Interoperability Analysis of Compensation Topologies for Inductive Power Transfer System

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Abstract. This paper aims to discuss the interoperability of compensation topologies for the inductive power transfer system. Based on the common practice of the compensation design, three possible cases which may happen are analyzed, including LCC-S, S-LCC, and LCC-P compensation topologies. In order to evaluate the performance of these three topologies, an analysis method is proposed to investigate the electrical characteristics. The output voltage, current and power of the different topologies affected by variations of the coupling coefficient and the ratio of secondary inductance to primary inductance are analyzed to evaluate their performances. Further simulation models are built to compare the output performance of different compensation topologies.

1. Introduction
The IPT technique has gained worldwide attention as it can enable the transfer of energy over large air gap through a high-frequency time-varying magnetic field. With a trade-off between the power transfer distance and efficiency, IPT technique is increasingly popularized in charging the low-power devices like biomedical implants, smartphones and the high-power equipment including factory automation, and EVs.

In order to maximize the output power and minimize the VA rating of the power supply, compensation circuits have to be deployed in both the primary and secondary side to compensate the inductances of two coils [1]. There are literatures [2,3] investigating the output characteristics, design considerations, and sensitivities for IPT system using single-element and multi-element compensation. Single-element compensation topologies include S-S, S-P, P-S and P-P. Multi-element compensation topologies include LCL and LCC. Compared with single-element compensation topologies, the multi-element compensation topologies which are suitable for EV could enhance the tolerance of the IPT system to parameters’ variation, but the system order, volume, weight, and cost increase.

The diversity of compensation design leads to issues about the interoperability between the EV and different wireless charger, which is one of the main barriers to the industrialization of the IPT technique. The research of the interoperability has been reported in [4], but it mainly focuses on coils. There are rare scholars investigating the interoperability of compensation topology. In this paper, a method on how to evaluate the electrical characteristics of different possible compensation topologies
is proposed. This method mainly focuses on the analysis of output voltage, current and power. Further simulations are conducted to analyze the output performance of different compensation topologies.

2. Topology analysis

In the EV charging application, the primary side circuit is supposed to operate with a specific corresponding secondary side circuit. The secondary coil may fail in picking up the power from the primary coil when the compensation circuits are not matched. Therefore, it is necessary to analyze the electrical performance of the IPT system when different topologies are coupled. Currently, the topologies in the IPT system mainly include S, P, and LCC, which are shown in figure 1. In order to study the performance of topological networks with different topologies, the impedance of each topology as the primary and secondary topology is analyzed.

![Figure 1. The network of topologies](image)

Table 1. The resonance relationship of the compensation topology

| Topology | LCC       | S          | P          |
|----------|-----------|------------|------------|
| $L_f,i$  | $\frac{1}{\omega^2 C_f,i}$ | $L_i = \frac{1}{\omega^2 C_i} + \frac{1}{\omega^2 C_f,i}$ | $L_i = \frac{1}{\omega^2 C_i}$ | $L_i = \frac{1}{\omega^2 C_i}$ |

where $i=1$ denotes primary side, $i=2$ denotes secondary side, $L_i$ is the self-inductance of the coil, $L_f$ is the compensation inductance, $C_i$ is the compensation capacitance of $L_i$, $C_f$ is the compensation capacitance of $L_f$. $\omega = 2\pi f$, where $f$ is the resonant frequency. $\omega = 2\pi f$, where $f$ is the resonant frequency.

Reflected impedance method is a common approach to analyzing the transformer. The reflected impedance $Z_f$ can be described:

$$Z_f = \frac{\omega^2 M^2}{Z_s}$$  \hspace{1cm} (1)

Taking the LCC topology as an example, the impedance and current of LCC topology are calculated.

When the LCC topology is used as the secondary topology, $Z_S$ and $Z_f$ can be expressed as

$$Z_s = \frac{\omega^2 L_i^2}{R}, \quad Z_f = \frac{M^2}{L_f^2}R$$  \hspace{1cm} (2)

The current $I_2$ through $L_2$ can be expressed as

$$I_2 = \frac{j\omega MI_1}{Z_s} = \frac{jMRI_1}{\omega L_f^2}$$  \hspace{1cm} (3)

The current $I_R$ through $R$ can be expressed as

$$I_R = \frac{MI_1}{L_f^2}$$  \hspace{1cm} (4)

When the LCC topology is used as the primary topology, $Z_P$ can be expressed as
The input current $I_{IN}$ can be expressed as

$$I_{IN} = \frac{U_{ab}}{Z_p} = \frac{U_{ab} Z_f}{\omega^2 L_{f1}}$$  \hspace{1cm} (6)

The current $I_1$ through $L_1$ can be expressed as

$$I_1 = I_{IN} \cdot \frac{1}{\frac{1}{j\omega C_{f1}} + \frac{1}{j\omega C_{f2}} + j\omega L_1 + Z_f} = \frac{j U_{ab}}{\omega L_f}$$  \hspace{1cm} (7)

The same method is used to calculate the impedance and current of the S and P topologies. The calculation results are shown in Table 2.

### Table 2. The calculation results of topologies

| Topology | Primary topology | Secondary topology |
|----------|------------------|--------------------|
|          | $I_{IN}$ | $I_1$ | $Z_p$ | $I_2$ | $I_R$ | $Z_s$ | $Z_f$ |
| S        | $\frac{U_{ab}}{Z_p}$ | $\frac{U_{ab}}{Z_p}$ | $Z_f$ | $\frac{j\omega M_1}{R}$ | $\frac{j\omega M_1}{R}$ | $R$ | $\frac{\omega^2 M^2}{R}$ |
| P        | $-\frac{U_{ab}}{\omega L_{f1}} e^{j\omega L_{f1}} + \frac{U_{ab}}{\omega L_{f2}} e^{j\omega L_{f2}}$ | $\frac{U_{ab}}{\omega L_{f1}} e^{j\omega L_{f1}} + \frac{U_{ab}}{\omega L_{f2}} e^{j\omega L_{f2}}$ | $\frac{M_1(jR + \omega L_1)}{\omega L_2}$ | $\frac{M_1 R}{L_2}$ | $\frac{j\omega L_2}{R}$ | $\frac{M^2}{L_2}$ | $\frac{\omega^2 L_2}{R}$ |
| LCC      | $\frac{U_{ab} Z_f}{\omega^2 L_{f1}}$ | $\frac{j U_{ab}}{\omega L_{f1}}$ | $\frac{\omega^2 L_1^2}{Z_f}$ | $\frac{j M R}{R}$ | $\frac{M_1}{L_{f1}}$ | $\frac{\omega^2 L_2}{R}$ | $\frac{M^2}{L_{f2}}$ |

3. **Investigated topology**

![Investigated compensation topologies](image)

Figure 2. Investigated compensation topologies

### Table 3. The parameters of the double-sided LCC compensation topology

| $U_{ab}$ | $L_1 / L_2$ | $L_{f1} / L_{f2}$ | $R$ | $k$ | $f$ |
|---------|-------------|-------------------|-----|-----|-----|
| 314V    | 360μH       | 67μH              | 40Ω | 0.3 | 85kHz |

Due to the simple structure and low cost of single-element compensation and the advantageous operation characteristics of LCC compensation, they are the main investigated objects of this paper.
Since the feasibility of SS, SP and double-sided LCC compensation topologies are proved, this paper targets to analyse S-LCC, LCC-S and LCC-P compensation. P-LCC is exclusive because of the extra need for the current-source inverter. These topologies are shown in figure 2.

In this paper, in order to verify the electrical characteristics analysis of these investigated compensation topologies, taking an 8kW double-sided LCC compensated IPT system as the reference, the parameters of the circuit are shown in table 3.

3.1. LCC-S
As can be seen from the data in table 3, the reflection impedance of the LCC-S topology is

$$Z_f = \frac{\omega^2 M^2}{R}$$  \hspace{1cm} (8)

The output voltage and output power of the LCC-S topology can be expressed as

$$U_{ab} = \frac{U_{ab} M}{L_{j1}}, \quad P_o = \frac{U_{ab}^2 M^2}{RL_{j1}^2}$$  \hspace{1cm} (9)

When the main coils of the two topologies are coupled, the self-inductance of the two main coils may be different. Therefore, assuming $L_2 = r L_1$[5], $M$ can be expressed as

$$M = k L_1 \sqrt{r}$$  \hspace{1cm} (10)

As can be seen from the expression of output voltage, the output of the LCC-S IPT system is a voltage source. In order to analyse the electrical performance of the system, the relationship between the output voltage and the output power as a function of $k$ and $r$ is analysed separately.

Combining the expression (9) and (10), the output voltage and output power can be expressed as

$$U_{ab} = \frac{U_{ab} k L_1 \sqrt{r}}{L_{j1}}, \quad P_o = \frac{U_{ab}^2 k^2 L_2 r}{RL_{j1}^2}$$  \hspace{1cm} (11)

Using the data in table 3 as the primary topology parameters of the LCC-S topology, the output voltage changes with $k$ and $r$ as shown in figure 3(a). It can be seen from the figure 3(a) that when the coupling coefficient is constant, the voltage output capability of the LCC-S topology increases as the ratio of secondary inductance to primary inductance increases. When the ratio is constant, the larger the coupling coefficient is, the higher the output voltage is. From the figure 3(b), it can be seen from the image that when the coupling coefficient is constant, the output power monotonically increases with the ratio. In addition, when the ratio is constant, the output power of the LCC-S topology increases as the coupling coefficient increases, which is consistent with the calculation result.

Figure 3. The relationship of the output voltage and power to the ratio of secondary inductance to primary inductance at different coupling coefficient. (a) the output voltage (b) the output power
3.2. LCC-P
According to the data in table 2, the output current, voltage and power of the LCC-P IPT system can be calculated as

\[
I_a = -\frac{jU_{ab}k}{\omega L_{f1}\sqrt{r}}, \quad U_{ab} = -\frac{jU_{ab}Rk}{\omega L_{f1}\sqrt{r}}, \quad P_o = \frac{U_{ab}^2k^3R}{\omega^2 L_{f1} r}
\] (12)

As can be seen from the expression of output current, the output of the LCC-S IPT system is a current source. Using the parameters in table 3, the output current changes with \(k\) and \(r\) as shown in figure 4(a). When the ratio is constant, the output current is proportional to the coupling coefficient. However, when the coupling coefficient is constant, the output current decreases as the ratio increases.

As shown in figure 4(b), when the ratio is constant, the output power increases as the coupling coefficient increases. However, when the coupling coefficient is constant, the output power decreases as the ratio increases.

![Figure 4](image-url)

Figure 4. The relationship of the output current and power to the coupling coefficient at different ratio of secondary inductance to primary inductance. (a) the output current (b) the output power

3.3. S-LCC
According to the data in table 2, the output current, voltage and power of the S-LCC IPT system can be calculated as

\[
I_a = \frac{U_{ab}L_{f2}}{kL_{f1}\sqrt{rR}}, \quad U_{ab} = \frac{U_{ab}L_{f2}}{kL_{f1}\sqrt{r}}, \quad P_o = \frac{U_{ab}^2L_{f2}^2}{k^2L_{f1} r R}
\] (13)

According to the expression (13), the output of the S-LCC IPT system is a voltage source. Using the parameters in table 3, the figure 5 shows the change of the output voltage and power with \(k\) and \(r\). When the ratio is constant, the output voltage decreases as the coupling coefficient increases. When the coupling coefficient is constant, the larger the ratio is, the smaller the output voltage becomes. When \(k \geq 0.3\) and \(r \geq 0.5\), the output voltage of the S-LCC topology is less than 300V, so the voltage gain of the S-LCC topology is less than 1 in this case. As shown in figure 5(b), the output power decreases as the ratio or coupling coefficient increases. When \(k=0.3\) and \(r=1\), the output power is about 0.95kw, which is much lower than the output power of the double-sided LCC topology.

![Figure 5](image-url)
Simulation
Using the parameters in table 3, the circuit models of the three topologies are built. In the circuit models, setting $L_2=L_1$, $k=0.3$, the coupling capacitors can be obtained by using equations in table 1. As shown in figure 6, the input current of the topologies is presented.

From figure 6, it is clear that the input currents of LCC-S and S-LCC compensated IPT system are in-phase with the input current. While there is an obvious phase delay between the input current and voltage of LCC-P compensated IPT system. This will lead to a reduction of the output power and efficiency of the IPT system.

Figure 7 shows the output currents and output voltages of the three topologies. Although the primary topology of the LCC-S and LCC-P topologies is the LCC topology with the same parameters, the output voltage and output current of the LCC-S topology are more than twice those of the LCC-P topology. As can be seen from figure 7, the output voltage and output current phases of the LCC-S and S-LCC topologies are basically the same, but the voltage and current values of the LCC-S topology are larger. Obviously, the LCC-S topology has better electrical output.

Conclusions
This paper proposes an analysis method to investigate the interoperability of the compensation topologies including series, parallel and LCC compensation. By using reflected impedance theory, the electrical characteristics of different topologies are derived. The output voltage, current and power of the different topologies affected by variations of the coupling coefficient and the ratio of secondary inductance to primary inductance at different coupling coefficient. (a) the output voltage (b) the output power

Figure 5. The relationship of the output voltage and power to the ratio of secondary inductance to primary inductance at different coupling coefficient. (a) the output voltage (b) the output power

Figure 6. Simulation results for input current of the different topologies

Figure 7. Simulation results for output voltage and current of the different topologies

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