Article

A Wireless Power Transfer Charger with Hybrid Compensation Topology for Constant Current/Voltage Onboard Charging

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Abstract: Compared with plugged-in chargers, wireless power transfer (WPT) systems for battery chargers have numerous advantages, e.g., safety, efficiency, and convenience. To satisfy the important wireless charging requirements of efficiency and safety of the battery, this paper proposes a constant current/voltage (CC/CV) charging compensation topology with near-communication based on receiving-side hybrid topology switching, which is unaffected by the dynamic loads. The proposed hybrid topology is systematically analyzed by using the M-mode, and the system parameters are designed to satisfy the constraints of zero phase angle (ZPA) and the specified CC output. In the CV mode, one shunt capacitor is employed to the compensation topology for the CV output and ZPA realization. Both the CC and CV modes are operated under the conditions of zero voltage switching (ZVS) for reducing the loss of the WPT systems. The proposed hybrid compensation topology is controlled by the receiving side and does not require real-time communication to avoid sophisticated control logic. Finally, a 1.1-kW experimental prototype charger based on DS-LCC and LCC-S topologies was established to verify the charging performance of the proposed WPT systems. The maximum efficiency of the proposed WPT charger was found to be approximately 91%. The experimental results were consistent with those of the theoretical analysis.

Keywords: wireless power transfer; hybrid compensation topology; constant current/voltage charging; zero phase angle; battery charging

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1. Introduction

Wireless power transfer (WPT) technology can transfer electrical energy from a high-frequency power supply to a load through a magnetic field instead of a wire connection [1]. It has considerable development potential given its unique advantages, such as safety, efficiency, convenience, and weatherproof-ness, which make it desirable for application in daily life, similar to WiFi. Owing to such advantages, WPT charging can be used in several fields, such as non-removable medical implants [2,3], underwater equipment [4], portable electronic devices [5,6], and other industrial fields. In particular, applications in the field of electric vehicles have attracted widespread attention [7] because of the environmental friendliness, high efficiency, and high success ratio of vehicle-to-grid interaction. However, most electric vehicles adopt conventional plugged-in chargers, which are unsafe, inconvenient, and space-occupying. The emergence of WPT technology is regarded as a preferred solution to the problems of traditional charging methods, boosting the development of the electric vehicle industry.

In general, most of the energy storage devices use lithium batteries, owing to their inherent advantages of high energy, light weight, and strong power tolerance. However, the equivalent resistance of the battery varies with respect to the charging voltage or current. To obtain the expected charging voltage or current for different modes under a dynamic load, the battery charging was mainly accomplished in two stages: an initial constant current (CC) charging stage and then a constant voltage (CV) charging stage, as shown

in Figure 1. First, the battery was charged at a constant charging current I_{BAT} , but the battery voltage continued to increase with the increase of the resistance. To avoid the damage of the battery caused by overcharging, while the output voltage of the charger rose to the preset voltage U_{BAT} , the charger needed to quickly switch to CV mode. Finally, the charging was completed when the charging current was reduced to near zero. However, the drastic change of battery resistance brought great challenges to the design of WPT charging systems.

Figure 1. Typical charging profile of the battery.

To achieve a high-efficiency CC/CV output under dynamic loads, researchers have proposed many schemes for WPT charging systems. These schemes can be roughly divided into three categories.

Category 1: Wu et al. [8] proposed a new two-way control scheme for optimizing the charging efficiency of the system, which involves the addition of a DC/DC converter on the primary or secondary side. Ahn et al. [9] proposed an automatic feedback control method with a fast response and simple hardware, which can perform impedance matching and obtain the CC/CV output by adjusting the duty cycle. Li et al. [10] proposed a maximum efficiency point-tracking control scheme to maximize the system efficiency while adjusting the output voltage. However, the additional DC/DC converter increases the cost of the WPT charging systems and reduces the transmission efficiency.

Category 2: Vu et al. [11] proposed a design for WPT systems, which can achieve CC/CV charging modes by adopting the load-independent characteristics under zero phase angle (ZPA) conditions with minimal frequency changes throughout the charging process. Yang et al. [12] proposed a novel inductor–capacitor–capacitor–capacitor series (LCCC-S) compensation topology and a parameter correction scheme for obtaining the CC/CV modes at two different ZPA working frequency points. Byeon et al. [13] proposed a hybrid control method for a limited operating frequency range, which by using frequency modulation control to realize zero-voltage switching (ZVS) operation and phase-switching control to adjust the output voltage. However, a wide range of pulse-width modulation is usually desired, which increases the switch losses and volt-ampere (VA) ratings. Additionally, the foregoing control methods is not only complicated, but also should maintain real-time communication between the primary and secondary sides.

In addition to the aforementioned complex control strategies that can provide a CC or CV output, researchers have considered using a switching hybrid topology to achieve a CC/CV output under dynamic loads without the need for complex control strategies [14]. There are four main types of compensation topologies studied, which have certain required characteristics at a specified resonant frequency [15]. For example, under the precondition of satisfying the ZPA, series–series (S–S) and parallel–parallel (P–P) compensation topologies can achieve a CC output under dynamic loads, while series–

parallel (S-P) and parallel-series (P-S) topologies can achieve a CV output [7,16]. However, research on charging the battery in two modes simultaneously is lacking. Additionally, Auvigne et al. [17] realized a charger with CC/CV output by using the combination between S-S and S-P topologies with different compensation parameters; however, the circuit was complex and contained a center loose circuit of taps. S-P compensation topologies were comprehensively analyzed by Qu et al. [18], and two types of load-independent output currents and voltages were realized by switching between S-S and P-S topologies. However, the hybrid topology requires not only three switches and an additional inductor, but also a wireless real-time communication link.

The CC or CV output of low-order WPT systems under dynamic loads are limited by the loosely coupled transformer (LCT) parameters, which reduces the system design freedom. In many WPT applications, the size or position of the LCT is limited within a certain range, and the available LCT parameters do not meet the requirements of the CC/CV charging mode. To obtain more freedom of the WPT system design, many high-order compensation topologies with multiple compensation components are proposed [19–24]. For instance, the double side-LCC (DS-LCC) compensation topology with a compensated inductor and two compensated capacitors on each side of the LCT [20–22] is used to achieve a CC output under dynamic loads. The LCC-S compensation topology has the advantage that there is no ZPA frequency fluctuation according to the load, and the current flowing to the transmitting coil can be constantly supplied regardless of the dynamic loads and coupling-coefficient fluctuations [25–28]. Additionally, both DS-LCC and LCC-S topologies can meet the requirements of low reactive power and soft switching at the same time, and the greater freedom of system design undoubtedly promotes the design of WPT converters. However, there are few ideas for implementing CC/CV charging by using a hybrid high-order compensation topology with near-communication on the secondary side.

On the basis of the foregoing studies, this paper proposes a secondary side near-communication switching hybrid compensation topology method for the battery charging. Two AC switches (ACSs) and one auxiliary capacitor are employed on the secondary side to realize CC/CV charging mode under dynamic loads. The advantages of the proposed WPT charging systems are as follows: (1) There is no need for real-time communication between the primary and secondary sides, which eliminates wireless communication equipment, reduces the cost, and improves the reliability of charging. (2) The proposed WPT charging systems can achieve a lower VA ratio under condition of ZVS at a fixed working frequency of 85 kHz, which effectively enhanced the system effectiveness. A 1.1-kW prototype is used to verify the proposed WPT systems. The experimental results showed that the maximum system efficiency of CC and CV charging stages were approximately 90.9% and 91%, respectively.

The structure of this paper is organized as follows: A systematic theoretical analysis of the DS-LCC and LCC-S topologies is described in Section 2. Section 3 proposes that a hybrid compensation topology can realize CC/CV output under dynamic loads with ZPA conditions, and the method of parameter correction. Section 4 establishes the experimental device and verifies the feasibility of the theoretical analysis. The conclusions of the study are described in Section 5.

2. Theoretical Analysis

2.1. Implementation of CC Mode with ZPA Condition

To achieve a load-independent CC output characteristic with high design freedom of the transfer gain, the DS-LCC compensation topology is proposed. Its design adopted the symmetric tuning scheme with the same compensation network parameters for the primary and secondary sides. The schematic diagram of the DS-LCC compensation wireless charging system is shown in Figure 2.

Figure 2. DS-LCC compensated WPT charging systems.

On the primary side, the DC source U_{DC} was converted to a square wave voltage U_{IN} through the full bridge inverter (FBI) and then flowed into the DS-LCC resonance compensation topology. L_1 , C_{P1} , and C_{F1} represent the primary side compensated inductor and capacitors. L_2 , C_{P2} , and C_{F2} are the secondary side compensation components. C_{F1} and C_{F2} are the DC blocking capacitors used to eliminate the DC current component. M is the mutual inductance between the two sides. Q_1 – Q_4 represent SiC metal–oxide semiconductor field-effect transistors (MOSFETs) of the FBI, while D_1 – D_4 represent diodes of the rectifier. U_O and I_O represent the output voltage and current of the DS-LCC topology, respectively.

The M -type and T -type models are widely used to analyze WPT charging systems. When the self-inductance and the compensation capacitor should interact in the compensation network, the M -type model has more advantages than the T -type model [29]. Therefore, the M -type model is adapted to investigate the DS-LCC compensation topology, as shown in Figure 3.

Figure 3. Equivalent M -type model of the DS-LCC topology for the CC charging.

To facilitate the analysis, the equivalent M -type model in Figure 3 can be converted into the model shown in Figure 4.

Figure 4. Primary side circuit diagram of the DS-LCC topology with reflected impedance.

According to the Kirchhoff's voltage law (KCL), the equivalent impedance Z_S and the reflection impedance Z_{R1} of the secondary side can be deduced as (1):

$$\begin{cases} Z_S = j\omega L_S + \frac{1}{j\omega C_{F2}} + \frac{1}{j\omega C_{P2}} \parallel (j\omega L_2 + R_{AC}) \\ Z_{R1} = \frac{\omega^2 M^2}{Z_S} \end{cases} \quad (1)$$

where the symbol “||” expresses the parallel connection.

The input equivalent impedance Z_{IN} and the input phase angle Q_{IN} of the simplified M-type model of the DS-LCC topology can be expressed as follows:

$$\begin{cases} Z_{IN} = j\omega L_1 + \frac{1}{j\omega C_{P1}} || (j\omega L_P + \frac{1}{j\omega C_{F1}} + Z_{R1}) \\ Q_{IN} = \frac{180^\circ}{\pi} \arctan \frac{I_m(Z_{IN})}{R_e(Z_{IN})} \end{cases} \quad (2)$$

To obtain the ZPA for achieving CC-output operation, the input equivalent impedance Z_{IN} can be represented by Equation (3) for eliminating the imaginary part.

$$Z_{IN} = j\omega L_1 + \frac{1}{j\omega C_{P1}} + \frac{1}{\omega^2 C_{P1}^2 (Z_P + Z_{R1})}, \quad (3)$$

where the $Z_P = j\omega L_P + \frac{1}{j\omega C_{F1}} + \frac{1}{j\omega C_{P1}}$, and Z_{IN} should satisfy the limited condition as follows:

$$\begin{cases} C_{P1}(\omega^2 L_P C_{F1} - 1) - C_{F1} = 0 \\ \omega^2 L_1 C_{P1} - 1 = 0. \end{cases} \quad (4)$$

Z_{IN} of the DS-LCC compensation topology can be rewritten as follows:

$$Z_{IN} = \frac{L_1 L_2}{C_{P1} C_{P2} \omega^2 M^2 R_{AC}}. \quad (5)$$

The input current I_{IN} and output current I_O can be expressed as follows:

$$\begin{cases} I_{IN} = \frac{U_{IN} C_{P1} C_{P2} \omega^2 M^2 R_{AC}}{L_1 L_2} \\ I_O = \frac{M U_{IN}}{j\omega L_1 L_2}. \end{cases} \quad (6)$$

As indicated by Equation (6), I_O only depends on U_{IN} , the operating angular frequency ω , and the compensation inductance parameters L_1 and L_2 . Therefore, the DS-LCC compensation topology can be equivalent to a current source, realizing the CC charging mode.

The transconductance gain G_{UI} of the DS-LCC compensation topology can be derived as follows:

$$G_{UI} = \left| \frac{I_O}{U_{IN}} \right| = \frac{M}{j\omega L_1 L_2}. \quad (7)$$

According to Equations (2) and (7), the input phase angle Q_{IN} of the input equivalent impedance and transconductance gain G_{UI} of the DS-LCC WPT charging systems are plotted in Figure 5, respectively. The diagrams of the transconductance gain G_{UI} , which are regarded as the absolute value of the ratio of I_O to U_{IN} . As shown in Figure 5a, the constant G_{UI} under the ZPA can be realized at the fixed frequency of 85 kHz, and the input phase angle of the associated input impedance against the effect of the dynamic loads. As shown in Figure 5, it can be seen that the DS-LCC compensation topology can also achieve constant current output under ZPA conditions at the frequency of 110 kHz, but the slope of the transconductance gain curve at 110 kHz was significantly higher than the slope at 85 kHz. Therefore, changes in the output current at 110 kHz were more sensitive to changes in the switching frequency than at 85 kHz. A small variation in frequency around 110 kHz could cause a significant change in the output current. In addition, the variation of the phase according to the switching frequency change at 110 kHz was larger than that at 85 kHz. Therefore, this article selected 85 kHz as the operating frequency.

Figure 5. (a) Transconductance gain of the DS-LCC topology; (b) input phase angle of the input equivalent impedance.

Additionally, it is worth noting that if the compensation parameters satisfy complex constraint conditions, the DS-LCC topology can implement CV-output by using the frequency-hopping under the conditions of ZPA [27]. However, frequency-hopping leads to the following issues:

- (1) Iteration is needed to determine the CV-output point of attachment of the parameter settings, which leads to a high required accuracy of the compensation parameters;
- (2) Under the resonant condition, the WPT systems are highly sensitive to changes in the coupling parameters of the LCT. If the coupling parameters change, the ZPA conditions cannot be realized in the CV output stage;
- (3) The increment of the working frequency inevitably increases the loss of the WPT system and can even lead to frequency bifurcation;
- (4) The operating frequency of the system is limited by relevant standards; thus, it cannot be improved in a wide range.

Therefore, this article analyzes the existing compensation topology that can realize the CV-output. It is found that the high-order compensation topology LCC-S can realize a load-independent CV-output. Next, a systematic theoretical analysis of the LCC-S topology is performed.

2.2. Implementation of CV Mode with ZPA Condition

The LCC-S topology has received considerable attention for its ability to provide a stable CV-output characteristic under dynamic loads. The circuit diagram of the LCC-S compensation topology is presented in Figure 6, where the C_{FF} represents the C_{F3} and L_2 in parallel, and in series with C_{F2} , which is described in detail in Section 3. The composition of the primary side of the LCC-S topology is the same as that of the DS-LCC compensation topology, which can generate a constant current in the transmitting coil. The difference between the two topologies is that the secondary side is a resonant network composed of L_S and C_{FF} in series.

Figure 6. LCC-S compensated WPT charging systems.

The M -type model analysis method is also applicable to the analysis of the LCC-S compensation topology. According to the foregoing analysis, the M -type model is applied to investigate the LCC-S compensation topology, as shown in Figure 7.

Figure 7. Equivalent M -type model of the LCC-S compensation topology for the CV-output.

To intuitively study the LCC-S compensation topology, the equivalent M -type model in Figure 7 can be converted into the model, as shown in Figure 8.

Figure 8. Primary side circuit diagram of the LCC-S topology with reflected impedance.

The equivalent impedance Z_S and the reflection impedance Z_{R2} of the secondary side can be derived as follows:

$$\begin{cases} Z_S = j\omega L_S + \frac{1}{j\omega C_{FF}} + R_{AC} \\ Z_{R2} = \frac{\omega^2 M^2}{Z_S} \end{cases} \quad (8)$$

The input equivalent impedance Z_{IN} and the input phase angle Q_{IN} can be represented as follows:

$$\begin{cases} Z_{IN} = j\omega L_1 + \frac{1}{j\omega C_{P1}} \parallel (j\omega L_P + \frac{1}{j\omega C_{F1}} + Z_{R2}) \\ Q_{IN} = \frac{180^\circ}{\pi} \arctan \frac{I_m(Z_{IN})}{R_e(Z_{IN})} \end{cases} \quad (9)$$

According to [27], when the operating angular frequency is operated at $\omega_{CV} = 1/\sqrt{L_1 C_{P1}} = 1/\sqrt{C_{F1}(L_P - L_1)} = 1/\sqrt{L_S C_{FF}}$, the input equivalent impedance Z_{IN} can be rewritten as (10):

$$Z_{IN} = \frac{\omega^2 C_{F1} L_1 R_{AC}}{j\omega(L_P - L_1 - \frac{1}{\omega^2 C_{F1}})R_{AC} + \omega^4 M^2 C_{P1} C_{F1}} \quad (10)$$

To achieve soft switching in the ZPA condition, it is required that the imaginary part of the Equation (10) must be equal to zero, which can be expressed as (11):

$$L_1 = \frac{C_{F1}}{C_{F1} + C_{P1}} L_P \quad (11)$$

As indicated from the Equation (10), Z_{IN} can be rewritten as (12):

$$Z_{IN} = \frac{L_1^2}{M^2} R_{AC} \quad (12)$$

The input and output currents of the LCC-S topology can be represented as (13):

$$\begin{cases} I_{IN} = \frac{U_{IN}}{Z_{IN}} = \frac{U_{IN}M^2}{L_1^2 R_{AC}} \\ I_P = \frac{U_{IN}}{j\omega L_1} \\ I_O = \frac{j\omega M I_P}{Z_S} = \frac{U_{IN}M}{L_1 R_{AC}} \end{cases} \quad (13)$$

The input voltage U_O of the rectifier and the voltage transfer gain G_{UU} can be represented as:

$$\begin{cases} U_O = I_O R_{AC} = \frac{MU_{IN}}{L_1} \\ G_{UU} = \left| \frac{U_O}{U_{AB}} \right| = \frac{M}{L_1} \end{cases} \quad (14)$$

Figure 9a,b is based on Equations (9) and (14), respectively. The LCC-S compensation topology can implement CV charging mode under ZPA conditions, regardless of the battery equivalent resistance, which varies from 7 to 40 Ω , as shown in Figure 9a. Moreover, the gradient of the voltage transfer gain G_{UU} line at approximately 85 kHz is insensitive to the change of the working frequency, indicating the LCC-S compensation topology can provide a stable CV-output over a wide frequency range. As shown in Figure 9b, when the operating frequency is less than the resonant frequency, Q_{IN} is positive under high load conditions, indicating that the system presents inductive, but when the operating frequency is greater than the resonant frequency, Q_{IN} is negative under high load conditions, indicating that the system shows capacitive. It is worth noting that Q_{IN} has three ZPA points when $R_L = 7 \Omega$, indicating that the system first appears as capacitive and then appears as inductive near the resonance frequency point. Therefore, in order to ensure the soft-switching of the AC switch, the parameter design of compensated inductance L_1 is designed to make the actual value slightly greater than the theoretical value.

Figure 9. (a) Voltage gain of the LCC-S topology and (b) phase angle of the input impedance.

3. Proposed CC and CV Charging Modes and Parameter Modification

3.1. Proposed CC and CV Charging Modes

According to the foregoing theoretical analysis, under the constraints of the ZPA conditions, the DS-LCC topology can realize a stable CC charging mode, and the LCC-S topology can implement a CV charging mode under dynamic loads.

Clearly, by combining the transfer characteristics of the two topologies and adopting reasonable switching control logic, a charger that can satisfy the CC/CV modes of the battery can be obtained. Therefore, this paper proposed a hybrid compensation topology by employing a shunt auxiliary capacitor C_{F3} and two additional ACSs (S_1 and S_2) on the secondary side to achieve onboard charging, as shown in Figure 10.

Figure 10. (a) Proposed hybrid compensation topology of the WPT systems; (b) DS-LCC topology for the CC output; (c) LCC-S topology for the CV output.

The two additional ACSs (S_1 and S_2) in the designed hybrid topology are shown in Figure 11. In general, ACSs can be designed via two MOSFETs connected back-to-back.

Figure 11. ACSs with two MOSFETs connected back-to-back.

As clearly shown in Figure 12a, the control logic of ACSs S_1 and S_2 of the battery charger is converted from the CC to CV charging mode. Figure 12b represents the circuit diagram for performing the switching action. U_{BAT} represents the charging voltage of the battery, and $k_v = U_{REF}/U_{BAT_MAX}$ represents the ratio of the reference voltage U_{REF} and the boundary voltage from CC to CV mode. Initially, the WPT charger operates in CC mode ($S_1 = 1, S_2 = 0$) while $U_{BAT} < U_{BAT_MAX}$. As the charging voltage increases, once it reaches the maximum U_{BAT_MAX} , the control logics of S_1 and S_2 are toggled and the WPT charger is operating in CV mode ($S_1 = 0, S_2 = 1$), and I_{BAT} begins to drop until the charge end current is reached.

Throughout the charging process, when the output voltage of the charger is less than U_{BAT} , switch S_1 is connected and switch S_2 is disconnected, and the WPT charging systems operate in the CC stage, as clearly shown in Figure 10b. In contrast, when the output voltage increases to U_{BAT} , S_1 is disconnected and S_2 is connected, and the WPT charging systems operate in the CV charging stage, as shown in Figure 10c.

Figure 12. (a) Control logic for S_1 and S_2 of the battery charger and (b) circuit diagram for performing the switching action.

3.2. The Parameter Modification

On the primary side of the WPT charging systems, the input voltage can be modulated by the FBI into a square wave voltage with a 0.5-T duty cycle. Assuming the output voltage U_{IN} is expanded by the Fourier series, it can be expressed as:

$$U_{IN} = \frac{4U_{DC}}{\pi} \sum_{n=1,3,5,\dots} \frac{\sin(n\varphi)}{n}. \quad (15)$$

where n is the number of harmonics and φ is the phase angle. Because the quality factor of the resonance compensation topology is quite high in the WPT system, the I_{IN} current component corresponding to the super-harmonics are very small. Therefore, fundamental harmonic analysis can be used without affecting accuracy. If only the fundamental component is considered, $n = 1$, the relationships between the input DC source and root-mean-square (RMS) values of the output voltage U_{IN} and current I_{IN} of FBI can be expressed as the following equation according to [30]:

$$U_{IN} = \frac{2\sqrt{2}}{\pi} U_{DC}, I_{IN} = \frac{2\sqrt{2}}{\pi} I_{DC}. \quad (16)$$

The secondary side, due to the output low-pass filter, is only composed of capacitance. Thus, the RMS input voltage U_O of the rectifier, and the connection between the charging current I_{BAT} of the battery charger and the RMS input current I_O of the rectifier can be derived according to [26], which is represented as (17):

$$U_O = \frac{2\sqrt{2}}{\pi} U_{BAT}, I_{BAT} = \frac{2\sqrt{2}}{\pi} I_O. \quad (17)$$

According to (17), the rectifier output resistance R_L can be expressed as (18):

$$R_L = \frac{\pi^2}{8} R_{AC}. \quad (18)$$

The parameter adjustment process of the proposed WPT systems typically includes two steps: First, the compensation inductors L_1 and L_2 are designed according to the CC-output I_{BAT} and the rated output power P_O required by the DS-LCC compensation topology. L_1 and L_2 symmetric design by using traditional tuning method [20] can be expressed as (19):

$$L_1 = L_2 = \frac{\pi\sqrt{2}MU_{IN}}{4U_{BAT}}. \quad (19)$$

Here, $M = k\sqrt{L_P L_S}$, by substituting Equation (16) into (19), L_1 and L_2 can be rewritten as follows:

$$L_1 = L_2 = \frac{k\sqrt{L_P L_S} U_{DC}}{U_{BAT}}. \quad (20)$$

Second, all the compensation capacitors can be determined according to the given resonance conditions.

$$\begin{aligned} C_{P1} &= \frac{1}{\omega_0^2 L_1}, C_{P2} = \frac{1}{\omega_0^2 L_2}, C_{F1} = \frac{1}{\omega_0^2 (L_P - L_1)}, \\ C_{F2} &= \frac{1}{\omega_0^2 (L_S - L_1)}, C_{FF} = \frac{1}{\omega_0^2 L_S}. \end{aligned} \quad (21)$$

On the secondary side of the LCC-S compensation topology, the sum of the impedances of C_{F2} , C_{F3} , and L_2 should be the same as the impedance value C_{FF} , as shown in Figure 10c.

$$\frac{1}{j\omega C_{FF}} = \frac{1}{j\omega C_{F2}} + \frac{1}{j\omega C_{F3}} || j\omega L_2. \quad (22)$$

According to Equations (21) and (22), the capacitance of C_{F3} can be expressed as:

$$C_{F3} = \frac{1}{L_2 \omega_0^2} - \frac{C_{FF} C_{F2}}{C_{FF} - C_{F2}}. \quad (23)$$

As indicated by Equations (15)–(23), the compensation capacitance and inductance values of the WPT charging systems can be obtained. In order to more clearly present the parameters design procedure of the proposed hybrid compensation topology is shown in Figure 13.

Figure 13. Flowchart for the topology parameters design of the proposed WPT charger.

Moreover, the proposed high-order hybrid compensation topology has high degree of freedom, and by designing compensation parameters of the WPT charging systems can yield different levels of charging current and charging voltage within a certain range.

4. Experiment Verification

It is necessary to confirm the feasibility of the proposed WPT charging systems. To validate the foregoing theoretical analysis results and the proposed hybrid compensation topology model, a 1.1-kW test prototype was constructed, as shown in Figure 14, according to the structure of Figure 10a. The specific parameter settings were presented in Table 1, and were measured by using the LCR meter (IM3536, Hioki). The parameter settings of this experimental prototype provided a CC-output of 11.8 A and a CV-output of 88 V. As indicated in Figure 14, DSP TMS320F28335 was selected in this experiment to control FBI and ACSs S_1 and S_2 composed of SiC MOSFETs (C3M0030090K, Wolfspeed), and Schottky

diodes (IDW20G120C5B) were used to form the rectifier. Chroma 63200A was adopted to simulate the dynamic loads.

Figure 14. Experimental prototype of the proposed WPT battery charger.

Table 1. Designed parameters of the proposed WPT charger.

Symbols	Symbols	Symbols	Symbols
U_{IN}	100 V	L_1	11.51 μ H
f	85 kHz	L_2	11.48 μ H
C_{F1}	122.9 nF	C_{P1}	305.7 nF
C_{F2}	123.8 nF	C_{P2}	305.9 nF
C_{F3}	610.48 nF		

In this experimental prototype, the measured parameters of manufactured LCT are presented in Table 2. These parameters met the requirements of the WPT1 standard of SAE J2954 recommended practices. There was a deviation of approximately 1% between the actual measured value and the theoretical value due to manufacturing deviations. The dimensions (length $\times$ width) of the transmitting-loop L_P and receiving-loop L_S were 65×50 cm and 32×32 cm, respectively. The transmission distance between the L_P and L_S was 15 cm. Litz wire was used to reduce the skin effect and proximity effect.

Table 2. Measured LCT parameters.

Symbols	Symbols	Symbols	Symbols
k	0.267	M	10.75 μ H
L_P	40.8 μ H	R_P	13.31 m Ω
L_S	39.9 μ H	R_S	23.65 m Ω

The overall charging curve of the battery is presented in Figure 15a. As shown, in the CC charging stage, the output voltage increased from 24 to 88 V as the equivalent resistance increased from 2 to 7.3 Ω (orange line). In contrast to the equivalent resistance, which changed by a factor of 2.6, the charging current changed by only 2.6%, indicating the realization of the CC mode. In the CV charging stage, the output current decreased from 11.8 to 1.9 A as the equivalent resistance increased from 7.3 to 45.9 Ω . In contrast to the equivalent resistance, which changed by a factor of 6.3, the charging voltage changed by only 5.5%, indicating the realization of the CV-output. Figure 15b presents the measured

experimental efficiency of the proposed hybrid compensation WPT systems under the dynamic loads in the total process (blue line). In the CC charging stage, the maximum efficiency of the entire system was 90.9%. When the rated charging voltage value was reached, the WPT charger switched to the CV charging mode. The system efficiency gradually increased from 90% to the maximum value of 91% and then gradually decreased to 85%.

Figure 15. Measured charging process under dynamic loads. (a) Charging diagram; (b) charging efficiency and output power.

The experimental waveforms were scanned by using an oscilloscope (HDO4034A, Teledyne LeCroy). The results obtained under the dynamic loads are presented in Figures 16 and 17. In the CC mode, the charging current I_{BAT} was basically constant while the output resistance R_L fluctuated from 4 to 7 Ω, as presented in Figure 16, and the charging voltage U_{BAT} and AC input current I_{IN} increased continuously. In contrast, in the CV charging stage, as shown in Figure 17, when R_L fluctuated from 8 to 11 Ω, the charging voltage U_{BAT} was nearly unchanged, I_{BAT} and I_{IN} continued to decrease over time. In both the CC and CV charging stages, U_{IN} was ahead of I_{IN} by a small phase angle to achieve the ZVS of FBI, which reduces reactive power loss of the WPT system.

Figure 16. Experimental waveforms of U_{BAT} , I_{BAT} , U_{IN} , and I_{IN} in the DS-LCC topology.

Figure 17. Experimental waveforms of U_{BAT} , I_{BAT} , U_{IN} , and I_{IN} in the LCC-S topology.

The output performance of the CC and CV modes under dynamic loads were shown in Figures 18 and 19. When the WPT system worked in the CC charging stage, U_{BAT} decreased from 81 to 47 V and then increased to 81 V and R_L varied between 4 and 7 Ω , as shown in Figure 18. The results indicated that I_{BAT} was stable at 11.8 A, satisfying the CC-output requirements. Figure 19 presented the waveforms for the CV charging mode. As shown, the output current increased from 7.9 to 10.7 A and then decreased to 7.9 A, and R_L varied from 8 to 11 Ω . The output voltage was stable at 88.3 V, satisfying the CV output requirements. The experimental results are consistent with the theoretical analysis results.

Figure 18. Experimental dynamic response waveforms of multi-load regulation in the CC mode.

Figure 19. Experimental dynamic response waveforms of multi-load regulation in the CV mode.

It is necessary to evaluate the transient response of the proposed WPT charging systems throughout the switching process. Figure 20 depicts the transient waveforms of U_{IN} , I_{IN} , U_{BAT} , and I_{BAT} when ACSs S_1 was turned off and S_2 was turned on. As shown in Figure 20, the throughout transition process from the CC to CV charging mode, U_{IN} always remained unchanged, whereas the I_{IN} in the CV mode was slightly larger than that in the CC mode. Throughout the charging process of the battery, U_{BAT} and I_{BAT} remained essentially constant. The whole switching process took approximately 80 ms to restore stability, which is short compared with entire charging process of few hours, and the impact of mode switching on the whole charging process can be ignored. The foregoing experimental results verify the feasibility of the proposed hybrid wireless power transfer charger.

Figure 20. Transient waveforms switching process from the CC to CV charging mode for U_{IN} , I_{IN} , U_{BAT} , and I_{BAT} .

5. Conclusions

The DS-LCC and LCC-S compensation topologies of the WPT systems were analyzed using a mutual inductance model. By combining the advantages of their respective CC and CV outputs, a shunt capacitor, and two ACSs were added on the secondary side, and a switch hybrid compensation topology was proposed. The proposed hybrid topology charger is designed to easily implement the ZPA feature, which contributes to reduce the VA ratio and enhance the WPT systems efficiency. Moreover, the control was applied directly to the secondary side, which avoids sophisticated control logic and is conducive to the robustness of the WPT systems. Additionally, the working frequency of the WPT systems was fixed throughout the charging process, which mitigates the problems caused by frequency hopping. Finally, a 1.1-kW experimental prototype was designed to validate the charging performance of the proposed WPT systems. The results of experimental indicated the proposed switching hybrid compensation topology can well accomplish CC and CV outputs under dynamic loads, and the maximum charging efficiencies were 90.9% and 91%, respectively. The experimental results were consistent with those of the theoretical analysis.

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