

Analysis and Comparison of the Compensation Topologies of Magnetic Coupled Resonant Wireless Charging for Electric Vehicles

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Abstract. In recent years, with the rise of electric vehicle industry and people's increasing demand for convenient life, wireless charging technology used on electric vehicles has become one of the research hotspots. Magnetic coupled resonant wireless power transmission (MCR-WPT) has also been widely concerned because of its high suitability for electric vehicles. This paper mainly focuses on the compensation topologies of magnetic coupled resonant wireless charging for electric vehicles, analyzes 3 types of compensation topologies: P-S, P-P and LCL-LCC. Firstly, the transmission efficiency of these 3 topologies is analyzed from the theoretical point of view. Then, their transmission capacity under different coupling coefficients is compared through simulation. It is found that, in the reality where the coupling coefficients are low, P-S compensation topology should be preferred. Furthermore, by changing the load resistance, it is found that LCL-LCC compensation topology has high stability, which is suitable for scenarios that have long usage period.

Keywords: Electric vehicle; wireless charging; magnetic coupled resonant; compensation topology.

1. Introduction

Recent years, with the promotion of renewable energy, electric vehicles have become increasingly popular all around the world. In the process of choosing electric vehicles by residents, the battery capacity and the battery life on a single charge have become an important reference index. Although the current wired charging method has a large application and dissemination, the problems affecting the ease of use such as the insufficient quantity of charging piles and the interface type to be unified have gradually emerged. In this case, wireless charging technology, which is expected to realize that electric vehicles are charged as soon as they are stopped and even being charged while driving, is regarded as a new path to solve the anxiety of electric vehicles.

At present, the wireless charging scheme and resonant wireless charging system of electric vehicles have been studied. The main methods of wireless charging include electromagnetic induction, electromagnetic resonance, electric field coupling, and microwave radiation [1]. Among them, electromagnetic resonant power transmission technology is suitable for wireless charging of electric vehicles due to its low requirements for coil alignment and distance [2]. With the in-depth research of resonant wireless charging technology, the commercialization process of this technology is progressing rapidly, and many well-known enterprises are now vigorously researching and using this technology. Worldwide, automobile manufacturers, including Mercedes-Benz and Tesla, have made certain research and technological breakthroughs in the compatibility, transmission efficiency and safety of resonant wireless charging systems [3]. The main purpose of magnetic coupling resonant charging mode is stable, safe, efficient, flexible, and convenient charging, one of the keys is how to design the magnetic coupling mechanism.

In order to increase the transmission efficiency of the structure, capacitance compensation is carried out according to the magnetic coupling resonant wireless charging mode of electric vehicles. Among the four basic combinations and a variety of complex combinations, the model structure of two basic compensation topologies and one complex topology are constructed, and the values of output power and transmission efficiency are obtained. After analysis and comparison, the influence

of each variable is obtained, and the appropriate compensation structure for wireless charging of electric vehicles is selected, which provides the basis for the subsequent complex structure analysis and scheme proposal.

2. Theoretical Analysis of MCR-WPT System of Electric Vehicle

2.1. Fundamental Operating Principle of Wireless Charging System

The primary technologies that have practical use in wireless charging systems include electromagnetic induction charging, magnetic resonant charging, radio charging, etc.

Electromagnetic induction wireless charging technique transmits electric energy through a primary coil and a subprime coil based on the electromagnetic field theory [4]. This pattern has significant advantages, such as high transfer efficiency and low cost, but there are also disadvantages, namely short transmission distance and high relevance with the placement of the devices.

Magnetic resonant wireless charging system consists of two parts, the sending unit and the receiving unit. When the two parts reach to a specific frequency at the same time, the sympathetic vibration will be generated and the wireless energy transmission can be achieved [5]. This system shows the shortcomings of low efficiency and difficulties in miniaturization.

Radio wave wireless charging technology realizes the input as well as the output of direct-current between radio transmitter and the radio [6]. While this method is able to achieve a higher transfer rate, its low security is a non-negligible problem.

2.2. Basic Structure of MCR-WPT System

MCR-WPT charging system, namely magnetic coupled resonant wireless power transfer system, is a type of newly developed technique of energy transmission which transmits fairly electric energy efficiently within moderate and short distance using the principle of coupled magnetic resonance. This structure is widely used in electric car charging system [7]. The system has five fundamental components: DC source, High frequency inverter, resonant tank, rectifier, DC load. The basic process of the energy transmission is shown in Fig 1. At the transmitter, steady current is supplied by the DC source and the high frequency inverter transforms it into AC current with high frequency. Through the resonant tank, the electricity comes to the receiver and it will be translated into DC current by the high frequency rectifier to supply energy for specific DC load [8]. The transmission efficiency of the system can be improved by changing the resonant frequency as well as the coupling coefficient [9].

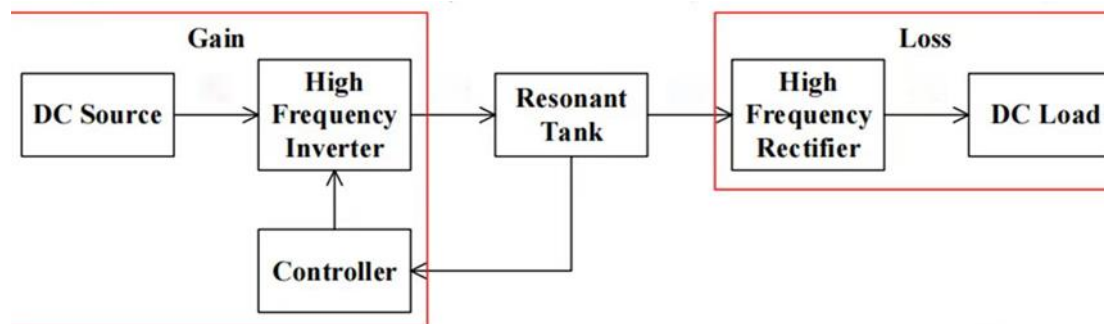


Fig. 1 The operating principle of the MCR-WPT system [10]

3. Compensation Topology Models

3.1. Basic Compensation Topology Models

Resonant wireless charging system transmits power through two inductors, and the inductors are inductive. Hence, compensation capacitors are required to keep the system resonant. Moreover, the

addition of compensation capacitors can improve the problem of high reactive power, low power and insufficient transmission efficiency due to the loose coupling of the structure [2].

Resonant wireless charging system has 4 basic compensation topologies, series-series(S-S), series-parallel(S-P), parallel-series(P-S), and parallel-parallel(P-P), which are shown in fig. 2.

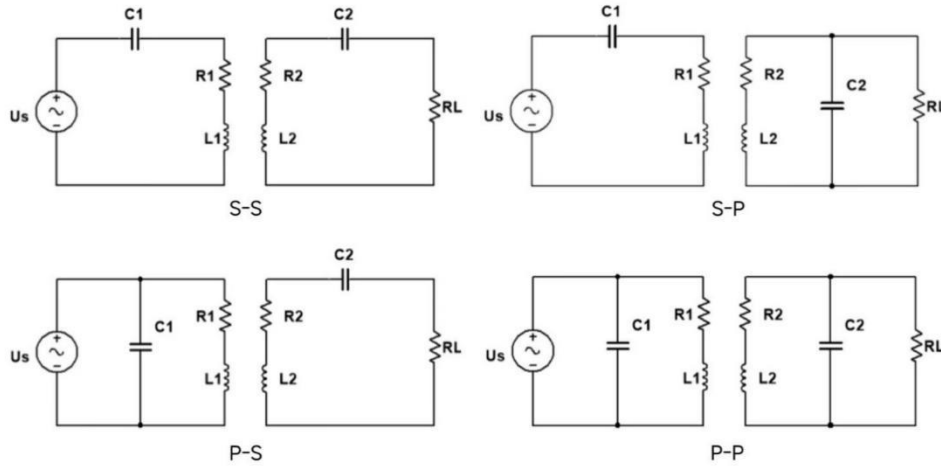


Fig. 2 Basic compensation topologies

U_s is the AC voltage source, L_1 and L_2 are the inductance of primary and secondary side coil respectively, R_1 and R_2 are the equivalent resistance of primary and secondary side coil respectively, C_1 and C_2 are the compensating capacitance of primary and secondary side respectively, R_L is the equivalent load resistance, M is the mutual inductance value.

Through calculations, the transmission efficiency of 4 basic compensation topologies can be organized into table 1.

Table 1. Transmission Efficiency of 4 Basic Compensation Topologies

Compensation topology	Transmission efficiency η
P-S	$\eta = \frac{\left \frac{j\omega MU_s}{(R_1 + j\omega L_1) \left(R_2 + R_L + j\omega L_2 + \frac{1}{j\omega C_2} \right) + \omega^2 M^2} \right ^2 R_L}{\operatorname{Re} \left\{ \frac{U_s^2 [1 + j\omega C_1 (R_1 + j\omega L_1)]}{(R_1 + j\omega L_1) + \frac{\omega^2 M^2}{R_2 + R_L + j\omega L_2 + \frac{1}{j\omega C_2}}} \right\}} \times 100\%$
P-P	$\eta = \frac{\left \frac{j\omega MU_s}{\left[(R_1 + j\omega L_1) \left(R_2 + j\omega L_2 + \frac{R_L}{1 + j\omega C_2 R_L} \right) + \omega^2 M^2 \right] (1 + j\omega C_2 R_L)} \right ^2 R_L}{\operatorname{Re} \left\{ \frac{U_s^2 [1 + j\omega C_1 (R_1 + j\omega L_1)]}{(R_1 + j\omega L_1) + \frac{\omega^2 M^2}{R_2 + R_L + j\omega L_2 + \frac{1}{j\omega C_2}}} \right\}} \times 100\%$

S-S	$\eta = \frac{\left \frac{j\omega MU_s}{\left(R_1 + j\omega L_1 + \frac{1}{j\omega C_1}\right)\left(R_2 + R_L + j\omega L_2 + \frac{1}{j\omega C_2}\right) + \omega^2 M^2} \right ^2 R_L}{\operatorname{Re} \left\{ \frac{U_s^2}{\left(R_1 + j\omega L_1 + \frac{1}{j\omega C_1}\right) + \frac{\omega^2 M^2}{R_2 + R_L + j\omega L_2 + \frac{1}{j\omega C_2}}} \right\}} \times 100\%$
S-P	$\eta = \frac{\left \frac{j\omega MU_s}{\left[\left(R_1 + j\omega L_1 + \frac{1}{j\omega C_1}\right)\left(R_2 + j\omega L_2 + \frac{R_L}{1 + j\omega C_2 R_L}\right) + \omega^2 M^2\right](1 + j\omega C_2 R_L)} \right ^2 R_L}{\operatorname{Re} \left\{ \frac{U_s^2}{\left(R_1 + j\omega L_1 + \frac{1}{j\omega C_1}\right) + \frac{\omega^2 M^2}{R_2 + j\omega L_2 + \frac{R_L}{1 + j\omega C_2 R_L}}} \right\}} \times 100\%$

3.2. Complex Compensation Topology Model

At present, the common complex compensation topologies include double LCC, LCC-S, LCL-LCC, double LCL and double T. This paper focuses on LCL-LCC, which is less studied. The circuit of LCL-LCC is shown in fig. 3.

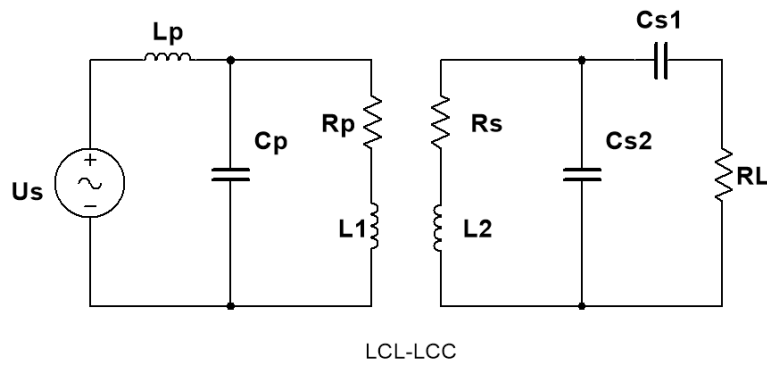


Fig. 3 LCL-LCC compensation topology

L_p is the series compensating inductance of primary side, C_p is the parallel compensating capacitance of primary side, R_p and R_s are the equivalent resistance of primary and secondary side coil respectively, C_{s1} is the series compensating capacitance of secondary side, C_{s2} is the parallel compensating capacitance of secondary side. Let I_1 be the emission current of primary side, I_2 be the receiving current of secondary side, Z_1 be the impedance of primary side, Z_2 be the impedance of secondary side, M be the mutual inductance value.

Impedance Z_1 , Z_2 :

$$Z_1 = R_p + j\omega L_1 \quad (1)$$

$$\begin{aligned} Z_2 &= R_s + j\omega L_2 + \frac{1}{j\omega C_{s2}} \parallel \left(\frac{1}{j\omega C_{s1}} + R_L \right) \\ &= R_s + j\omega L_2 + \frac{1 + j\omega C_{s1} R_L}{j\omega C_{s1} + j\omega C_{s2} - \omega^2 C_{s1} C_{s2} R_L} \end{aligned} \quad (2)$$

By KVL:

$$I_1 \frac{\frac{1}{j\omega C_p} + Z_1}{\frac{1}{j\omega C_p}} \cdot j\omega L_p + I_1 Z_1 - j\omega M I_2 = U_s \quad (3)$$

$$I_2 Z_2 - j\omega M I_1 = 0 \quad (4)$$

By (23) and (24):

$$I_1 = \frac{U_s}{(1+j\omega C_p Z_1)j\omega L_p + Z_1 + \frac{\omega^2 M^2}{Z_1}} \quad (5)$$

$$I_2 = \frac{j\omega M U_s}{(1+j\omega C_p Z_1)j\omega L_p + Z_1 + \frac{\omega^2 M^2}{Z_1}} \quad (6)$$

Output power P_{out} and input power P_{in} :

$$P_{out} = \left| I_2 \frac{\frac{1}{j\omega C_{s2}}}{\frac{1}{j\omega C_{s2}} + \frac{1}{j\omega C_{s1}} + R_L} \right|^2 R_L$$

$$= \left| \frac{-\omega^2 M U_s C_{s1}}{[(1+j\omega C_p Z_1)j\omega L_p + Z_1 + \frac{\omega^2 M^2}{Z_1}](j\omega C_{s1} + j\omega C_{s2} - \omega^2 C_{s1} C_{s2} R_L)} \right|^2 R_L \quad (7)$$

$$P_{in} = Re \left\{ U_s I_1 \frac{\frac{1}{j\omega C_p} + Z_1}{\frac{1}{j\omega C_p}} \right\} = Re \left\{ \frac{U_s^2 (1+j\omega C_p Z_1)}{(1+j\omega C_p Z_1)j\omega L_p + Z_1 + \frac{\omega^2 M^2}{Z_1}} \right\} \quad (8)$$

Transmission efficiency η :

$$\eta = \frac{P_{out}}{P_{in}} = \frac{\left| \frac{-\omega^2 M U_s C_{s1}}{[(1+j\omega C_p Z_1)j\omega L_p + Z_1 + \frac{\omega^2 M^2}{Z_1}](j\omega C_{s1} + j\omega C_{s2} - \omega^2 C_{s1} C_{s2} R_L)} \right|^2 R_L}{Re \left\{ \frac{U_s^2 (1+j\omega C_p Z_1)}{(1+j\omega C_p Z_1)j\omega L_p + Z_1 + \frac{\omega^2 M^2}{Z_1}} \right\}} \times 100\% \quad (9)$$

From the transmission efficiency formulas of 4 basic compensation topologies and LCL-LCC compensation topology, it can be seen that the main factors that influence the transmission efficiency include mutual inductance and load resistance. In this research, the mutual inductance is changed by changing the coupling coefficient.

4. Simulation and Comparison of Results

Based on the above analysis, a circuit simulation model is built in Multisim to verify its correctness.

4.1. PP/PS Circuit Simulation Parameter Selection

According to the electric vehicle wireless charging system and Chinese voltage regulations, the supply voltage (U_s) is set to $U_s = 380V$. The supply frequency (f) which is the resonant frequency is set to $f = 85kHz$. The coil inductance (L_1, L_2), the primary side coil inductance and the secondary side coil inductance, is set to $L_1 = 100\mu H$ and $L_2 = 100\mu H$ respectively. The primary side coil resistance is set to $R_1 = 0.5\Omega$, and the secondary side coil resistance is $R_2 = 0.5\Omega$. In this study, 0, 0.1, 0.2, ..., 0.9, 1 (example Settings $k = 0.8$) will be set in order to test the performance of each compensation topology under different coupling coefficients. To maintain the resonant state, the compensating capacitor (C_1, C_2) is set to $C_1 = C_2 = \frac{1}{(2\pi f)^2 L} \approx 35.06nF$. The load resistance (R_L) is set to $R_L = 50\Omega$ in this experiment. In order to obtain the effect of load resistance, the load resistance is set to $R_L = 20\Omega$ to compare with $R_L = 50\Omega$ in LCL-LCC.

4.2. Simulation Circuit Construction and Experiment

4.2.1 P-S compensation topology

The P-S topology simulation circuit diagram is shown in Fig.4.

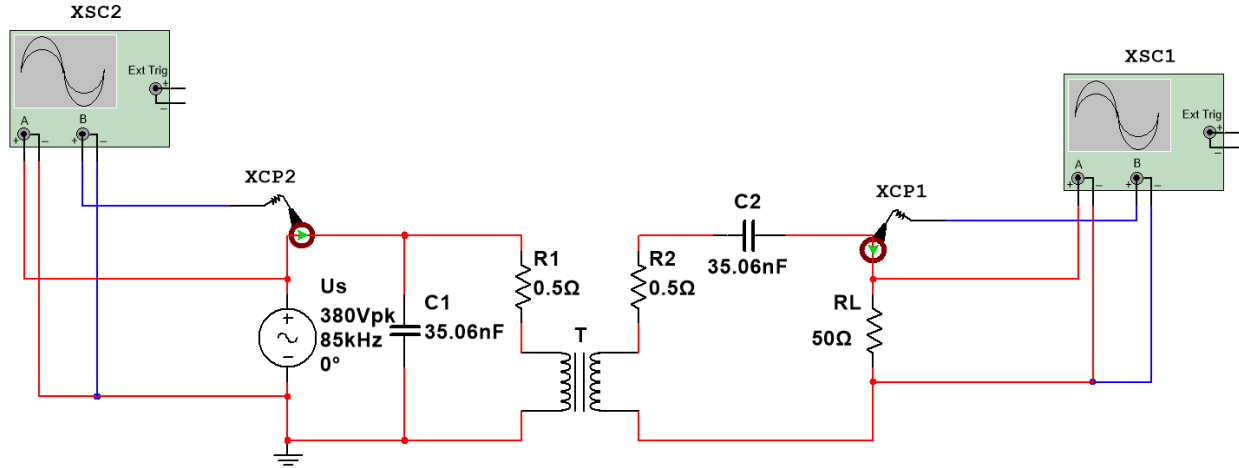


Fig. 4 P-S topology simulation circuit

The simulation results of P-S topology with a coupling coefficient of 0.8 is shown in Fig.5.

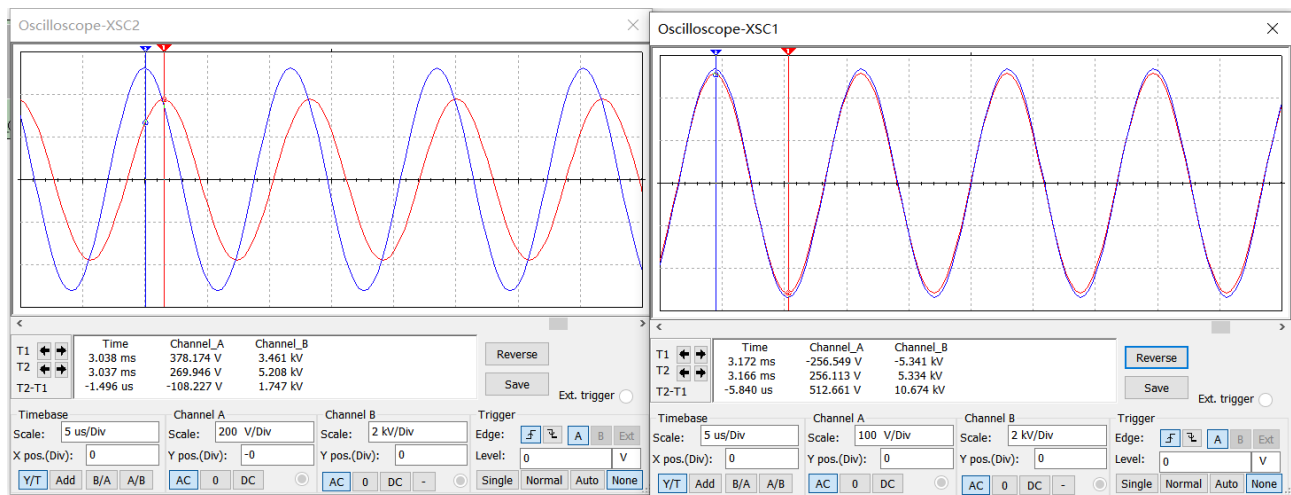


Fig. 5 P-S topology simulation results with coupling coefficient of 0.8

Through simulating, testing and calculating the transmission efficiency performance under all coupling coefficients, the charging efficiency curve of the P-S compensation topology can be obtained, as shown in Fig.6.

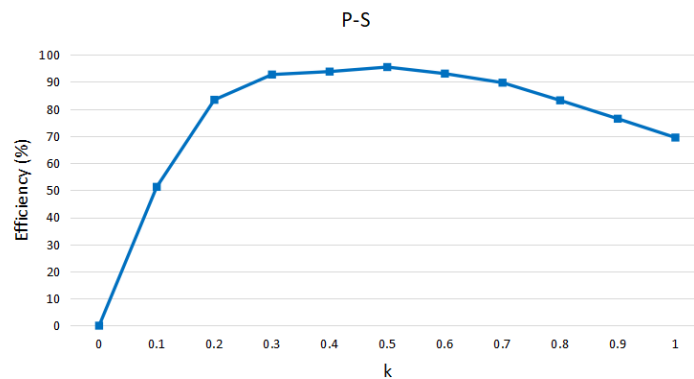


Fig. 6 P-S topology charging efficiency curve

As can be seen from Fig.6, the transmission efficiency of P-S compensation topology increases remarkably first before 0.4 and then starts decreasing at 0.7, and the charging efficiency is ideal when the coupling coefficient is from 0.3 to 0.7.

4.2.2 P-P compensation topology

The P-P topology simulation circuit diagram is shown in Fig.7.

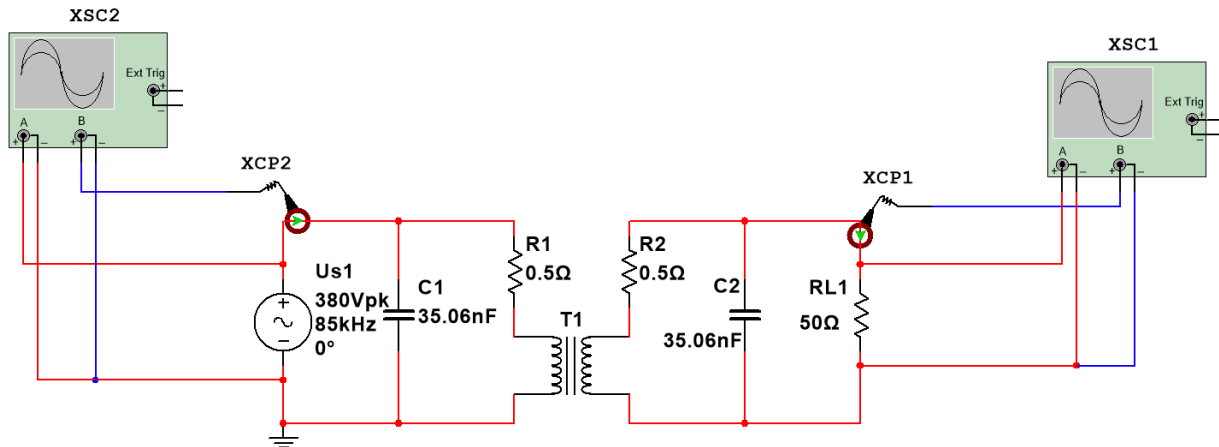


Fig. 7 P-P topology simulation circuit

The simulation results of P-P topology with a coupling coefficient of 0.8 is shown in Fig.8.

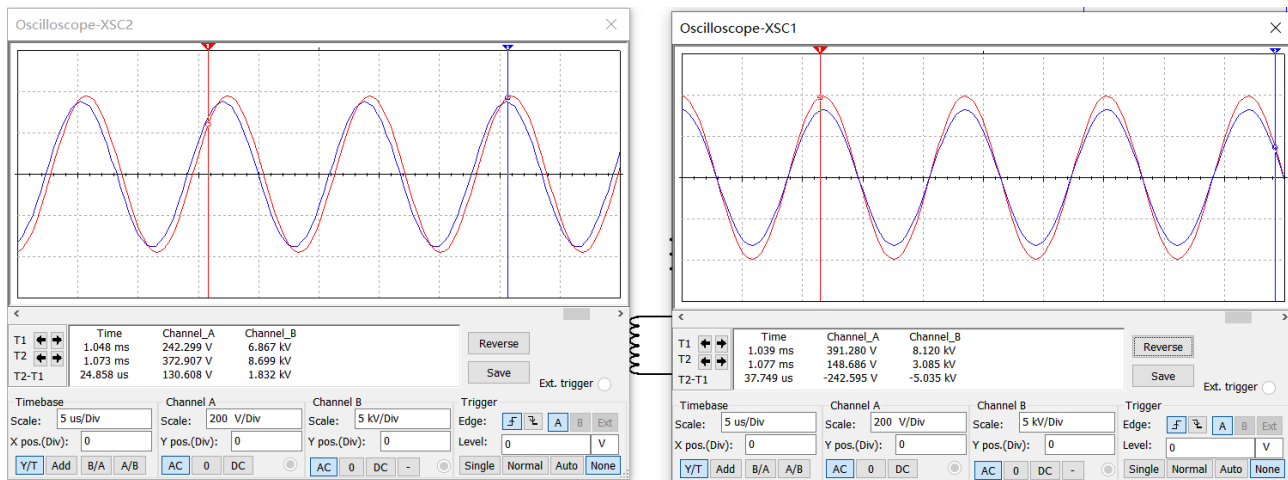


Fig. 8 P-P topology simulation results with coupling coefficient of 0.8

Through simulating, testing and calculating the transmission efficiency performance under all coupling coefficients, the charging efficiency curve of the P-P compensation topology can be obtained, as shown in Fig.9.

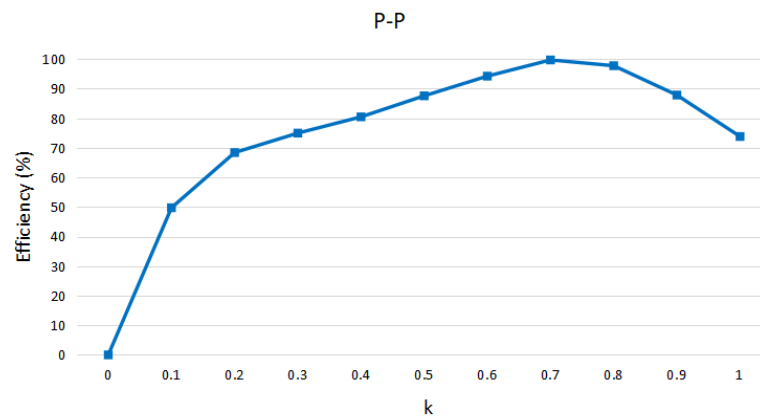


Fig. 9 P-P topology charging efficiency curve

As can be seen from Fig. 9, the transmission efficiency of P-P compensation topology increases with the increase of coupling coefficient and the turning point to decrease is 0.8, and the charging efficiency is ideal when the coupling coefficient is between 0.6 and 0.8.

4.2.3 LCL-LCC compensation topology

The LCL-LCC topology simulation circuit diagram is shown in Fig.10.

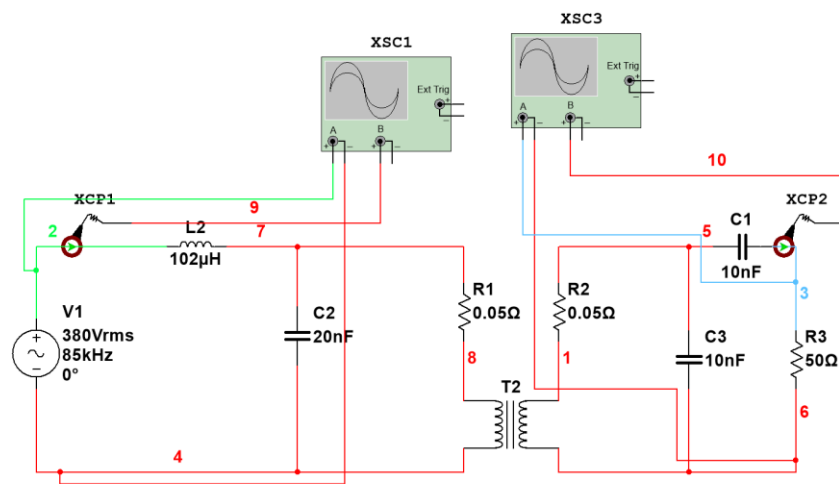


Fig. 10 LCL-LCC topology simulation circuit

The simulation results of LCL-LCC topology with a coupling coefficient of 0.8 is shown in Fig.11.

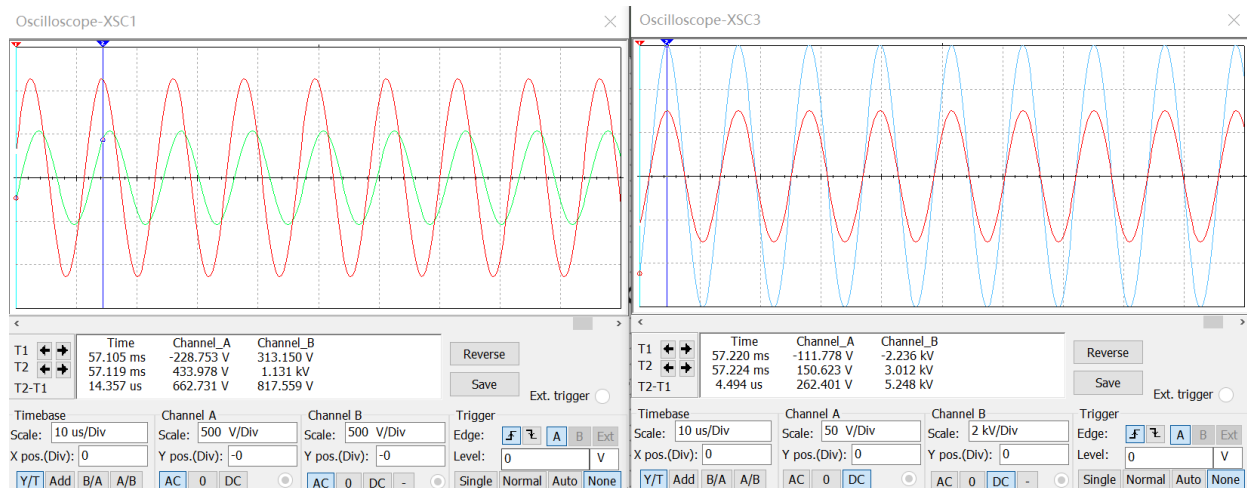


Fig. 11 LCL-LCC topology simulation results with coupling coefficient of 0.8

Through simulating, testing, and calculating the transmission efficiency performance under all coupling coefficients, the charging efficiency curve of the LCL-LCC compensation topology can be obtained, as shown in Fig.12.

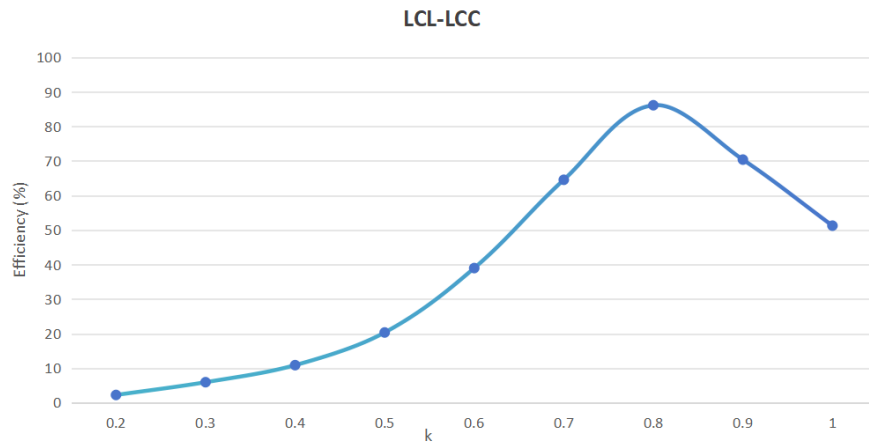


Fig. 12 P-P topology charging efficiency curve

As be shown in Fig.12, transmission efficiency of LCL-LCC gently increases and then decreases with the increase of coupling coefficient, and the charging efficiency is ideal when the coupling coefficient is 0.8.

In order to investigate other charging properties of the LCL-LCC compensation topology, the load resistance is switched to. Fig.13 and Fig.14 show the simulation results of LCL-LCC compensation topology and the voltage and current curve of LCC side at load resistance set to 20Ω respectively.

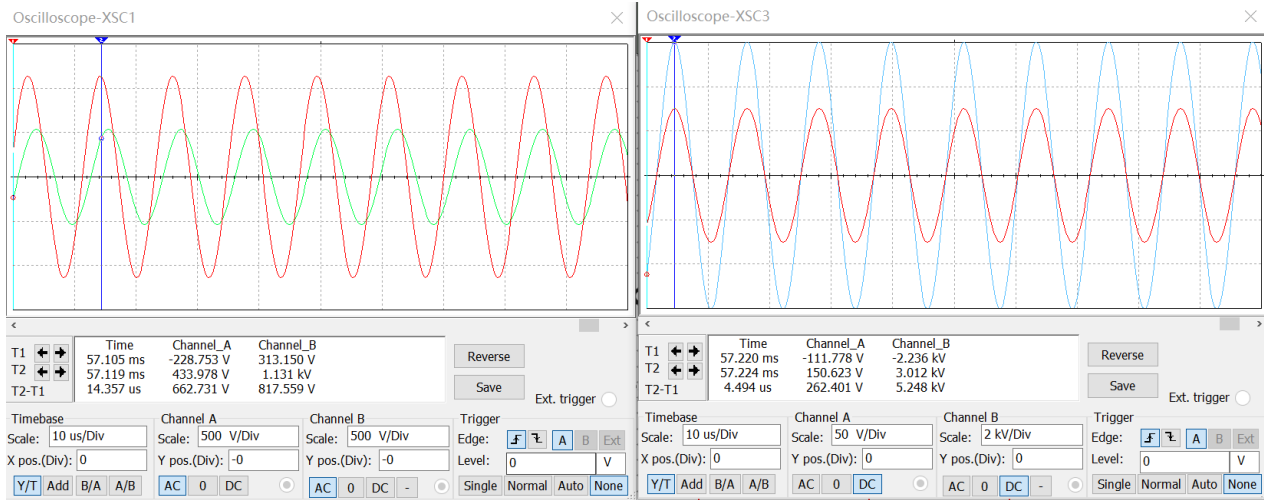


Fig. 13 LCL-LCC compensation topology simulation results after load resistance switching to 20Ω

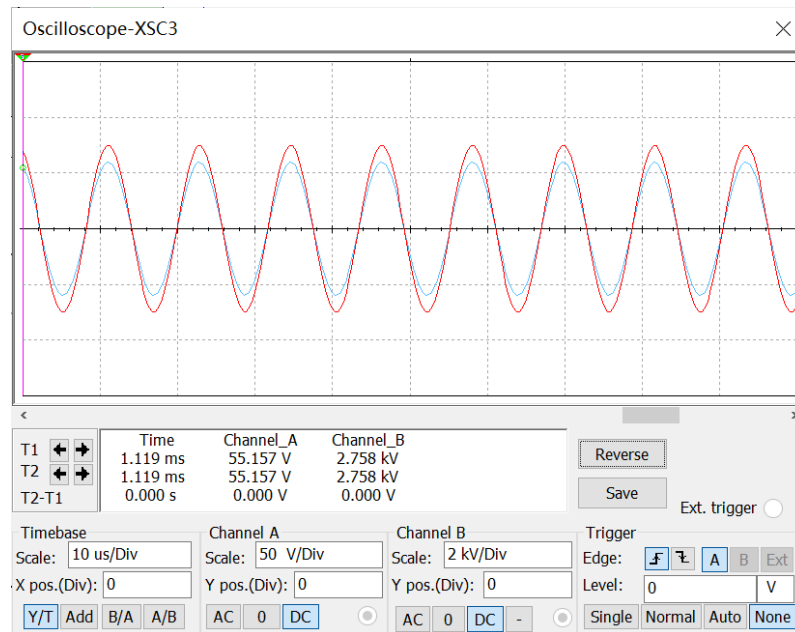


Fig. 14 voltage and current curve on the LCC side after load resistance switching to 20Ω

The effect of voltage charging is verified by comparing the load resistance of 50Ω and the load resistance of 20Ω, in which the effect of current charging and voltage charging is obvious, and the two curves in the two figures are completely coexisting, which well verifies the previous derivation. After switching from the LCL side to the LCC side, the charging power decreases significantly, indicating that the current charging is faster than the voltage charging, which accords with the battery charging model.

Voltage and current jump during transition from LCL side to LCC side is screen captured in Fig.15.

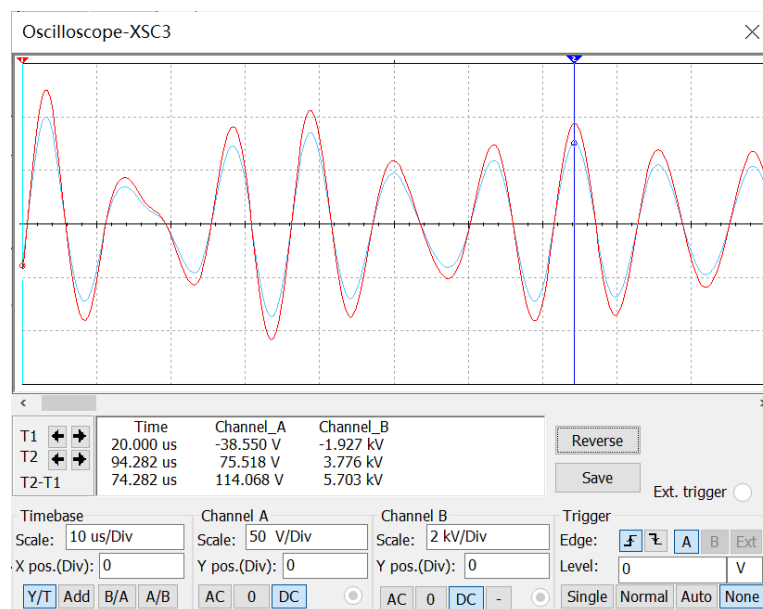


Fig. 15 voltage and current Jump during transition

After switching from LCL to LCC, although the current and voltage jump, but the jump time is short, it is still consistent with the actual battery charging process model.

In the actual model, there are power losses such as wire loss and leakage flux in the line, but it is expected that the actual charging efficiency can still reach about 80%, which is higher than the current research on wireless charging of electric vehicles, and avoids problem that bilateral resonant frequency of the traditional charging mode will jump, produce harmonics, and affect the charging quality.

4.2.4 Discussion

After comparing the three compensation topologies of PP, PS and LCL-LCC, it is found that the transmission coefficients of the three circuits all decay to a certain extent under the condition of low coupling coefficients, especially the LCL-LCC topology. In the reality that the coupling coefficients of wireless charging of electric vehicles are mostly 0.2-0.3, transmission efficiency of PS topology is higher. In the case of high load, the LCL-LCC compensation has a short jump time, which makes the charging process stable. Under the premise that the coupling coefficient can be improved, from the perspective of the whole usage life cycle, reliability and maintenance-free are more important factors to consider, especially when it comes to wireless charging of electric vehicles with the characteristics of public transport operation. LCL-LCC compensation is a good choice.

5. Conclusion

In order to adapt to the increasing popularity of electric vehicles worldwide and the trend of intelligent development to match the vision of charging right after parking, to perfectly design a wireless charging system for electric vehicles with high transmission efficiency and strong anti-drift and anti-jump ability has become an important research content in this field. The key technologies of electric vehicle wireless charging system are studied, and transmission characteristics of different compensation topologies are compared and analyzed to maximize transmission efficiency.

In this study, two basic compensation topologies and one compound compensation topological circuit model were established, and the influences of operating frequency, coupling coefficient and load resistance on output power and transmission efficiency were analyzed. It was concluded that the transmission coefficient of the three circuits all attenuates to a certain extent under the condition of low coupling coefficient. In the daily life that the coupling coefficient of wireless charging of electric vehicles is mostly 0.2-0.3. The transmission efficiency of P-S topology is high, which can reach 93% in theory, and may be slightly lower in practice, with a transmission efficiency of nearly 90%. However, the short jump time of LCL-LCC compensation makes the charging process stable, which has the development potential for wireless charging with high coupling coefficient, and is also a good choice for public transportation operations that need stability and safety.

Due to time, many different topologies cannot be adequately experimented to find out the best transmission efficiency choice for wireless charging of electric vehicles under low coupling coefficient. Further and more detailed analysis of the overall trend of coupling coefficient and load resistance on transmission efficiency cannot be tasted as well. In addition, due to the limitations of equipment and funds, this study cannot carry out actual experimental tests, and cannot give how much transmission efficiency will be lost in practice and analyze the reasons. If conditions permit in the future, this study will complement the analysis and simulation of various basic topologies and more complex topologies to further improve the system performance. It will also build a low-power experimental platform as far as possible to conduct simple verification of the design scheme. If conditions permit, it is hoped that the high-power experimental platform can be further built.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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