International Journal of Power Electronics and Drive System (IJPEDS)
Vol. 16, No. 4, December 2025, pp. 2156~2169
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v16.i4.pp2156-2169

A comprehensive review of efficient wireless power transfer for electric vehicle charging: advancements, challenges, and future directions

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Article Info

Article history:

Received Jan 27, 2025
Revised Oct 2, 2025
Accepted Oct 17, 2025

Keywords:

Compensation circuit
Coupling pad
EV transportation
Misalignment
Wireless power transfer

ABSTRACT

Electric vehicles (EVs) have transformed the transportation sector, offering a sustainable alternative to fossil-fuel-powered vehicles. However, their widespread adoption faces challenges such as inadequate charging infrastructure, range anxiety, and concerns about user convenience. Wireless power transfer (WPT) technology provides an efficient, reliable, and user-friendly charging solution that eliminates physical connections, enabling both static and dynamic charging applications. This review explores key components of WPT systems, including wireless charging schemes, compensation circuits, coupling pad structures, and misalignment tolerance, emphasizing their impact on system efficiency and reliability. Findings highlight that WPT can enhance charging convenience, reduce dependence on large battery capacities, and support seamless EV integration into daily life. Additionally, WPT systems improve safety, lower maintenance needs, and create opportunities for autonomous charging. Key advancements in compensation topologies, coupling pad geometries, and misalignment-tolerant capabilities are discussed alongside their role in enhancing power transfer efficiency. By offering insights into the current state-of-the-art and future directions, this paper aims to support the development and deployment of WPT systems, contributing to the global transition toward sustainable transportation.

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1. INTRODUCTION

The global automotive industry is undergoing a paradigm shift toward cleaner and more sustainable transportation systems, driven by the dual challenges of depleting fossil fuels and rising environmental concerns. Vehicles powered by Internal Combustion Engines (ICE) are major contributors to greenhouse gas emissions, air pollution, and climate change. In response, governments, industries, and researchers are increasingly focusing on electric vehicles (EVs) as a viable alternative. EVs offer advantages such as zero tailpipe emissions, reduced reliance on fossil fuels, and lower operational costs [1]. However, widespread EV adoption is still hindered by challenges such as limited battery range, long charging times, and the lack of efficient and convenient charging infrastructure [2].

Charging infrastructure is a critical component for the successful deployment of EVs. Traditional conductive charging systems, while reliable, have inherent drawbacks such as the need for physical cables, risk of electric shock, long wait times at charging stations, and the inconvenience of manual connections [3]. These limitations have prompted researchers and industries to explore wireless charging technologies, also known as wireless power transfer (WPT). This innovative approach enables EVs to be charged without physical connectors, offering enhanced safety, user convenience, and the potential for automated charging.

WPT can broadly be categorized into three modes: static charging, where vehicles charge while stationary (e.g., at homes or parking lots); quasi-dynamic charging, which charges vehicles during brief stops (e.g., traffic lights or bus stops); and dynamic wireless charging (DWC), enabling on-the-move charging along specially equipped roadways. DWC eliminates range anxiety and reduces the need for large, heavy batteries, making it ideal for long-distance transportation and freight systems [4].

Despite the promise of wireless charging, several challenges need to be addressed to enable its widespread adoption. These include efficiency losses due to coil misalignment, electromagnetic interference (EMI) with nearby devices, high costs of infrastructure deployment, and limited standardization across manufacturers. Moreover, dynamic wireless charging systems require substantial investment in roadway modifications, which poses economic and logistical challenges. Efforts are ongoing to improve system efficiency, standardization, and integration with smart grids, including vehicle-to-grid (V2G) applications [5]. Figure 1 illustrates the basic setup of a wireless charging system for EVs, which includes components such as the primary coil, secondary coil, compensation circuits, and AC/DC converters, highlighting the flux linkage between the primary and secondary coils.

This manuscript explores the state-of-the-art developments in WPT for EVs, focusing on technological advancements, practical implementations, standards, and future prospects. By addressing the current challenges and highlighting innovative solutions, this review aims to provide insights for advancing wireless EV charging systems to support the global transition toward sustainable transportation. The manuscript is organized as follows: i) Section 2 elaborates wireless charging schemes for EVs; ii) Section 3 covers compensation circuit designs; iii) Section 4 delves into coupling pad technologies; iv) Section 5 examines misalignment issues; and v) Section 6 concludes with challenges and future directions.

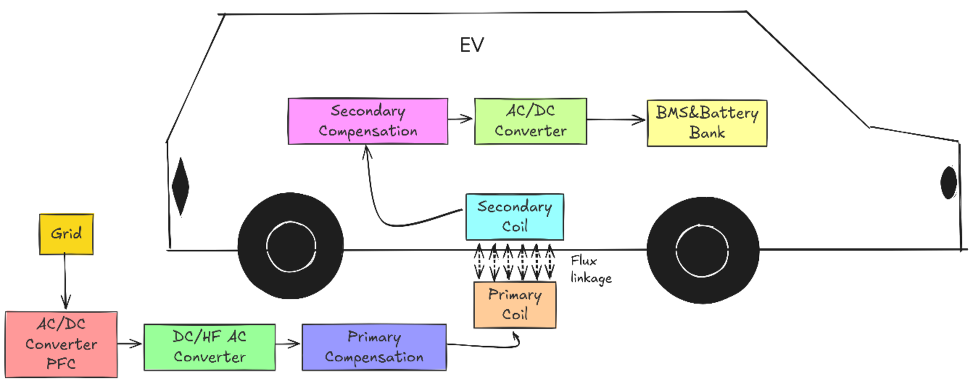


Figure 1. A schematic representation of a wireless charging system for EVs

2. WIRELESS CHARGING SCHEMES FOR ELECTRIC VEHICLES

Electric vehicle (EV) charging technologies are broadly categorized into conductive and wireless (inductive) charging systems. Conductive charging involves physical connections for energy transfer, while wireless charging eliminates such connections by utilizing electromagnetic fields. Among wireless charging systems, several techniques and modes of operation are being developed to enhance convenience, efficiency, and adaptability to different EV applications.

2.1. Conductive charging

Conductive charging remains the most prevalent method for EV energy replenishment due to its straightforward implementation and efficiency. This technology is divided into two key types based on the charging equipment used:

2.1.1. On-board charging

On-board chargers are integrated into the vehicle, where they convert alternating current from the grid into direct current suitable for EV battery charging. These chargers are widely employed in home and workplace settings for slow AC charging. Typical power levels for on-board charging reach up to 19.2 kW, with charging times ranging from 2 to 7 hours, making them suitable for overnight or long-duration parking [6].

2.1.2. Off-board charging

Off-board chargers provide high-power direct current (DC) directly to the EV's battery, bypassing the on-board rectification process. These systems deliver over 50 kW of power, enabling rapid charging within 15 to 30 minutes, and are commonly deployed at public and highway charging stations. Despite their efficiency, the reliance on physical cables presents potential drawbacks, including wear and tear, safety risks, and reduced convenience for users [7].

2.2. Inductive (wireless) charging

Wireless charging, also known as WPT, is an emerging technology that overcomes many of the limitations of conductive systems. By eliminating the need for physical connectors, it provides safer, more user-friendly solutions. WPT techniques are classified into inductive, capacitive, and resonant inductive methods. Table 1 provides a detailed comparison of these coupling methods, and Figure 2 illustrates the classification of WPT methods. Additionally, these systems operate in three primary modes: static, dynamic, and quasi-dynamic charging.

Table 1. Comparative analysis of different wireless power transfer methods

Feature	Inductive WPT	Resonant inductive WPT	Capacitive WPT
Principle	Magnetic induction using Ampère's and Faraday's laws.	Resonant coupling using tuned reactive circuits (capacitors/inductors).	Electric field coupling between parallel metallic plates.
Energy transfer mechanism	The magnetic field generated by a time-varying current in the transmitter coil induces a voltage in the receiver coil.	Magnetic field resonance between transmitter and receiver coils.	An electric field is established between pairs of metallic plates.
Operating frequency	Low to medium (10–50 kHz).	Medium to high (10–150 kHz).	Medium to high (100–600 kHz).
Air gap	0–50 cm.	50 cm – 5 m (Up to 1 meter in dynamic applications).	Proximity: typically, 12–15 cm separation.
Efficiency	Up to 90% for small air gaps (<10 cm).	Up to 90% over larger distances (>1 meter).	Up to 88.4% for small plate separations.
Power transfer capability	3–60 kW.	10–100 kW (depending on resonant circuit design).	500 W to 1.2 kW (based on plate size and separation).
Size of components	Larger coils are required for high power transfer.	Moderate coil sizes with reactive elements (capacitors/inductors).	Compact plates, smaller overall system footprint.
Alignment sensitivity	High, precise alignment of coils is required.	Moderate; less sensitive due to resonant coupling.	Low: can tolerate misalignment to some extent.
System complexity	Simple circuit design; requires basic coil optimization.	Complex; involves reactive compensation and precise tuning.	Moderate; requires precise plate alignment and high-frequency converters.
Electromagnetic interference (EMI)	Moderate; magnetic fields can extend beyond system boundaries.	Moderate; magnetic fields still pose EMI concerns.	Low electric fields are confined between plates.
Metallic object tolerance	Low; metallic objects interfere with the magnetic field and efficiency.	Low; metallic objects still impact resonance and efficiency.	High; minimal impact on efficiency or safety.
Applications	Stationary EV charging, smartphones and wearables, electric toothbrushes.	Dynamic and stationary EV charging, medical implants, and factory automation.	Biomedical implants, low-power consumer electronics, and autonomous underwater vehicles.

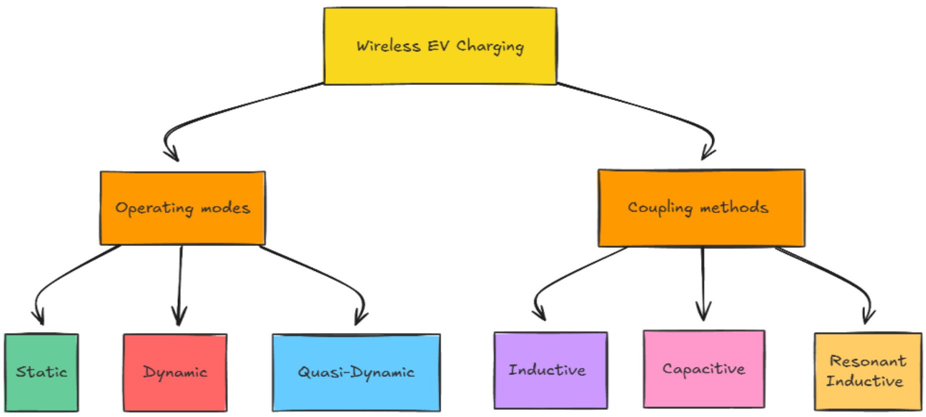


Figure 2. Classification of wireless power transfer (WPT) systems

2.2.1. Inductive wireless power transfer (inductive WPT)

Inductive WPT relies on the principles of electromagnetic induction, where a time-varying magnetic field generated by a transmitter coil induces voltage in a receiver coil. This technology supports power levels ranging from 3 kW to 60 kW, with transfer distances of 4 to 10 cm and efficiencies reaching up to 90% [8]. High-frequency operation and the inclusion of ferromagnetic cores enhance efficiency by concentrating magnetic flux. However, inductive WPT faces challenges such as coil misalignment, sensitivity to distance variations, and limited transfer range. Figure 3(a) illustrates a basic inductive WPT system, where AC power is converted by power electronics, transferred wirelessly through magnetically coupled coils across a small air gap, and then rectified for battery charging. System efficiency depends on coil alignment and coupling strength.

2.2.2. Resonant inductive wireless power transfer (resonant inductive WPT)

Resonant Inductive WPT builds on inductive principles by employing resonance to extend transfer distances and improve efficiency. By tuning both transmitter and receiver coils to resonate at the same frequency, this method minimizes energy losses and maximizes coupling efficiency. Resonant Inductive systems can achieve efficiencies of up to 90% over distances of up to 1 meter, making them suitable for both stationary and dynamic applications [9]. Advanced compensation circuits ensure reliable operation under resonant conditions, addressing challenges such as varying air gaps and coil alignment. Figure 3(b) presents a resonant inductive WPT system, where additional compensation circuits on both the transmitter and receiver sides improve efficiency by maintaining resonance. This setup allows greater transfer distances and reduces sensitivity to misalignment compared to basic inductive WPT.

2.2.3. Capacitive wireless power transfer (capacitive WPT)

Capacitive WPT employs electric fields to transfer energy via parallel metallic plates, forming capacitors. One plate in each pair is connected to the power source, while the other is connected to the load [10]. This method offers compact designs suitable for confined spaces, with demonstrated power densities of up to 51.6 kW/m² and efficiencies reaching 88.4% [11]. Despite these advantages, capacitive WPT's application is limited by its lower power transfer capacity and susceptibility to misalignment [12]. Figure 3(c) depicts a typical capacitive WPT system, where power transfer occurs through capacitive coupling instead of inductive coils. The transmitter and receiver plates are separated by an air gap, and compensation circuits are used to maintain efficient energy transfer.

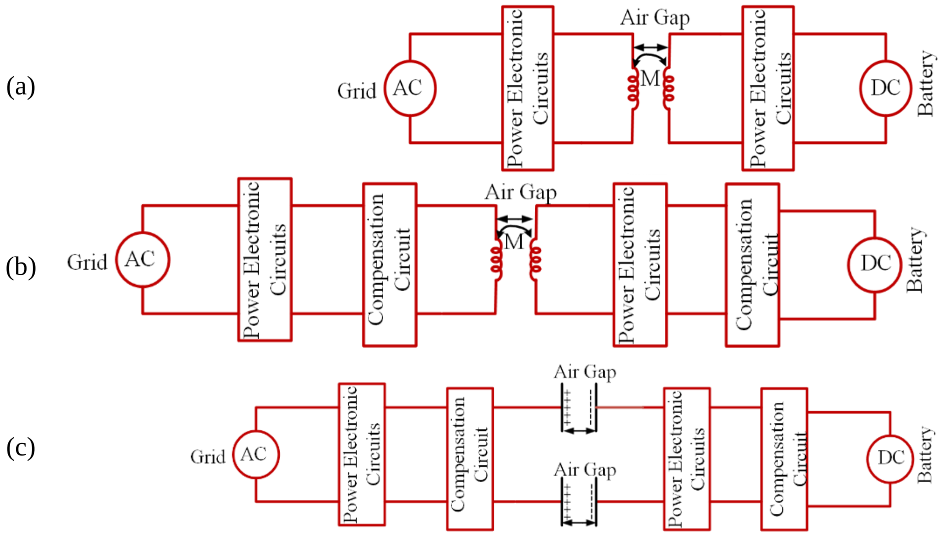


Figure 3. Coupling method: (a) inductive WPT, (b) resonant inductive WPT, and (c) capacitive WPT

2.2.4. Operating modes of wireless charging

a) Static wireless charging (SWC)

Static charging allows EVs to charge wirelessly while stationary, such as in parking lots or garages. Inductive Power Transfer (IPT) technology underpins most SWC systems, achieving efficiencies exceeding 95% in advanced implementations. Power level varies from 3.7 kW for private EVs to 200 kW for buses, with guidelines provided by standards like SAE J2954 [13].

b) Dynamic wireless charging (DWC)

Dynamic charging enables EVs to charge while in motion on specially equipped roadways. This approach addresses range anxiety, reduces reliance on large battery packs, and offers seamless energy replenishment. Segmented power transfer systems improve efficiency by energizing only the track section beneath the vehicle, minimizing stray electromagnetic fields and power losses [14]. Despite its promise, DWC faces challenges such as high infrastructure costs and alignment precision [15].

c) Quasi-dynamic wireless charging (QWC)

Combining elements of static and dynamic systems, QWC allows vehicles to charge during intermittent stops, such as at traffic signals or bus stops. This hybrid approach enhances energy utilization and reduces infrastructure costs compared to fully dynamic systems. QWC is particularly suitable for urban public transport systems, where frequent stops are common [16].

3. COMPENSATION CIRCUITS

Compensation circuits play a vital role in wireless power transfer systems, particularly for electric vehicle applications, as they address the inherent challenges of high leakage inductance and low mutual inductance caused by the loosely coupled transformer design. The primary purpose of compensation circuits is to provide reactive power to counteract the inductive reactance of the primary and secondary coils. This minimizes the volt-ampere (VA) rating of the supply and ensures maximum power transfer capability [17]. Additionally, they stabilize the system by maintaining a constant output voltage or current, regardless of variations in air gap, alignment, or load resistance. Proper design prevents bifurcation, a phenomenon where multiple operating frequencies cause instability and efficiency losses.

3.1. Principles of compensation circuits

3.1.1. Reactive power compensation

Due to the large air gap in WPT systems, high leakage inductance results in significant reactive power demand, increasing losses, and requiring a high VA-rated supply [18]. Compensation circuits provide local reactive power, canceling the inductive reactance (X_L) of the coils. This allows the active power required for energy transfer to be delivered more efficiently. Mathematically, the reactance XL of an inductor is given by (1), where f is the operating frequency and L is the inductance.

$$X_L = 2\pi \mathrm{fL} \tag{1}$$

A properly designed capacitor compensates for this reactance by satisfying the resonance condition:

$$X_C = X_L \tag{2}$$

By achieving this resonance condition, the compensation circuit reduces the VA requirement, minimizes losses, and maximizes the energy transfer to the secondary.

3.1.2. Voltage and current control

Compensation circuits regulate the voltage and current at the receiver side to match the requirements of the load, typically an EV battery. Most batteries require a constant current (CC) phase at low states of charge (SOC) and a constant voltage (CV) phase at higher SOCs [19]. Compensation networks maintain these output characteristics by adjusting the resonant conditions and ensuring stability despite variations in the load, air gap, or coil alignment.

3.1.3. Soft switching for high efficiency

To minimize switching losses in the power electronics, compensation circuits enable soft switching techniques, such as zero voltage switching (ZVS) or zero current switching (ZCS) [20]. By ensuring that the switches operate at zero voltage or zero current during transitions, the system achieves high efficiency, particularly at high power levels. For instance, ZVS is achieved when the resonant circuit is tuned such that the voltage across the switching component is zero at the moment of switching.

3.1.4. Bifurcation avoidance

Bifurcation refers to the presence of multiple operating frequencies at which the system can achieve zero phase angle (ZPA) [20]. This phenomenon can lead to instability and inefficient operation. Compensation circuits are designed to avoid bifurcation by ensuring a single, well-defined resonant frequency [21]. This is achieved by carefully selecting the topology and tuning the compensation components.

3.2. Classifications of compensation topologies

Compensation topologies are categorized into basic and hybrid configurations based on their circuit design and application requirements. Basic topologies are the foundation of WPT systems, while hybrid configurations address specific challenges such as misalignment tolerance, high-power demands, and dynamic load variations. Figure 4 provides a classification diagram of compensation topologies, categorizing them into basic and hybrid types. Basic topologies include series-series (SS), series-parallel (SP), parallel-series (PS), and parallel-parallel (PP), as shown in Figure 5, while Figure 6 depicts some hybrid topologies that incorporate additional components, such as inductors and resonant networks, to improve efficiency and stability under variable conditions.

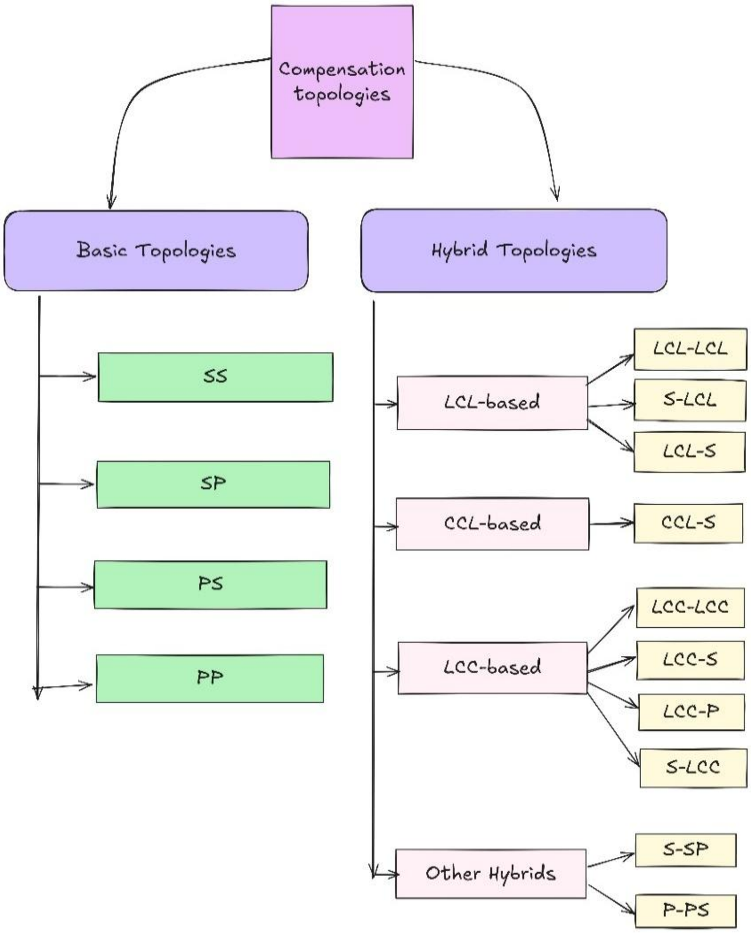


Figure 4. Classification of compensation topologies

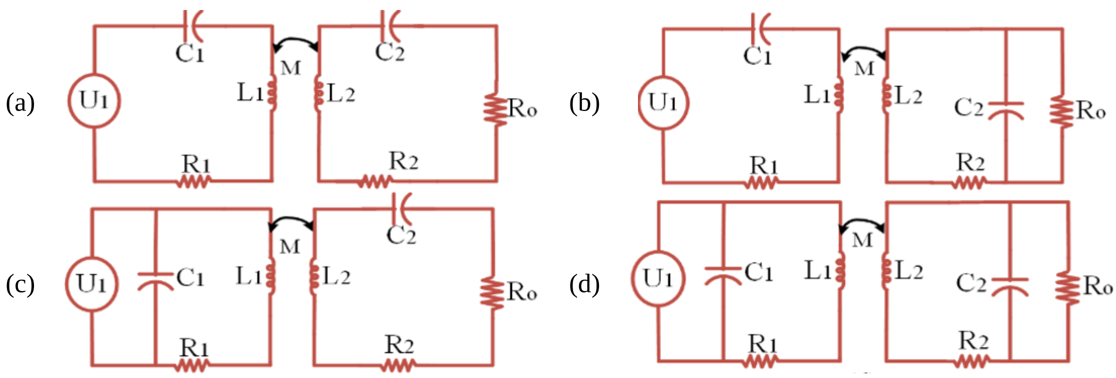


Figure 5. Basic compensation topologies: (a) SS, (b) SP, (c) PS, and (d) PP

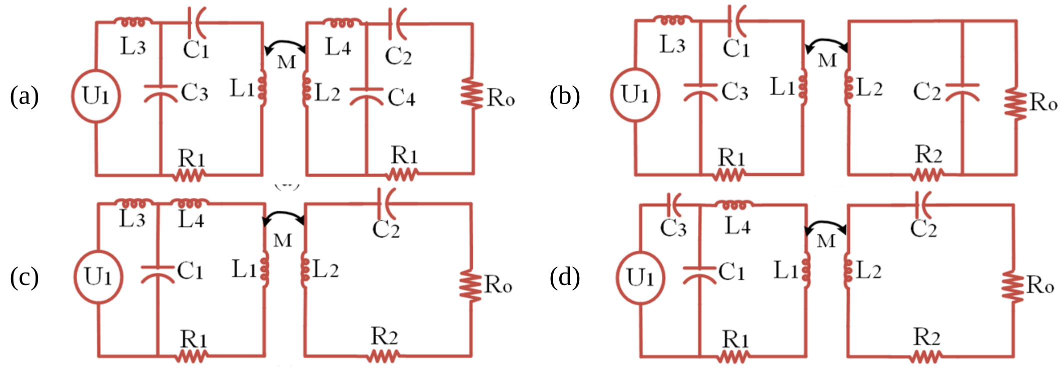


Figure 6. Some hybrid compensation topologies: (a) LCC-LCC, (b) LCC-P, (c) LCL-S, and (d) CCL-S

3.2.1. Basic compensation topologies

Table 2 provides a comprehensive comparison of basic topologies based on different parameters, where L1 is the transmitter coil inductance, M is the mutual inductance, and L2 is the receiver coil inductance, ω is the resonant frequency, R is the resistance of the coil, U1 is the source AC RMS voltage applied to the coil, and Z1 and Z2 are the impedances of the transmitter and receiver coils without the compensation circuit. Additionally, Ro represents the load resistance.

a) Series-series (SS)

In this topology, compensation capacitors are connected in series with both the transmitter and receiver coils. SS compensation is ideal for high-power applications due to its efficiency and independence from the coupling coefficient [19], [22]. It is commonly used in dynamic WPT systems where the coupling coefficient varies, as it maintains high efficiency even under fluctuating conditions. However, it requires careful design to avoid unsafe high terminal voltages under light-load or no-load conditions [18].

b) Series-parallel (SP)

This topology combines series compensation on the transmitter side with parallel compensation on the receiver side. It is well-suited for systems with changing mutual inductance and variable load conditions [19]. However, the efficiency and power factor depend on the coupling coefficient, requiring adjustments in capacitance to maintain resonance.

c) Parallel-series (PS)

PS compensation involves parallel compensation on the transmitter side and series compensation on the receiver side. This topology is effective for systems with low mutual inductance and offers a good balance of efficiency and power factor. However, it necessitates a current source input and additional inductors to manage primary-side currents effectively [17].

3.2.2. Hybrid compensation topologies

Hybrid compensation topologies in WPT systems are advanced configurations designed to overcome limitations of basic topologies, such as inefficiency under misalignment, sensitivity to load variations, and limited power capacity [23]. They are primarily categorized into LCL-based, CCL-based, and LCC-based topologies, with other specialized configurations tailored for specific requirements.

LCL-based topologies use additional inductors to form LCL networks on the primary and secondary sides, providing current-source characteristics and stabilizing power delivery. The LCL-LCL topology employs LCL networks on both sides, ensuring high efficiency and excellent misalignment tolerance, making it ideal for high-power applications [23]. The LCL-S topology combines an LCL network on the primary side with series compensation on the secondary side, maintaining consistent power transfer despite coupling variations.

CCL-based topologies combine inductors and capacitors for stability and efficiency. The CCL-S topology applies current-controlled compensation on the primary side with series compensation on the secondary side, ensuring stable power output in dynamic scenarios [24]. The CCL-LCC configuration extends this by using LCC compensation on the secondary side, offering high power factor and efficiency even under load and alignment changes.

LCC-based topologies use resonant circuits with series and parallel elements to achieve zero current switching (ZCS) and high efficiency. The LCC-LCC topology applies LCC compensation on both sides, providing load independence, misalignment tolerance, and high-power transfer efficiency, making it ideal for dynamic WPT systems like EV charging [23]. The LCC-P topology, with LCC compensation on the primary side and parallel compensation on the secondary side, enhances performance under misalignment [24]. Specialized hybrid configurations, such as the S-SP topology, combine series compensation on one side with series-parallel compensation on the other, ensuring consistent power delivery under misalignment [25]. The P-PS topology integrates parallel compensation with parallel-series configurations, suited for high-power and dynamic load applications [23].

Table 2. Parameters summary of basic WPT topologies

WPT topology	Primary quality factor (Q_1)	Secondary quality factor (Q_2)	Resonant reflected impedance (Z_{ref})	Total impedance (Z_t)	Primary current at resonance (I_1)	Output behavior
Series-Series (SS)	$\frac{L_1R}{\omega M^2}$	$\frac{\omega L_1}{R}$	$\frac{\omega M^2}{R}$	$\frac{\omega^2M^2}{Z_2+\frac{1}{j\omega C_2}+R_o}+Z_1+\frac{1}{j\omega C_1}$	$\frac{U_1R}{\omega M^2}$	Voltage source at receiving coil
Series-Parallel (SP)	$\frac{\omega L_1L^2{}_2}{RM^2}$	$\frac{R}{\omega L_1}$	$\frac{RM^2}{L^2{}_2}-\frac{j\omega M^2}{L_2}$	$\frac{\omega^2M^2}{Z_2+\frac{R_o}{1+j\omega R_oC_2}}+Z_1+\frac{1}{j\omega C_1}$	$\frac{U_1L^2{}_2}{RM^2}$	Current source at receiving coil
Parallel-Series (PS)	$\frac{L_1R}{\omega M^2}$	$\frac{\omega L_1}{R}$	$\frac{\omega M^2}{R}$	$\frac{1}{\frac{\omega^2M^2(1+j\omega R_oC_2)}{Z_2(1+j\omega R_oC_2)+R_o}+Z_1+j\omega C_1}$	$\frac{U_1R}{\omega M^2}$	Voltage source at receiving coil
Parallel-Parallel (PP)	$\frac{\omega L_1L^2{}_2}{RM^2}$	$\frac{R}{\omega L_1}$	$\frac{RM^2}{L^2{}_2}-\frac{j\omega M^2}{L_2}$	$\frac{1}{\frac{\omega^2M^2(1+j\omega R_oC_2)}{Z_2(1+j\omega R_oC_2)+R_o}+Z_1}+j\omega C_1$	$\frac{U_1L^2{}_2}{RM^2}$	Current source at receiving coil

4. COUPLING PAD STRUCTURES

Coupling pad structures are fundamental to the performance and efficiency of WPT systems, particularly for electric vehicle (EV) applications. These structures consist of transmitter and receiver coils separated by an air gap, enabling inductive or resonant energy transfer. Their design critically influences key factors such as power transfer efficiency, coupling coefficient, quality factor, and tolerance to misalignment, making the coupling pad the backbone of the WPT system [25].

The magnetic coupler, also referred to as the coupling pad, facilitates energy transfer through a magnetic link established between the transmitter and receiver coils. A well-designed magnetic coupler minimizes energy losses, enhances misalignment tolerance, and ensures stable operation under various conditions. The efficiency of the WPT system is primarily governed by the coupling coefficient (k) and the quality factor (Q), with their product (kQ), determining the effectiveness of energy transfer [26]. Achieving a high (kQ) value requires an optimized coil design that balances self-inductance, resistance, and flux distribution.

The design of coupling pads involves optimizing the coil geometry, material selection, and arrangement to achieve high self-inductance and low resistance. The self-inductance of a coil is determined by its number of turns, the magnetic permeability of the material, and the cross-sectional area of the flux path. Increasing the number of turns enhances self-inductance but also raises the equivalent series resistance (ESR), which includes both DC and AC resistance [26]. Advanced materials such as Litz wire are employed to reduce AC resistance, mitigating skin and proximity effects at high operational frequencies (typically around 85 kHz, as standardized by SAE J2594/1) [13].

Material selection is another critical aspect of coupling pad design. Ferrite materials are often incorporated into the coils to guide magnetic flux, reduce leakage, and improve coupling. Ferrites with high relative permeability significantly enhance the mutual inductance and overall efficiency of the system. However, the inclusion of ferrite can introduce additional core losses and increase the weight of the system, posing challenges in applications requiring lightweight components, such as unmanned aerial vehicles (UAVs) [26], [27]. Table 3 presents the detailed comparison of different coupling pads on various parameters.

4.1. Circular coils

Circular coils shown in Figure 7(a) are widely used due to their simplicity and uniform magnetic flux distribution. They offer single-sided flux patterns, reducing leakage and enabling effective shielding [27]. However, their coupling coefficient decreases significantly under lateral misalignments. Circular coils are optimal for stationary applications with minimal misalignment [27]. Researchers have demonstrated high efficiencies with circular pads, such as achieving a 96.5% transfer efficiency with a 210-mm diameter coil and a 52-mm air gap [28]. However, their performance can be constrained by thermal limitations, necessitating current densities below 3–5 A/mm² in the Litz wire to ensure acceptable operation [28].

4.2. Rectangular coils

Rectangular coils, as depicted in Figure 7(b), are optimized for applications requiring larger coverage areas [28]. These geometries exhibit improved lateral misalignment tolerance compared to circular pads, which enhances their reliability in practical scenarios [29]. This feature makes them particularly suitable for dynamic wireless charging of electric vehicles (EVs), where exact alignment between transmitter and receiver coils cannot always be guaranteed [28].

4.3. Double-D (DD) coils

DD coils consist of two D-shaped sub-coils connected in reverse polarity. This design, represented in Figure 8(a), combines the advantages of flux pipe and circular coil geometries, offering improved coupling strength and reduced leakage flux [29]. Ferrite plates are often placed under the coils to further guide the flux, enabling higher coupling coefficients. DD coils are widely used in EV applications due to their robustness and reliability under moderate misalignment [30].

4.4. Double-D quadrature (DDQ) coils

The DDQ configuration presented in Figure 8(b) extends the DD coil by adding a quadrature coil in the center. This architecture collects d-axis flux through the DD coils and q-axis flux through the quadrature coil, significantly improving tolerance to misalignments [30]. However, DDQ coils require more space and a complex control system, increasing system cost [31].

4.5. Bipolar (BP) coils

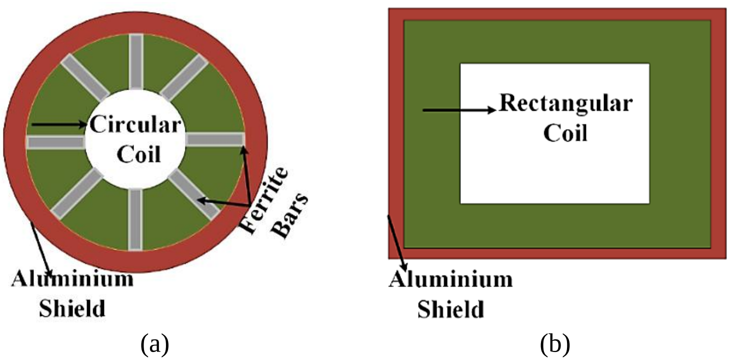
Bipolar pads are a simplified alternative to DDQ coils, featuring overlapping D-shaped coils. They achieve high coupling coefficients with less copper usage compared to DDQ pads [32]. The bipolar design offers a balance between cost, efficiency, and misalignment tolerance [31], [33]. Moreover, Figure 8(c) depicts the bipolar coils.

4.6. Tripolar coils

Tripolar pads consist of three mutually decoupled coils, allowing independent control of each coil [34]. This structure in Figure 8(d) exhibits high rotational misalignment tolerance and achieves high coupling coefficients by modulating the voltage and phase of each coil [32]. However, tripolar pads require three separate inverters, increasing complexity and cost [34].

Table 3. Comparative analysis of different coil structures presented in the literature

Coil structure	Ref	Type	Misalignment tolerance	Coupling coefficient	Magnetic field orientation	Effect of shielding on coupling	EMF exposure
Circular	[27]	Non-polarized	Poor	Low	Single-sided	Minimal	High
Rectangular	[28]	Non-polarized	Moderate	Moderate	Single-sided	Minimal	High
Double-D (DD)	[30]	Polarized	Poor	High	Double-sided	High	Low
Double-D Quadrature (DDQ)	[31]	Polarized	High	High	Double-sided	High	Low
Bipolar	[33]	Polarized	Moderate	High	Double-sided	High	Low
Tripolar	[34]	Polarized	High	High	Single-sided	Minimal	Low



(a) (b)

Figure 7. Coupling pads of (a) circular and (b) rectangular

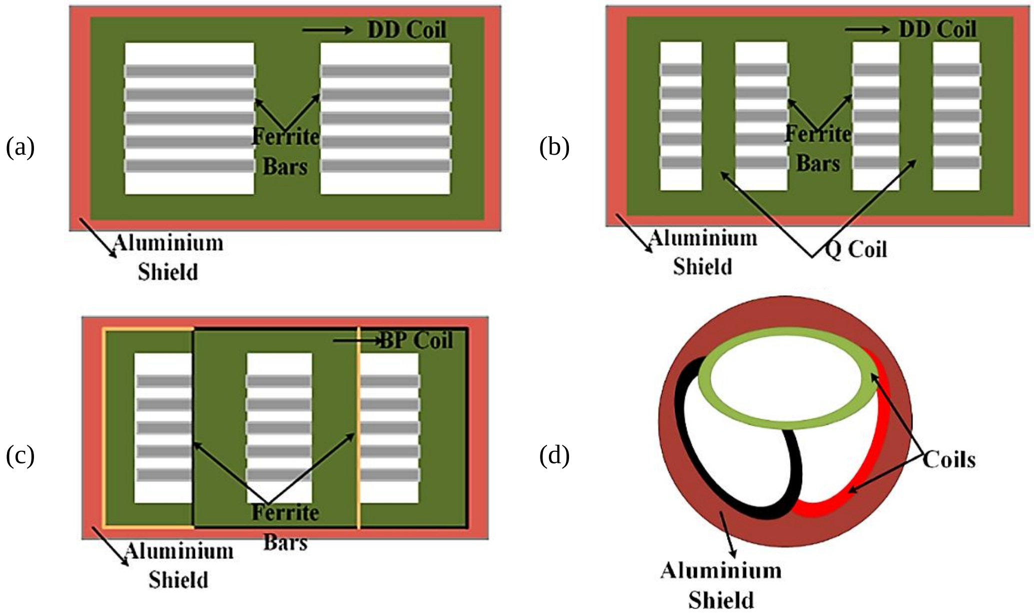


Figure 8. Coupling pads of (a) DD, (b) DDQ, (c) BP, and (d) tripolar

5. COIL MISALIGNMENT

Coil misalignment is a critical challenge in WPT systems, particularly in electric vehicle charging applications, where the alignment of the transmitting and receiving coils directly affects the efficiency and reliability of power transfer. Misalignment can occur in various forms, including longitudinal, lateral, vertical, angular, and rotational displacements, due to improper vehicle positioning, uneven surfaces, or dynamic movement during charging. These misalignments result in reduced coupling coefficient, mutual inductance, and power transfer efficiency, while increasing flux leakage, impedance mismatches, and thermal stress on system components [35].

Table 4. Misalignment tolerance guidelines [13]

Criteria	Tolerance
Longitudinal offset (△X)	±75 mm
Lateral offset (△Y)	±100 mm
Vertical offset (△Z)	Specified by Manufacturer
Rotational offsets	Tested at 2° and 3°

Table 5. Z-Class guidelines for ground clearance [13]

Z-class level	Ground clearance (mm)
Z1	100 - 150
Z2	140 - 210
Z3	170 - 250

Misalignment poses significant challenges in both static and dynamic charging scenarios. In static charging, improper parking or ground irregularities lead to horizontal or vertical offsets between the coils, while dynamic charging introduces continuous positional variations as vehicles move over the charging infrastructure. Addressing these challenges is crucial for achieving efficient and reliable WPT performance [36]. SAE J2594/1 standards specify that WPT systems must maintain at least 80% efficiency under typical misalignment conditions and provide detailed guidelines for tolerances in longitudinal, lateral, and vertical misalignments, as well as angular and rotational deviations [13], which are presented in Tables 4 and 5.

To mitigate the effects of misalignment, researchers have explored a variety of solutions [28], [30]. Advanced coil designs such as double-D (DD), double-D quadrature (DDQ), and bipolar (BP) coils have shown significant promise. DD coils, consisting of two D-shaped sub-coils connected in reverse polarity, create a unidirectional flux path that reduces leakage and enhances coupling efficiency. The DDQ design extends this concept by incorporating a quadrature coil to capture perpendicular flux components, significantly improving misalignment tolerance. Bipolar coils, which feature overlapping D-shaped coils, offer a cost-effective alternative with similar performance under misaligned conditions [27].

Modular coil designs, using multiple smaller coils instead of a single large one, further improve coupling by distributing the magnetic field more evenly [37]. In addition to innovative coil geometries, electrical compensation techniques play a critical role in addressing misalignment. Compensation networks, such as inductor-capacitor-capacitor (LCC) and inductor-capacitor-inductor (LCL), dynamically adjust the system's electrical parameters to maintain efficiency despite variations in the coupling coefficient [38].

Double-sided LCC networks are particularly effective for high-power applications, providing enhanced tolerance to misalignment without requiring additional power electronics. Recent advancements include reconfigurable rectifiers that adapt to varying coupling coefficients by switching between operational modes, maintaining high efficiency even under severe misalignments [39].

Control strategies also contribute to mitigating the impact of misalignment. Techniques such as adjusting the switching frequency and phase shift of the inverter optimize power transfer under changing conditions [40]. Parity-time symmetric (PTS) circuits, based on resonance principles, maintain constant output power despite misalignment, though they are more suitable for low-power static applications [41].

Multi-element compensation and dual-frequency systems further enhance performance by switching between frequency channels to stabilize power output under wide coupling coefficient variations [29]. Mechanical and sensor-based solutions offer additional avenues for improving misalignment tolerance [42]. Electromagnetic induction position sensors detect misalignment and guide servo motors to reposition the transmitter pad dynamically, optimizing alignment in real-time. While effective, these solutions add complexity and cost to the system. Reconfigurable resonant designs with multiple operational modes have also been proposed to handle wide air gap variations and severe misalignments [43]. For example, systems with adjustable architecture and multiple transmitting coils can maintain high efficiency across a broad range of coupling coefficients and positional offsets [44].

6. CONCLUSION

Wireless power transfer (WPT) systems offer transformative potential for addressing the challenges of electric vehicle (EV) charging infrastructure. This paper reviewed the critical components and advancements in WPT technology, including wireless charging schemes, compensation circuits, coupling pad structures, coil misalignment solutions, and associated challenges. The findings highlight that WPT systems provide efficient, reliable, and user-friendly charging solutions that eliminate physical connections and enable innovative applications like dynamic wireless charging. The need for WPT is driven by the global shift toward sustainable transportation. WPT systems can alleviate "range anxiety," reduce reliance on large battery sizes, and support the seamless integration of EVs into everyday life. They also enhance safety, reduce maintenance, and enable opportunities for autonomous charging. However, significant challenges remain, including improving efficiency, reducing costs, addressing misalignment, and mitigating electromagnetic field (EMF) exposure risks. Future research must focus on designing high-power, cost-effective systems with robust misalignment tolerance, scalable infrastructure, and minimal environmental impact. Developing advanced compensation circuits, lightweight coupling pads, and real-time communication networks is essential. Moreover, ensuring compliance with health and safety standards while addressing economic and regulatory barriers will accelerate the commercial adoption of WPT systems. By addressing these challenges, WPT technology can significantly contribute to the widespread deployment of EVs and the transition to a sustainable transportation future.

FUNDING INFORMATION

Authors state no funding involved.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
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D : **D**ata Curation
O : Writing - **O**riginal Draft
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Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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