E-모빌리티 응용을 위한 6.78MHz 정전압 정전류 무선 충전기

A 6.78 MHz Constant Current and Constant Voltage Wireless Charger for E-mobility Applications

Tran Manh Tuan and Woojin Choi
Department of Electrical Engineering, Soongsil University

ABSTRACT

Nowadays, multi-MHz wireless power transfer (WPT) system has received a great concern of study due to its desirable characteristics such as user convenience, system compact and better safety as compared to the conventional DC-DC with cord. This paper presents a solution for WPT Lithium Batteries charger with Constant Current (CC) and Constant Voltage (CV) charging process. The proposed system consists of a high frequency class D power amplifier, a pair of PCB coil, transformable high-order resonant network and a full-bridge rectifier. The charger can be implemented CC /CV charging profile thanks to automatic reconfigurable resonant compensator. Therefore, the battery can be fully charged without the help of an additional DC/DC converter. The simulation and 50W-6.78-MHz hardware experimental results are presented to verify the feasibility of the proposed method and to evaluate the performance of the proposed wireless battery charger.

Index Terms –6.78 MHz class D, CC/CV, reconfigurable resonant network, Lithium Batteries charger.

1. INTRODUCTION

The Wireless Power Transfer technology becomes more and more popular for electronic devices because it can eliminate the inconvenience of traditional plug-in charger by removing the connection wire between the charger and the devices to be charged. As the switching frequency of the inductive power transfer (IPT) system increases to high MHz range, the higher quality factor of the coil can be achieved and it alleviates the effect of lower coupling coefficient caused by the longer distance or the misalignment, which in turn results in a better efficiency. Moreover, size and weight of the resonant components such as coils and capacitors can be reduced as the operating frequency is increased. It is a desirable condition for the portable electronic devices.

Lithium batteries are widely used in various portable electronic devices such as laptops, cell phones or E-mobility. The charge process for Lithium battery normally includes constant current (CC) charge and constant voltage (CV) charge to fully charge the batteries. Initially, the battery is charged with a constant current and the battery voltage increases gradually during this mode. When the battery voltage reaches the maximum charge voltage, the battery is charged by the CV mode. To realize CC/CV, closed-loop control methods are generally used by using a back-end DC-DC converter in receiver side or frequency modulation. However, those methods would increase the cost, complexity and power loss of the system [3]-[5]. Another approach for CC/CV in WPT systems without closed-loop control is adopting load independent characteristics of resonant networks. Therefore, in order to realize both CC and CV charge with a multi MHz-WPT system transformation of the resonant compensation configuration would be essential. There are four basic compensation topologies, series-series (SS), series-parallel (SP), parallel-series (PS) and parallel-parallel (PP), which can be introduced for the CC/CV charge of the WPT system. With these resonant compensation circuits, the instinctive Zero Phase Angle (ZPA), load independent constant voltage output characteristics and load independent constant current output characteristics can be achieved. However, these topologies have a drawback in terms of the degree of freedom since the output value highly depends on the coil parameters. To overcome this constraint, higher order resonant compensator have been preferred and studied in the earlier works. Among many high-order compensation configurations, S-LCC [1], and LCC-S [2] get more interested because of owning the intrinsic features of constant voltage and ZPA. A double side LCC-LCC topology is adopted for achieving constant current and ZPA condition [13]. It is also well-known that T-LCL type, π-CLC type, T-CLC type and π-LCL type are four basic configurations of immittance converter which is able to transform a constant voltage source into constant current source and vice versa [3].Hence, it is very desirable for applying constant current WPT system. However, most of the above WPT systems are designed to operate at KHz range, thus the power density of the system may not be enough for the portable devices or E-Mobility.

This paper introduces a 6.78-MHz class D inductive power transfer (IPT) system which can implement both CC and CV charge by transforming the resonant compensation circuits. For the CV charge the Inductor-Capacitor-Capacitor- Series (LCC-S) is used and the LCC-S combined with T-type LCL circuit is used for CC charge. The high efficiency can be achieved thanks to its soft switching characteristics over the wide range of load and the absence of a back-end DC-DC converter. It is flexible in implementing CC/CV charge with different design specifications due to its high order resonant compensator. In addition, the reactive power can be fully compensated by the zero-phase-angle (ZPA) operation and hence the power ratings of the switches and resonant tank components can be reduced. The operation principle is presented by using an intuitive equivalent circuit. A 50W prototype of the proposed WPT charger is fabricated to verify the validity and feasibility of the proposed method

2. OPERATION PRINCIPLE

A. Proposed Topology.

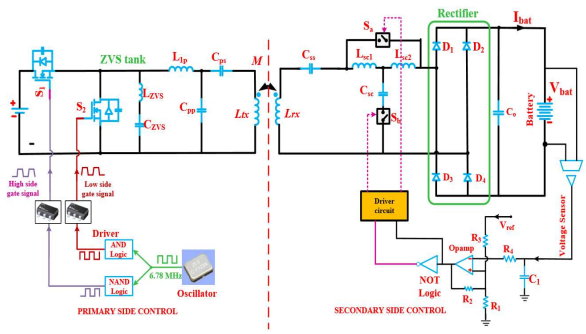


Fig. 1. Proposed class D CC/CV WPT charger operating at 6.78-MH

B. Analysis of LCC-S topology for Constant Voltage Charge

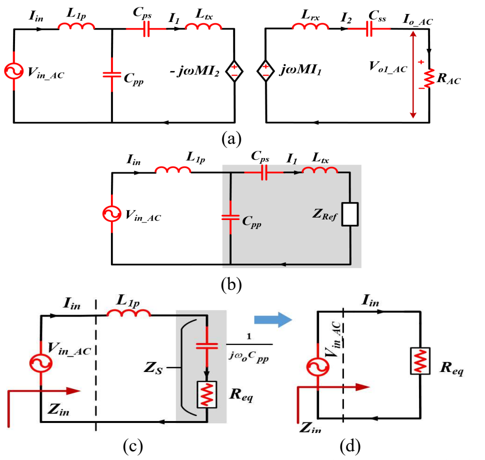


Fig.2. LCC-S compensation analysis using equivalent circuit method

In this section the analysis for the frequency characteristic of LCC-S by using fundamental harmonic approximations (FHA) method is presented. To simplify the analysis, all the parasitic resistances in the resonant components are neglected. The simulation and experimental results will validate the accuracy of the approximation in the next sections. Fig. 2 (a) is configured as circuit model of the LCC-S network when the switch *Sa* is ON and *Sb* is OFF. L_{tx} and L_{rx} are the self-inductance of transmitter and the receiver coil, respectively. M is the mutual inductance between two coils and C_{pp} , C_{ps}, C_{SS} and L_{1p} are the resonant capacitors and the inductor at the primary and the secondary side. The WPT system is supplied by the voltage source V_{in_AC} and the DC resistance load is represented by the equivalent resistance R_{AC}. The equations in the circuit model shown in Fig.2 are derived as following.

$$I_2 = \frac{j\omega M I_1}{1/j\omega C_{ss} + j\omega L_{rx} + R_{ac}} \; , I_{2(\omega_o)} = \frac{j\omega_o M I_1}{R_{ac}} \quad (1)$$

$$Z_{ref(\omega_o)} = \omega_o{}^2 M^2 / R_{ac} \quad (2)$$

$$Z_S = (C_{ps} + L_{rx} + Z_{ref}) // C_{pp} \quad (3)$$

$$Z_{S(\omega_o)} = \frac{1}{j\omega_o C_{pp}} + \left(\frac{L_{rx}}{C_{pp}} - \frac{1}{\omega_o{}^2 C_{ps} C_{pp}}\right) / \, Z_{ref(\omega_o)} \quad (4)$$

Where the resonant frequency ω_o is selected to satisfied the conditions in Eq. (5)

$$\frac{1}{j\omega_o C_{ss}} + j\omega_o L_{rx} = \frac{1}{j\omega_o C_{pp}} + j\omega_o L_{tx} + \frac{1}{j\omega_o C_{ps}} = 0 \quad (5)$$

As shown in Fig.2(c)-(d), the input impedance Z_{in} become a pure resistance when L_{1p} resonate with C_{pp} at ω_o

$$\frac{1}{j\omega_o C_{pp}} + j\omega_o L_{1p} = 0 \quad (6)$$

$$Z_{in(\omega_o)} = \left(\frac{L_{rx}}{C_{pp}} - \frac{1}{\omega_o{}^2 C_{ps} C_{pp}}\right) / \, Z_{ref(\omega_o)} = R_{eq} \quad (7)$$

The input current is obtained in Eq. (8)

$$I_{in(\omega_o)} = V_{in} Z_{ref(\omega_o)} / \left(\frac{L_{rx}}{C_{pp}} - \frac{1}{\omega_o{}^2 C_{ps} C_{pp}}\right) \quad (8)$$

It can be noticed that there is no imaginary part in input current equation. Thus, Zero Phase Angle (ZPA) can be achieved and reactive power is minimized. The transmitter current I_1 is derived as following equation

$$I_1 = \frac{I_{in} Z_S}{\frac{1}{j\omega_o C_{ps}} + j\omega L_{rx} + Z_{ref}} \; ; \; I_1(\omega_o) = -j\omega_o C_{pp} V_{in} \quad (9)$$

Substituting (9) into (1) gives

$$I_{2(\omega_o)} = \frac{\omega_o{}^2 M C_{pp} V_{in}}{R_{ac}} = \frac{M V_{in}}{L_{1p} R_{ac}} \quad (10)$$

Finally, Output voltage equation is obtained in Eq.(11)

$$V_{O(\omega_o)} = I_{2(\omega_o)} R_{ac} = \frac{M V_{in}}{L_{1p}} \quad (11)$$

It is obvious that the output voltage is constant with the variation of load resistor at the resonant frequency ω_o.

C. Analysis of T-type LCL network for Constant Voltage Charge

The T-type LCL circuit is connected to the output of LCC-S structure when Sa is OFF and Sb is ON as shown in Fig. 3. The LCL circuit is fed by constant voltage source V_{in_T} which is the output voltage $V_{O_{AC}(\omega_o)}$ of the LCC-S stage.

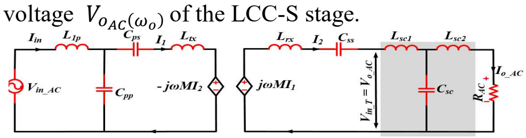


Fig. 3. LCC-S+T-type LCL configuration for CC charge

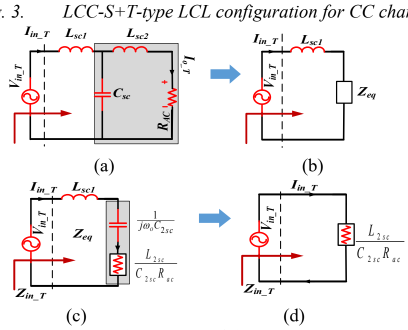


Fig. 4. Equivalent circuit of the T-type LCL network

The constant current characteristic of T-LCL circuit can be represented by the equivalent circuit in Fig. 4 which consists of two inductors L_{sc1} and L_{sc2}, and one capacitor C_{sc}. R_{ac} is the equivalent load resistance.

$$Z_{eq(\omega_o)} = (L_{sc2} + R_{ac}) // C_{sc} = L_{sc2} / C_{sc} R_{ac} + 1/j\omega_o C_{sc} \quad (13)$$

$$Z_{in\_T(\omega_o)} = Z_{eq(\omega_o)} + j\omega_o L_{sc1} = L_{sc2} / C_{sc} R_{ac} \quad (14)$$

$$1/j\omega_o C_{sc} + j\omega_o L_{sc2} = 1/j\omega_o C_{sc} + j\omega_o L_{sc1} = 0 \quad (15)$$

As observed from Fig.4 (c)-(d), the equivalent impedance $Z_{eq(\omega_o)}$ and input impedance $Z_{in\_T(\omega_o)}$ are derived as in Eq.(13)-(14) when the resonant frequency ω_o is selected by Eq.(15). $Z_{in\_T(\omega_o)}$
is become pure resistance. As a result, ZPA characteristic can be achieved and the input current $I_{in\_T(\omega_o)}$ given in Eq.(16) is in phase with the input voltage V_{in_T}.

$$I_{in\_T(\omega_o)} = V_{in_T} / Z_{in_{T(\omega_o)}} = V_{in_T} C_{sc} R_{ac} / L_{sc2} \quad (16)$$

$$I_{o\_T(\omega_o)} = -V_{in\_T} j\omega_o C_{sc} = \frac{V_{in\_T}}{j\omega_o L_{sc2}} \quad (17)$$

D. Design procedure of 6.78 MHz wireless charger

In this section, the design procedure of the resonant tank is illustrated for a WPT system with the specifications given in Table I.

TABLE I
DESIGN SPECIFICATIONs OF 6.78 MHz-WPT CHARGER

Parameter	Designators	Value
Input Voltage Range	V_{in}	50 [V]
Output Constant Voltage	V_{O_cv}	25.2 [V]
Output Constant Current	I_{O_cv}	2 [A]
Maximum Output Power	P_O	50 [W]
Switching frequency	f_{sw}	6.78 [MHz]

The CC current for the Lithium battery module is 2 A and the maximum voltage of it is 25.2 V in CV mode. All parameters are calculated at fixed resonant frequency of 6.78 MHz. Based on the FHA analysis, the relationship between DC input values and AC input values are given in Eq. (18)

$$V_{in} = \frac{\sqrt{2}}{\pi}V_{dc}, V_{O_{ac}} = \frac{2\sqrt{2}}{\pi}V_{O_{dc}}, I_{O\_ac} = \frac{\pi}{2\sqrt{2}}I_{O\_dc}, R_{ac} = \frac{8}{\pi^2}R_o \quad (18)$$

Substituting (18) into (11) and (17) gives

$$Gv(\omega_o) = \frac{V_{O\_AC(\omega_o)}}{V_{in\_AC}} = \frac{2V_{O\_DC}}{V_{in\_DC}} = \frac{M}{L_{1p}} \quad (19)$$

$$G_{i(\omega_o)} = Gv(\omega_o)G_{i_{T(\omega_o)}} = \frac{\pi^2}{4}\frac{I_{O\_DC}}{V_{in\_DC}} = \frac{M}{L_{1p}j\omega_o L_{sc2}} \quad (21)$$

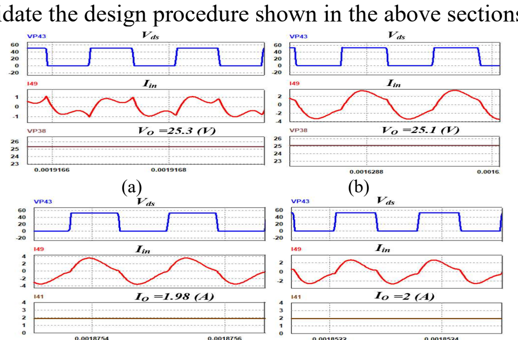
The resonant component can be designed with the specification of the system which includes the rated power (Po), input voltage V_{O_DC}, output voltage V_{in_DC}, and the switching frequency f_o. The parameters for the compensation network should be calculated precisely to provide 2A constant output current for CC mode and 25.2 V constant output voltage. This process is repeated to optimize the performance of the charger including several perspectives such as efficiency, soft-switching and the fluctuation in outputs.

3. SIMULATION AND EXPERIMENT RESULTS.

TABLE II
COMPANSATION CIRCUIT PARAMETERS FOR THE PROPOSED SYSTEM

Parameters	Simulation	Measurement
Transmitter coil Ltx	1.15 μH	1.08 μH
Receiver coil Lrx	1.15 μH	1.08 μH
Coil's resistance Rrx = Rrx	0 Ω	0.12 Ω
Coils distance		3cm
Mutual inductance M	257 nH	260 nH
Resonant capacitance Cps	615 pF	670 pF
Resonant capacitance Cpp	2.16 nF	2.13 nF
Resonant capacitance Css	479pF	510 pF
Resonant inductance L1p	254 nH	257 nH
Resonant capacitance Csc	2.34 nF	2.29 nF
Resonant inductance Lsc2,1	235 nH	237 nH

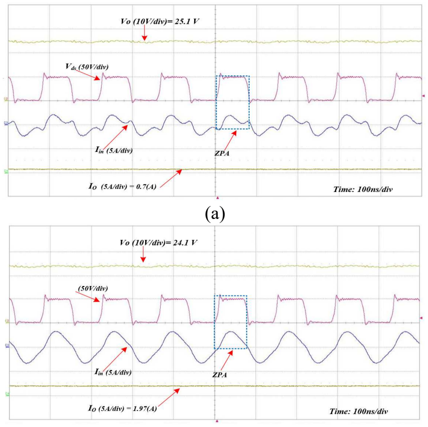
In this section, the design of the 6.78 MHz wireless charger with PSIM software and experimental results are presented to validate the design procedure shown in the above sections.



(a) (b) (c) (d)

Fig. 5. Key waveforms of proposed WPT system: (a) CV mode at 15W,(b) CV mode at 50W, (c) CC mode at 30W, (d) CC mode at 50W(full load)

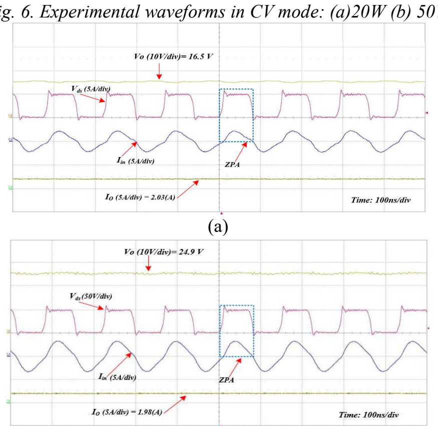
The feasibility of proposed topology is investigated by the key experimental waveforms shown in Fig. 7 and Fig. 8, which includes the drain to source voltage V_{ds}, transmitter coil current I_{tx}, output voltage V_O and output current I_O in CC and CV mode under load variation condition. As shown in Fig. 7(a) and Fig. 8, it can be noticed that the ZVS turn on and the ZCS turn off for primary switches can be achieved under various load conditions thanks to ZPA characteristics of the resonant tank.



(a)

(b)

Fig. 6. Experimental waveforms in CV mode: (a)20W (b) 50W



(a)

(b)

Fig. 7. Experimental waveforms in CC mode: (a) 33W, (b) 50W

4. CONCLUSION

In this paper a hybrid topology for the CC/CV charge of the wireless charger system operating at 6.78 MHz has been proposed. The CC/CV charge for the Lithium battery module has been successfully implemented at one frequency by changing the resonant compensators with the help of a switch. The advantage of the proposed method is that the back-end DC/DC converter is not required for the CC/CV charge and hence the loss and cost of the system can be reduced. Due to the automatic transfer function from CC to CV charge of the proposed system the battery can be fully charged in a continuous manner and it is suitable for the chargers for portable electronics and E-mobility.

5. References

[1] Y. Chen, Z. Kou, Y. Zhang, Z. He, R. Mai and G. Cao, "Hybrid Topology With Configurable Charge Current and Charge Voltage Output-Based WPT Charger for Massive Electric Bicycles," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 6, no. 3, pp. 1581-1594, Sept. 2018.

[2] Z. Pantic, S. Bai and S. M. Lukic, "ZCS LCC-Compensated Resonant Inverter for Inductive-Power-Transfer Application," in IEEE Transactions on Industrial Electronics, vol. 58, no. 8, pp. 3500-3510, Aug. 2011.

[3] S. B. Afzal, M. M. Shabab and M. A. Razzak, "A combined π- and T-type immittance converter for constant current applications", Proc. 2 nd IEEE International Conference on Informatics, Electronics & Vision (ICIEV)