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Design and demonstration of a dynamic wireless power transfer system for electric vehicles

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The usage of electric vehicles is being globally promoted with the development of clean energy. However, the development of electric vehicles is limited by the battery capacity and the charging technology. Traditional charging facilities mainly involve plugging in vehicles in an electrical interface, which is inconvenient and inherently hazardous. When compared with the traditional charging methods, the wireless charging method can solve several problems, such as the interface limitation, and will be gradually developed as the main charging mode for electric vehicles [1]. Based on the driving states of electric vehicles, the wireless charging technologies can be mainly classified as static wireless charging and dynamic wireless charging. Static wireless charging requires an electric vehicle to be parked at a fixed charging point, whereas dynamic wireless charging can charge the electric vehicles when they are being driven. When compared with static wireless charging, dynamic wireless charging can improve the driving range and charging convenience of the electric vehicles, thereby reducing the waiting time between the charging cycles.

Thus far, a few research teams have published studies on system modeling methods, topological structures, and electromagnetic shielding technologies related to dynamic wireless charging systems [2]. In a dynamic wireless charging experiment conducted by the Oak Ridge National Laboratory, it was observed that the transmission power and efficiency are affected by the position of the electric vehicle. Researchers from the University of Tokyo proposed a technique to maximize the charging efficiency by estimating the real-time changes in the coupling factor because of the duty cycle of DC/DC (direct current) converters. Further, the researchers at the Chongqing University proposed an energy flow model based on the parameter identification theory to simplify the adjustment of secondary side parameters when the primary side is controlled [3]. By analyzing the electromagnetic field induced by the wireless charging system in vehicles and in the charging device of the wireless charging system, a method was proposed for installing the magnetic shielding devices in the launcher device [4].

Different research teams worldwide have promoted the rapid development of dynamic wireless charging systems for electric vehicles; however, a series of key technical problems has to be further investigated. First, it is essential to study the structure of magnetic coupled resonant coils. Second, studying the corresponding circuit topology, including the inverter on the transmitting side, resonant compensation network, and control circuit of the receiving side, is important [5]. Further, studying the efficiency optimization control

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strategies for dynamic wireless charging, including the corresponding algorithm, is an important aspect to guarantee the stability of dynamic wireless charging and the enhancement of power and efficiency [6].

The energy capacity and power of the vehicle batteries are limited, which are among the main challenges that hinder the mass uptake of the electric vehicles. To solve these problems, a dynamic wireless power transfer system for electric vehicles is designed in this study. In our design, a DC/DC converter is connected to the secondary side of the wireless charging system, and the input voltage of the DC/DC converter is considered to be the controller variable. Further, the double closed-loop control strategy is implemented, and the outer loop controls the current of the system, whereas the inner loop controls the intermediate voltage. The essence of the double closed-loop control strategy is to control the input voltage of DC/DC converter to control the system power. Further, a constant power output under a high coupling coefficient and a maximum power output under a low coupling coefficient can be achieved. Moreover, the experimental results in the supporting videos denote the effectiveness and good performance of the proposed dynamic wireless power transfer (DWPT) system.

Design of dynamic wireless power transfer system. (1) DWPT modeling. In the designed-dynamic wireless charging system depicted in Figure 1, the transmission terminal comprises several sets of energy transmission equipment as well as an energy receivier. The energy transmission terminal comprises a high-frequency inverter, a primary compensation network, and a transmission coil, which is a ground pad. The energy receiver comprises an energy-receiving coil, a secondary compensation circuit network, a rectifier, and a DC/DC converter that can be used to control the system power.

Generally, DC/DC converters have two basic circuit structures, BUCK and BOOST. In the posterior circuit of the proposed wireless charging system, the maximum power that the BOOST circuit can control and the minimum power that the BUCK circuit can control are observed to be equal. Therefore, the DC/DC converter selects the BUCK circuit. Furthermore, because the system operates at high frequencies, the switch tube will be switched on and off frequently, and the switching loss is the main energy loss in the circuit. Therefore, to improve the efficiency of the system, the switching loss must be reduced, and soft switching should be achieved.

(2) Controller design. The power transferred by the dynamical wireless charging system can be given as follows [7]: $P = U_{\mathrm{AB}}I_{Lf_1} = \frac{U_{\mathrm{AB}}U_{\mathrm{ab}}\times k\sqrt{L_1L_2}}{w_0L_{f_1}L_{f_2}}$, where U_{AB} is the first-order rms value of the input voltage applied to the primary side; U_{ab} is the first-order rms value of the output voltage before the rectifier is used; L_1 and L_2 are the self-inductances of the transmission coil and receiving coil, respectively; and k is the coupling coefficient between the transmission and receiving coils. w_0 denotes the resonant frequency, L_{f_1} denotes the primary-side compensation inductance, and L_{f_2} denotes the secondary-side compensation inductance. During the movement of the receiving coil, $U_{\mathrm{AB}}, L_1, L_2, w_0, L_{f_1}$, and L_{f_2} remain unchanged; however, the coupling factor k changes. Therefore, the power can be maximized by increasing U_{ab}. Using the dynamic wireless charging system, the power can be increased by increasing U_{ab}. If the DC/DC converter is not controlled, the duty cycle of IGBT (insulated gate bipolar transistor) is always 1, and the output power will decrease to become the minimum when the coupling factor k decreases to 0. Further, the power can be increased during the movement of the receiving coil within a certain range by increasing U_{ab} with some control strategy.

In the proposed controller design, double closed-loop control is adopted. The outer loop controls the output current of the DC/DC converter, and the inner loop controls its input voltage, which ensures the reliability. The output of the outer loop controller is the reference value of the input voltage of the DC/DC converter. The inner loop controller outputs the duty cycle signal to control the IGBT. In a double closed-loop control system, the input voltage of the DC/DC converter should be controlled although the output current is the given controlled variable. The value of the input voltage of the DC/DC converter is equal to the amplitude of the output voltage before the rectifier. U_{ab} is the first-order rms value of the output voltage before the rectifier. Therefore, the system power can be controlled by controlling the input voltage of the DC/DC converter, which is the controlled variable.

Demonstration. The values of the system parameters and the dynamic wireless charging system designed herein are presented in the supporting videos. When the receiving coil gradually deviates from the transmission coil, the fundamental frequency of the output current is observed to decrease. However, the turn-off current of the MOSFET (metal-oxide-semiconductor field-effect transistor) is always positive, therefore, zero voltage switching (ZVS) of the MOSFET can be realized, which will considerably increase the reliability and

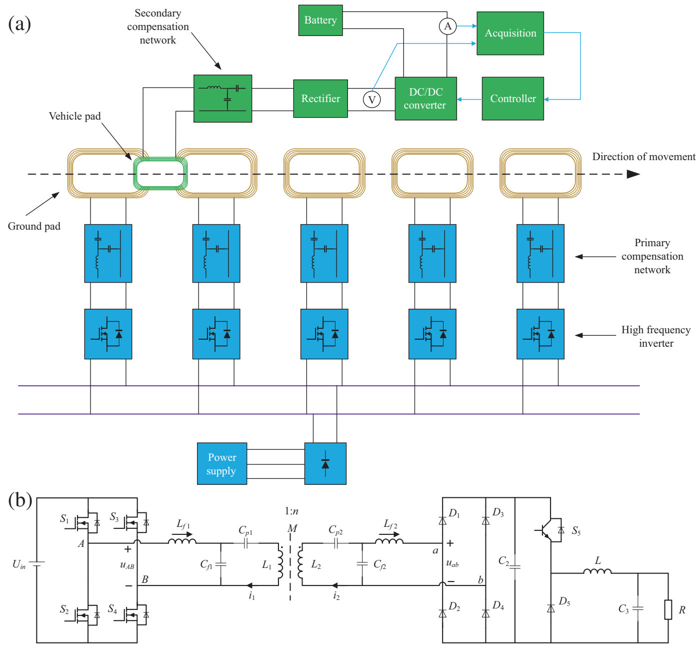

Figure 1 (Color online) Dynamic wireless power transfer. (a) Schematic diagram; (b) topology.

efficiency of the system.

The power and efficiency of the proposed system at each position are presented in the videos. The receiving coil is aligned with the first and second transmitting coils, which are at distances of 0 and 90 cm, respectively. As can be observed from the figures in the supporting video, the power and the efficiency of the system are the highest when the receiving coil and the transmission coil are aligned. The maximum input power is approximately 7.3 kW, and the maximum output power is about 6.1 kW. The maximum efficiency is approximately 85%.

Conclusion and future work. In this study, we presented the design and demonstration of the dynamic power transfer system, and explained our motivation for selecting the DC/DC converter structure type and the controlled variables. Further, the system topology, soft-switching, and magnetic field of the DWPT system are analyzed. A double-loop PID (proportion integration differentiation) control scheme is proposed in this study for improving the system power. The experimental and simulation results, denote that the design and PID control of the proposed DWPT systems for electric vehicles are effective and exhibit good performance. The demonstration in the supporting video denotes the efficiency of the designed DWPT system.

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Supporting information Videos and other supplemental documents. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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