Compensation Network Topologies for a Wireless Power Transfer in Electric Vehicle Charging: A Comprehensive Review

[1]Sangavi J, [2]Dr. Y. R. Manjunath

[1]Post Graduate Student, [2]Professor
[1]Power electronics, Dept of Electrical Engineering
[1]UVCE, Bengaluru, India

***Abstract*: Wireless power transfer (WPT) has emerged as a key enabler for electric vehicle (EV) charging due to its ability to provide safe, efficient, and user-friendly energy delivery. The efficiency and reliability of WPT systems depend strongly on the design of the compensation network, which ensures resonance, reduces reactive power, and enhances power transfer capability. Over the past decade, several compensation topologies—such as series–series (SS), series–parallel (SP), LCC, and hybrid structures—have been investigated to achieve high efficiency, improved misalignment tolerance, and robust voltage or current regulation. Despite considerable advancements, the selection of an appropriate compensation topology remains highly application-dependent, with trade-offs in terms of circuit complexity, control strategy, cost, and interoperability. This review paper provides a systematic discussion on the evolution of compensation topologies for EV wireless charging, highlighting their design principles, comparative performance, and suitability for different operating scenarios. The objective is to consolidate current knowledge and identify emerging directions that can support the deployment of next-generation wireless charging systems for electric mobility.**

I. INTRODUCTION

Electric vehicles (EVs) are gaining rapid global adoption, and the need for efficient, safe, and convenient charging solutions has led to increasing interest in wireless power transfer (WPT) systems [1], [2]. Compared to conventional plug-in charging, WPT offers unique advantages such as user convenience, reduced wear of connectors, and the possibility of dynamic charging while vehicles are in motion [3], [4]. A critical factor influencing the performance of WPT systems is the compensation network, which is employed to achieve resonance between the transmitter and receiver coils, thereby maximizing efficiency and minimizing reactive power flow [5]. Numerous compensation topologies have been developed, including the series–series (SS), series–parallel (SP), LCC, and double-sided LCC configurations [6], [7]. Each topology presents specific characteristics in terms of voltage/current gain, zero-phase angle operation, soft-switching capability, and tolerance to load variations [8]–[10]. For example, SS networks are simple and widely adopted but show limitations under misalignment and variable load, while LCC networks enable constant-current or constant-voltage output with greater design flexibility [11], [12]. Hybrid compensation structures have further been introduced to combine the strengths of different topologies, enabling wide operating ranges and improved stability [13], [14]. Recent works also emphasize the importance of optimization in compensation design. Evolutionary algorithms, multi-objective optimization, and analytical models have been applied to fine-tune circuit parameters, achieving improvements in transfer efficiency and reducing circulating reactive power [15], [16]. Despite these advances, challenges remain in scaling WPT compensation networks for high-power EV applications, ensuring interoperability across different vehicle platforms, and reducing implementation cost without sacrificing performance [17], [18].

This review focuses on the design principles, comparative performance, and latest advancements in compensation networks for EV wireless charging. By consolidating recent literature, it aims to provide researchers and engineers with practical guidance for selecting, optimizing, and innovating compensation topologies suitable for next-generation charging infrastructures [19], [20]. To provide a comprehensive perspective, this review is structured as follows. Section 1 introduces the fundamentals of wireless power transfer for EVs, highlighting the role of resonance, coil design, and compensation in achieving efficient energy transfer. Section 2 discusses classical compensation topologies, including Series–Series, Series–Parallel, Parallel–Parallel, and LCC configurations, analyzing their operating principles, advantages, and limitations. Section 3 extends the discussion to advanced and hybrid topologies, such as LCC-S, LCC-P, LCC-LCC, and multi-coil systems, with emphasis on their suitability for high-power and dynamic charging scenarios. Section 4 focuses on design methodologies and optimization strategies, covering analytical modeling, quality factor considerations, and modern optimization techniques. Section 5 addresses practical challenges, including coil misalignment, parasitic effects, thermal management, interoperability, and compliance with standards. Section 6 highlights recent trends and future research directions, including high-power charging, dynamic WPT, superconducting coils, and integration with smart grids. Finally, Section 7 concludes the review by summarizing key insights and emphasizing the importance of tailored compensation design for the widespread adoption of EV wireless charging.

II. FUNDAMENTALS OF WIRELESS POWER TRANSFER OF EV

Wireless power transfer (WPT) for electric vehicles is primarily based on inductive power transfer (IPT), which uses magnetic fields to transfer energy between two coils separated by an air gap [1], [2]. When the transmitter coil (Tx) is excited by an alternating current, it generates a time-varying magnetic flux that induces a voltage in the receiver coil (Rx) according to Faraday's law. The efficiency of this coupling depends strongly on the mutual inductance (M) between the coils, which is a function of geometry, coil alignment, distance, and the magnetic properties of materials used in the coupler [3], [4]. A major challenge in IPT systems is the inherently low coupling coefficient (k) due to the large air gap and inevitable misalignments in EV applications [5]. To mitigate this, the coils are designed to operate at resonance, where the natural frequency of the transmitter and receiver circuits match, maximizing energy transfer and minimizing reactive power flow [6]. The resonant frequency is given by

$$\omega_0 = \frac{1}{\sqrt{LC}}$$

where L and C represent the inductance and compensation capacitance of the network, respectively. Resonance ensures that even weakly coupled coils can transfer power with high efficiency [7].

The role of the compensation network is crucial in this process. Without compensation, the transmitter would have to supply large reactive currents to drive the magnetic field, leading to poor efficiency and higher losses. By carefully choosing appropriate compensation elements (capacitors and sometimes additional inductors), the system cancels reactive power, improves power factor, and boosts transfer efficiency [8], [9]. Different compensation topologies, such as series–series (SS), series–parallel (SP), and LCC, modify the impedance seen by the source and load, directly impacting current distribution, voltage gain, and tolerance to load or misalignment [10]. Another important aspect is the quality factor (Q) of the coils, defined as

$$Q = \frac{\omega L}{R}$$

where R is the coil resistance. Higher Q-factors indicate lower losses and sharper resonance characteristics, which are desirable for efficient power transfer [11]. However, extremely high Q values may lead to sensitivity against misalignment and frequency drift, requiring careful balance between coil design and compensation network tuning [12]. In addition to coil design and compensation, control strategies also influence the fundamental operation of WPT systems. Techniques such as frequency tuning, phase shift control, and voltage/current regulation are often employed to maintain resonance and deliver stable power under varying load and alignment conditions [13], [14]. Overall, the fundamentals of WPT establish that efficient power delivery relies on three interconnected aspects:

(i) coil geometry and mutual inductance,

(ii) resonance through compensation networks, and

(iii) control and regulation strategies. Understanding these basics is essential before comparing the merits of different compensation topologies in EV applications [15].

III. CLASSICAL COMPENSATION TOPOLOGY

Series-Series (SS) Compensation Topology: The Series–Series (SS) compensation topology is one of the simplest and most widely adopted structures in wireless power transfer (WPT) systems, particularly for electric vehicle (EV) charging applications. In this topology, both the transmitter (Tx) and receiver (Rx) coils are connected in series with compensation capacitors, tuned to resonate at the system's operating frequency. The primary purpose of the SS configuration is to achieve resonance on both sides of the power link, which minimizes reactive power circulation and maximizes active power transfer efficiency [8]. A key advantage of the SS topology is its relative simplicity of design and control, making it a popular choice in early WPT implementations. The series capacitors provide impedance matching such that the overall input impedance seen by the power source remains resistive at resonance, facilitating efficient power transfer without complex active control schemes [9]. Furthermore, the SS topology tends to naturally offer constant-current behavior, which suits EV battery charging requirements. However, this configuration is not without its limitations. The most critical drawback is its high sensitivity to coil misalignment and load variations. Since both coils are in series with fixed capacitors, any deviation in mutual inductance caused by vehicle mispositioning directly impacts the resonant condition, causing a drop in power transfer efficiency and possible voltage/current stress [10]. Additionally, as the coupling coefficient (kkk) decreases (common in practical applications with large air gaps), the SS topology struggles to maintain stable operation without sacrificing performance. Despite these challenges, SS remains widely used in commercial and experimental EV wireless chargers, especially when cost, simplicity, and moderate power ratings are prioritized [11]. Advances in control strategies and supplementary tuning mechanisms (such as dynamic frequency adjustment) have been proposed to partially mitigate its sensitivity issues, though they do not fully overcome the inherent limitations of the SS approach [12].

Series-Parallel (SP) Compensation Topology: The Series–Parallel (SP) compensation topology is another commonly explored configuration in wireless power transfer (WPT) systems for electric vehicle (EV) charging. In this topology, the transmitter (Tx) coil is connected in series with a compensation capacitor, while the receiver (Rx) coil is connected in parallel with its own compensation capacitor. This arrangement provides a different way of impedance matching compared to the Series–Series (SS) topology and offers some unique advantages [9]. One of the main benefits of the SP topology is its ability to support higher current levels at the receiver side for a given input voltage. This makes it particularly suitable for applications requiring low-voltage and high-current outputs, which is beneficial when directly interfacing with battery management systems in EVs [10]. Additionally, the parallel connection at the receiver helps reduce the voltage across the Rx coil, allowing the design to manage voltage stress more effectively under certain operating conditions. However, similar to the SS topology, the SP topology is highly sensitive to changes in coupling coefficient and load variations. As the coupling coefficient decreases due to misalignment or variations in the air gap, the resonant condition is disturbed, causing significant performance degradation [8]. Furthermore, the SP topology typically has a more complicated impedance profile compared to SS, making its control more challenging, especially when wide load or alignment tolerances are required [11].

To overcome some of these limitations, advanced control strategies such as frequency tuning and adaptive impedance matching have been proposed in recent literature [13]. Nonetheless, the SP topology remains less popular than SS in practical EV WPT implementations, primarily due to its relatively higher design complexity and control requirements [12]. Despite that, it is often considered in specialized applications where current handling or voltage regulation at the receiver is of higher priority [10].

Parallel-Parallel (PP) Compensation Topology: The Parallel–Parallel (PP) compensation topology is less commonly used in wireless power transfer (WPT) systems for electric vehicle (EV) charging, but it presents specific applications where its characteristics are advantageous. In this topology, both the transmitter (Tx) and receiver (Rx) coils are connected in parallel with their respective compensation capacitors. This results in a fundamentally different impedance behaviour compared to the Series–Series (SS) and Series–Parallel (SP) configurations [10]. One key advantage of the PP topology is its ability to offer lower circulating current in the compensation network, which reduces conduction losses and can improve overall efficiency in some designs. The parallel arrangement allows for greater flexibility in matching the system impedance to the source and load, especially in scenarios where the load varies significantly [10]. Additionally, this topology can offer better tolerance to load variations because the output voltage tends to remain more stable as the load changes.

However, the PP topology also suffers from several critical drawbacks. Its complexity in design and control is significantly higher than that of SS or SP configurations. Specifically, achieving resonance and maintaining a stable operating point under varying coupling and load conditions is more difficult, often requiring sophisticated control algorithms [12]. Furthermore, the parallel nature of both sides increases the risk of circulating reactive currents if not properly tuned, which can lead to additional power losses and reduced efficiency [8]. Due to these limitations, the PP topology is rarely used in commercial EV wireless chargers. It is generally considered for specialized applications where precise load regulation and system flexibility are required, such as in dynamic wireless power transfer (DWPT) systems or applications with highly variable coupling [10], [12]. Recent research continues to investigate adaptive compensation schemes and hybrid combinations involving PP elements to improve robustness and efficiency, though the majority of practical implementations still favor SS and LCC-based topologies [15].

LCC and Double-Sided LCC Compensation Topology: The LCC (Inductor-Capacitor-Capacitor) compensation topology, including its double-sided variant, is one of the most advanced and widely researched configurations in wireless power transfer (WPT) systems for electric vehicle (EV) charging. In the LCC topology, the transmitter (Tx) side is typically compensated using a series inductor and two capacitors arranged in an LCC structure, while the receiver (Rx) side can be compensated using either a series or parallel capacitor [11]. One of the primary advantages of the LCC topology is its ability to provide constant current or constant voltage output characteristics, which is highly desirable for EV battery charging applications. This enables the system to maintain stable power delivery across a range of coupling coefficients and load variations without the need for complex active control strategies [12]. The double-sided LCC configuration extends this advantage by applying the same LCC structure to both the Tx and Rx sides, further improving the system's capability to maintain resonance and power stability even under misalignment and dynamic conditions [11], [12].

Additionally, the LCC topology offers improved soft-switching capability, which helps in achieving Zero Voltage Switching (ZVS) over a wide operating range. This significantly reduces switching losses, improving overall system efficiency and thermal management [12]. Compared to SS and SP topologies, the LCC is much less sensitive to changes in coupling coefficient and load, making it ideal for practical EV wireless charging where parking alignment can vary significantly [11]. However, these benefits come at the cost of increased circuit complexity and additional components, which can increase system size, weight, and cost [13]. Careful design and optimization of the inductance and capacitance values are required to balance efficiency, cost, and performance [14]. Moreover, although the LCC topology improves system stability, control strategies such as frequency tuning or adaptive compensation may still be necessary to maintain optimal performance across a wide range of operating conditions [15]. Due to its robustness and adaptability, the LCC and double-sided LCC topologies are widely adopted in commercial and experimental EV wireless chargers and are considered the industry standard in many high-power applications [12], [13]. Recent research continues to explore further enhancements in topology design, dynamic operation, and integration with smart grid infrastructure [14].

Table 1: Comparison of Compensation Topologies for EV Wireless Charging

Topology	Affordability	Durability	Efficiency	Control Complexity	Sensitivity to Misalignment	Most Used In	Suitable for Vehicle Types
Series–Series (SS)	High	Moderate	Moderate	Low	High	Entry-level EVs, low-power applications	Urban EVs, short-range vehicles
Series–Parallel (SP)	Moderate	Moderate	High	Moderate	Moderate	Mid-range EVs, commercial applications	Urban and suburban EVs
Parallel–Parallel (PP)	Low	Low	Low	High	High	Specialized applications, experimental setups	Not commonly used in commercial EVs
LCC (Single-Sided)	Moderate	High	High	Moderate	Low	High-power EVs, commercial charging stations	Long-range EVs, commercial fleets
Double-Sided LCC	Low	High	Very High	High	Very Low	High-end EVs, dynamic wireless charging systems	Long-range EVs, dynamic charging scenarios

IV. ADVANCED AND HYBRID COMPENSATION NETWORKS

As the demand for higher efficiency, greater flexibility, and robustness in electric vehicle (EV) wireless power transfer (WPT) grows, researchers and engineers have increasingly focused on advanced and hybrid compensation topologies**.** These topologies aim to combine the strengths of classical configurations while addressing their inherent limitations, especially under variable coupling, load, and misalignment conditions.

Integrated Compensation Networks (LCC-S, LCC-P): Integrated compensation networks like LCC-S (LCC on Tx side and Series on Rx side) and LCC-P (LCC on Tx and Parallel on Rx) provide a more flexible way of controlling power flow and managing system stability compared to traditional SS or SP topologies [13]. These configurations offer the ability to control both the input impedance and the output power characteristics by proper tuning of inductance (L) and capacitance (C) values. Basic Operating Principle: For the LCC-S topology, the equivalent circuit model can be simplified as:

$$V_{in} = I_{in}\left(R_s + j\omega L_s + \frac{1}{jwC_s}\right)$$

- R_s, L_s, and C_s: Series components in the transmitter side
- The receiver side has a simple series compensation ensuring resonance.

This structure offers a better balance between load variations and coupling changes by adjusting the Tx-side parameters without active regulation [13].

Hybrid topologies (e.g., lcc-lcc, double-sided lc): The LCC-LCC topology applies the LCC compensation structure to both Tx and Rx sides. This significantly improves system stability under varying coupling conditions, enhances Zero Voltage Switching (ZVS) performance, and achieves constant current (CC) output [14]. Resonance Condition: At resonance, the reactive components cancel out, and the system achieves maximum power transfer when the following condition holds,

$$\omega_0 = \frac{1}{\sqrt{L_{eq} C_{eq}}}$$

Where L_{eq} and C_{eq} represent the equivalent inductance and capacitance of the entire system. This topology is especially useful in dynamic wireless charging scenarios, where the vehicle may move over the charging pad, resulting in fluctuating coupling coefficients [14].

Multi-coil and multi-bridge system: In higher-power applications and dynamic scenarios, multiple coils (both Tx and Rx) are deployed to create a wider charging area and better tolerance to vehicle positioning [16]. A typical multi-coil system connects several Tx coils in parallel or series, with each being individually compensated and driven. Example circuit configuration:

- Multiple Tx coils, each compensated by individual LC networks, connected to a common inverter.
- Rx coils are designed to form a modular receiver that can dynamically activate based on vehicle position.

The total mutual inductance M_{total} expressed as the sum of individual mutual inductances

$$M_{total} = \sum_{i=1}^{n} M_i$$

This enables adaptive power delivery depending on active coupling sections [16].

Dynamic WPT Compensation Strategies: Dynamic Wireless Power Transfer (DWPT) introduces further complexity as the mutual inductance and coupling coefficient *k* vary continuously as the vehicle moves over the charging path. To maintain resonance and high efficiency, advanced control techniques are necessary. Frequency Tuning Strategy: The system dynamically adjusts the operating frequency to maintain the resonant condition

$$f_{opt} = \frac{1}{2\pi\sqrt{L_{eq}(t) C_{eq}(t)}}$$

Where $L_{eq}(t)$ *and* $C_{eq}(t)$ vary based on position and alignment [17]. This strategy is simpler but less efficient compared to dynamic component switching or adaptive impedance matching.

V. DESIGN METHODOLOGY AND OPTIMIZATION

The performance of a wireless power transfer (WPT) system for electric vehicles (EVs) is strongly dependent on the proper design and optimization of the compensation network. While compensation topologies define the basic structure of the system, their effectiveness in real-world operation is governed by how accurately the network parameters (inductance, capacitance, and sometimes resistance) are chosen and tuned. Several design methodologies exist, ranging from analytical circuit modelling to computational optimization techniques.

Analytical Modelling and Resonant Condition: The first step in designing any compensation network is to satisfy the resonant condition of the system. For a simple series-compensated coil, the resonance frequency is given by:

$$\omega_0 = \frac{1}{\sqrt{LC}}$$

where L is the coil self-inductance and C is the compensation capacitance. At resonance, the reactive power cancels out, and the input impedance becomes purely resistive:

$$Z_{in}=R_{eq}$$

where R_{eq} is the equivalent reflected resistance from the load to the source. For LCC-based topologies, the design also ensures a zero phase angle (ZPA) condition at the input:

$$\angle Zin(\omega_0)\approx 0°$$

which enables high efficiency and soft-switching operation (ZVS/ZCS).

Q-Factor and Efficiency Considerations: The quality factor (Q) of the compensated network plays a critical role in efficiency and power transfer capability. For a series-compensated circuit:

$$Q = \frac{\omega_0 L}{R}$$

where R represents the coil resistance. High-Q values increase efficiency but also lead to narrow bandwidth, making the system more sensitive to frequency drift and misalignment. The link efficiency between Tx and Rx can be expressed as:

$$\eta = \frac{k^2 Q_{tx} Q_{rx}}{1 + k^2 Q_{tx} Q_{rx}}$$

where k is the coupling coefficient, and Q_{tx}, Q_{rx} are the quality factors of the transmitter and receiver coils.

Optimization Approaches: Analytical models are often limited when multiple objectives must be considered (e.g., efficiency, misalignment tolerance, voltage gain). To address this, several optimization approaches have been proposed

Analytical Optimization

- Closed-form equations to size compensation capacitors and inductors [18].
- Advantage: fast and intuitive.
- Limitation: less effective in multi-variable, real-world scenarios.

Evolutionary Algorithms (EAs)

- Genetic algorithms (GA), particle swarm optimization (PSO), and differential evolution are commonly applied to tune network parameters [19].
- Objective functions often maximize efficiency while minimizing circulating reactive power.

Multi-Objective Optimization

- Targets several goals simultaneously (e.g., efficiency, voltage/current stress, cost).
- Produces a Pareto front, allowing designers to select the best trade-off [19], [20].

Model-Based and Control-Oriented Design

- Incorporates misalignment scenarios, load variations, and grid-side constraints directly into the optimization model.
- Increasingly popular for high-power EV chargers [21].

Practical Design Example: Consider an SS-compensated EV charger operating at *f=85 kHz* with a transmitter coil inductance of $L_{tx}=150\,\mu H$. To achieve resonance:

$$C_{tx} = \frac{1}{\omega_0^2 L_{tx}} = \frac{1}{(2\pi \times 85 \times 10^3)^2 \cdot 150 \times 10^{-6}}$$

$$C_{tx} \approx 23nF$$

This analytical design provides the starting point, which can then be fine-tuned using optimization algorithms to improve misalignment tolerance or reduce coil stress.

VI. PRACTICAL CONSIDERATIONS AND CHALLENGES

Although compensation networks for wireless power transfer (WPT) in electric vehicles (EVs) are well-established in theory, practical implementations face several challenges. These challenges arise from coil misalignment, parasitic effects, thermal issues, interoperability, and compliance with standards. Addressing these issues is essential to transition from laboratory prototypes to robust commercial systems.

Coil Misalignment and Coupling Variations: In real EV charging scenarios, perfect coil alignment between the transmitter (Tx) pad and receiver (Rx) pad is rarely achieved. Parking position variations cause shifts in the mutual inductance (M) and coupling coefficient (k). Since:

$$M = k\sqrt{L_{tx} L_{rx}}$$

a reduction in k directly reduces the effective power transfer. For instance, in SS compensation, misalignment leads to poor efficiency and higher reactive currents, while LCC-based networks offer improved tolerance [21].

Misalignment also introduces lateral (x–y) and vertical (z) displacement effects, which must be analyzed. Advanced compensation designs or multi-coil configurations are often employed to reduce sensitivity to these variations [22].

Parasitic Effects and Non-Idealities: In practice, coils and capacitors are not ideal. Parasitic resistance (Rcoil) leakage inductance, and stray capacitances alter the resonant frequency and increase losses. The effective Q-factor with parasitic is given by:

$$Q_{eff} = \frac{\omega L}{R_{Coil} + R_{Parasitic}}$$

A lower Q_{eff} reduces efficiency and broadens the resonance peak, making the system less selective. Compensation networks must therefore be designed with parasitic modeling included, often requiring finite-element simulations (FEM) and experimental validation [23].

Thermal Issues: Resistive losses in coils and power electronics generate heat, which impacts efficiency and component lifetime. Thermal effects also cause drift in component values (e.g., capacitor ESR increases with temperature). The copper loss in a coil is: $P_{copper} = I^2 R_{ac}$

where *Rac* includes skin effect and proximity effect resistance. Using Litz wire**,** improved ferrite materials, and forced cooling are common countermeasures [24].

Interoperability and Standardization: For widespread adoption, EV WPT systems must comply with SAE J2954 and similar international standards. These define frequency ranges (typically 79–90 kHz), power levels (up to 22 kW), and safety limits for electromagnetic field (EMF) exposure. The challenge for compensation design is to ensure universal compatibility: a charging pad from one manufacturer should work efficiently with multiple EV models. This requires compensation topologies that adapt across varying coil designs and power levels [25].

Control and Regulation Challenges: Maintaining stable operation under variable load and grid-side conditions requires advanced control. Common approaches include:

- **Frequency tuning**: adjusting switching frequency to maintain resonance.
- **Phase shift control**: regulating output power by controlling inverter phase.
- **Adaptive impedance matching**: electronically reconfiguring compensation values for best performance [26].

While effective, these methods increase system complexity and cost.

Safety and EMC (Electromagnetic Compatibility): High-power WPT systems generate strong magnetic fields, which can interfere with nearby electronics or exceed human exposure limits. Compensation networks influence leakage flux and harmonic distortion. Shielding materials, ferrite structures, and active EMF reduction methods are being investigated to address these concerns [27].

Trends and Future Research Directions: As wireless power transfer (WPT) for electric vehicles (EVs) transitions from research prototypes to commercial deployment, new trends are emerging in the design and optimization of compensation networks. These trends aim to address the limitations of existing topologies and prepare WPT systems for higher power, wider adoption, and dynamic charging scenarios. A major trend is the push toward high-power WPT systems (>100 kW) for heavy-duty vehicles, trucks, and buses [28]. Compensation topologies such as double-sided LCC and hybrid structures are increasingly preferred due to their ability to maintain efficiency under varying load and coupling conditions. Scaling to high power requires compensation networks that minimize circulating reactive currents while enabling wide Zero Voltage Switching (ZVS) ranges to reduce losses in semiconductor devices.

Another significant trend is the development of dynamic wireless charging (DWPT), where vehicles are charged while in motion [29]. In such cases, mutual inductance varies continuously, creating a challenge for compensation design. Adaptive compensation, real-time frequency tuning, and modular multi-coil pads are being researched to maintain stable power transfer in these dynamic conditions. Integrating artificial intelligence (AI) and machine learning (ML) for predictive misalignment correction is also an emerging direction. Research is also advancing toward superconducting coils and high-temperature superconductors (HTS) [30]. These drastically reduce coil resistance, allowing extremely high quality factors (Q) and efficiency. However, the compensation network must be carefully redesigned to handle non-linear AC losses and cryogenic constraints. This opens up new opportunities for ultra-high efficiency WPT, though cost and practicality remain significant barriers. Finally, interoperability and standardization remain critical. The SAE J2954 standard defines frequency bands, power levels, and safety limits, but future systems must incorporate adaptive compensation to ensure compatibility across different vehicle platforms and charging pads. Integration with smart grids and bidirectional power transfer (V2G) will further influence compensation design, as the networks must accommodate both charging and discharging modes while maintaining grid stability. In summary, future research in compensation networks will likely focus on scalable high-power designs, dynamic charging adaptability, superconducting technologies, and smart-grid integration, ensuring that EV wireless charging evolves into a mainstream, robust, and sustainable technology.

VII. CONCLUSION

Compensation networks form the backbone of wireless power transfer systems for electric vehicle charging. From classical topologies such as Series–Series and Series–Parallel to advanced configurations like LCC and double-sided LCC, each approach offers distinct trade-offs in efficiency, controllability, misalignment tolerance, and implementation complexity. Over the years, significant progress has been made in analytical design, optimization methods, and practical adaptation to ensure stable and efficient operation under real-world conditions.

Despite these advancements, challenges remain in scaling compensation networks for high-power EV applications, maintaining interoperability across diverse platforms, and meeting safety and electromagnetic compatibility requirements. With the rise of dynamic charging, superconducting coils, and smart grid integration, the role of compensation networks will become even more central to enabling seamless, high-efficiency wireless charging. Continued innovation in topology design, optimization strategies, and adaptive control will ultimately shape the path toward widespread adoption of wireless charging in future electric mobility.

REFERENCES

[1] **Compensation topologies of high-power wireless power transfer systems** — W. Zhang & C. C. Mi — *IEEE Trans. Vehicular Technology*, 2016. doi:10.1109/TVT.2015.2454292.

[2] **A review of wireless power transfer for electric vehicles: prospects to enhance sustainable mobility** — Z. Bi, T. Kan, C. C. Mi, et al. — *Applied Energy*, 2016.

[3] **Resonant wireless charging scheme** — X. Guo, Y. Qi, L. Liu, S. Jia, L. Mi — *Energy Reports*, 2023.

[4] **Integrated LCC compensation topology for wireless charger in electric and plug-in vehicles** — W. Li, H. Zhao, S. Li, J. Deng, T. Kan, C. C. Mi — *IEEE Trans. Ind. Electron.*, 2015.

[5] **Comparison study on SS and double-sided LCC compensation topologies for EV/PHEV wireless chargers** — W. Li et al. — *IEEE Trans. Veh. Technol.*, 2016.

[6] **Design of LCC-S compensation topology and optimization of misalignment tolerance for IPT** — J. Yang et al. — *IEEE Access*, 2020.

[7] **Compensation network optimal design based on evolutionary algorithm for IPT** — W. Chen, W. Lu, H. H.-C. Iu, T. Fernando — *IEEE Trans. Circuits Syst. I*, 2020. doi:10.1109/TCSI.2020.3012700.

[8] **Modeling and analysis of series-none compensation for WPT systems with strong coupling** — Y. Zhang, T. Kan, Z. Yan, et al. — *IEEE Trans. Power Electron.*, 2019.

[9] **Design for efficiency optimization and voltage controllability of series-series compensated IPT** — W. Zhang, S.-C. Wong, C. K. Tse, Q. Chen — *IEEE Trans. Power Electron.*, 2014.

[10] **Frequency and voltage tuning of series-series compensated WPT system to sustain rated power** — Y. Zhang & C. C. Mi — *IEEE J. Emerg. Sel. Top. Power Electron.*, 2019.

[11] **A review of recent trends in WPT technology and its applications in EV wireless charging** — L. Sun, D. Ma, H. Tang — *Renewable & Sustainable Energy Reviews*, 2018.

[12] **Comparison of compensation topologies for wireless charging systems in EV applications** — W. Zhang et al. — *AIE 2022 (proc.)*, 2022.

[13] **Dual-coupled LCC-compensated IPT system with a compact magnetic coupler** — F. Lu, H. Zhang, H. Hofmann, W. Su, C. C. Mi — *IEEE Trans. Power Electron.*, 2018.

[14] **Maximum efficiency and power point tracking for hybrid compensated wireless charging** — (multiple authors) — *IEEE/Elsevier papers (2020–2024)* (papers in your PDF).

[15] **Optimization of series-series compensated WPT using alternative secondary rectification** — (authors in uploaded file) — *journal/conference in PDF*.

[16] **Analysis of four-coil magnetic resonance coupling WPT based on LCC-SSS compensation** — Z. Chen, X. Sun, B. Ren, et al. — *Energy Reports*, 2023.

[17] **A hybrid compensation topology with single switch for battery charging of IPT systems** — H. Zhang, Y. Chen, S. J. Park, D. H. Kim — *IEEE Access*, 2019.

[18] **Multicoil dynamic WPT topology with shared primary-side compensation** — B. Pakhaliuk et al. — *RTUCON Proc.*, 2021.
[19] **Design and experimentation of WPT charger for electric city car** — G. Buja, M. Bertoluzzo, K. N. Mude — *IEEE Trans. Ind. Electron.*, 2015.
[20] **Mutual inductance behavioral modeling for WPT coils** — G. Di Capua, N. Femia, et al. — *IEEE Trans. Ind. Electron.*, 2021.
[21] **Advances in high-power wireless charging systems: overview and design considerations** — H. Feng, R. Tavakoli, O. C. Onar, Z. Pantic — *IEEE Trans. Transp. Electrific.*, 2020.
[22] **Comparison of magnetic couplers for IPT-based EV charging using multi-objective optimization** — S. Bandyopadhyay, P. Venugopal, J. Dong, P. Bauer — *IEEE Trans. Veh. Technol.*, 2019.
[23] **LCC-LCC hybrid compensation and wide ZVS operation** — N. Fu, J. Deng, Z. Wang, W. Wang, S. Wang — *IEEE Trans. Power Electron.*, 2022.
[24] **Analysis and design of DD coupler for dynamic wireless charging of EVs** — H. K. Dashora, G. Buja, M. Bertoluzzo — *J. Electromagnetic Waves & Appl.*, 2018.
[25] **Optimization of compensation network for WPT in dynamic conditions: circuit analysis approach** — M. Bertoluzzo, P. Di Barba, M. Forzan, M. E. Mognaschi, E. Sieni — *Algorithms*, 2022. doi:10.3390/a15080261.
[26] **Design methodology and circuit analysis of WPT systems applied to EV wireless chargers** — T. Bouanou et al. — *World Electric Vehicle Journal*, 2023.
[27] **Wide design range of constant output current using double-sided LC compensation** — X. Qu et al. — *IEEE Trans. Power Electron.*, 2019.
[28] **Practical considerations of SS and SP compensation topologies in WPT applications** — C. Fang, J. Song, L. Lin, Y. Wang — *PELS WoW 2017 (proc.)*.
[29] **A review map of comparative designs for wireless high-power transfer systems in EV applications: max efficiency, ZPA, CC/CV** — H. T. Nguyen et al. — *IEEE Trans. Power Electron.*, 2022.
[30] **Advances in EV wireless charging technology — systematic review and future trends** — B. Latha, M. M. Irfan, V. Flah, V. Blazek, L. Prokop, S. S. Rangarajan — *e-Prime / other review*, 2024.