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Load characteristics of wireless power transfer system with different resonant types and resonator numbers

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Wireless Power Transfer (WPT) has been the research focus and applied in many fields. Normally power is transferred wirelessly to charge the battery, which requires specific load characteristics. The load characteristics are essential for the design and operation of the WPT system. This paper investigates the load characteristics of the WPT system with different resonant types and resonator numbers. It is found that in a WPT system with series or LCL resonance under a constant voltage source, the load characteristic is determined by the number of inductors. Even number of inductors results in a constant current characteristic and odd number constant voltage characteristic. Calculations, simulations, and experiments verify the analysis. [http://dx.doi.org/10.1063/1.4972851]

I. INTRODUCTION

Wireless power transfer (WPT) has received intense research attention in the last decade.[1] WPT can be applied in numerous aspects, such as electric vehicles,[2] consumer electronics, wireless sensor networks,[3,4] and implantable medical devices. There are two different connections of the inductor and the capacitor,[5] namely the series connection (S) and the parallel connection (P). In the parallel resonance, an extra inductor is added to form an LCL topology to be connected to the voltage source. These two different resonant types[6] result in different load characteristics. To extend the transfer distance, relay resonators are utilized in the WPT system.[7,8] The load characteristics of the WPT system with different relay resonator numbers under different resonant types are not fully explored yet.

The rest of this paper is organized as follows. Section II establishes the model of the WPT systems with different resonant types. Their load characteristics are investigated. Section III analyzes the load characteristics of the N-resonator WPT system. Calculations, simulations and experiments are offered in Section IV. Finally, Section V concludes the whole paper.

II. LOAD CHARACTERISTICS OF DIFFERENT RESONANT TYPES

According to the different resonant types in the primary and secondary sides, there are four topologies in the WPT system, namely the S-S, S-LCL, LCL-S, and LCL-LCL, as displayed in Fig. 1. The equivalent resistances of the inductors and the capacitors are ignored. Assume that the resonant frequencies of the primary side and the secondary side are the same, i.e.

$$f_0 = \frac{1}{2\pi\sqrt{L_S C_1}} = \frac{1}{2\pi\sqrt{L_1 C_1}} = \frac{1}{2\pi\sqrt{L_2 C_2}} = \frac{1}{2\pi\sqrt{L_R C_2}}. \tag{1}$$

The secondary loop impedance of the four topologies at the resonant frequency are

$$Z_{2,\text{S-S}} = Z_{2,\text{LCL-S}} = R_\text{L}, Z_{2,\text{S-LCL}} = Z_{2,\text{LCL-LCL}} = \frac{(\omega L_2)^2}{R_\text{L}}. \tag{2}$$

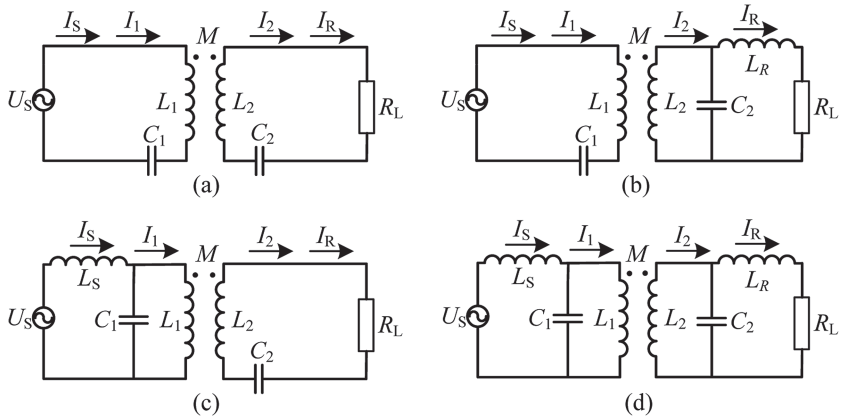

FIG. 1. Four topologies of WPT system: (a) S-S; (b) S-LCL; (c) LCL-S; (d) LCL-LCL.

Therefore, the reflected impedances of the four topologies are

$$Z_{\text{ref,S-S}} = Z_{\text{ref,LCL-S}} = \frac{(\omega M)^2}{R_{\text{L}}}, Z_{\text{ref,S-LCL}} = Z_{\text{ref,LCL-LCL}} = \left(\frac{M}{L_2}\right)^2 R_{\text{L}}. \tag{3}$$

The currents are calculated as

$$\begin{aligned}
&I_{\text{S,LCL-S}} = \left(\frac{M}{L_1}\right)^2 \frac{U_{\text{S}}}{R_{\text{L}}}, I_{\text{S,LCL-LCL}} = \left(\frac{M}{\omega L_1 L_2}\right)^2 U_{\text{S}} R_{\text{L}},\\
&I_{\text{1,S-S}} = \frac{U_{\text{S}} R_{\text{L}}}{(\omega M)^2}, I_{\text{1,S-LCL}} = \left(\frac{L_2}{M}\right)^2 \frac{U_{\text{S}}}{R_{\text{L}}}, I_{\text{1,LCL-S}} = \frac{U_{\text{S}}}{\omega L_1}, I_{\text{1,LCL-LCL}} = \frac{U_{\text{S}}}{\omega L_1},\\
&I_{\text{2,S-S}} = \frac{U_{\text{S}}}{\omega M}, I_{\text{2,S-LCL}} = \frac{U_{\text{S}}}{\omega M}, I_{\text{2,LCL-S}} = \frac{M}{L_1}\frac{U_{\text{S}}}{R_{\text{L}}}, I_{\text{2,LCL-LCL}} = \frac{M}{L_1}\frac{U_{\text{S}} R_{\text{L}}}{(\omega L_2)^2},\\
&I_{\text{R,LCL-S}} = \frac{L_2}{M}\frac{U_{\text{S}}}{R_{\text{L}}}, I_{\text{R,LCL-LCL}} = \frac{M}{L_1}\frac{U_{\text{S}}}{\omega L_2}.
\end{aligned} \tag{4}$$

The load voltages and the load currents of these four topologies at the resonant frequency are

$$\begin{aligned}
&I_{\text{L,S-S}} = \frac{U_{\text{S}}}{\omega M}, I_{\text{L,S-LCL}} = \frac{L_2}{M}\frac{U_{\text{S}}}{R_{\text{L}}}, I_{\text{L,LCL-S}} = \frac{M}{L_1}\frac{U_{\text{S}}}{R_{\text{L}}}, I_{\text{L,LCL-LCL}} = \frac{M}{L_1}\frac{U_{\text{S}}}{\omega L_2},\\
&U_{\text{L,S-S}} = \frac{R_{\text{L}} U_{\text{S}}}{\omega M}, U_{\text{L,S-LCL}} = \frac{L_2 U_{\text{S}}}{M}, U_{\text{L,LCL-S}} = \frac{M U_{\text{S}}}{L_1}, U_{\text{L,LCL-LCL}} = \frac{M}{L_1}\frac{R_{\text{L}} U_{\text{S}}}{\omega L_2}.
\end{aligned} \tag{5}$$

Therefore, the load currents of the S-S and LCL-LCL topologies are constant while the load voltages of the S-LCL and LCL-S topologies are constant. From (2) and (3), we can see that the reflected impedance is in reverse proportion to the secondary loop impedance. One mutual inductance with resonance can reverse the constant voltage source in the primary side to a constant current source in the secondary side and vice versa. The function of the LCL topology is like adding another resonator so as to reverse its characteristics.

Conclusions can be drawn that in the WPT system with either S or LCL topologies, the total number of inductors determine the load characteristics. For a constant voltage power supply, the load current is constant with an even number of inductors, while the load voltage is constant with an odd number of inductors. This conclusion can be extended to N-resonator WPT system with combinations of S and LCL topologies.

III. LOAD CHARACTERISTICS OF DIFFERENT RESONATOR NUMBERS

For an N-Resonator WPT system consisting of S or LCL topologies, the aforementioned rule still applies here. The load characteristics are determined by the number of inductors. Even

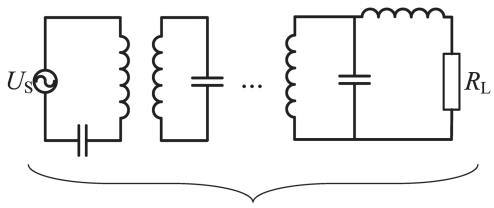

FIG. 2. Load characteristics of N-resonator WPT system.

number of inductors results in the constant current characteristics, while odd number constant voltage characteristics, as demonstrated in Fig. 2.

IV. CALCULATIONS, SIMULATIONS, AND EXPERIMENTS

The models of the four topologies are established in MATLAB/Simulink. All of the inductances are set as 320 μH and all of the capacitances are 10 nF. The mutual inductance M is 39.6 μH. The peak value of the source voltage is 100 V. The calculations and the simulations of the load voltages and load currents in these four topologies are shown in Fig. 3. The load currents of the S-S and LCL-LCL topologies are constant and the load voltages of the S-LCL and LCL-S topologies are constant.

An experimental prototype is implemented, as shown in Fig. 4. An inverter is added in the primary side to for the power supply, whose DC bus voltage is 200V. A rectifier is connected in the secondary side to convert the AC power into DC power, supplying power for the battery. The experimental results of the DC load voltage and current are demonstrated in Fig. 5. The reason why the load current is not constant is that the equivalent resistances, including the source internal resistance and the equivalent resistances of the inductors and the capacitors cannot be ignored. The experimental waveforms are displayed in Fig. 6.

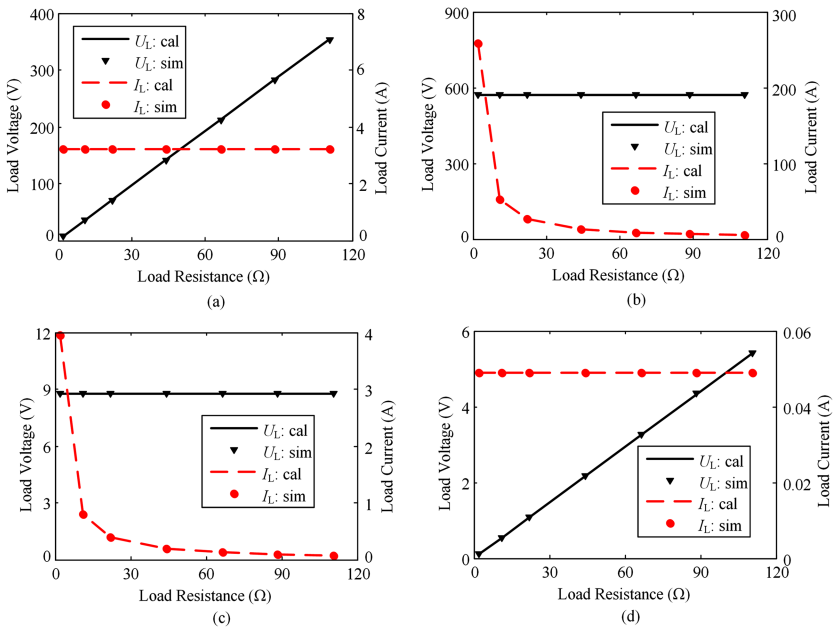

FIG. 3. Calculations and simulations of load voltages and load currents: (a) S-S; (b) S-LCL; (c) LCL-S; (d) LCL-LCL.

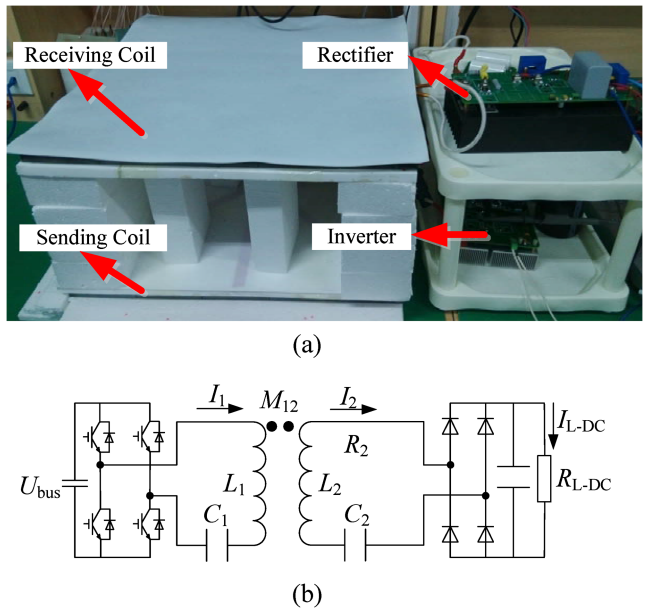

FIG. 4. Experimental prototype: (a) Photograph; (b) Topology.

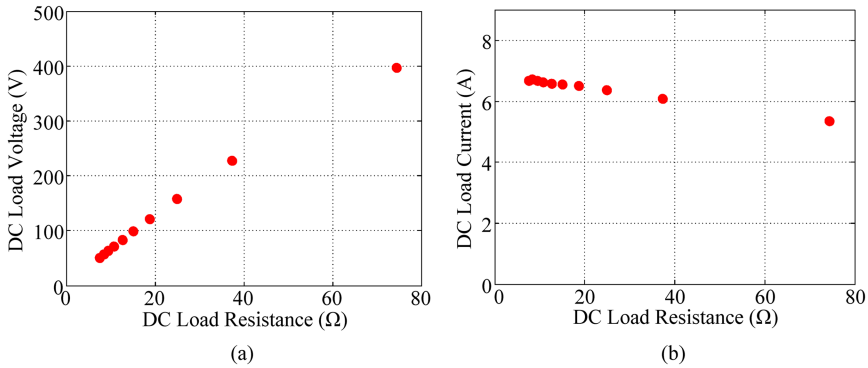

FIG. 5. Experiments of load voltage and load current of S-S topologies.

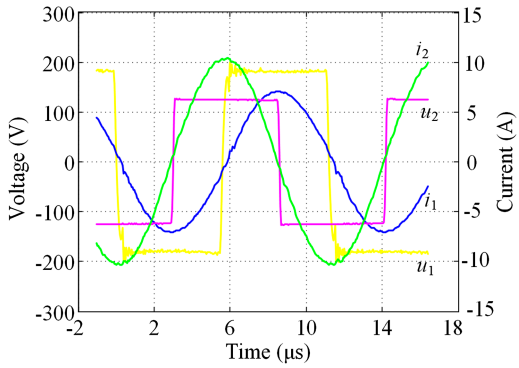

FIG. 6. Experimental waveforms.

V. CONCLUSION

This paper has investigated the load characteristics of the WPT system with different resonant types and resonator numbers, which are essential for the design and operation of the WPT system. The models of the S-S, S-LCL, LCL-S, and LCL-LCL have been established. The load currents of the S-S and LCL-LCL topologies are constant while the load voltages of the S-LCL and LCL-S topologies are constant. Conclusions can be drawn that for a constant voltage power supply, the WPT system has a constant-current load characteristic if the number of inductors is even and constant-voltage if odd. The results have been verified by calculations, simulations, and experiments. The analysis is beneficial for the understanding and design of a WPT system.

ACKNOWLEDGMENTS

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[1] Y. M. Zhang, Z. M. Zhao, and K. N. Chen, IEEE Trans. Power Electron. **29**, 1058 (2014).
[2] C. S. Wang, O. H. Stielau, and G. A. Covic, IEEE Trans. Ind. Electron. **52**, 1308 (2005).
[3] C. Liu, K. T. Chau, Z. Zhang, C. Qiu, F. Li, and T. W. Ching, J. Appl. Phys. **117**, 17A743 (2015).
[4] C. Liu, K. T. Chau, C. Qiu, and F. Lin, J. Appl. Phys. **115**, 17E702 (2014).
[5] Y. H. Sohn, B. H. Choi, E. S. Lee, G. C. Lim, G. H. Cho, and C. T. Rim, IEEE Trans. Power Electron. **30**, 6030 (2015).
[6] Z. N. Low, R. A. Chinga, R. Tseng, and J. Lin, IEEE Trans. Ind. Electron. **56**, 1801 (2009).
[7] D. Ahn and S. Hong, IEEE Trans. Ind. Electron. **60**, 360 (2013).
[8] W. Zhong, C. K. Lee, and S. Y. R. Hui, IEEE Trans. Ind. Electron. **60**, 261 (2013).