2MIN}	8Ω
L_{R1}	152.43μH	C_{R1}	21.76nF	R_{O2MAX}	60Ω
L_{SR2}	322.1μH	C_{SR2}	23nF	U_{o1}	100V
L_{RS2}	322.1uH	C_{RS2}	23nF	U_{o2}	50V
L_{R2}	152.42uH	C_{R2}	10.88nF	U_{in}	120V
f	85kHz	n	2		

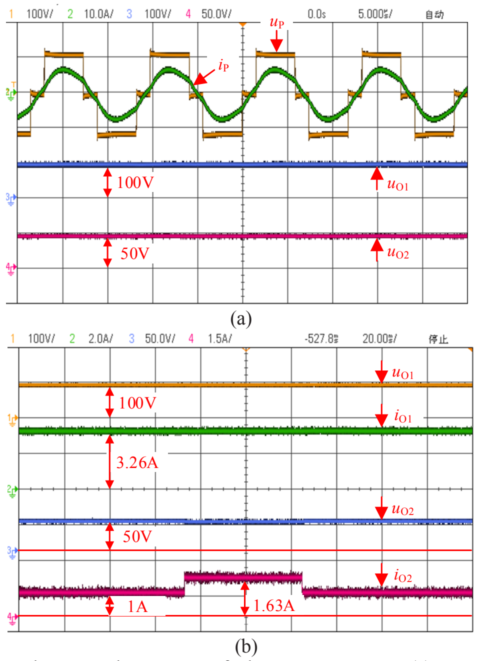

Fig. 8. Voltages and currents of the WPT system. (a) steady-state performance, (b) load variation.

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IV. Conclusions

A flexible load-independent multi-output WPT system is developed. It can successfully generate multiple constant outputs with different voltage levels avoiding using multiple DC-DC converters. This load-independent multi-output characteristic makes it very suitable in applications where electric appliances requires various DC supply voltages.

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