양면 LCC 보상 회로를 가진 무선 전력 충전기용 공진 컨버터의 설계

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Design of the Resonant Converter with a Double Sided LCC Compensation Circuit for Wireless Charger.

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ABSTRACT

The aim of this paper is to propose a design method for the double-sided LCC compensation circuit for 6.6kW electric vehicle (EVs) wireless charger. The analysis and comparison with several compensation topologies such as SS, SP, PS, PP and the hybrid LCC compensation is presented. It has been found that the hybrid LCC compensation has superior performance in comparison with other topologies. The design procedure for the EV charger is presented and the PSIM simulation results are provided.

Index Terms – Compensation topology, wireless power transfer, electric vehicle, on-board charger.

1. Introduction

Nowadays, most commercial electric vehicles are plugged into the grid to charge the battery. Due to the advantages such as user convenience and safety, WPT in EVs have been researched by many laboratories and companies all over the world[1]. Basically, the structure of one WPT system contains the converters (DC/AC in primary side and AC/DC in secondary side), coils system and the compensation tanks in both sides. In comparison with Plug-in charger, WPT system has low coupling coefficient between the primary coil and secondary coil. When two coils suffer from misalignment or an increase in the distance between them, the mutual inductance of coils system is reduced and the leakage inductance is increased. It leads to a significant decrease in overall efficiency because of the large circulating current in primary side. To solve the problem, the compensation tank needs to be added in both sides to cancel the effect of high leakage inductance. There are four basic compensation topologies such as SS, SP, PS and PP, and their advantages and disadvantages were discussed in [1]. Recently, LCC compensation is drawing an interest due to several advantages over the other four basic topologies. In this paper the comparison of the four basic topologies with LCC topology is presented and the design procedure of the LCC topology is presented. Finally, the design is verified by the PSIM simulation.

2. Comparison of the compensation topologies

There are four basic compensation topologies as shown in Fig 1. In general, the series-compensated secondary resembles a voltage source, while the parallel-compensated secondary looks like a current source.

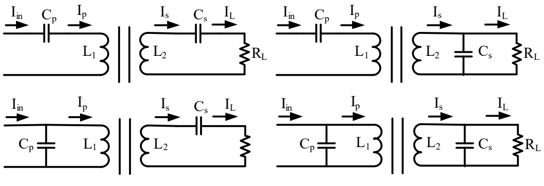


Fig. 1 Four basic compensation topology SS, SP, PS and PP

In order to reduce the VA rating of converter, the capacitor in both sides needs to be adjusted to resonate with the self-inductance of both side of the converter. This is called zero-phase-angle (ZPA) method. When ZPA is reached, the power factor becomes nearly 1 with an increase of the efficiency. By applying the ZPA method to the four basic topologies, it is simple to get the value of the primary capacitance C_p when the secondary capacitor C_s is chosen as in the Table I.

Table I. Compensation capacitance of each topology

Topology	Primary capacitance C_p	Secondary capacitance C_s
SS	$\frac{C_s L_2}{L_1}$	$\frac{1}{\omega^2 L_2}$
SP	$\frac{C_s L_2}{L_1} \frac{1}{1-k^2}$	$\frac{1}{\omega^2 L_2}$
PS	$\frac{C_s L_2}{L_1} \frac{1}{1+Q_2^2 k^2}$	$\frac{1}{\omega^2 L_2}$
PP	$\frac{C_s L_2}{L_1} \frac{1-k^2}{Q_2^2 k^4 + \left(1-k^2\right)^2}$	$\frac{1}{\omega^2 L_2}$

It can be found from the Table I, the value of C_p in SS method does not depend on the coupling factor and load conditions. However, the value of C_p varies with the coupling factor in SP method and it varies with the coupling factor and load condition in PS and PP method. This is considered as an advantage of the SS method in comparison with other topologies. On the other hand, the imaginary part of the input impedance Z_1 at resonant frequency ω_0 is equal to 0 only in the SS method[1]. It means that the reactive power is absolutely compensated and the ZPA condition is satisfied at resonant frequency. This leads to a high efficiency of the SS method compared to the other topologies. However, the SS method also has disadvantages in designing a WPT system. Firstly, the primary current I_p varies with the load which makes it difficult to design the controller and to select the components. Secondly, the voltage of the resonant capacitor is very high thereby causing a safety concerns for the user. To overcome these problems, an LCC topology was proposed in [2] as shown in Fig 2.

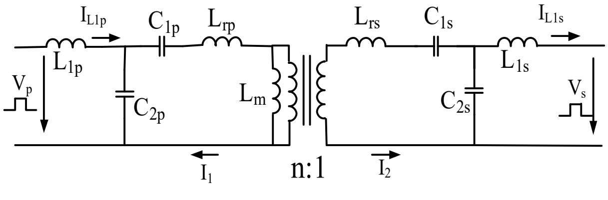


Fig. 2. Circuit configuration of the LCC compensation topology

In the Fig. 2, the primary current I_1 can be found by applying Kirchhoff's voltage laws as (1) and it can be easily found from (1) that the primary coil current I_1 does not depend on the load.

$$I_1 = \frac{V_p}{j\omega L_{1p}} = \frac{V_p}{\omega L_{1p}} \angle -90^{\circ} \tag{1}$$

In order to compare the voltage stress of the capacitors in SS and LCC method it is assumed that both has same mutual inductance and transfers the same amount of power. It is simple to know that the voltage and current stresses of the primary and secondary coils are the same, but the voltage stress of the resonant capacitor in the LCC topology is smaller. The resonant frequency can be derived as (2) by applying the Kirchhoff's laws to the circuit shown in Fig. 2 and analyzing the input impedance.

$$\omega_0 = \frac{1}{\sqrt{L_{1p}.C_{2p}}} = \frac{1}{\sqrt{L_{1s}.C_{2s}}} = \frac{1}{\sqrt{(L_1 - L_{1p}).C_{1p}}} = \frac{1}{\sqrt{(L_2 - L_{1s}).C_{1s}}} \tag{2}$$

3. Design of the 6.6 kW WPT charger using LCC compensation topology

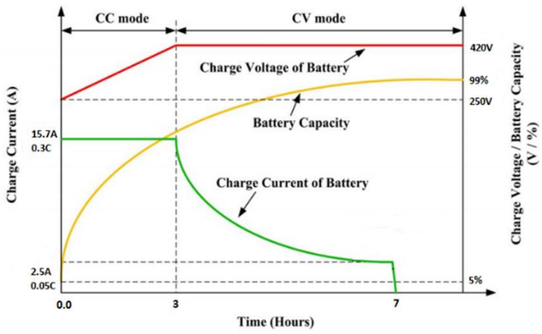


Fig. 3. Charge profile of the battery with V_{out}=250~450V, V_{nor}=420V, P_{out}=6.6kW, I_{out}=15.7A.

At first step, the coil parameters are decided to be able to transfer the power and to guarantee the high efficiency. In this case, the output power P_{out}=6.6kW and the efficiency of coil system η_{max}=98%. From [3], the relationship between P_{out}, η_{max} and the coil parameters can be represented as in (3) and (4).

$$P_{out} = \omega I_1^2 \frac{M^2}{L_2} Q_2 = V_{in} I_1 k^2 Q_2 \tag{3}$$

$$\eta_{max} = \frac{k^2 Q_1 Q_2}{1 + \sqrt{1 + k^2 Q_1 Q_2}} \tag{4}$$

Where, Q_1 and Q_2 are quality factor of transmitter coil and receiver coil, respectively.

Since the copper loss in the coil is significant, it is desired to select the parameters of the coil such as self-inductance and the coupling factor to be as large as possible to get the smaller primary coil current. All the other parameters in Table 2 can be obtained by using (3) and (4)

Table 2 Coil design parameter

Self-inductance of Tx coil L_1	230-250 uH
Self-inductance of Rx coil L_2	230-250 uH
Magnetizing inductance M	70-75 uH
Coupling factor k	0.18-0.30
Operating frequency	65 kHz
Resistor of Litz wire	0.1Ω

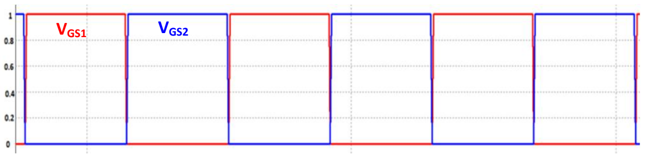
From the review and analysis of the different coil structures in [3], DD Coil seems to be the best structure with higher coupling factor k and higher tolerance to the misalignment. Hence, DD coil is chosen for the design of the coil in this paper. Next step, the compensation tank is designed to satisfy the operating condition of the proposed converter. In the LCC compensation topology, the output power P_{out} can be written as (5)

$$P_{out} = \frac{M V_s V_p}{\omega L_{1p} L_{1s}} \tag{5}$$

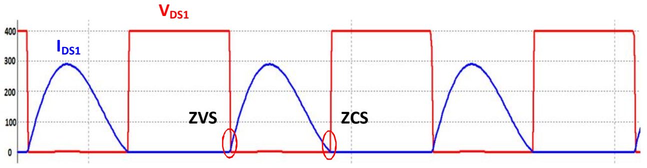
Where, V_p=400V, V_s=420V and P_{out}=6.6kW. From (5), we have L_{1p}=L_{1s}=59.3 µH. From (5) and (2), C_{1p}=C_{1s}=33nF and C_{2p}= C_{2s}=101nF.

4. Simulation results

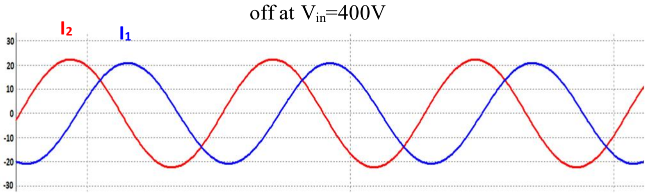
In this section, the designed 6.6 kW LCC compensation topology for 6.6kW WPT charger is simulated with PSIM software to prove the effectiveness of the design process in the previous section. It can be noticed from the simulation results in Fig. 4 that the voltage of the resonant capacitor is only V_{C1p}=1.09kV, V_{C1s}= 1.19kV, V_{C2p}=658V and V_{C2s}=648V at full load condition with V_{out}=420V and I_{out}=15.7A.



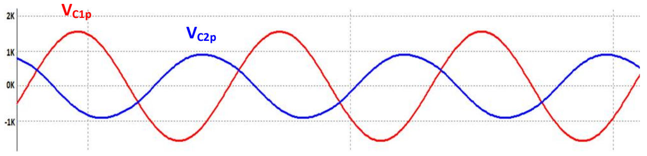
a. Gate signal for the switches with 50% duty cycle



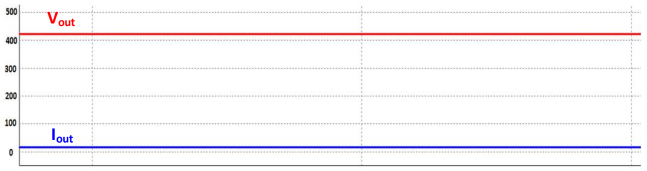
b. Voltage and current of the Mosfet Q1 with ZVS turn on and ZCS turn off at V_{in}=400V



c. Primary coil current I_1 (15A) and secondary coil current I_2 (15.2A)



d. Voltage of the capacitor C_{1p} (1.09kV) and C_{2p} (645V)



e. Output voltage V_{out} (420V) and output current I_{out} (15.7A)

Fig. 4. PSIM simulation results of the 6.6kW LCC topology

5. Conclusion and future works

In this paper, the design method for the 6.6 kW WPT charger for EVs is presented. It has been found from the analysis that the SS topology has advantages in choosing resonant capacitor and achieving the high efficiency compared to the other topologies. However, the SS topology also possesses disadvantages such as the varying primary coil current with the load and the high voltage stress of the resonant capacitor. Those drawbacks can be overcome by using the LCC topology and the design procedure has been presented. High voltage stress of the resonant capacitor can be successfully alleviated through the design and the results have been validated through the PSIM simulation. The results would be verified through the experiments soon and presented in the next conference.

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