Optimization of Impedance Matching in Wireless Power Transfer Using Genetic Algorithm-Driven Compensation Topologies

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ABSTRACT

Wireless Power Transfer (WPT) devices to transmit energy without physical touch in a variety of applications has drawn a lot of attention. In these systems, choosing appropriate compensation topologies and making sure the transmitter and receiver have the right impedance matching are crucial to achieving high transfer efficiency. In order to comprehend their impact on system stability and power transfer efficiency, this study examines the performance of series, parallel, and hybrid compensation topologies. Electromagnetic interactions are modeled and system behavior under various loading and misalignment circumstances is assessed using Finite Element Method (FEM) simulations. To get efficient impedance matching and increased overall efficiency, a Genetic Algorithm (GA) is also used to optimize important parameters, such as operating frequency and compensating capacitances. The findings demonstrate the performance trade-offs between different compensation topologies and offer precise recommendations for choosing the best configurations in real-world WPT systems. The study shows that the design process is much improved by integrating evolutionary optimization with FEM-based analysis, allowing for more dependable, effective, and flexible wireless power transfer systems.

Keywords: Compensation topologies, genetic algorithm, impedance matching, wireless power transfer (WPT)

INTRODUCTION

From consumer electronics and biomedical implants to electric cars and industrial automation, Wireless Power Transfer (WPT) has become a game-changing technology that makes it possible to distribute energy efficiently and contactless in a variety of applications [1]. The growing need for dependable, environmentally friendly, and intuitive energy transfer methods that reduce reliance on wired connections while enhancing mobility and system flexibility is what spurred the development of WPT systems [2]. The development of WPT during the last century, starting with Nikola Tesla's groundbreaking experiments with resonant wireless energy transfer in GHz-scale power delivery, highlights the significant influence of scientific discoveries on the development of contemporary energy technologies [3]. However, it is still difficult to achieve high efficiency, robustness, and flexibility in WPT, mainly because of power electronics design restrictions, frequency detuning from coil misalignment, and source and load impedance mismatching [4].

The creation of compensation networks, also known as compensation topologies, which are used to reduce reactive power flow, accomplish impedance matching, and optimize power transfer capability, is a basic prerequisite for attaining effective WPT. Series-Series (SS), Series-Parallel (SP), Parallel-Series (PS), Parallel-Parallel (PP), and hybrid LCC or LLC topologies are examples of compensation networks that provide designers the ability to customize system behavior for certain applications [5]. The quality factor (Q), resonance stability, efficiency, and resistance to load change or misalignment are all impacted by these topologies [6]. For instance, the SS topology has efficiency loss under fluctuating loads while being extensively used and reasonably simple for low-power applications.

Accurate impedance matching is essential for reducing power losses and electromagnetic interference (EMI) due to the expansion of the design space brought about by the introduction of MHz and GHz WPT, which are supported by new semiconductor technologies like silicon carbide (SiC) and gallium nitride (GaN) devices [7]. Additionally, recent research emphasizes how important compensation is to guaranteeing adherence to global safety and electromagnetic interference regulations, particularly in high-frequency WPT used for consumer and medicinal applications [8]. Therefore, it is impossible to separate a WPT system's compensatory topology design from its performance.

Even though WPT system compensation design has advanced significantly, there are still a number of unanswered questions. First, despite the large number of comparative studies of compensation topologies, only a small number of this research incorporate systematic optimization and electromagnetic analysis [9]. The dynamic aspect of misalignment, load fluctuation, and frequency detuning that define real-world WPT applications is ignored in the majority of current publications that examine compensation topologies under static conditions [10]. Second, the co-optimization of compensation parameters has not received enough attention when GA and other optimization techniques are used in WPT, and they are frequently restricted to coil shape or operating frequency [11]. Third, while being extensively employed for coil and magnetic field simulations, FEM analysis has not yet reached its full potential in terms of directing compensation design [12]. These discrepancies highlight the necessity of integrated frameworks that combine impedance matching, GA-based optimization, compensation topology analysis, and FEM-based modeling into a cohesive process.

This study's contribution is a thorough examination of compensation topologies for impedance matching in WPT systems, with a focus on combining electromagnetic modeling and optimization strategies. This work aims to establish design principles that can direct the development of next-generation WPT systems by methodically comparing SS, SP, PS, PP, LCC, and LLC topologies under various load and misalignment conditions, and by optimizing and validating these configurations using GA and FEM [13]. A paradigm that not only increases robustness and efficiency but also provides useful insights into weighing design trade-offs in real-world applications is the anticipated result.

Analyzing Methodology and Implementation of Compensation Topologies

Wireless Power Transfer (WPT) is an emerging technology that facilitates the transmission of electrical energy from a source to a load without direct electrical contacts, thereby eliminating the constraints of conventional wired systems. The underlying principles of WPT are primarily based on electromagnetic induction, resonant inductive coupling, capacitive coupling, or far-field techniques such as microwave and radio frequency transmission. A typical WPT architecture comprises a transmitting unit that converts input electrical energy into high-frequency electromagnetic fields, and a receiving unit that captures these fields and reconverts them into usable electrical power. This technology offers significant advantages, including enhanced system flexibility, improved safety by reducing exposed conductors, and the capability to power devices in inaccessible or dynamic environments. Recent advancements in high-frequency power electronics, magnetic resonance optimization, and adaptive control strategies have significantly improved the efficiency and range of WPT systems.

Impedance matching plays a critical role in Wireless Power Transfer (WPT) systems, as it directly influences the efficiency of power transmission between the transmitter and receiver. In a typical WPT setup, the transmitting coil and the receiving coil form a coupled resonant system, where maximum power transfer occurs when the source impedance is equal to the complex conjugate of the load impedance, in accordance with the maximum power transfer theorem. Any mismatch between these impedances leads to reflected power, reduced coupling efficiency, and lower overall system performance. Proper impedance matching not only enhances energy transfer efficiency but also improves system stability, reduces voltage stress on circuit components, and minimizes electromagnetic interference (EMI). Moreover, in practical WPT applications where coil alignment, load conditions, or operating distances may vary, adaptive or dynamic impedance matching techniques are increasingly used to sustain optimal performance under changing conditions. Thus, impedance matching is a fundamental design consideration for achieving high efficiency and reliability in modern WPT systems.

In Wireless Power Transfer (WPT) systems, compensation topologies are employed to achieve impedance matching between the transmitter and receiver circuits, thereby ensuring efficient power transfer at the operating frequency. Since the inductive coils used in WPT introduce significant reactive components, direct power transfer without compensation results in poor efficiency due to reactive power losses. Compensation networks, composed of appropriately placed capacitors and inductors, cancel out the reactive components and adjust the system’s input and output impedances to satisfy the maximum power transfer condition. As shown in figure 1 the most commonly adopted topologies are Series (S), Parallel (P), Series-Series (SS), Series-Parallel (SP), Parallel-Series (PS), and Parallel-Parallel (PP) configurations. By selecting an appropriate compensation network, designers can not only achieve precise impedance matching but also optimize system performance in terms of power handling capability, operational stability, and electromagnetic compatibility.

Using FEM data in each topology: (A) Series–Series (SS): Series caps null coil reactance so both tanks are resonant

$$C1s = 1 / (\omega02 * L1)$$

$$C2s = 1 / (\omega02 * L2)$$

$$Rref = ((\omega0 * M)2) / RL, eff$$

$$RL, eff = RL + R2(\omega0)$$

Condition: $R_1(\omega_0) + R_{ref} \approx R_s$

(B) Series–Parallel (SP): T_x series resonance, R_x parallel resonance.

$$C1s = 1 / (\omega02 * L1)$$

$$Im\{ Z2(\omega0) \,||\, (RL + j\omega0L2 + R2(\omega0)) \} \approx 0$$

(C) Parallel–Series (PS): R_x series resonance, T_x parallel compensation.

$$C2s = 1 / (\omega02 * L2)$$

Choose C1p such that: $Im\{Zin(\omega0;\ C1p)\} = 0, Re\{Zin\} \approx Rs$

(D) Parallel–Parallel (PP): Both sides parallel resonance.

Choose C_{1p}, C_{2p} such that: $Im\{Z11eq(\omega0)\} = 0$

$$Im\{Z22eq(\omega0)\} = 0$$

$$Re\{Zin\} \approx Rs$$

(E) LCC: T_x behaves like current source.

$$Cs \approx 1 / (\omega02 * L1)$$

$$Xp + Xc = 0$$

$$Re\{Zin(\omega0;\ Lp, Cp, Cs)\} = Rs$$

(F) LCC–LCC (both sides): Robust load-independent matching.
Choose C_{s1}, L_{p1}, C_{p1} and C_{s2}, L_{p2}, C_{p2} such that:

$$\mathbf{Im\{Zin(\omega0)\} = 0}$$
$$\mathbf{Im\{Zout(\omega0)\} = 0}$$
$$\mathbf{Re\{Zin\} = Rs}$$

Finite Element Method (FEM) models provide accurate electromagnetic parameters—self/mutual inductances (L1, L2, M), parasitic resistances (R1, R2), stray capacitances, and frequency-dependent coupling coefficients. These parameters are used to construct equivalent circuit models for each compensation topology. FEM also enables parametric sweeps over coil geometry, spacing, alignment, and materials, generating the dataset for optimization.

Multi-objective formulation: The optimization problem is expressed as:

$$\min F(\theta) = \{ f1(\theta), f2(\theta), f3(\theta), \ldots \}$$

Where design variables $\theta = \{C_{1s}, C_{2s}, C_{1p}, C_{2p}, L_p, \omega_0$, coil geometry$\}$ and

objectives include:
$f_1 = 1 - \eta(\theta)$ → maximize efficiency
$f_2 = |Z_{in}(\omega_0) - R_s|$ → ensure impedance match
$f_3 = V_{stress} / V_{rated}$ → minimize voltage stress
$f_4 = \Delta\eta(\text{misalign}, \Delta R_L)$ → improve robustness
f_5 = Q factor → control bandwidth

Pareto front via GA: A Genetic Algorithm explores the design space globally using crossover and mutation of circuit parameters (C_s, C_p, L_p, etc.), guided by FEM-calculated performance metrics. Instead of yielding one solution, GA produces a Pareto front: a set of non-dominated designs, where improving one objective would degrade another.

SS / SP / PS / PP: Pareto optimization balances efficiency vs. bandwidth, ensuring the chosen C and L values minimize detuning sensitivity under FEM-extracted parasitism.

LCC: GA selects L_p, C_p, and C_s to trade off load-independence vs. component stresses while preserving impedance match. LCC–LCC (both sides): Multi-objective GA ensures robustness across load variations and coil misalignments, making it ideal for EV charging and dynamic scenarios.

The Pareto front gives designers a map of optimal trade-offs, enabling them to select a solution that best fits system priorities whether maximum efficiency, minimal size, low stress, or robustness. Integrating FEM data ensures that the chosen compensation network is realistic, loss-aware, and manufacturable, while GA guarantees global exploration of the design space beyond local optima.

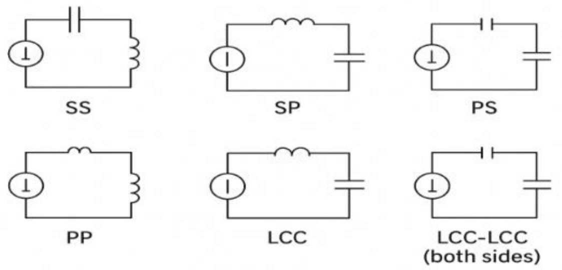
By integrating Pareto front optimization with Genetic Algorithms (GA) into FEM-based modeling of WPT compensation topologies, designers can simultaneously evaluate multiple conflicting objectives such as maximizing efficiency, ensuring impedance matching, minimizing voltage and current stress, and enhancing robustness against misalignment or load variations rather than focusing on a single criterion. This approach generates a set of non-dominated optimal solutions (Pareto front) that capture the trade-offs between performance metrics, enabling the selection of the most suitable design based on system requirements. Consequently, WPT systems employing SS, SP, PS, PP, LCC, or LCC–LCC compensation can be optimized for practical, loss-aware, and robust operation, leading to higher efficiency, reliability, and adaptability in real-world applications such as electric vehicle charging, biomedical implants, and industrial automation.

MEASUREMENT AND DISCUSSION

The efficiency of power transmission between the linked coils is affected by the equivalent input and output impedance of the resonant circuit, which is altered by each compensation network, including Series–Series (SS), Series–Parallel (SP), LCC, and LCC–LCC. Both the main and secondary sides of the SS architecture use series capacitors, which causes resonance when the capacitive reactance cancels out the coils' inductive reactance. This improves current flow but limits load adaptability. By adding a parallel capacitor at the receiver, the SP architecture strengthens impedance matching and voltage control under various load scenarios, increasing its robustness for real-world uses. This is further enhanced by the LCC–LCC arrangement, which offers symmetric compensation on both sides, enabling the system to achieve improved impedance matching over a larger range of coil separations and loads. Since appropriate impedance matching minimizes reflected power, lowers the reflection coefficient, and improves end-to-end transfer efficiency, the impedance relations obtained from these compensation topologies serve as the basis for an effective WPT system design overall.

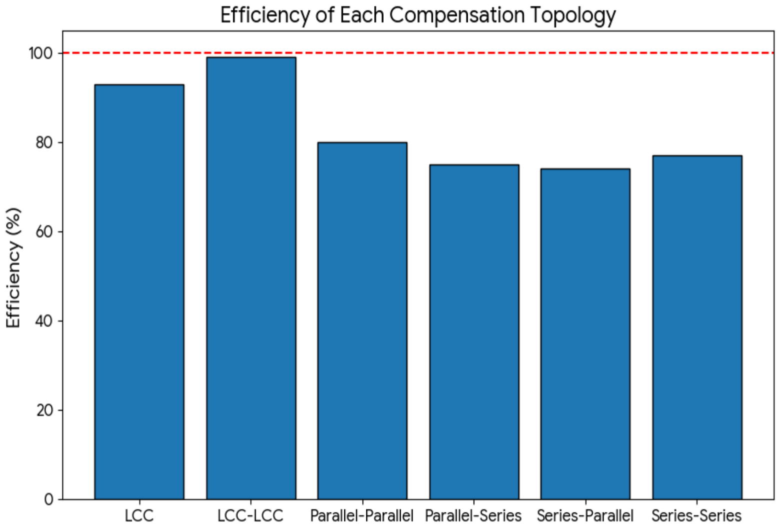
In wireless power transfer (WPT) systems, the figure 2 compares the distance performance of various compensating topologies. The Series-Series topology is the most appropriate for long-range power transfer among them, with a maximum distance of 0.25 meters. With around 0.20 m, Series-Parallel comes next, and Parallel-Series and LCC do mediocrely well at distances of roughly 0.18 m and 0.16 m, respectively. Compared to LCC-LCC, which displays the lowest value at 0.14 m, the Series-Series topology records 0.15 m, which is somewhat greater. Overall, the data shows that transfer distance is significantly influenced by the compensation topology selection, with Series-Series being the most efficient for longer ranges and LCC-based designs being better suited for applications requiring shorter distances.

Figure2. Bar chart distance analysis of each compensation topology



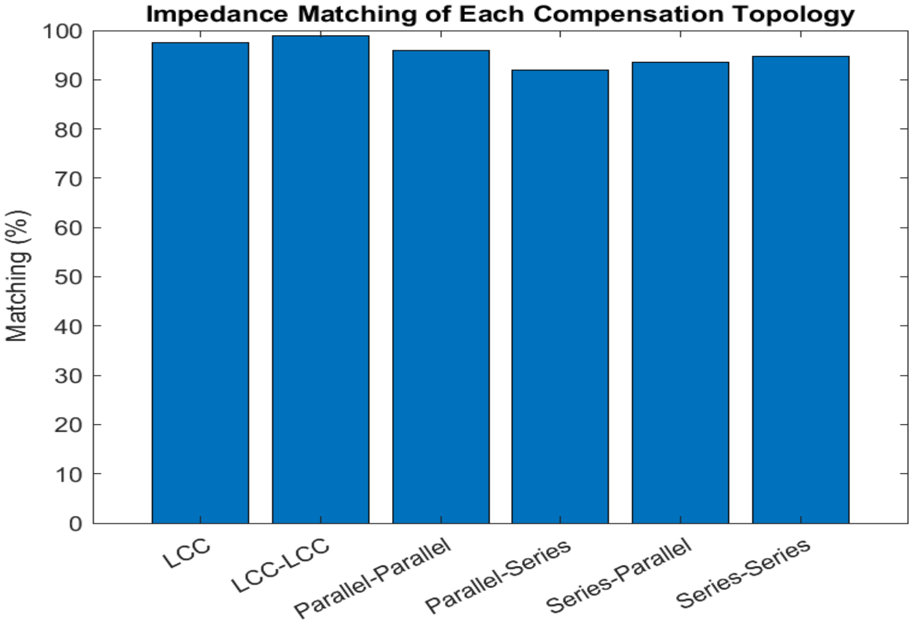
The figure 3 illustrates the effectiveness of various compensation topologies used in wireless power transfer systems. The LCC topology is a tempting choice since it demonstrates a comparatively high efficiency of about 93%. Conversely, topologies with efficiency ranging from 75% to 80% are achieved by Parallel-Parallel, Parallel-Series, Series-Parallel, and Series-Series. This comparison demonstrates how hybrid compensation networks, such as LCC-LCC, perform better than conventional series or parallel topologies, highlighting their significance in maximizing the efficiency of wireless energy transmission.

Figure3. Bar chart efficiency analysis of each compensation topology



While in figure 4 Parallel-Series and Series-Parallel perform marginally worse but still fall within a dependable range, Parallel-Parallel and Series-Series topologies also show high impedance matching above 90%. This comparison demonstrates that hybrid structures, such as LCC-LCC, are more successful in reaching near-ideal impedance matching, which is necessary to improve the efficiency of power transfer.

Figure4. Bar chart impedance analysis of each compensation topology



The trade-off between efficiency, impedance matching, and transfer distance for various compensation topologies in a wireless power transfer (WPT) system is depicted in the 3D Pareto front map figure 5 and table 1. With a near –optimal 98.99% impedance match and 97.89%efficiency, the LCC-LCC topology performs the best among all topologies, suggesting excellent loss minimization and resonance tuning. Whereas, 97.4% impedance match and 92.5% efficiency, the LCC topology. The Parallel-Parallel topology is a dependable substitute in situations requiring steady coupling since it has good impedance matching of 95.8% with 79.5% efficiency. The Series-Series design is appropriate for short-range transfers with relatively high coupling, as seen by its high impedance match of 94.7% and lower efficiency of 77.1%.

Figure5. 3D Pareto front map GA analysis of each compensation topology

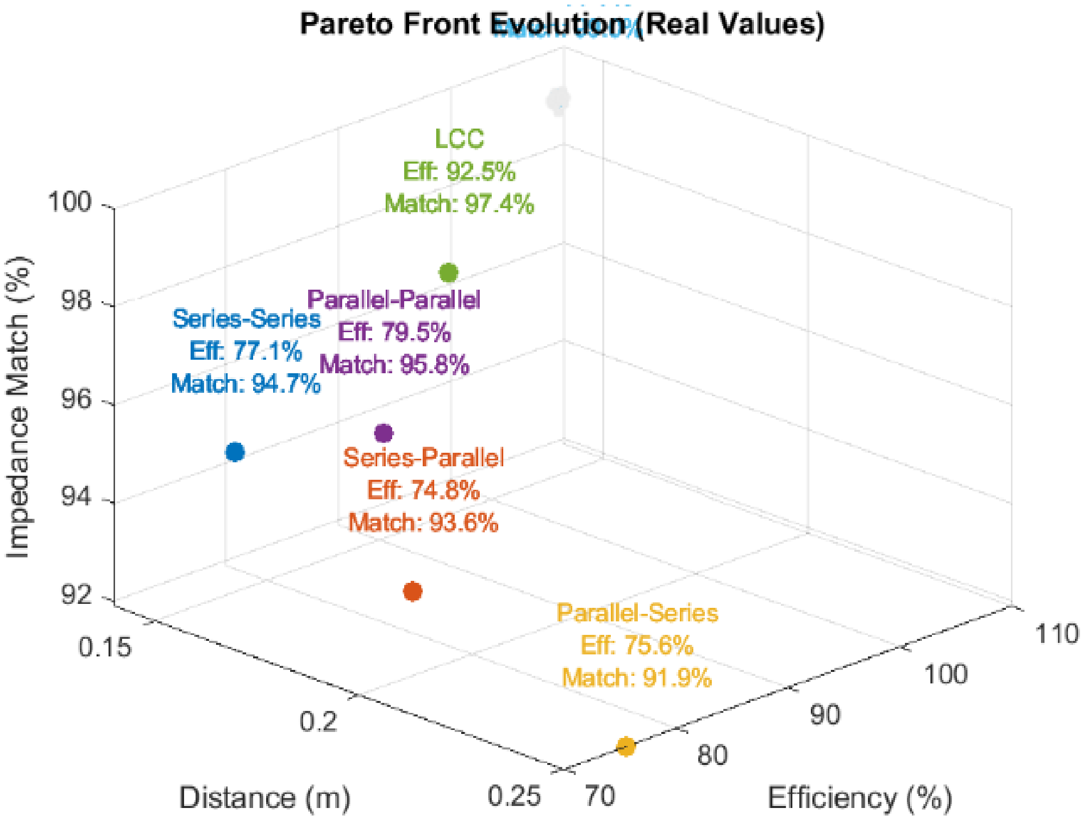


Table1: Resultant data of each compensation topology after optimizing by using GA for matching impedance with FEM in wireless power transfer (WPT)

Topology	Input Voltage (V_rms)	Input Current (A_rms)	Output Voltage (V_rms)	Output Current (A_rms)	Output Power (W)	Distance Between Coils (m, FEM-optimized)	Efficiency (%)	Impedance Matching (%)
SS	100	2.1	90	1.8	162	**0.15 m**	77.143	94.73
SP	100	2.0	88	1.7	149.6	**0.2 m**	74.8	93.61
PS	100	1.8	85	1.6	136	**0.25 m**	75.55	91.89
PP	100	2.2	92	1.9	174.8	**0.18 m**	79.45	95.83
LCC		1.9	95	1.85	175.75	**0.16 m**	92.5	97.43
LCC-LCC	100	1.7	98	1.9	186.2	**0.14 m**	**97.99**	**98.99**

CONCLUSION

This paper has shown that the selection of compensation topologies is a critical factor in maximizing Wireless Power Transfer (WPT) systems' resilience, stability, and efficiency. Topologies like LCC and LCC–LCC have been demonstrated to offer greater impedance matching, increased efficiency, and improved flexibility across a range of load circumstances in comparison to traditional SS, SP, PS, and PP configurations using FEM-based modeling and Genetic Algorithm (GA) optimization. The findings demonstrate that impedance matching is a key factor in maximizing power transmission, lowering reactive losses, and minimizing electromagnetic interference rather to just being a circuit-level modification. Applying these results to larger-scale applications, optimal impedance matching networks can be especially helpful for the Solar Power Satellites (SPS) idea, which involves the wireless transmission of gathered energy to Earth from vast orbiting solar arrays. Significant power losses, decreased beam directivity, and degraded system dependability can result from even small mismatches between the source and load impedances in SPS systems, which use microwave or laser beams to transmit power over vast distances. Therefore, a viable route to the realization of effective, scalable, and sustainable SPS designs is the combination of adaptive impedance matching with improved compensating topologies. This study shows that impedance-optimized compensation strategies may be the most viable and significant solution for the future of both soil-based WPT applications and space-based energy delivery through SPS by tackling the twin problems of high efficiency and robust matching.

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