

# 전기 자동차 배터리 충전 애플리케이션을 위한 무선 전력 전송 시스템의 CC/CV

## 충전의 구현

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### Implementation of the CC/CV Charge of the Wireless Power Transfer System for Electric Vehicle Battery Charge Applications

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#### ABSTRACT

Inductive Power Transfer (IPT) method becomes more and more popular for the Electric Vehicle (EV) battery charger due to its convenience and safety in comparison with plugged-in charger. In recent years, Lithium batteries are increasingly used in EVs and Constant Current/Constant Voltage (CC/CV) charge needs to be adopted for the high efficiency charge. However, it is not easy to design the IPT Battery Charger which can charge the battery with CC/CV charge under the wide range of load variation due to the wide range of variation in its operating frequency. This paper propose a new design and control method which makes it possible to implement the CC/CV mode charge with minimum frequency variation (less than 1kHz) during all over the charge process. A 6.6kW prototype charge has been implemented and 96.1% efficiency was achieved with 20cm air gap between the coils.

*Index Terms* – Inductive power transfer, Electric Vehicle Battery Charger, LCC Compensation Circuit, CC/CV Charge

#### 1. Introduction

The IPT System always suffers from low coupling coefficient between transmitter and receiver coils, thus the compensation tank is an indispensable part which contributes to the reduction in high circulating current and the improvement of the power transfer capability and overall efficiency as well. There are four basic compensation topologies, SS, SP, PS and PP (Series-Series, Series-Parallel, Parallel-Series and Parallel-Parallel). Among them the LCC topology has several advantages over the other topologies due to its lower voltage stress of the resonant capacitor, constant current characteristics at the primary coil and unit power factor in the secondary side [1].

The charge process for EV battery normally includes constant current (CC) charge and constant voltage (CV) charge as already mentioned. In order to guarantee the lifetime of the battery, it is required for the charger to provide accurate charge current and voltage with stable operation. To implement it with conventional resonant converters, the duty or frequency needs to be controlled and wide range of variation in duty or frequency under the variations in load and coupling coefficient is inevitable[2]. This paper introduces a new approach to implement the CC/CV charge with double-sided LCC converter operating at almost constant frequency. With the proposed method, CC/CV mode can be easily implemented with minimum frequency variation and hence the reliable charge operation for the EV battery module can be guaranteed and also the high efficiency can be achieved due to its soft switching characteristics over the wide range of operation. A 6.6kW prototype is implemented to prove the validity of the proposed method and its maximum efficiency is 96.1%.

#### 2. Proposed CC/CV charge with LCC compensation tank

The circuit diagram of the proposed battery charger is shown in Fig.1 (a). The circuit consists of the full-bridge inverter, LCC compensation tank in both sides and the secondary rectifier. The primary compensation tank is composed of a resonant inductor ( $L_{1p}$ ) and two resonant capacitors ( $C_{1p}$  and  $C_{2p}$ ). Here, the  $C_{1p}$  and

$C_{2p}$  are connected in series and in parallel with the coil, respectively, to take the advantages of both series and parallel topology. Similarly, secondary compensation tank is composed of  $L_{1s}$ ,  $C_{1s}$  and  $C_{2s}$ . The primary and secondary coils are identical to optimize the efficiency. The equivalent circuit of the proposed converter can be drawn based on the first harmonic approximation for the simplicity as shown in Fig.1 (b). The CC/CV charge can be implemented by analyzing the frequency characteristics of the proposed converter.

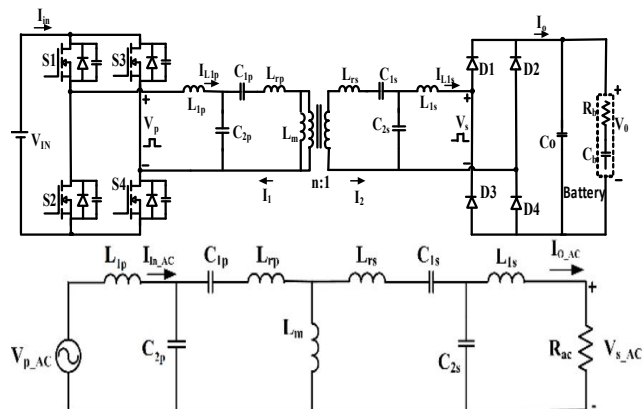


Fig. 1. (a) LCC converter topology for IPT system (b) AC equivalent circuit of the proposed IPT system

At first, the voltage gain, current gain and input impedance of the circuit need to be derived. The voltage gain of the proposed converter can be expressed as (2) by using the Kirchhoff's laws.

$$G_v = \left| \frac{V_o}{V_{in}} \right| = \left| \frac{V_{s,AC}}{V_{p,AC}} \right| = \frac{s^3 L_m R_{AC}}{M_o + sM_1 + s^2 M_2 + s^3 M_3 + s^4 M_4 + s^5 M_5 + s^6 M_6 + s^7 M_7 + s^8 M_8} \quad (1)$$

Where, the coefficient  $M_i$  depends on the value of load and components of the compensation tank as (2).

$$M_i = f(L_{1p}, C_{1p}, C_{2p}, L_m, L_{rs}, C_{1s}, C_{2s}, L_{1s}, R_{ac}); i = 1, 8 \quad (2)$$

On the other hand, the transconductance gain can also be derived from (1) as (3).

$$G_I = \left| \frac{I_o}{V_{in}} \right| = \frac{8}{\pi^2} \frac{V_{s,AC}}{V_{p,AC} R_{ac}} = \frac{G_v}{R_o} \quad (3)$$

Hence, the input impedance can be calculated as follows.

$$Z_{IN} = sL_{1p} + \frac{1}{sC_{2p}} // \left( sL_{rp} + \frac{1}{sC_{1p}} + sL_m // \left( sL_{rs} + \frac{1}{sC_{1s}} + \frac{1}{sC_{2s}} // (sL_{1s} + R_{ac}) \right) \right) \quad (4)$$

The frequency characteristics of the proposed converter can be derived as in (1) ~ (4) and they are drawn in Fig 2. As shown in the Fig. 2, transconductance gain  $G_I$  is constant regardless of the  $R_L$  at a certain frequency  $f_0$  and it varies in the rest of frequency domain. It can be easily deduced from the fact that the CC mode charge can be implemented at this switching frequency even under the load variation. Since the phase of  $Z_{IN}$  is equal to zero at

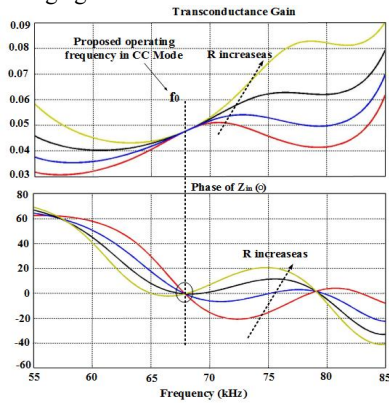
$f_0$ , there is no reactive power and no circulating current in the circuit, which contributes to the high energy transfer efficiency. The resonant frequency  $f_0$  can be written as (5).

$$f_0 = \frac{1}{2\pi\sqrt{L_{1p}C_{2p}}} = \frac{1}{2\pi\sqrt{L_{1s}C_{2s}}} = \frac{1}{2\pi\sqrt{(L_1 - L_{1p})C_{2p}}} = \frac{1}{2\pi\sqrt{(L_2 - L_{1s})C_{2s}}} \quad (5)$$

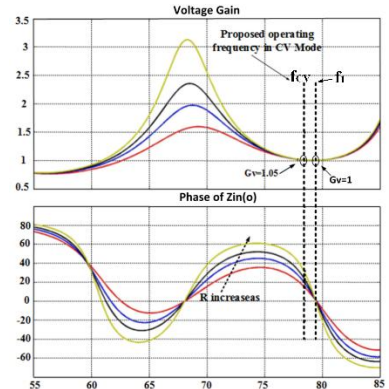
By substituting (5) into (3) the output current can be obtained as (6).

$$I_o = (8M/(2\pi f_0)\pi^2 L_{1p}L_{1s})V_{IN} \quad (6)$$

Fig. 2(b) shows the voltage gain of the system. It is shown that the voltage gain is fixed at  $f_i$  regardless of the load variation. Hence the CV mode charge can be implemented by operating the converter at this frequency. Since the converter needs to be designed to charge the EV battery up to 420V with 400V input, voltage gain of  $G_v=1.05$  is required. In order to deal with it the operating frequency for CV Mode  $f_{CV}$  needs to be adjusted slightly. If the converter operates at the slightly higher frequency than  $f_i$ , ZVS condition cannot be achieved since the phase of  $Z_{in}$  becomes negative and resonant tank operates in the capacitive region. Thus slightly higher frequency than  $f_i$  is selected to achieve the voltage gain for the CV mode.



(a) Transconductance gain and phase angle of  $Z_{in}$ , when  $R_{load}=15, 20, 25, 30 \Omega$ .



(b) Voltage gain and phase angle of  $Z_{in}$ , when  $R_{load}=40, 50, 60, 80 \Omega$ .

Fig. 2 Frequency characteristics of the proposed converter with the parameters in Table I.

TABLE I SPECIFICATION AND PARAMETERS OF IPT CHARGER

Parameter	Symbol	Value
Input Voltage	$V_{in}$	400V
Output Voltage	$V_o$	250V~420V
Output Current	$I_o$	15.7A
Self-inductance	$L_1, L_2$	218.3uH
Mutual inductance	$L_m$	58.15uH
Normal distance	$D$	20cm
Additional inductor	$L_{1p}, L_{2p}$	53.1uH
Series Capacitors	$C_{1p}, C_{1s}$	33.26nF
Parallel Capacitors	$C_{2p}, C_{2s}$	102.56nF

The specification of the system is listed in the Table I.

### 3. Experimental results

This section shows the experimental results of the 6.6kW IPT using double-sided LCC converter with the proposed method during the CC mode charge. Fig. 3 shows the input voltage  $V_{AB}$ , input current  $I_{in}$  and output current  $I_o$ . It is clearly shown in the Fig. 3 that ZVS, ZCS and ZPA condition are achieved perfectly. The efficiency is 96.1% at 6.6kW in the CC mode. Due to the discrepancies in values of components in the resonant tank, the actual switching frequency is 69.1 kHz in CC Mode, which is slightly different from the designed value, 68.8 kHz.

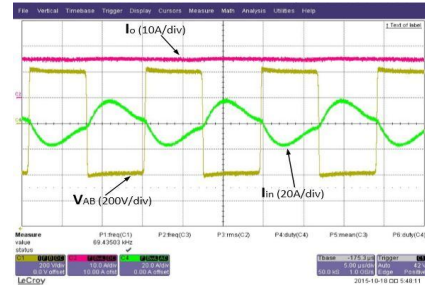


Fig. 3. Waveforms of  $V_{AB}$ ,  $I_{in}$  and  $I_o$  in CC Mode operation when  $V_o=420V, P_o=6.6kW$ .

Fig. 4 shows the CV mode operation. In the CV Mode, the frequency varies from 77 kHz to 78 kHz to obtain constant output voltage. As shown in Fig 4, the ZVS condition is achieved in the CV Mode. Here,  $I_{in}$  is slightly leading to  $V_{AB}$ , indicating that the converter is working in the inductive region. When the load  $R_L$  increases, the phase of  $Z_{in}$  increases as well, which results in a slight decrease in efficiency due to the hard switching at turn-off. The efficiency is 95% at 5.88 kW.

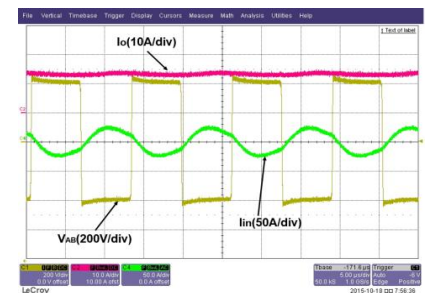


Fig. 4. Waveforms of  $V_{AB}$ ,  $I_{in}$  and  $I_o$  in CV Mode operation (a)  $I_o = 6.5A, P_o = 2.73kW$ . (b)  $I_o = 14A, P_o = 5.88kW$ .

### 4. Conclusion and future works

In this paper, a new method to achieve CC/CV charge of the WPT system with double-sided LCC converter was presented for EV applications. The frequency characteristic of the LCC compensation circuit is analyzed and a method to implement the CC/CV charger with minimum frequency variation was suggested. With the proposed method, stable charge operation of the LCC converter for WPT can be guaranteed. The experimental results verifies that the high efficiency and the reliable performance of the proposed system.

### References

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