Comparison and selection strategy of compensating topologies in two coil resonant wireless power transfer system

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ABSTRACT

In this study comparisons of different compensation topologies are investigated for two coil resonant wireless power transfer systems. Compensation circuits are examined individually according to system parameters such as efficiency, equivalent impedance, frequency, load resistance, and phase angle. This paper aims to compares the system variables in order to address the constraints in the system applicability regarding the compensation topology selection in Wireless Power Transfer (WPT) systems. Topology selection schemes related to circuit parameters are given. The main motivation of this study is that it presents a suitable topology selection scheme and flow diagram according to applications with various voltages, currents, power and loads. Simulations performed for four main topologies under various load conditions concludes that choosing the proper compensation topology for appropriate load is essential. Simulation studies are carried out with the Simulink software. The results obtained from here are validated with both Matlab calculation codes and C# calculation codes. The analyses according to the frequency in various load conditions have shown that variation of efficiency depends on the compensation topology of the receiver side. Moreover, in this study, it has been revealed that the topology of the transmitter side only affects the equivalent impedance together with the amount of power drawn from the input hence it has no effect on the efficiency and load characteristics. Consequently in the case of working with low load
resistance such as an electric vehicle or mobile phone charging, topologies with series compensation on the receiver side can be preferred. Correlatively, topologies with parallel compensation on the receiver side can be evaluated as suitable for high load resistance, low current, and low power operations such as biomedical appliance charging.

**Key words:** Series-series compensation; Series-parallel compensation; Parallel-series compensation; Parallel-parallel compensation; Wireless power transfer.

**INTRODUCTION**

The purpose of the Wireless Power Transfer (WPT) system is to transfer electrical energy from one point to another through the air gap without any direct electrical connections. Energy is transferred from the primary coil to the secondary coil via electromagnetic induction over the air gap. Due to the lack of contact, this system has advantages such as ease of use, high safety, high reliability, low maintenance cost, and long service life. This technology is used for applications such as electrical vehicles, consumer electronics, and biomedical applications where the conventional wired system is undesirable (Hasanzadeh and Vaez-Zadeh, 2015; Tang and Cheng, 2020; Keerthi et al., 2018). The basic principle of the electromagnetically coupled resonance based WPT system is that two coils with the same resonant frequency can efficiently transfer energy (Agcal et al., 2016). Since the efficiency of inductive power transfer based on magnetic induction becomes lower as the air gap distance increases, their popularity has decreased in recent years and has been replaced by electromagnetic resonance coupling (Nataraj et al., 2018; Zeng et al., 2021; Aydin et al., 2021; Bekiroglu et al., 2018; Heidarian and Burgess, 2020). When the distance between primary and secondary coils is large, the coupling coefficient becomes low. Therefore it is necessary to work at higher frequencies to provide the required power. For high power applications, the operating frequency is limited to below 100 kHz due to switching losses. Additionally, the primary and secondary parts are enabled to operate in resonance in order to minimize the amount of energy to be drawn from the power source and increase the power transfer. There are two major disadvantages in
sizing/planning the system in magnetically coupled resonance theory, first of which is the physical dimensions of the system. If the size of the secondary side coil becomes smaller, the magnetic flux of the primary side coil decreases drastically. For the magnetic flux to transfer energy efficiently enough, a large current must flow through the primary side coil (Heidarian and Burgess, 2020). The second disadvantage is the fact that as the frequency becomes higher, the impedance of the primary side becomes more inductive. As a result, the power factor gets very small and starts to approach zero as the frequency increases leading to higher VA rating with reduced efficiency. In WPT applications, four types of compensation circuit topologies are used (Agcal et al., 2016; Ravikiran and Keshri, 2017; Zavrel and Kindl, 2018). In this study comparisons of different compensation topologies have been investigated for WPT systems. The main aim of this study is to address the constraints in the system applicability regarding the compensation topology selection in WPT systems. Compensation circuits have been examined individually regarding system parameters such as efficiency, equivalent impedance, frequency, load resistance, and phase angle. Simulations performed in this study for four topologies under various load conditions exhibit that choosing the proper topology for appropriate load is very important. The analyses according to the frequency in different load conditions have shown that the variation of efficiency depends on the topology of the receiver side. Moreover, in this study, it has been revealed that the topology of the transmitter side only affects the equivalent impedance and the amount of power drawn from the input hence it has no effect on the efficiency and load characteristics.

**WPT SYSTEM AND BASIC COMPENSATION TOPOLOGIES**

Magnetically coupled WPT is based on the principle of transferring energy from one side to the other by the magnetic connection between the receiver and transmitter coils. Magnetically coupled WPT system without compensation is shown in Figure 1 where $V_s$ is the voltage source, $L_1$ and $L_2$ are the self-inductance of both coils, $R_1$ and $R_2$ are the inner resistance of transmitting and receiving coils, $L_m$ is the mutual inductance between two coils and $R_L$ is the
load resistance. \( I_T \) and \( I_R \) are the current of the transmitter and the receiver respectively.

\[
L = \frac{N^2(D_0-N(w+p))^2}{16D_0+28N(w+p)} \times 10^6 \quad (1)
\]

\( L \): self-inductance, \( N \): number of turns, \( D_0 \): outer diameter, \( w \): cable diameter \( p \): spacing between turns. When Equation (1) is examined, the single-layer spiral inductance self-inductance depends on the number of turns, the coil outer diameter, the cable diameter and the spacing between turns.

\[
L_m = \frac{\mu_0N_1N_2}{4\pi} \int_{\Phi_1}^{\Phi_2} \int_{\Phi_1}^{\Phi_2} \frac{dl_1 dl_2}{r} \quad (2)
\]

\( N_1 \) and \( N_2 \) are the number of turns of transmit and receive coils respectively. The mutual inductance depends on the number of turns of transmit and receive coils, and also related to geometric position at the axial and radial axis. So, \( L \) and \( L_m \) are important circuit parameters affect the efficiency and \( Z_{Eq} \) in the WPT system. In addition, the topologies formed according to the way \( L \) and \( C \) are connected to the circuit also determine the way the WPT system works.

In this study, compensation circuit topologies are analyzed and a topology selection scheme related to circuit parameters is given. SS topology circuit is represented in Fig 2.
In SS topology, the resonator capacitance of the transmitter and receiver capacitors are $C_1$ and $C_2$ respectively. The formulation of the equivalent impedance and the efficiency are shown in Equation (4) and Equation (5), respectively. $Z_{Eq_{SS}}$ is the equivalent impedance of SS topology and $\eta_{SS}$ is the efficiency of this system.

$$Z_{1,2} = R_{1,2} + j\omega L_{1,2}$$

$$Z_{Eq_{SS}} = Z_1 + \left(\frac{1}{j\omega C_1}\right) + \left(\frac{L_m^2\omega^2}{Z_2 + \left(\frac{1}{j\omega C_2}\right) + R_L}\right)$$

$$\eta_{SS} = \left|\frac{jL_m\omega}{Z_2 + \left(\frac{1}{j\omega C_2}\right) + R_L}\right|^2 \frac{R_L}{Z_{Eq}}$$

SS topology is more efficient at low $R_L$ therefore SP topology is preferred over SS for systems with higher $R_L$. SP topology circuit is shown in Figure 3.

The equation of the equivalent impedance ($Z_{Eq_{SP}}$) and the efficiency ($\eta_{SP}$) for SP topology
are presented in Equation (7) and Equation (8), respectively.

\[
Z_L = \frac{R_L}{1 + j\omega C_2 R_L} \quad (6)
\]

\[
Z_{EqSP} = Z_1 + \frac{1}{j\omega C_1} + \frac{\omega^2 L_m^2}{Z_2 + Z_L} \quad (7)
\]

\[
\eta_{SP} = \left| R_L \left( \frac{j\omega L_m}{Z_2 + Z_L} \frac{1}{1 + j\omega C_2 R_L} \right)^2 / Z_{EqSP} \right| \quad (8)
\]

PS topology works efficiently at low \( R_L \) with the same load range as the SS topology, however, unlike SS topology, its equivalent impedance at resonance frequency is much higher than SS topology. PS topology circuit is illustrated in Figure 4.

![Figure 4 PS topology.](image)

The equivalent impedance equation and the efficiency formula of PS topology, are given in Equation (9) and in Equation (10) respectively, are derived from Figure 4 where \( Z_{EqPS} \) stands for equivalent impedance of PS topology and \( \eta_{PS} \) stands for the efficiency of this system.

\[
Z_{EqPS} = \frac{Z_1 + \frac{\omega^2 L_m^2}{Z_2 + \frac{1}{j\omega C_2} + R_L}}{1 + j\omega C_1 \left( Z_1 + \frac{\omega^2 L_m^2}{Z_2 + \frac{1}{j\omega C_2} + R_L} \right)} \quad (9)
\]

\[
\eta_{PS} = \left| R_L \left( \frac{j\omega L_m}{Z_2 + \frac{1}{j\omega C_2} + R_L} \frac{1}{j\omega C_1} \frac{\omega^2 L_m^2}{Z_2 + \frac{1}{j\omega C_2} + R_L} \right)^2 / Z_{EqPS} \right| \quad (10)
\]

The PP topology which has the properties of the secondary side of the SP topology and the primary side of the PS topology works efficiently at high load values and has high equivalent impedance at resonant frequency. PP topology circuit is depicted in Figure 5.
The equivalent impedance equation and the efficiency formula of PP topology, given in Equation (11) and in Equation (12) respectively, are derived from Figure 5.

\[
Z_{EqPP} = \frac{Z_1 + \omega^2 L_m^2}{1 + j\omega C_1 (Z_1 + \frac{\omega^2 L_m^2}{Z_2 + Z_L})} \quad (11)
\]

\[
\eta_{PP} = \left| \frac{R_L \left( \frac{1}{Z_2 + Z_L} \frac{j\omega L_m}{1 + j\omega C_2 R_L} \frac{1}{Z_1 + \frac{\omega^2 L_m^2}{Z_2 + Z_L}} I_1 \right)}{Z_{EqPP}} \right|^2 \quad (12)
\]

\(Z_{EqPP}\) is the equivalent impedance of PP topology and \(\eta_{PP}\) is the efficiency of this system.

SIMULATIONS FOR COMPARATIVE EVALUATIONS

Circuit parameters are determined to compare the efficiency and equivalent impedance of the four topologies under various load conditions. WPT system parameters used for simulation study are shown in Table 1.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmitter inductance (L₁)</td>
<td>100 µH</td>
</tr>
<tr>
<td>Receiver inductance (L₁)</td>
<td>100 µH</td>
</tr>
<tr>
<td>Transmitter capacitance (C₁)</td>
<td>37 nF</td>
</tr>
<tr>
<td>Receiver capacitance (C₂)</td>
<td>37 nF</td>
</tr>
<tr>
<td>Transmitter Coil resistance (R₁)</td>
<td>0.2 Ω</td>
</tr>
<tr>
<td>Receiver Coil resistance (R₂)</td>
<td>0.2 Ω</td>
</tr>
<tr>
<td>Mutual inductance (Lₘ)</td>
<td>20 µH</td>
</tr>
</tbody>
</table>

The variation of efficiency according to frequency in different load conditions is shown in Figure 6 by Equations (5,8,9,10) for SS, SP, PS, and PP topologies respectively. In order to examine the effects of different topologies on \(Z_{Eq}\), by equations (4,7,9,10) variation of equivalent impedance in different load conditions is shown in Figure 7.
In all four SS, SP, PS, and PP topologies, the efficiency of the energy transferred to load resistance depends on the topology of the receiver side. When results of all of the topologies are compared, it was revealed that the topologies with serial compensation on the receiver side have higher efficiency for low load resistances therefore the efficiency decreases as the load resistance increases and vice versa. As the load resistances go below the critical value, bifurcation phenomenon occurs. Even though the efficiency becomes maximum, the resonance frequency bifurcates from one resonant frequency to three separate resonance frequencies. If the load resistance is lowered too much, the efficiency starts to decrease even in the bifurcation state since the secondary side will operate as a short circuit. On the other hand, the efficiency of the topologies having parallel compensation on the receiver side is higher the efficiency decreases as load resistance decreases and vice versa. In parallel topology, the frequency bifurcates when the value of load resistance rises above the critical value. In this range, the efficiency is maximum however there are three resonance frequencies. If the load resistance is increased too much, the efficiency decreases again in the region of three resonance frequencies, since the secondary side starts working as an open circuit.

Figure 6 Efficiency-frequency graph (a) SS Topology, (b) SP Topology, (c) PS Topology, and (d) PP Topology
Figure 7 Equivalent impedance-frequency graph (a) SS Topology, (b) SP Topology, (c) PS Topology, and (d) PP Topology.

Figure 7 shows that the compensation topology of the transmitter side in SS, SP, PS, and PP topologies determines the range of the equivalent impedance at the resonant frequency. Figure 7 (a) and (b) reveal that SS and SP topologies provide an operation at low equivalent impedance whereas Figure 7 (c) and (d) reveal that PS and PP topologies provide an operation at high equivalent impedance. In WPT systems the topologies with serial compensation on their transmitter side, the resonance frequency becomes the frequency at which the equivalent impedance value is minimum. In the case of the topologies with parallel compensation on transmitter side, the resonance frequency is becomes the frequency at which the equivalent impedance is maximum. At the resonance frequency, the equivalent impedance of the series topologies is low (1-10 Ω), while the equivalent impedance is high (100 - 10 kΩ) in the parallel topologies. Therefore, when both compensation topologies are supplied from a constant voltage AC source, the serial compensated topology draws more power from the AC source than what is drawn by the parallel compensated topology. The case of the amount of current drawn the effect of the load resistance on the efficiency should be investigated. Figure 8 shows the change in efficiency according to the load resistance in SS and PS topologies.
Figure 8 Efficiency-load resistance graph for SS, SP, PS, and PP topologies.

Figure 9 shows that the topologies with the same compensation on the receiver side have the same efficiency-load characteristics. In order to observe the transition between capacitive and inductive operation points which are essential to avoid power factor getting smaller, the change of phase angle with the respect to frequency should be investigated.

Figure 9 Efficiency-load resistance-frequency graphics (a) SS, (b) SP, (c) PS, and (d) PP.

As seen in Figure 10, when the variation of the phase angles of the four topologies vs. frequency is examined, the phase angles are zero at resonance frequencies.
SS and SP topologies which are similar with respect to their transmitter sides are capacitive below the resonant frequency and inductive above the resonant frequency. On the other hand PS and PP topologies having parallel compensation on their transmitter side are inductive below the resonant frequency and capacitive above the resonant frequency.

**COMPARISONS AND DISCUSSIONS**

Topology selection in WPT systems can vary greatly depending on the load characteristic, transferred power, input source, and many other factors. The efficiency, transmittable input power, load resistance range, equivalent impedance range, and load conditions at over and under resonant frequencies are compared in Table 2 for SS, SP, PS, and PP topologies.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>SS topology</th>
<th>SP topology</th>
<th>PS topology</th>
<th>PP topology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Transmittable power</td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Equivalent impedance</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Load resistance</td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Power source</td>
<td>Voltage source</td>
<td>Voltage source</td>
<td>Current source</td>
<td>Current source</td>
</tr>
<tr>
<td>Under resonant frequencies</td>
<td>Capacitive</td>
<td>Capacitive</td>
<td>Inductive</td>
<td>Inductive</td>
</tr>
<tr>
<td>Over resonant frequencies</td>
<td>Inductive</td>
<td>Inductive</td>
<td>Capacitive</td>
<td>Capacitive</td>
</tr>
</tbody>
</table>

The topology of the receiver side is determined according to the load resistance range for high efficient operation. Low load resistance such as an electric vehicle or mobile phone charging, topologies (SS and PS) with series compensation on the receiver side are preferred. Topologies with parallel compensation on the receiver side (SP and PP) are more suitable for high load resistance, low current, and low power operations such as medical implant charging. In applications with low input voltage, SS and SP topologies are preferred because their
equivalent impedance is low and can draw higher current from the input. Although SS and SP topologies are supplied by a voltage source, PP and PS topologies cannot be driven directly with voltage sources such as full or half bridge inverter due to the parallel connected capacitor. If it is supplied by a voltage source, it draws very high instantaneous currents since there is no inductance to limit the current between the voltage source and the capacitor at the output of the inverter. Since the switches cannot withstand this high short circuit current and high di/dt, they are likely to be destroyed. Therefore, PS and PP topologies are fed supplied by current sources. Since SS and SP topology circuits operate at resonant frequencies where the equivalent impedance is minimum, they draw more power from the source. Unlike SS and SP, the equivalent impedance is maximum at the resonance frequency in circuits with PS and PP topologies, hence the power drawn from the source is less. When phase angles with respect to frequency are examined, SS and SP topologies operate in capacitive region under the resonance frequency and work in inductive region above the resonance frequency. On the contrary, with PS and PP topologies, operation is in inductive region below resonant frequency and in capacitive region above resonant frequency.

![Figure 11](image)

**Figure 11** Topology related input source and resonance frequency determination flow chart

Figure 11 shows the flow chart for the selection of the appropriate topology, the selection of the appropriate source, and the determination of the appropriate resonance frequency. PA is the phase angle and F is the frequency. The selection of circuit parameters suitable for the
topology is as important as the determination of the topology. In Figure 12, flow chart is given to determine the appropriate circuit parameters according to the topologies.

![Figure 12. Topology related circuit parameter determination flow chart](image)

PS and PP systems, where compensation topology of the transmitter side is parallel, the capacitor cannot be connected directly to the input voltage source. A series inductance \( L_s \) is connected between the parallel resonator and either the full-bridge or half-bridge inverter. Inductance value of \( L_s \) is determined according to the topology as shown in Figure 12.

**CONCLUSION**

This paper presents simulation-based comparison analysis of four main compensation topologies for two coil resonant wireless power transfer systems. The behavior of the system is examined for various parameters such as efficiency, equivalent impedance, frequency, load resistance, and phase angle. The selection of suitable circuit parameters for the topology is as important as the determination of the topology. In this study, a topology selection scheme related to circuit parameters is given. This study addresses a wide range of loads, voltages, and power ranges for topology selection. Simulations were performed for four main topologies under different load conditions. The results clearly show that selecting the proper compensation topology for appropriate load is crucial for the correct operation the system to be designed. The analyses according to the frequency in various load conditions have shown
that the variation of efficiency depends on the compensation topology of the receiver side whereas the topology of the transmitter side only affects the equivalent impedance together with the amount of power drawn from the input. Since SS and SP topologies operate at resonant frequencies where the equivalent impedance is minimum and higher current is drawn, in applications with low input voltage, SS and SP topologies are preferred and can draw higher current from the input. Unlike SS and SP, the equivalent impedance is maximum at the resonance frequency in circuits with PS and PP topologies so, transmittable power is lower.

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