Analysis and Evaluation of Compensation Topologies in Wireless Charging Systems for Electric Vehicles

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Abstract. This paper comparatively analyses the four fundamental compensation topologies (series-series (SS), series-parallel (SP), parallel-series (PS), parallel-parallel (PP)) for wireless power transfer (WPT) systems applied to electric vehicle (EV) charging, evaluating by MATLAB/Simulink the energy efficiency, voltage/current constraints and misalignment tolerance. The results show that: SS topology achieves the best efficiency with stable voltage regulation but increased sensitivity to coupling variations; SP has the advantage of reducing stress on switches while increasing circuit complexity; while PS and PP configurations demonstrate better output current stability but higher losses under misalignment conditions. The analysis provides clear recommendations for the choice of topologies according to target applications, highlighting the trade-offs between energy performance, robustness and implementation complexity in wireless charging systems for electric vehicles (EVs).

1 Introduction

Wireless Power Transfer (WPT) systems have become a key technology for electric vehicle (EV) charging, offering benefits in terms of convenience, safety and sustainability [1]. Unlike traditional wired charging methods, WPT solutions eliminate the need for physical connections, reducing component wear and improving the user experience. However, the performance of these systems is highly dependent on the compensation topologies used to optimise the magnetic coupling between coils and minimise energy losses. Among the different configurations, series-series (SS), series-parallel (SP), parallel-series (PS) and parallel-parallel (PP) topologies are the most commonly studied, each presenting distinct trade-offs in terms of efficiency, stability and complexity, [2].

Selecting the appropriate compensation topology is crucial to meeting the requirements of high-power applications, where energy efficiency and misalignment tolerance are critical parameters. WPT systems for EVs have to operate under varying conditions, including

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positioning differences between the transmitting and receiving coils, which can significantly degrade performance, [3]. For example, one topology may excel in terms of energy efficiency under ideal conditions, but show increased sensitivity to coupling variations, while another may offer greater robustness at the expense of reduced efficiency. In-depth comparative analysis is therefore needed to guide design choices based on the specific constraints of the target applications [4], [5].

In this study, we systematically evaluate the four fundamental topologies (SS, SP, PS, PP) through MATLAB/Simulink simulations, focusing on three main criteria: energy efficiency, voltage/current constraints, and power delivery. These metrics are essential for determining the viability of topologies in real environments, where operational variations and high-power requirements impose major challenges. Our approach quantifies the advantages and disadvantages of each configuration, providing practical insights for engineers and researchers.

The remainder of this paper is organised as follows: Section 2 presents the basic principles of WPT systems and compensation topologies. Section 3 details the modelling and simulation methodology used to compare the different topologies. Section 4 analyses the simulation results, highlighting the relative performance of the SS, SP, PS and PP configurations. Finally, Section 5 concludes the study by summarising the main findings and proposing prospects for future work.

2 WPT system principles and compensation topologies

Magnetically coupled WPT systems rely on the principle of magnetic resonance between two coils, a transmitter (primary) and a receiver (secondary), to transfer energy without physical contact as shown in Fig. 1 [6]. In EV charging applications, the efficiency and stability of the transfer is highly dependent on the compensation circuits used to offset leakage inductances and optimise the coupling. Four basic topologies are commonly used: SS, SP, PS and PP, each with distinct characteristics in terms of voltage and current management and response to coupling variations.

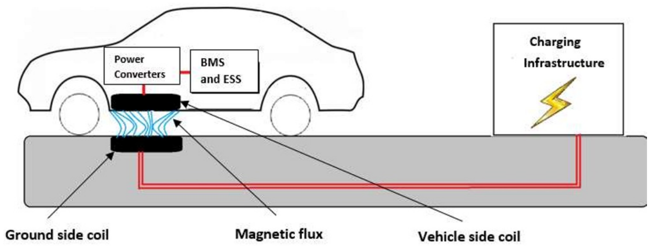

Fig. 1. Wireless EV charger.

2.1 SS topology

In this configuration, a compensation capacitor is placed in series with each coil, forming a resonant circuit at the operating frequency as shown in Fig. 2 [7]. The SS topology offers high efficiency and stable voltage regulation, but is sensitive to coupling and load variations. It is particularly suited to high-power applications where minimising losses is critical.

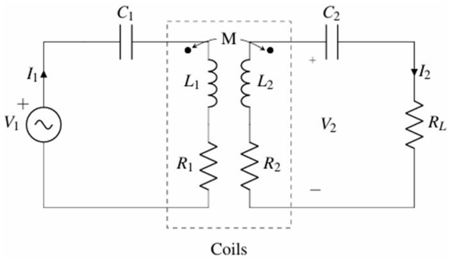

Fig. 2. SS topology.

The expression of compensation capacities is given by:

$$\omega_0 = \frac{1}{\sqrt{L_1 C_1}} = \frac{1}{\sqrt{L_2 C_2}} = 2\pi f_0 \quad (1)$$

Where:

L_1 is the primary side coil,

L_2 is the secondary side coil,

$f_0 = 85kHz$ is the resonance frequency as recommended by the SAE J2954 standard.

2.2 SP topology

This architecture uses series compensation on the primary side and parallel compensation on the secondary side as shown in Fig. 3 [8]. It reduces the voltage stress on receiver-side components, making it attractive for systems requiring galvanic isolation. However, its design complexity and sensitivity to misalignment can limit its performance under certain conditions.

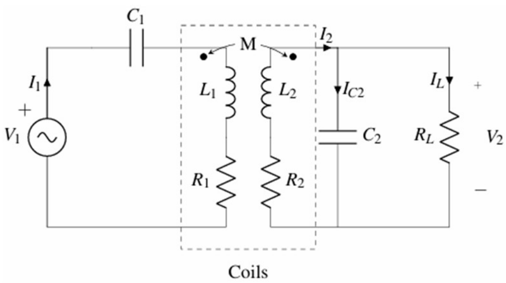

Fig. 3. SP topology.

The expression of compensation capacities is given by:

$$C_1 = \frac{L_2^2 C_2}{L_1 L_2 - M^2} \quad (2)$$

Where:

M is the mutual inductance between ground side and vehicle side coils.

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2.3 PS topology

The opposite of the SP, this configuration places a capacitor in parallel on the primary and in series on the secondary as shown in Fig. 4 [9]. It provides greater output current stability, which is useful for constant current loads, but can lead to increased losses if the coupling is incorrect.

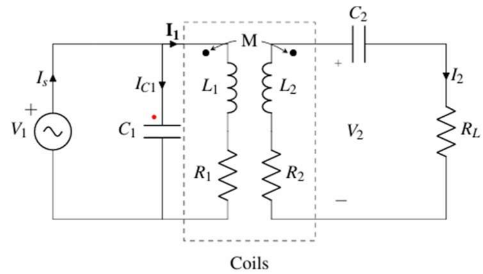

Fig. 4. PS topology.

The expression of compensation capacities is given by:

$$C_1 = \frac{L_2 C_2}{L_1 + \frac{M^4}{L_1 L_2 C_2 R_L^2}} \tag{3}$$

Where:
R_L is the load resistance.

2.4 PP topology

With parallel compensation on both sides, this topology offers good tolerance to load variations, but suffers from reduced efficiency due to the higher circulating currents [10]. It is generally less used in high-power applications because of its increased losses. Fig. 5 shows this type of compensation topology.

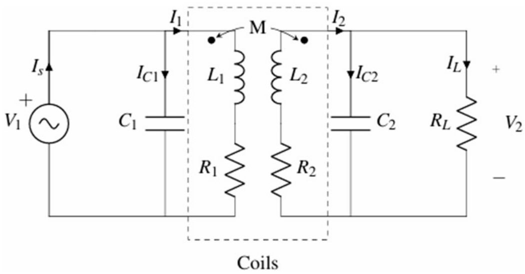

Fig. 5. PS topology.

The expression of compensation capacities is given by:

$$C_1 = \frac{C_2 L_2^2 (L_1 L_2 - M^2)}{(L_1 L_2 - M^2) + \frac{M^4 R_L^2 C_2}{L_2}} \tag{4}$$

3 Modelling and simulation methodology

The choice between these topologies depends on specific system requirements, including power level, allowable misalignment range and component constraints. The following section details the modelling and methodology used to compare their performance quantitatively.
To analyse the performance of the different compensation topologies, we have developed equivalent models based on the theory of magnetically coupled circuits. Each configuration (SS, SP, PS, PP) has been modelled considering:

- Coupled coil parameters:
  - ✓ Self-inductances (L_1, L_2)
  - ✓ Coupling coefficient (k)
  - ✓ Parasitic resistances (R_1, R_2)
- Compensation networks:
  - ✓ Resonance capacitors (C_1, C_2)
  - ✓ Common resonance frequency (f_0 = 85 kHz)
- Equivalent load:
  - ✓ Load resistance (R_l) representing the battery system R_L=15 Ohm
  - ✓ Rated output voltage (400 V for EV applications)

Fig. 6 illustrates the simplified equivalent circuit used to simulate and compare the performance of different compensation topologies in a wireless charging system. Although this figure specifically presents the SS topology as a reference, the model is designed to be modular, allowing the compensation components to be easily replaced in order to evaluate other configurations (SP, PS, or PP).

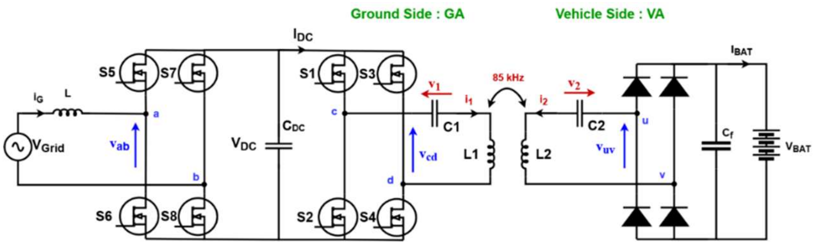

Fig. 6. WPT modular equivalent circuit for comparative analysis of compensation topologies (example: SS).

Fig.6 provides a reproducible framework for testing any compensation topology experimentally or by simulation, maintaining identical initial conditions (same coils, frequencies and load). This allows an objective comparison of the advantages/disadvantages of each approach.

4 Simulation results and discussion

To evaluate the performance and dynamic behaviour of the different compensation topologies used in WPT systems, a set of simulations was carried out using MATLAB/Simulink. The objective is to compare the topologies in terms of efficiency, voltage and current profiles, and the quality of power transfer under various load and alignment conditions.

The studied configurations include SS, SP, PS, and PP topologies. Each topology was modelled using equivalent circuit representations incorporating realistic component values, magnetic coupling effects, and load characteristics corresponding to an EV battery.

All simulations were performed under identical operating conditions: the resonant frequency was tuned to 85 kHz, the input DC voltage was set to 400 V, and the coupling coefficient varied between 0.2 and 0.5 to emulate different misalignment scenarios. The load resistance was selected to reflect a typical EV battery charging scenario. The following subsections present and compare the key performance indicators of each topology.

The simulation parameters are given in Table 1:

Table 1. Simulation parameters

Designation	**Value**
DC bus voltage	400 V
Self-inductance of the ground side coil	419 µH
Self-inductance of the vehicle side coil	119 µH
Mutual inductance M	23 µH
C1 (SS)	9.5 nF
C2 (SS)	40 nF
C3 (SP)	25.5 nF
C4 (SP)	47 nF
C5 (PS)	1.56 pF
C6 (PS)	50 nF
C7 (PP)	50 nF
C8 (PP)	100 nF
Output Filter capacitor Cf	1.5 mF
Resonance frequency f	85 KHz

Before beginning the evaluation and comparison of the different compensation topologies used in the WPT system, it is essential to present the fundamental characteristic quantities of this system. The following figures illustrate the time profiles of the voltage and current on the primary side, as well as the signals observed on the secondary side, in particular the voltage applied to the load and the load current. The simulation results provide crucial insights into the WPT system's baseline performance, serving as a foundation for comparing different compensation topologies. Fig. 7 specifically examines the system's dynamic behaviour during battery charging in current regulation mode, where a PI controller adjusts the phase shift of the HF inverter in the primary-side to track a predefined current reference that meets battery specifications. The results demonstrate excellent tracking performance, with the load current closely following its reference (showing less than 1% steady-state error), fast dynamic response to changes, and effective rejection of operational disturbances, thereby confirming the controller's ability to maintain stable charging conditions under transient operations while establishing important benchmarks for subsequent topology comparisons. Fig. 8 shows the corresponding ground side power delivered by the grid to the WPT charger.

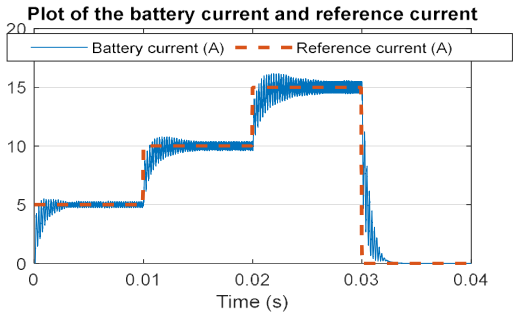

Fig. 7. Battery current in tracking test with its reference.

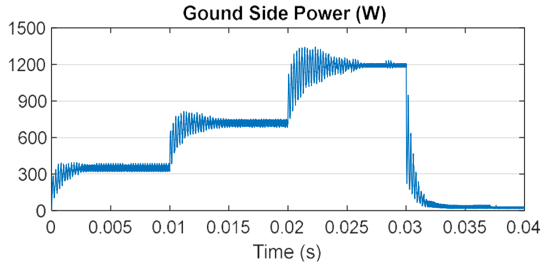

Fig. 8. The corresponding input power or ground side power.

Fig. 9 shows the power outputs obtained at the load for different compensation topologies of the WPT system. These results make it possible to assess the impact of each configuration on energy transfer. It can be seen that the SS topology delivers a power of around 890 W, while the SP reaches 875 W, indicating relatively similar performance. These results reveal significant differences in power transfer capabilities between compensation topologies. While the SS configuration delivered 890 W, topologies incorporating parallel compensation demonstrated superior performance: the PS reached 1140 W and PP achieved 1135 W. These findings suggest that parallel compensation at either primary or secondary side enhances power transfer under specific operating conditions, particularly with fixed resistive loads and consistent magnetic coupling. Fig. 10 presents detailed current and voltage measurements that explain these power variations. The SS topology produced 7.65 A at 115 V, while the SP configuration showed slightly higher values (7.85 A at 117 V), corresponding to their similar power outputs (890 W and 875 W respectively). More notably, the PS and PP configurations generated significantly higher currents (8.70 A) and voltages (up to 122 V), enabling their superior power transfer exceeding 1100 W. These results confirm that parallel compensation improves power transfer. The increased current and voltage levels observed in PS and PP topologies demonstrate their ability to maintain higher power.

Table 2 summarises the advantages and disadvantages of each topology:

- The SS topology offers the best efficiency (93.5%) and excellent voltage regulation, but is more sensitive to coupling variations.
- The SP topology is a good compromise, reducing switch stress while maintaining efficiency above 90%.
- The PS and PP configurations, although stable in current and voltage, suffer from reduced efficiency under misalignment conditions.

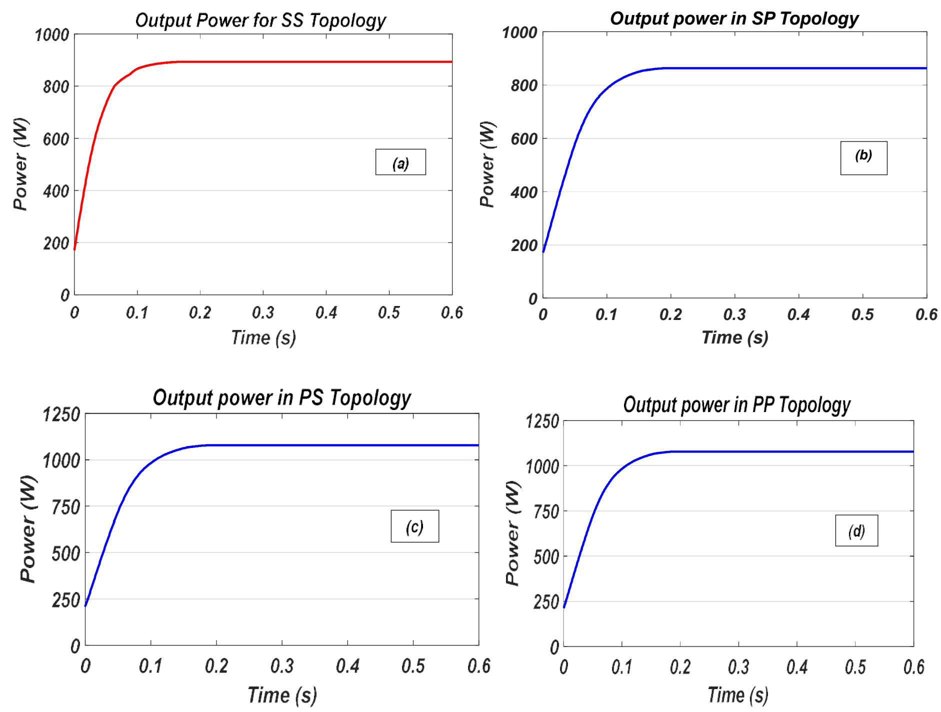

Fig. 9. Output powers in different topologies: SS (a), SP (b), PS (c), and PP (d)

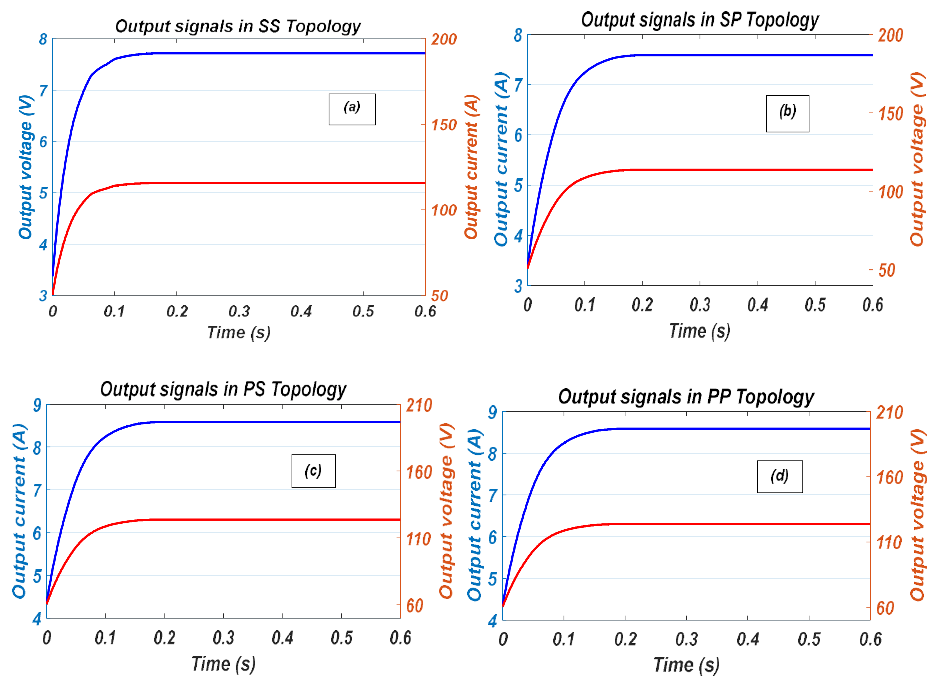

Fig. 10. Output voltage and current in different topologies: SS (a), SP (b), PS (c), and PP (d)

Table 2. Comparing performance of compensation topologies

Topology	Efficiency	Advantages	Disadvantages
SS	93.5%	High efficiency, precise regulation	Sensitive to coupling
SP	90%	Reduced stress on switches	Control complexity
SP	84%	Stable output current	High losses under misalignment
PP	82%	Good load tolerance	Low efficiency

5 Conclusion and perspectives

Our comprehensive study comparing wireless charging compensation topologies (SS, SP, PS, PP) revealed distinct performance trade-offs through MATLAB/Simulink simulations, showing that while the SS configuration achieves optimal efficiency 93.5% with precise voltage regulation, it suffers from misalignment sensitivity; the SP topology offers better robustness to positional variations while reducing switch stress, and the PS/PP configurations provide excellent current stability but with higher losses under misalignment. These findings provide clear implementation guidelines: SS for fixed charging stations with guaranteed alignment, SP for dynamic applications with potential misalignment, and PS/PP for current-sensitive systems where stability outweighs efficiency concerns. Future work should focus on experimental validation using a test bench to verify real-world performance, particularly during dynamic charging scenarios, along with exploring hybrid topologies that combine the strengths of different configurations. Also, the exploration of Artificial intelligence (AI) tools to find the best configuration from the desired performance of the WPT system.

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