Interoperability Analysis of Resonance Compensation Network for Wireless Charging System of Electric Vehicles

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Abstract. The compensation network of wireless charging system has many combinations, and the magnetic coupling mechanism of different network compensation combinations is usually inconsistent. How to realize matching control between power transmission and receiving devices is a key problem to the wireless charging. This paper studies the interoperability of different topologies of wireless charging system compensation network, and deduces the transmission characteristics of typical and complex topologies. A simulation model of resonant topology is established, which can simulate the switching of primary and secondary topologies in practical application scenarios. The changes of transmission and load characteristics of the system are analyzed, the interoperability of different topologies is evaluated, and suggestions for the production of wireless charging equipment are put forward.

1. Introduction

Electric vehicle wireless charging technology has the characteristics of non-contact friction, strong environmental adaptability, good compatibility, user-friendly and so on, so it has been widely concerned by many scholars and industry. At present, wireless charging technology can be roughly divided into three categories: microwave, electromagnetic induction and magnetic coupling resonance. Among them, the magnetically coupled resonant wireless power transmission has the advantages of long transmission distance, high system efficiency and large transmission power, and has been widely concerned by researchers and successfully applied in many fields. Wireless charging system itself has many branches of technology. There are great differences in power level, transmission distance, coil type and structure, working frequency, compensation network topology and other structural parameters. If different billing systems are not interoperable, it will result in waste of resources and potential security hazards [1]. Therefore, how to ensure the interoperability of the magnetic coupling resonance wireless charging system has become one of the key factors in the development of the industry.

Magnetically coupled resonance wireless charging system is mainly composed of high frequency power supply, coupling coil, compensation network and load. The compensation network is an important part of resonant circuit, which directly affects the output characteristics of the system. The current compensation networks can be roughly divided into two types: typical topology and composite topology. According to the connection mode between compensation capacitor and primary and secondary coils, the typical structure can be divided into four types: series-series (S-S), series-parallel (S-P), parallel-series (P-S), and parallel-parallel (P-P). The LCC structure in composite topology is...
widely used because of its greater power transmission capability. Considering the coexistence of typical and composite topologies, the following five combinations may occur: LCC-LCC, LCC-P, LCC-S, S-LCC and P-LCC. Different systems with different topologies have different output characteristics. In the process of interoperability, the influence of the change of the primary and secondary topologies must be fully considered, and the interoperability of the primary and secondary topologies must be given.

There are many studies on the design and parameter optimization of compensation network. Reference [2] discusses four typical topologies and compares the output characteristics of different structures with the system frequency and transmission distance. Based on the analysis of transmission characteristics of different topologies, different parameters and outputs are discussed and optimized in reference [3]. Reference [4] analyses the impedance frequency of double LCC topology and the characteristics of constant current and constant voltage. On the basis of theoretical analysis, the optimal design of circuit parameters is carried out. Reference [5] compares the double LCC and LCC-S topologies under constant current and constant voltage. Reference [6] analyses the load characteristics and parameter design method under pressure conditions, studied the output characteristics of S-LCC and S-S resonant topology respectively, and optimized the parameters of resonant topology. The above literature studies different topological properties, optimization parameters and specific objectives, but does not consider the interoperability between different topological structures.

In order to achieve the optimal matching of power transmission and receiving devices in wireless charging system compensation network, this paper studies the interoperability between different topologies of compensation network, and deduces the transmission characteristics of typical and complex topologies. The simulation model of resonant topology is established, the changes of transmission and load characteristics of the system are analysed. And the interoperability of different topologies is evaluated.

2. Analysis of transmission characteristics of compensation network

2.1. Transmission characteristics analysis of typical topology

The methods of wireless transmission of magnetically coupled resonance can be roughly divided into two categories: coupled mode theory and mutual inductance equivalent theory. The coupled mode theory establishes a more accurate and intuitive analysis system. Based on the theory of mutual inductance equivalent model, the circuit model between the transmitting coil and the receiving coil is established, and the equivalent relation of the system is given according to Kirchhoff’s law. The mutual inductance equivalent theory is also a widely used analytical method. In this paper, the various topological structures of the magnetically coupled resonant wireless charging system are analyzed by using the mutual inductance equivalent theory. The four typical topologies are shown in Figure 1:

![Figure 1. Four typical topological structures.](image)

The topological form of the primary and secondary resonant capacitors in Figure 1(a) is a series-series(S-S) structure. Where $U_S$ is the input voltage, $R_1$ and $R_2$ are the internal resistances of the primary coil and the secondary coil, respectively, $L_1$ and $L_2$ are the self-inductance of the two coils respectively, $C_1$ and $C_2$ are the resonant compensation capacitors on both sides, $M$ is the mutual inductance of the coil, $R_L$ is the load resistance of the receiving end.
The loop voltage equation is obtained by Kirchhoff’s voltage law:

\[
\begin{align*}
U_s &= \begin{pmatrix} R_1 + j\omega L_1 \\ -j\omega M \end{pmatrix} - \begin{pmatrix} -j\omega M \\ R_1 + R_L + j\omega L_2 + \frac{1}{j\omega C} \end{pmatrix} \begin{pmatrix} I_1 \\ I_2 \end{pmatrix}
\end{align*}
\]

(1)

When the system is in resonance state, the resonant angle of the transmitting and receiving ends is the same. When the Q value of the coil is designed to be large enough, the internal resistance of the coil is negligible with respect to the load, and the current of the transmitting end and the receiving end can be obtained by solving:

\[
\begin{align*}
I_1 &= \frac{U_s (R_2 + R_L)}{(\omega M)^2} \\
I_2 &= \frac{jU_s}{\omega M}
\end{align*}
\]

(2)

The voltage can be calculated as:

\[
U_L = I_2 R_L = \frac{jU_s R_L}{\omega M}
\]

(3)

It can be seen from Equation (3) that when the system adopts the S-S type compensation mode, the output current is not affected by the change of the load resistance, while the internal resistance of the coil is neglected. It has a certain constant current characteristic, and the voltage is proportional to the load resistance.

A similar analysis is performed on the other three topologies. The output voltage and current of the S-P topology are intuitively coupled to the load resistance. However, according to the operating frequency and load range of the system under normal conditions, the number level of \( R_L \) can be estimated to be much less than \( 1/j\omega C_2 \), and the system can be approximated as a constant current output. The output voltage and current of the P-S topology in solution results are analysed. It can be seen that \( \omega L_1 R_L \) is far less than the order of \( \omega^2 M^2 \), and the load variation does not have a large influence on the output current, so it can be determined that the system has a constant current output characteristic. The loop current and the load output voltage for the P-P topology are solved. It can be concluded that \( \omega^2 M^2 C_2 R_L \) in the solution results is much less than the order of magnitude of \( L_1 \), so the influence of load variation on the output current can be neglected within a certain range, and the system exhibits a constant current characteristic.

2.2. Transmission characteristics analysis of composite topology

The LCC topology in the composite structure is widely used due to its good robustness and power transmission energy. This paper uses the LCC topology as an example to study its interoperability. Five composite topologies of compensation networks with LCC structure are shown in Figure 2.

The mutual inductance equivalent model of LCC-LCC topology is shown in Figure 2(a). Where \( R_1 \) and \( R_2 \) represent the equivalent resistance of the transmitting and receiving coils, respectively. \( C_1 \) and \( C_2 \) are the compensation capacitors, \( R_L \) is the equivalent resistance load. \( L_{f_1} \) and \( C_1 \) constitute a low-pass filter. The advantage of LCC-LCC topology is that compensating capacitor is used to reduce the inductance reactance of branch circuit, at the same time, it ensures the larger inductance, enlarges the current flowing through the coil, thus enhances the magnetic field and improves the power transmission ability.
The output current of the load is not affected by the load change, so it has quasi-constant current characteristics. The magnitude of the factor directly coupled with the equivalent impedance of the load, so the output of this topology exhibits constant voltage characteristics. The magnitude of the factor coupled with the load, and the output of the system is constant voltage. From the result of calculation, the internal resistance of the coil is negligible, and the current and load voltage of the loop can be obtained:

\[
\begin{align*}
I_s &= \omega^2 M^2 U_s C_1^2 C_4^2 \\
I_1 &= -jV_s \omega C \\
I_2 &= -\omega^3 MU_s R_L C_1 C_4^2 \\
V_L &= -j\omega^3 MU_s R_L C_1 C_4
\end{align*}
\]  

The calculation results of the LCC-LCC topology show that the output current of the load is not directly coupled with the equivalent impedance of the load, so the output of this topology exhibits constant current characteristics.

Similar analysis is performed on other composite topologies. The output current of the LCC-S topology is inversely proportional to the load resistance. The corresponding output voltage is not coupled with the load, and the output of the system is constant voltage. From the result of calculation, the output of the LCC-P type topology exhibits constant current characteristics. The output current of the S-LCC topology is inversely proportional to the load, and its output voltage is independent of the load resistance, so the output exhibits constant voltage characteristics. The magnitude of the factor in the denominator of load output current of P-LCC topology is much larger than that, so we can assume that the output voltage is not affected by the load change, so it has quasi-constant voltage characteristics.

3. Interoperability analysis of resonant compensation network

3.1. Interoperability status and evaluation criteria

The structure parameters of wireless charging system are different in power level, transmission distance, coil type and structure, working frequency and compensation network topology. This paper chooses the compensation network topology as the research direction. The possible interoperability state in practical application is shown in Figure 3.
It can be seen from Figure 3, when the ground end structure of primary side is determined, any LCC type of topology can be used on the secondary side of the electric vehicle. Conversely, when the same type of electric vehicle charges in different areas, the charging device of the ground terminal can also adopt the different structures. Therefore, for the interoperability of topology, the primary edge and secondary edge should be compared separately. The coexistence of multiple topologies leads to the interoperability. Taking the primary side topology as an example, assuming that the S-type structure has been determined, the secondary side topology can be converted between the S, P and LCC types. The topology will switch between S-S, S-P and S-LCC corresponding to different combinations of system compensation networks. Similarly, the main P, LCC topology and the secondary interoperability state can also be analyzed.

The influence of compensation network on system is mainly reflected in transmission power and controllability. Therefore, the study of the output characteristics of different topologies and the output characteristics of load voltage and current under the same excitation conditions can be used as compensation for the evaluation criteria of network topology interoperability.

3.2. Interoperability simulation analysis

Based on the analysis of the interoperability status of compensation network, the simulation circuit of topology switching is built by the Simulink. The schematic diagram of the circuit is shown in Figure 4.

In addition to excitation power supply, compensation network and rectifier module, the main part of the circuit includes switching circuit which adjusts the connection state of compensation network by setting CB delay of circuit breaker and setting input voltage of wireless charging system to 50V. The inductance of the coils on both sides is 590 $\mu$H, the resonant frequency is 85 kHz. $C_1$, $C_2$, $C_3$ and $C_4$ in the compensation capacitors are 6nF, $C_5$ and $C_8$ are 86nF, $C_6$ and $C_7$ are 5.6nF, $L_{F1}$ and $L_{F2}$ are 41 $\mu$H, the load is 50 $\Omega$.

The simulation of interoperability between primary and secondary topology types is analyzed. When the primary side is S-type topology, CB1 is closed, CB2 and CB3 are disconnected, and the initial states and switching times of CB4, CB5 and CB6 are set respectively. The output power changes during system interoperability are obtained as shown in Fig. 5.

The trend of simulation curve shows that when the primary side of the system is S-type topology, it can still transmit normally in the interoperable state. When the primary side of the system is S-type topology, it can still transmit normally in the interoperable state. The output power is converted to 25W, 30W and 8W in turn. In order to compare with other topology types, the ratio of power difference to minimum power is expressed as the change range, and the S-type topology corresponds to 275% change.
When the primary side is P-type, the connected CB2 is closed, CB1 and CB3 are closed, and CB4, CB5 and CB6 are set in the same switching state. The power change of the system is shown in Figure 6. When the primary side is P-type, the power is converted to 31W, 33W and 3W in turn, so we can know that the power conversion range is 1000%.

The power change curve of primary side LCC-topology interoperability is shown in Figure 7. When the primary side is LCC topology, the power is converted to 180W, 5W and 145W in turn, and the power conversion range is 3500%. By comparing the simulation results of the three kinds of topologies mentioned above, it can be seen that the power change of S-type topology is the smallest and that of LCC-type topology is the largest.

It can be concluded from Fig. 8, 9 and 10 that the output power of the corresponding three sub-topologies is 500%, 1000% and 4700%, respectively, which indicates that the secondary side LCC topology is also much larger than the magnitude of the change in the P and S-type topology.

In order to comprehensively evaluate the interoperability of compensation network, it is necessary to analyze the control performance of compensation network. In order to verify the analysis of constant voltage or current characteristics of various compensation network combinations in the previous section, the output voltage and current of typical and composite topologies under variable load conditions are given below.

When the system load changes from $50\,\Omega$ to $25\,\Omega$, the changes of output voltage and current of the different topologies are shown in Figure. 11, 12, 13 and 14. As can be seen from the information in Figure 11, 12, 13 and 14, all topological combinations have constant current or constant voltage characteristics within a certain range of load variation. Therefore, the wireless charging system can adopt a corresponding control strategy. Except for the three voltage structures of S-LCC, P-LCC and LCC-S, which output constant voltage characteristics, most of the compensation networks are constant currents.
In practical applications, the three topologies of the primary side may vary between constant current and constant voltage characteristics. This means that the system can adjust control strategies in time to meet interoperability requirements. For the secondary side, the P topology is the third level. These combinations have constant current characteristics, while the S and LCC models still require constant voltage or constant current control to be adjusted under certain conditions.

The integrated output power and controllability form the evaluation criteria for compensating network interoperability. In order to more intuitively compare the various topologies on the primary secondary side, nine combinations of interoperable state trees are plotted, as shown in Figure 15 and 16. The above state tree summarizes the changes of system output characteristics when the wireless charging system interoperates between primary and secondary compensation network topology switching. The red font label indicates that there is no interoperability between the two topological combinations. For the primary side topology type, S, P and LCC can change the output characteristics of the system, that is, when the constant voltage and current characteristics are converted to each other,
the control mode of the system needs to be changed in time. When S-type is interoperable, the power changes are minimal. When the input of the system remains unchanged, the system can ensure that the system does not overload or the power is too small to damage the load. Therefore, it can be concluded that the interoperability of main-edge S-type and P-type topologies is stronger than that of LCC-type topologies. The same criteria are used to evaluate the interoperability of quadratic side topologies. The P-type topology maintains constant current characteristics when interoperable. At the same time, because the range of power change is similar to that of S-type and much smaller than that of LCC-type, it can be considered that the P-type topology on the secondary side has stronger interoperability.

4. Conclusion
This paper establishes a typical composite topology equivalent circuit model for wireless charging system compensation network. The basic characteristics of various topological combinations are theoretically derived and analyzed. An interoperability assessment standard based on power and control strategies was established. The original secondary side interoperation and system variable load simulation are carried out. The results show that the main S, P and LCC topologies need to change the control mode during interoperability, but the S-type topology can minimize the system power variation. The secondary side P-type topology maintains a constant current characteristic during interoperability and reliability, and the system output power does not change much. Therefore, the S-type and the P-type are the topological types with the strongest interoperability of the primary side and the secondary side, respectively. The compensation network interoperability studied in this paper can provide a basis for the research of wireless vehicle charging and ground terminal interoperability standardization.

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