



Review



Recent Advancements in Wireless Charging of Electric Vehicles

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Abstract: Wireless power transfer (WPT) is emerging as a promising technology for convenient, safe, and contactless charging of electric vehicles (EVs). The performance of a WPT system is strongly influenced by the magnetic coupler, compensation network, and power electronic converter. This paper presents a systematic review of basic and advanced coil structures, compensation networks, and converter configurations. Various advanced coil geometries developed to improve coupling, power density, and tolerance to lateral misalignment are discussed, along with compensation techniques aimed at achieving soft switching, reduced reactive power, and improved misalignment tolerance and charging characteristics. Recent power electronic converter topologies and their suitability for reliable, efficient, scalable, and bidirectional EV charging are also reviewed. In addition, a systematic design methodology of a series-series compensated WPT system is presented by considering key operating constraints, including bifurcation phenomenon, zero voltage switching (ZVS), maximum power transfer, and maximum efficiency. The paper further discusses emerging challenges and future research trends. The review provides a comprehensive perspective on the current state of EV-WPT technology and identifies potential directions for developing high-performance, reliable, and cost-effective charging systems.

Keywords: coil design; compensation; static and dynamic wireless charging; electric vehicles; wireless power transfer

1. Introduction

Wireless power transfer (WPT) technology is used to transmit electrical power without physical connectors/cables [1]. WPT has emerged as one of the most promising technologies for next-generation electric vehicle (EV) charging and the only technology to charge implantable medical devices [2]. The first ever demonstrations of WPT were conducted in the late 19th century by Nikola Tesla. Despite those early demonstrations, the widespread development of WPT had to wait for several decades due to limited technological capability, poor efficiency, and the dominance of wired power delivery systems. WPT experienced a major revival toward the end of the 20th and early 21st century with the advancements in semiconductor devices, high-frequency power electronics, and high-permeability magnetic materials, to name a few [3]. In addition, the growing dependence on unmanned aerial vehicles (UAVs) [4], electric vehicles (EVs) [5], implantable medical devices [6], portable electronics [7] and automated industrial systems has created a strong demand for WPT systems for convenient and safe charging. Among these applications, WPT is particularly attractive for EV charging because it enables automated charging, and improves charging convenience and reliability. According to the IEA Global EV Outlook 2023 [8], the global EV fleet is projected to reach approximately 240 million vehicles by 2030 under the Stated Policies Scenario, highlighting the rapidly increasing demand for charging infrastructure and advanced



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charging technologies. Organizations like the International Electrotechnical Commission (IEC), International Organization for Standardization (ISO), and Society of Automotive Engineers (SAE) [9] have established standards that are enhancing wide scale acceptance of WPT systems. The demonstrations by some of the research laboratories like Oak Ridge National Laboratory (ORNL), and automotive manufacturers like WiTricity, Tesla, Electreon, etc., indicate that wireless charging is being increasingly adopted in EVs. Despite these advancements, several challenges, such as technical, economic, regulatory and infrastructural development still remain that limit the adoption of WPT systems.

WPT is primarily realized using two principles: (a) the electromagnetic induction principle that uses magnetic fields (inductive, shown in Figure 1a), (b) the electrostatic principle that relies on electric fields (capacitive, shown in Figure 1b). In most of the WPT applications, the energy gets transferred via an air gap. Therefore, the permittivity and permeability of the air is an important factor in WPT systems. Typically, the permittivity (capacitive) of air is five orders of magnitude smaller than its permeability (inductive). Therefore, in order to transfer the same amount of power, the operating frequency of capacitive power transfer (CPT) [10,11] has to be relatively very high (approx. MHz range). This limits the implementation of CPT as it is difficult to operate existing power electronic components at higher frequencies. It is for this reason that inductive power transfer (IPT) [12] is the preferred technology in several areas today, including consumer electronics, wearable devices, and medical devices, with applications ranging from electric toothbrushes and smartwatches to smartphones. In recent times, IPT has been increasingly extended to electric vehicles (EVs). As cities seek cleaner transportation, EVs have become the default choice. Conventionally, these EVs are being charged conductively (wired). Wired charging, while efficient, requires maintenance and is not convenient under all weather conditions. Conductive charging also needs human intervention. Considering that the world is moving towards autonomous systems, it is not surprising that the wireless systems are the preferred choice.

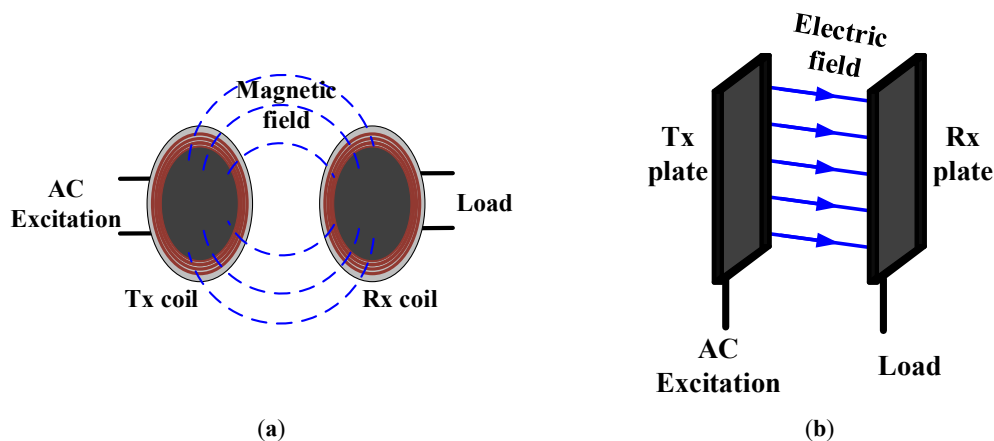


Figure 1. (a) Inductive power transfer. (b) Illustration of capacitive power transfer between parallel plates.

Wireless charging can be broadly categorized based on its application into three types: (1) Static Wireless Charging (SWC) [2]; (2) Quasi-Dynamic Wireless Charging (QWC) [2], and (3) Dynamic Wireless Charging (DWC) [2,13]. In SWC, the vehicle is charged while it is stationary. SWC is suitable for homes, workplaces, and public parking areas where vehicles remain parked for a sufficiently long period. However, a major limitation of SWC is range anxiety, which refers to the concern that the vehicle may not have sufficient battery energy to reach its destination or a charging station before the battery is depleted. This limitation can be mitigated by DWC, where power is transferred to a moving vehicle through transmitter coils installed along the roadway and a receiver (Rx) pad mounted underneath the vehicle chassis. In DWC, the transmitter (Tx) coils are typically embedded under the road surface to avoid interaction with traffic. DWC enables continuous charging while the vehicle is in motion, thereby reducing the required battery size and, consequently, the vehicle weight and battery cost. In DWC systems, the charging track can be broadly classified into long-track (Figure 2) and segmented-track (Figure 3) configurations. A long-track configuration uses a continuous Tx coil extending along the roadway, enabling continuous power transfer as the vehicle moves. On the other hand, a segmented-track configuration divides the charging path into multiple independently controlled array of Tx coils, which are excited according to the vehicle position to reduce power losses and improve system efficiency. One of the major disadvantages of segmented track is power pulsation, in which the power delivered to the battery fluctuates, as shown in Figure 3. Moreover, DWC requires extensive charging infrastructure along the roadway, resulting in high capital cost. An alternative is QWC,

in which the vehicle gets charged either while moving at a low speed or when it is stationary for a short period. QWC can be implemented at locations where vehicles naturally slow down or stop, such as bus stops, taxi stands, and traffic signals. Although QWC can provide additional charging opportunities, the relatively short charging duration limits the amount of energy that can be transferred and, therefore, is generally not sufficient to fully charge the vehicle battery.

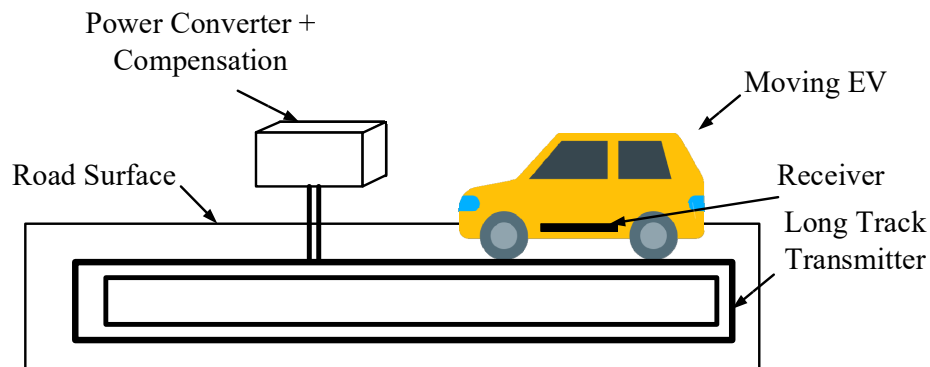


Figure 2. Long track dynamic wireless charging system.

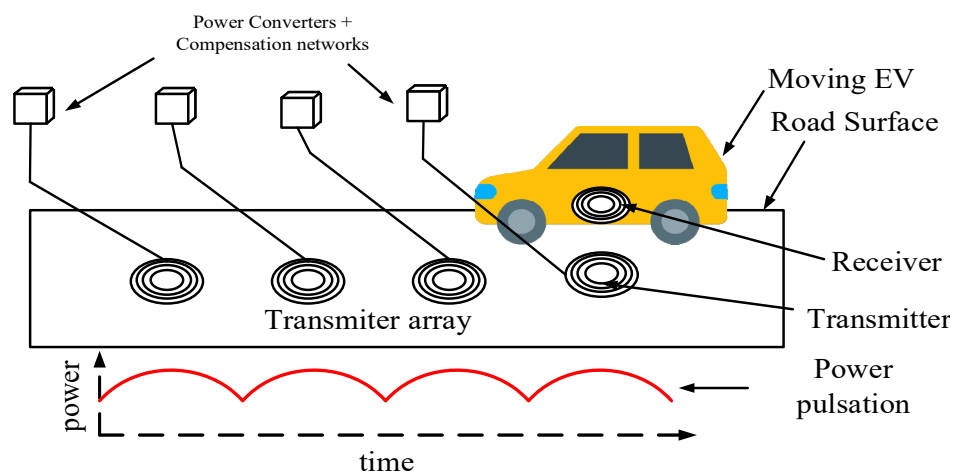


Figure 3. Segmented track dynamic wireless charging system.

This paper discusses the fundamentals of wireless EV charging along with the recent advances in this technology. The advances in compensation networks, coil (pad) design, and power converter architecture, etc., are delineated. The major challenges and future research directions that are expected to shape the evolution of wireless charging technology are highlighted.

2. Basic Concepts Related to WPT

Before understanding the various aspects of WPT system, it is important to first understand its fundamental principles.

2.1. Fundamentals of WPT

Wireless charging of EVs is achieved by employing a transmitter (Tx) coil either mounted on the surface of the ground (surface mounted) or installed beneath the ground surface (flush mounted) and a receiver (Rx) coil mounted onboard the EV. The power transfer is governed by Faraday's law of electromagnetic induction, according to which an alternating magnetic field created by a coil induces an EMF in another coil that is linked to it. The alternating magnetic field is generated by connecting the Tx coil to an inverter (DC–AC power converter) output that supplies high-frequency AC voltage (V_{in}). The self-inductance represents the total amount of magnetic field created by a coil, while the leakage inductance represents the amount of magnetic field that is not linked with the Rx coil. The self-inductances of Tx and Rx coils are L_T and L_R respectively. The mutual inductance (M) represents the extent of magnetic coupling between the Tx and Rx coils, where an alternating current in the Tx coil induces a proportional EMF in the Rx coil. The leakage inductances of Tx and Rx coils are L_{Tl} and L_{Rl} respectively. These two coil systems can be modelled in many different ways. For simplicity, this paper utilizes

the mutual inductance (M -model) equivalent circuit as shown in Figure 4, where V_{in} is the RMS value of the fundamental output voltage of the inverter, I_{in} and I_0 are the RMS values of the input and output currents, respectively, and ω is the angular frequency of the WPT system. The voltage induced in the Rx coil (V_R) due to the Tx coil current (I_T) can be given as:

$$V_R = j\omega MI_T \quad (1)$$

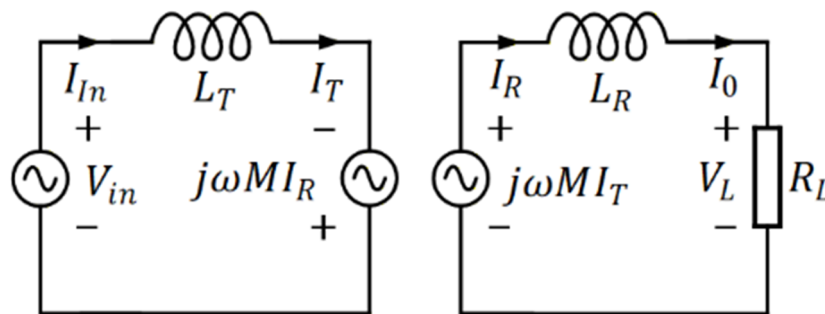


Figure 4. M-model of a basic two coil WPT system.

When these coils are placed close to each other, the coupling coefficient (k , which ranges from 0 to 1) between them becomes high, and the leakage inductance decreases. This reduces the reactive power and circulating current required to transfer a given amount of active power. Consequently, the VA rating of the resonant components and power converter can be reduced, which also helps reduce the overall size of the system. Furthermore, the reduction in leakage inductance and associated circulating current significantly improves the overall efficiency of the system. However, the typical distance (airgap) between the Tx and Rx coils of an EV charging system is relatively large (around 100 mm to 300 mm). This makes the flux linkage between these coils to be relatively lower, which reduces the coupling coefficient (k) between them, thereby resulting in reduced power transfer capability, lower efficiency and increased reactive power requirement. To mitigate these issues, coil design and compensation networks have become the essential components of WPT systems. Compensation networks can be designed to operate the system at resonant frequency (ω_0), thereby achieving unity power factor.

2.2. Functional Aspects of WPT System

In practical applications, many aspects like misalignment, charging characteristics, the directional power flow, etc., influence the performance of the WPT systems. In this subsection, these aspects are briefly discussed.

2.2.1. CC–CV Charging

The battery charging process in WPT systems generally follows a constant-current (CC) and constant-voltage (CV) charging profile [12]. During the CC stage, the battery is charged with a nearly constant current, while its terminal voltage gradually increases as the state of charge (SOC) rises. When the voltage of the battery reaches its maximum value, the charging process shifts from CC to CV. During CV mode, the battery voltage is maintained constant and battery current gradually decreases. Thus, CC–CV charging strategy enables fast charging during the initial stage while preventing overcharging and reducing battery stress during the final stage.

2.2.2. Misalignment

In wireless power transfer (WPT) systems, particularly for DWC, coil misalignment remains a major operational challenge. When the Tx and Rx coils are not properly aligned, the mutual coupling coefficient drops sharply, which directly impacts the overall power transfer efficiency. In practical driving conditions, such spatial deviations can occur across several directions—namely lateral (y -axis), longitudinal (x -axis), combined planar (xy -axis), and rotational tilts arising from vehicle vibrations, road undulations, and suspension variations (as highlighted in Figure 5) [14]. Apart from restricting the delivered power, these misalignments lead to significant leakage of magnetic flux and can cause instability in system operation. Therefore, improving misalignment tolerance has emerged as a crucial thrust area in current research, driving the development of optimized coil designs, enhanced magnetic couplers, and robust compensation circuits to ensure stable power delivery despite varying road conditions.

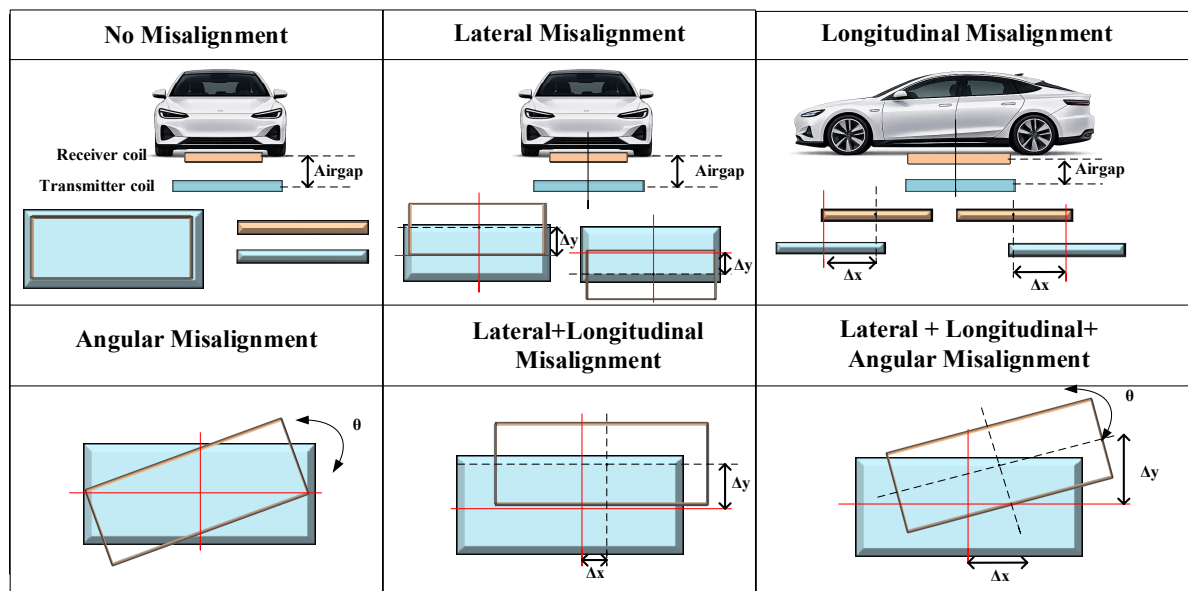


Figure 5. Various types of misalignments in EV wireless charging.

2.2.3. Bidirectional Capability

The rapid adoption of electric vehicles (EVs) has shifted their role from being a simple mode of transportation to becoming distributed energy resources capable of interacting with the electrical grid and surrounding infrastructure. This transformation has been enabled by the bidirectional power transfer (BPT) [15] capability of the WPT system, which allows energy to flow in both directions between the EV battery and external systems. A typical block diagram of bidirectional WPT is shown in Figure 6. Unlike conventional unidirectional charging, where power flows only from the grid to the vehicle, bidirectional power transfer enables EVs to provide stored energy back to the grid, buildings, homes, other vehicles, or electrical loads. As a result, BPT has become the cornerstone technology for Vehicle-to-Everything (V2X) applications, including Vehicle-to-Grid (V2G), Vehicle-to-Building (V2B), Vehicle-to-Load (V2L), and Vehicle-to-Vehicle (V2V), as given in Table 1 [16].

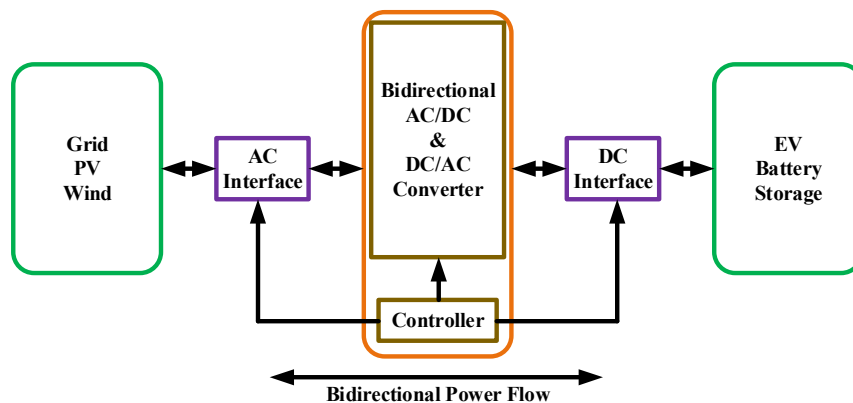


Figure 6. Block diagram of a bidirectional WPT system.

Table 1. Applications of bidirectional WPT.

Application	Power Flow	Main Function	Key Benefits
V2G	EV ↔ Grid	Grid support, peak shaving, frequency/voltage regulation	Grid stability, cost optimization.
V2B	EV ↔ Building	Peak reduction, backup supply	Lower energy cost, improved resilience
V2L	EV → Load	Supply appliances and emergency loads	Portable/off-grid power
V2V	EV ↔ EV	Direct EV-to-EV energy sharing	Improved energy accessibility
V2X	EV ↔ External systems	Intelligent energy management	Flexible and coordinated energy transfer

3. Recent Advancements in Architecture of WPT System

The general architecture of a wireless power transfer (WPT) system consists of a power source, high-frequency inverter (DC–AC converter), compensation network, transmitter coil, receiver coil, rectifier, and load [Figure 7]. The inverter converts the input DC power into high-frequency AC, which is transferred wirelessly through magnetic coupling between the transmitter and receiver coils. The received AC power is then rectified and regulated to supply the load or charge the battery.

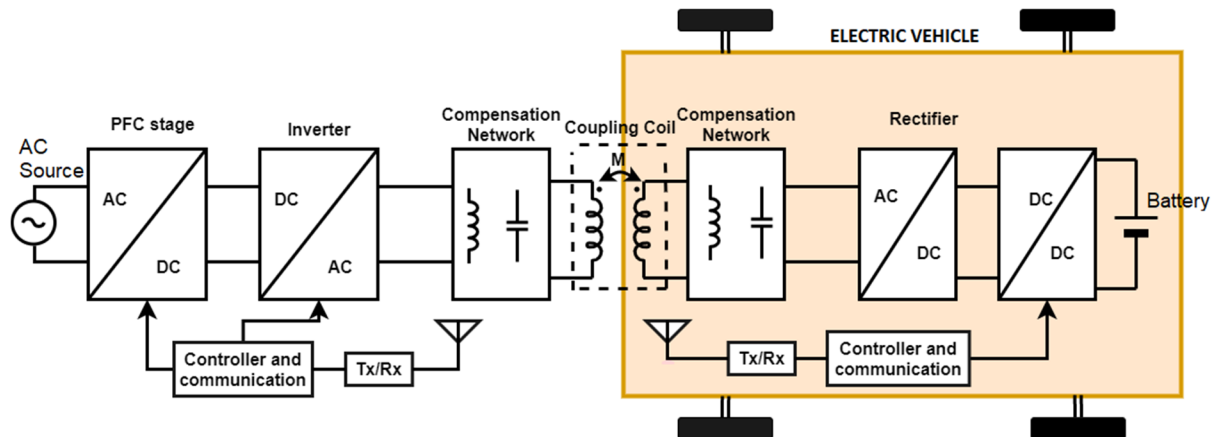


Figure 7. General architecture of WPT system.

3.1. Power Electronic Converters on Tx and Rx Sides

Power electronic converters are the significant part of WPT systems, enabling efficient energy conversion between the grid, the resonant inductive link, and the electric vehicle (EV) battery. Their performance directly influences power transfer capability, conversion efficiency, power quality, switching losses, and system reliability. They are responsible for AC–DC conversion, high-frequency DC–AC inversion, secondary-side rectification, and DC–DC voltage regulation to ensure efficient power transfer from the grid to the battery. Based on their function, the basic converter topologies are classified into front-end AC–DC converters with power factor correction (PFC), high-frequency voltage-source, secondary-side rectifiers, and secondary DC–DC converters. The basic converter topologies employed in the EV wireless charging system are summarized in Table 2. A typical power converter architecture of a WPT system is shown in Figure 8a. Typical output waveforms of an inverter developed at applied power electronics laboratory (APEL), IIT Bombay, are shown in Figure 8b. To meet the growing demands for higher efficiency, bidirectional power flow, fast charging, and compact system design, advanced converter topologies have been adopted for wireless power transfer systems. These are summarized in Table 3. Some advanced power converter topologies are also shown in Figure 9.

Table 2. Basic Power Converter Topologies.

Basic Converters	Topologies	Primary Function
Front-End AC–DC Converters (Tx-Side)	Boost PFC [17], Interleaved Boost PFC [18], SEPIC PFC [19], Z-Source PFC [20], Quasi-Z-Source (qZSI) PFC [21]	Power Factor Correction (PFC) and DC link voltage regulation
High-Frequency Voltage-Source Inverters (VSI) (Tx-Side)	Half-Bridge (HB), Full-Bridge (FB) [22], Class-D (HB) [23], Class-DE, H3 Bridge [24], H5 Bridge [25], Single-Switch Parallel LC Resonant Converter [26]	Generate high-frequency voltage for exciting the transmitter coil
Rx-Side Rectifiers	Diode Rectifier, Active Full-Bridge Rectifier [27], Semi-Active Rectifier [28], Current-Doubler Rectifier (CDR) [29], Half-current-multiplier rectifier [30], Improved Current-Doubler Rectifier (ICCDR) [31], Voltage Doubler Rectifier [32]	AC–DC conversion and battery charging regulation
Rx-Side DC–DC Converters	Buck [33], Boost [34], Buck–Boost [35], Ćuk [36], SEPIC, Interleaved SEPIC Converter [37].	Output voltage/current regulation for battery charging

Table 3. Advanced Power Converter Topologies.

Advanced Converter Architecture	Examples	Purpose/Application
Bidirectional Converters	Quasi-resonant inverter [38], Matrix Converter [39]	V2G, V2V, bidirectional wireless charging
Multi-modular (Modular) Structures	Multi-port converter [40], Series-parallel modular WPT [41], Integrated Modular Multilevel Converter (MMC) [42], Multi-coil modular transmitter systems [43]	High-power charging, fault tolerance, scalability, DWC
Single-Stage AC-AC/AC-DC Architectures	Single-stage PFC converter [44], Single-stage AC-DC Converter [45], Direct AC-AC Matrix Converter [46], Active-Clamped Half-Bridge AC-AC Converter [47], Three-phase Matrix Converter [48], Oak Ridge AC-DC Converter [49]	Reduced converter stages, elimination of DC-link capacitor, compact WPT systems
Multilevel Converter Architectures	Neutral Point Clamp (NPC) [50], Cascaded Multilevel Converter [51], Integrated MMC [52], Combinational MLI [53]	High-power and fast wireless charging with reduced harmonic distortion

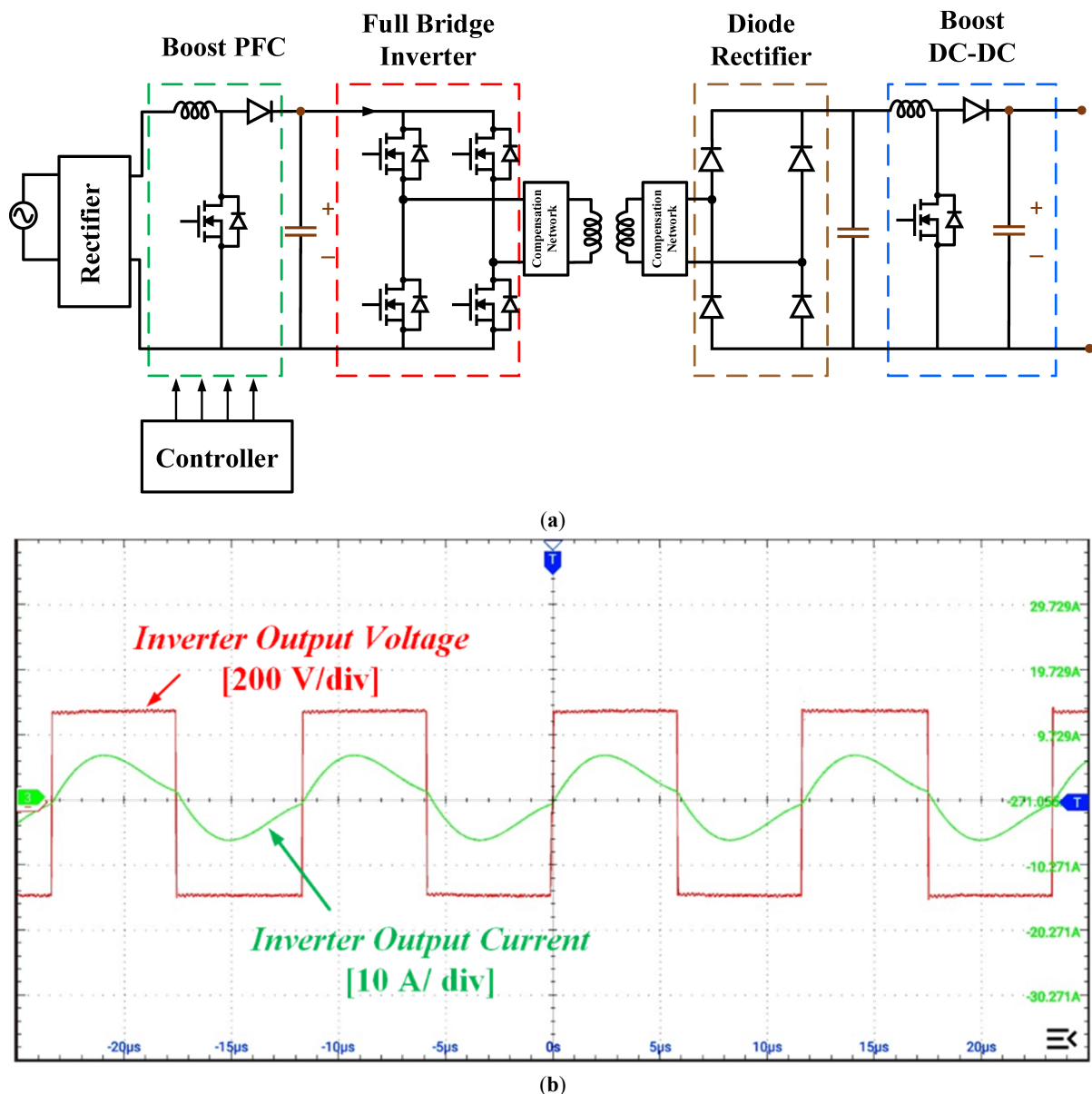


Figure 8. (a) A typical power converter architecture of a WPT system. (b) Typical waveforms of an inverter developed at applied power electronics laboratory (APEL), IIT Bombay.

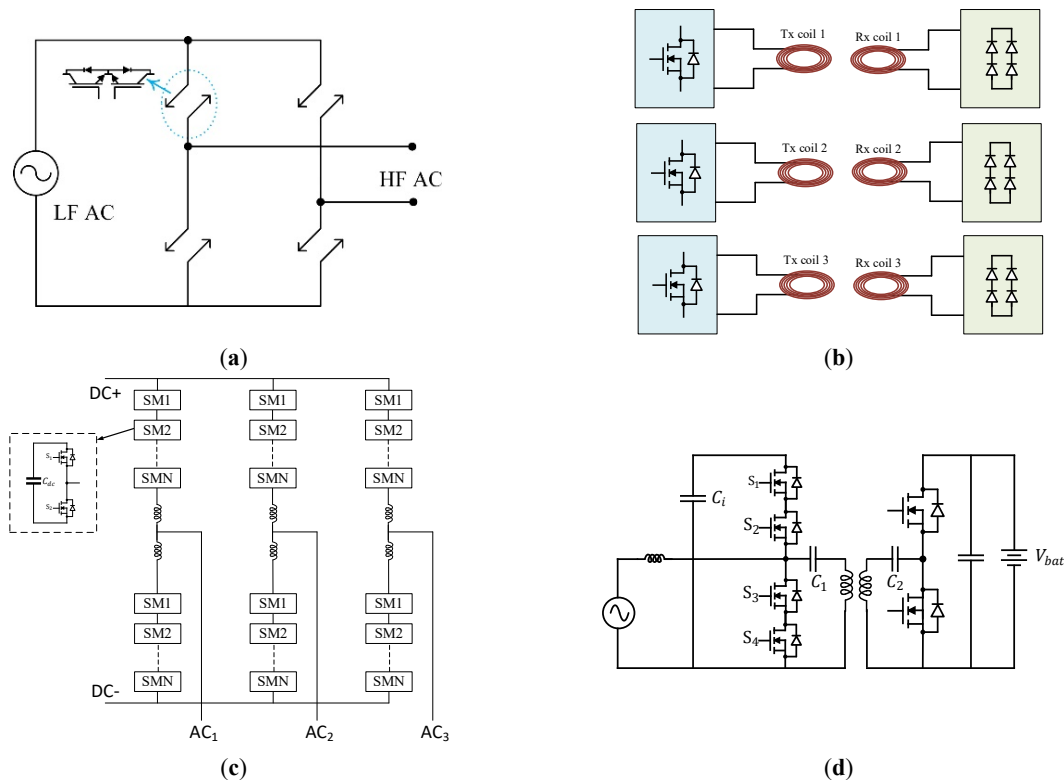


Figure 9. Advanced Power Converter Topologies. **(a)** Matrix Converter. **(b)** Multi-coil Modular Converter. **(c)** Multilevel Converter. **(d)** Direct AC-AC Active-Clamped Half-Bridge Converter. Prepared by the author; based on Reference [47].

Recent Advances in Power Electronic Converters

The recent advancements and trends in the context of power electronic converters have focused on improving power density, reliability, and controllability, which include:

- WBG:** Increasing adoption of Wide-Bandgap (WBG) semiconductor devices, particularly SiC and GaN, for high-frequency and high-power converters to achieve higher power density and lower switching losses, although cost and reliability remain challenges [54–56].
- Reliability:** Research on fewer-switch and fault-tolerant multilevel converter (MLI) topologies for reducing voltage stress, improving reliability, and enhancing converter performance in fast-charging applications [57,58].
- Scalability:** Growing interest in modular and multi-modular converter architectures because of their scalability, flexibility, redundancy, and fault tolerance for high-power wireless charging systems [59,60].
- Renewable Integration:** Development of modular converter structures compatible with renewable energy sources such as solar and wind, together with matrix converters to reduce the number of power conversion stages and simplify WPT charging stations, in particular DWC implementation [61].
- AI/ML Integration:** Integration of Artificial Intelligence (AI) and Machine Learning (ML) for adaptive control, misalignment compensation, system optimization, and AI-based load estimation in wireless charging systems [62,63].
- Integrated Architectures:** Traction components (like inverter, motor windings) are being considered for potential utilization in the wireless charging process. Few studies have even considered integrating the components of wired charging into the wireless charging [64,65].

3.2. Compensation Networks

In WPT systems, the relatively large air gap and weak magnetic coupling introduce significant reactive power, which increases the volt-ampere (VA) rating of the inverter, reduces power transfer capability, and lowers overall efficiency. Compensation networks are the passive LC networks used in WPT systems to minimize these effects. The basic compensation networks (summarized in Table 4) consist of only one capacitor on each side of the coupled coils, giving rise to four classical compensation configurations: Series-Series (SS), Series-Parallel (SP), Parallel-Series (PS), and Parallel-Parallel (PP) [2] as shown in Figure 10.

Table 4. Summary of basic compensation networks.

	Efficiency	Current Gain	Voltage Gain	Input Impedance	Charging Method
SS	$\frac{(\omega M)^2}{[(\omega M)^2 + R_L R_T]}$	$\frac{j\omega M}{R_L}$	$\frac{j\omega M R_L}{(\omega M)^2 + R_L R_T}$	(R)	CC
SP	$\frac{[\omega M]^2 R_L}{[R_R((\omega M)^2 + R_R R_T) + \omega^2(L_R + C_R R_L R_R)[C_R R_L((\omega M)^2 + R_R R_T) + R_T L_R]]}$	$\frac{M}{L_R + R_R C_R \left(R_L + \frac{1}{s C_R}\right)}$	$\frac{R_L}{[-j\omega M + M(\omega)^2 C_R R_L + \frac{R_T L_R}{M}]}$	(C)	CV
PS	$\frac{1}{\left[1 + \frac{R_T R_L}{(\omega M)^2}\right]}$	$\frac{1}{\omega^2 C_T M}$	$\frac{R_L M}{R_L L_T - j\left(\omega M^2 + \frac{R_L R_T}{\omega}\right)}$	(C)	CC
PP	$\frac{R_L(\omega M)^2 C_T}{R_R[C_T((\omega M)^2)] - (L_R + C_R R_L R_R)[- \omega^2 C_T(C_R R_L(\omega M)^2 + R_T L_R)]}$	$\frac{L_T}{M} \frac{1}{1 + j\omega C_R R_L}$	$\frac{R_L M}{\omega(M^2 - L_R L_T)}$	(L)	CV

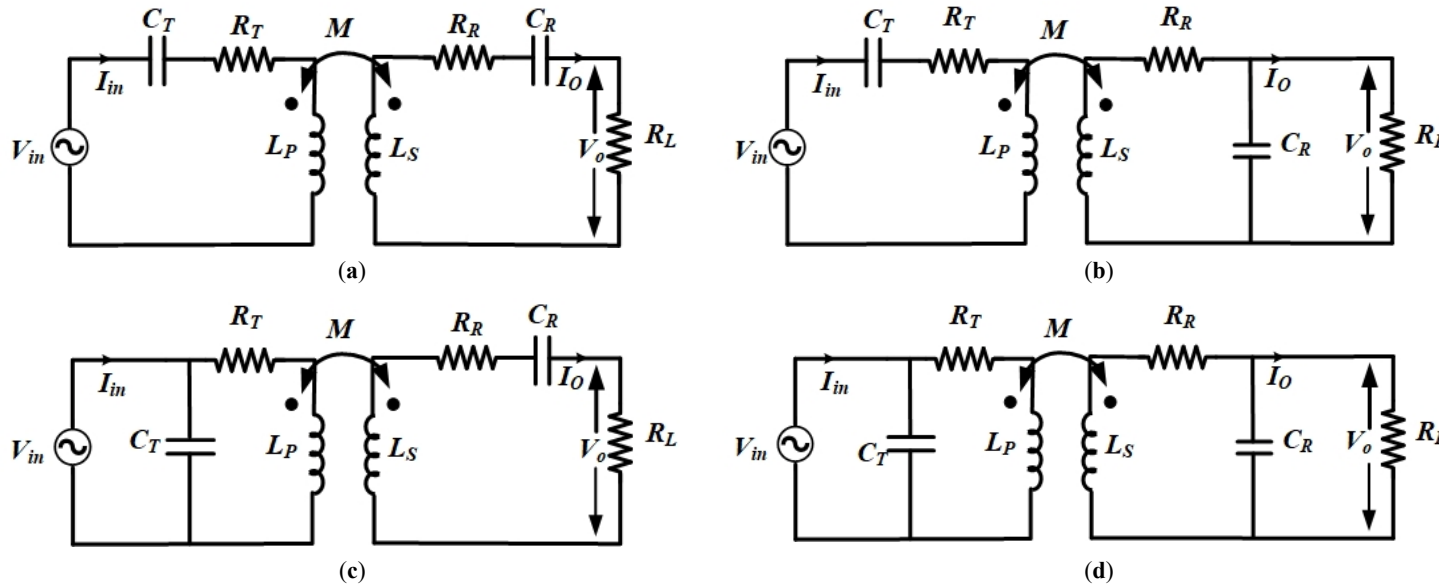


Figure 10. Basic compensation networks. (a) Series-Series (SS). (b) Series-Parallel (SP). (c) Parallel-Series (PS). (d) Parallel-Parallel (PP).

Although SS, PP, SP and PS are the four fundamental compensation networks used in WPT systems, their ability to maintain stable power transfer under severe coil misalignment is limited, which restricts their suitability for practical WPT systems, also it is impossible to achieve multiple objectives like zero phase angle (ZPA) operation, soft switching and efficiency simultaneously. Therefore, to improve misalignment tolerance and provide greater performance flexibility, higher-order compensation networks such as S/SP [66,67], LCL-LCL [68], and LCC-LCC [69–71] are reported. Other combinations reported in the literature include S-LCC [72], CLC-S [73], LCC-S [74,75], LCL-S [76], LCC-P [77,78], and S-CLC [79,80]. The summary of these topologies is given in Table 5. These networks introduce additional reactive components and degrees of freedom, allowing the system characteristics to be optimized for varying coupling conditions. Some of the higher order topologies are shown in Figure 11.

Despite their superior performance, their misalignment tolerance remains insufficient for highly dynamic charging scenarios, particularly when the receiver experiences large variations in position and mutual inductance. Also, a higher number of passive elements increases the size, weight and manufacturing cost of the system. Moreover, several higher order topologies have resonant frequencies that depend on the coupling. Therefore, there is a need to either optimize the available compensation topologies or introduce a hybrid or reconfigurable systems.

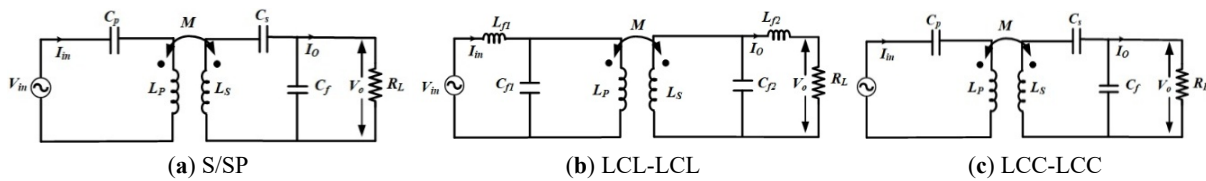


Figure 11. Higher order compensation networks.

Table 5. Summary of higher order compensation networks.

Topology	Resonance Condition	Input Impedance	Output Characteristics	Advantages
S/SP	$\omega = \frac{1}{\sqrt{(L_p + \omega^2 M_p^2 C_f)}} = \frac{1}{\sqrt{(L_s C_s)}}$	$Z_{in} = \frac{\omega^2 M^2}{R_L}$	Provides load-independent output voltage and ZPA operation	Better voltage regulation than SS; simple implementation
S-LCC	$\omega = \frac{1}{\sqrt{(L_p C_p)}} = \frac{1}{\sqrt{(L_s - L_f) C_s}} = \frac{1}{\sqrt{(L_f C_f)}}$	$Z_{in} = \frac{M^2 R_L}{L_f^2}$	Additional resonant branch improves output regulation	High efficiency, load-independent output, improved design flexibility
S-CLC	$\omega = \frac{1}{\sqrt{(L_p C_p)}} = \frac{\sqrt{L_s + L_f}}{\sqrt{L_f^2 C_f}} = \frac{\sqrt{L_s + L_f}}{\sqrt{L_s L_f C_s}}$	$Z_{in} = \frac{\omega^2 M^2 L_f^2}{L_s^2 R_L}$	Enhances resonant tuning with additional capacitor	Greater parameter flexibility; good voltage regulation
CLC-S	$\omega = \frac{1}{\sqrt{(L_p + L_f) C_s}} = \frac{1}{\sqrt{(L_s C_s)}} = \frac{1}{\sqrt{(L_f C_f)}}$	$Z_{in} = -\frac{L_f^2 R_L}{M_p^2}$	Higher-order compensation on primary side	Reduced receiver complexity; lower compensation inductance; ZPA operation
LCL-S	$\omega = \frac{1}{\sqrt{(L_p C_f)}} = \frac{1}{\sqrt{(L_s C_s)}} = \frac{1}{\sqrt{(L_f C_f)}}$	$Z_{in} = \frac{L_f^2 R_L}{M_p^2}$	Current source behaviour with constant output current	Excellent soft-switching and load-independent characteristics
LCC-S	$\omega = \frac{1}{\sqrt{(L_p - L_f) C_s}} = \frac{1}{\sqrt{(L_s C_s)}} = \frac{1}{\sqrt{(L_f C_f)}}$	$Z_{in} = \frac{L_f^2 R_L}{M_p^2}$	Independent control of transmitter current	High efficiency, reduced current stress, flexible parameter design
LCC-P	$\omega = \frac{1}{\sqrt{((L_p - L_f - \frac{M_p^2}{L_s}) C_s)}} = \frac{1}{\sqrt{(L_s C_s)}} = \frac{1}{\sqrt{(L_f C_f)}}$	$Z_{in} = \frac{\omega^2 L_f^2 L_s^2}{M^2 R_L}$	Voltage-source characteristics	Constant output voltage capability; improved impedance matching
LCL-LCL	$\omega = \frac{1}{\sqrt{(L_{f1} C_{f1})}} = \frac{1}{\sqrt{(L_p C_{f1})}} = \frac{1}{\sqrt{(L_s C_{f2})}} = \frac{1}{\sqrt{(L_{f2} C_{f2})}}$	$Z_{in} = \frac{\omega^2 L_{f1}^2 L_{f2}^2}{M^2 R_L}$	Symmetrical compensation with current regulation on both sides	Excellent controllability and load independence
LCC-LCC	$\omega = \frac{1}{\sqrt{(L_{f1} C_{f1})}} = \frac{1}{\sqrt{(L_p - L_{f1}) C_p}} = \frac{1}{\sqrt{(L_s - L_{f2}) C_s}} = \frac{1}{\sqrt{(L_{f2} C_{f2})}}$	$Z_{in} = \frac{\omega^2 L_{f1}^2 L_{f2}^2}{M^2 R_L}$	Maximum design flexibility with independent control of current, voltage and impedance	High efficiency, ZPA operation, load-independent output, superior robustness

Recent Advances in Compensation Networks

- (a) **Optimized Compensation Networks:** Optimizing conventional compensation networks and their parameters is one of the approaches adopted to reduce output-power sensitivity to coupling variation. Optimized S–S [81], LCC [82], and X-type [83] compensation have been proposed to flatten the P–k characteristic and improve misalignment tolerance. Similarly, the topologies like SS, SP, S/SP [84], LCC-S, LCC-LCC, etc. can be optimized to obtain load-independent CC or CV characteristics. Although these topologies improve tolerance

to moderate misalignment, they can still produce substantial output power variation under large misalignment, indicating that compensation network optimization alone is insufficient for achieving robust performance. These limitations have motivated recent research towards reconfigurable, integrated, and hybrid compensation architectures, which combine multiple operating modes or adaptive switching mechanisms to achieve higher misalignment tolerance and improved overall system performance.

- (b) **Detuned Compensation Networks:** Detuned compensation shifts the system away from the resonance condition to obtain a flatter P-k characteristic. Dual-side-detuned S-S [85,86], slight-frequency-detuned S-S/LCC-S [87], and two-frequency detuned S-S network [88] have been developed to extend the stable operating range under coupling variation. These approaches improve misalignment tolerance without requiring continuous real-time modulation of the WPT system.
- (c) **Hybrid Compensation Networks:** Hybrid compensation combines two networks with complementary P-k characteristics so that their variations partially cancel. Combinations such as SS with LCC-LCC and S-LCC with LCC-S, as well as IPOP, IPOS, ISOP, and ISOS configurations [89], have been investigated for improved CC/CV regulation and misalignment tolerance. However, they generally require more components and increase system complexity.
- (d) **Reconfigurable Compensation Networks:** Reconfigurable systems switch between different compensation configurations or operating conditions according to coupling or charging requirements. SS-SP and SS-S-LCC switching has been used for CC-CV charging, while reconfigurable LCL [90], detuned S-S [91], rectifier-based detuned S-S [92], and dual-transmitter SS/LCCC-S [93] approaches extend the stable operating range. Frequency-based reconfiguration [94] further achieves different compensation characteristics at discrete frequencies without additional topology-switching devices.
- (e) **Intermediate-Coil-Based Compensation:** Intermediate-coil-based compensation modifies the magnetic structure by inserting additional resonant coils. A four-coil IPT system [95] provides inherent constant-current operation while improving tolerance to misalignment and reducing excessive primary current under weak or no coupling. However, additional coils increase system size and design complexity.

3.3. Magnetic Coupler

A magnetic coupler primarily consists of a coil made of litz wire, ferrite cores, and shielding materials [shown in Figure 12], which together guide the magnetic flux and minimize electromagnetic leakage. The performance of a magnetic coupler affects the coupling coefficient, thereby impacting the power transfer efficiency, power density, and misalignment tolerance. Therefore, designing an efficient magnetic coupler is essential for achieving reliable, high-efficiency, and safe wireless charging of electric vehicles. The Basic coil structures available are circular, rectangular, DD coil, DDQ coil, and bipolar coil (shown in Figure 13). Circular and rectangular coils are the traditional coil geometries and widely adopted in WPT due to their simple structure. However, they experience a rapid decrease in coupling and transferred power under misaligned conditions. To overcome this, DD, DDQ and bipolar coils are developed that produce a more uniform magnetic field over a wide charging range to maintain stable power transfer under misaligned conditions. The coils mentioned above can be used both as transmitter and receiver depending on the requirement for a particular application.

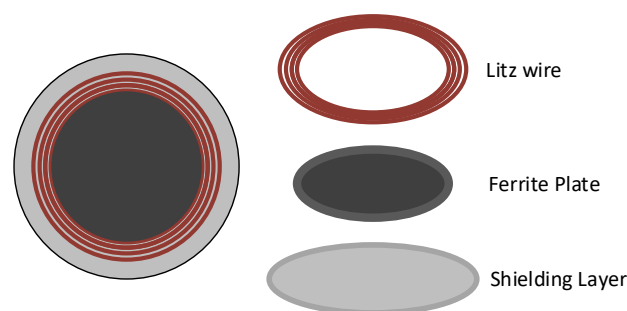


Figure 12. Magnetic coupler used in WPT.

Basic power rails for long track DWC on transmitter-side power rails include E-, U-, W-, I-, S-, and Ultra-slim S-type structures [2], each offering different trade-offs among cost, efficiency, misalignment tolerance, and leakage EMF. Pickup-side structures commonly include E-, U-, S-, and Flat-types, with E- and U-types being widely adopted due to their simple construction, while S-type provides higher power density at the expense of structural complexity.

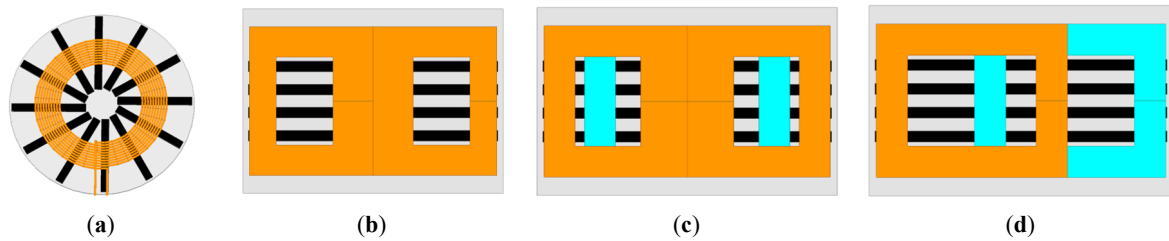


Figure 13. Types of coils: (a) Circular Coil, (b) DD Coil, (c) DDQ Coil, (d) Bipolar coil.

Although conventional configurations such as DD, DDQ, and bipolar coils provide high magnetic coupling under misaligned conditions compared with circular and rectangular coils, they can still suffer from performance degradation at higher misalignment levels and relatively large coil volume. These limitations have motivated the investigation of advanced coil geometries, as shown in Figure 14, which aim to provide improved coupling characteristics, enhanced misalignment tolerance, and/or reduced coil volume. A summary of these advanced WPT coil structures is provided in Table 6, while selected physical implementations (from APEL, IIT Bombay) are shown in Figure 15.

Table 6. Summary of advanced WPT coil structures.

Charging Type	Advanced Coil Geometries	Main Benefits
Static WPT	Cross [96], Hexagonal [97], Pentagonal [98], Octagonal [99], X-pad [100], Segmented [101], Flux-pipe [102], Homogeneous [103]	Improved magnetic-field uniformity, misalignment tolerance, coupling, and reduced leakage flux
Segmented Dynamic WPT	Layered DD [104], Crossed DD [105], DDC [106], Booster Module [107], Mender Coil [108]	Higher coupling, wider charging range, and reduced power fluctuation
Advanced Dynamic WPT	QDQ [109], Quadrupole [110], Integrated Bipolar [111], Poly-phase [112], Tripolar [113], Integrated Tripolar [114]	Multiple flux paths, improved interoperability, and reduced leakage
Multi-coil Dynamic WPT	DSSq [115], Bipolar Double Layer [116], Two-Pair Auxiliary [117], Three-Pair Auxiliary [118], Repeater Array [119], Rectangular Central Solenoid [120]	Stable power transfer and reduced power pulsation during pad transitions

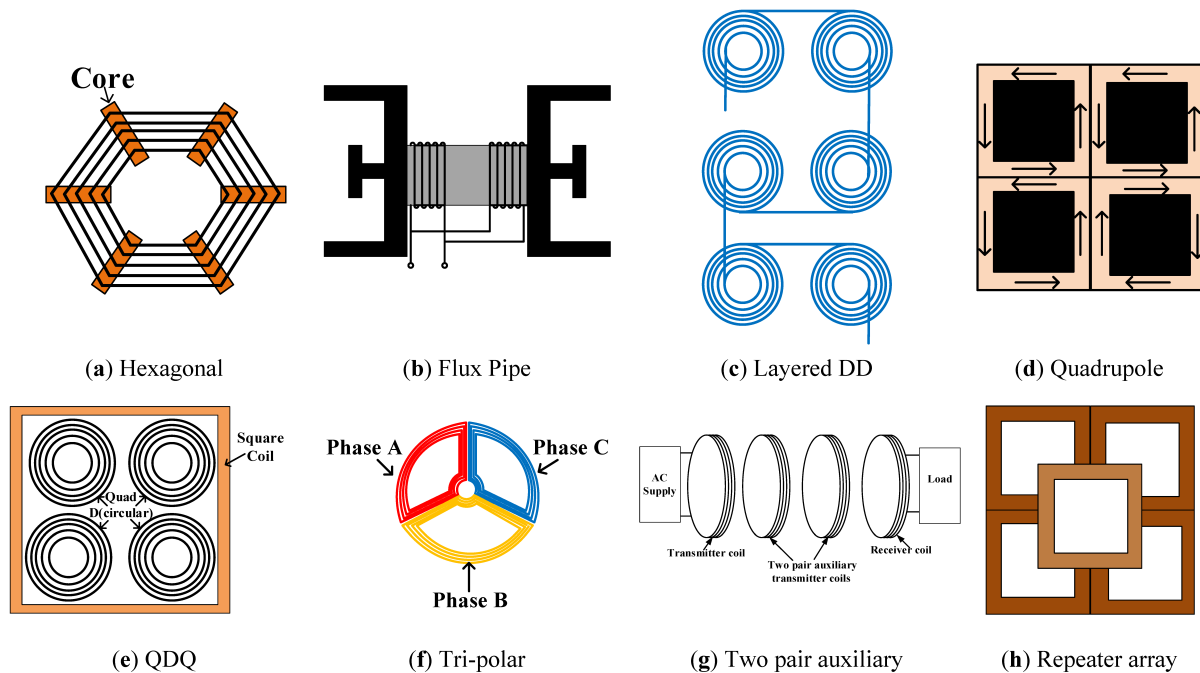


Figure 14. Advanced coil geometries. Prepared by the author; based on Reference [14].

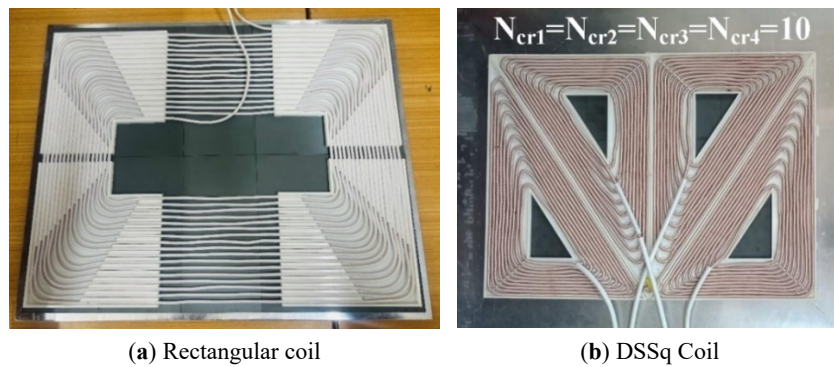


Figure 15. Physical coil geometries (developed at APEL, IIT Bombay).

Recent Advances in Magnetic Coupler

While early research primarily focused on conventional coils, recent developments have shifted toward advanced coil and coupler designs that improve charging performance under practical operating conditions. Recent advancements are no longer focused on developing entirely new coil geometries to overcome the limitations of basic coil structures. Instead, current research emphasizes enhancing the performance of widely adopted coil topologies by improving misalignment tolerance, increasing power density, reducing weight and material consumption, enhancing interoperability, and enabling high-power wireless charging.

- (a) **Optimized Spiral coils:** Recent advancements have focused on optimizing the parameters of spiral coils. These parameters include the number of turns, the spacing between those turns, the width of the conductor, and the inner and outer diameters, as well as the use of ferrite shielding. The goal is to maximize the coupling coefficient and power transfer efficiency while minimizing the copper losses and leakage of magnetic flux. Researchers have utilized finite element analysis (FEA) [121] and optimization algorithms, such as genetic algorithms, particle swarm optimization (PSO), and machine learning techniques, to determine optimal coil dimensions for various air gaps and operating conditions. These optimized designs improve quality factor, reduce AC resistance caused by skin and proximity effects, and enhance the overall system efficiency. For DWC applications, optimized spiral coils have been further modified to enhance tolerance against both lateral and longitudinal misalignment. Various techniques have been reported to realize a more uniform magnetic field across the charging area, including overlapping spiral windings, asymmetric spiral layouts, segmented spiral structures, and multi-layer spiral coils. These improvements help minimize power fluctuations during vehicle movement and increase charging reliability without significantly adding to the complexity of the system.
- (b) **Multi-Coil and Multi-Phase Couplers:** Researchers are increasingly using multi-coil and multi-phase magnetic couplers instead of just one transmitter and receiver coil [115]. These systems have several coils that are not magnetically linked and can be activated separately based on where the receiver is located. Multi-coil designs increase the charging area, improve coupling when coils are misaligned, and reduce power fluctuations. Recently developed three-phase magnetic pads create a rotating magnetic field. This approach leads to higher power density, higher misalignment tolerance, and reduced ferrite requirement compared to conventional single-phase couplers.
- (c) **Advanced Magnetic Materials and Shielding:** Reducing the weight of the receiver pad is important because heavy magnetic couplers make vehicles heavier and lower their driving range. Recent research is focused on using less ferrite by optimizing magnetic circuits, arranging ferrite in segments, and improving winding designs [122–124]. Researchers have already created lightweight couplers that are efficient while using less magnetic material. They are also exploring ferrite-free designs to lower costs and weight without losing efficiency. Recent studies show that good coil performance comes from improving both the design and the material used. High-permeability ferrites, composite materials, improved aluminum shielding [125,126], and magnetic flux guides help direct magnetic flux to the receiver and reduce interference.
- (d) **Interoperable Coil Designs:** The rapid growth of wireless charging has caused a higher demand for interoperable magnetic couplers [127,128] that can work with charging pads from different manufacturers. Current research is exploring transmitter designs that can send power effectively to different shapes of receiver coils without losing performance. Researchers are working on self-decoupled transmitting coils and universal pad designs to meet interoperability standards while ensuring high efficiency, even when the alignment is not perfect.

- (e) **Metamaterial-Assisted Magnetic Couplers:** Metamaterials have recently emerged as a promising approach for improving magnetic coupling [129]. These specially designed layers can control magnetic flux to increase mutual inductance between the Tx and Rx coils [Figure 16]. Experiments have shown improved power transfer efficiency, longer transmission distances, and improved electromagnetic field control without making the coils bigger. Although this technology is still being researched, metamaterial-assisted couplers are seen as a promising option for future high-power wireless charging systems.
- (f) **High-Power and Fast-Charging Couplers:** As wireless charging advances to power levels between 22 and 300 kW, researchers are focusing on creating couplers that can manage higher currents while reducing heat stress. Modern designs optimize the shape of conductors, use litz wire with many strands, enhance cooling methods, and better distribute magnetic flow. These improvements are crucial for enabling fast wireless charging for cars, buses, and commercial vehicles.

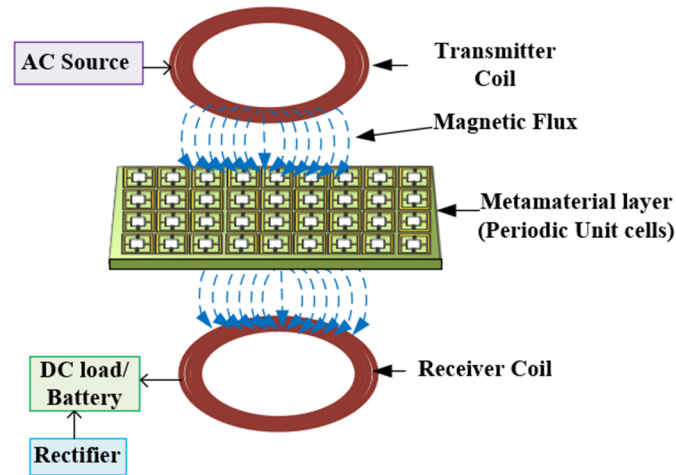


Figure 16. Metamaterial-Assisted Magnetic Couplers.

4. Design of WPT System

The WPT system design mainly depends on the selection of suitable coil parameters and compensation component values. Proper optimization of these parameters is essential to achieve the desired resonant frequency, efficient power transfer, and CC–CV operation [130]. Before presenting the design methodology, it is necessary to establish the key expressions for system efficiency, power transfer, and voltage and current gains, etc. Here, an SS-WPT system is considered for the analysis.

- (i) **CC and CV operating modes:** This can be achieved by designing the system in a way to establish both CC and CV operating points within the desired operating frequency range. At resonance, the output current of an SS-WPT system is independent of the load resistance R_L and is given by

$$I_R = \frac{j\omega_0 M V_S}{(\omega M)^2} \quad (2)$$

At $\omega = \omega_{cv} = \frac{\omega_o}{\sqrt{1 \pm k}}$, the voltage gain becomes independent of R_L and can be expressed as: $A_{cv} = \sqrt{\frac{L_R}{L_T}}$.

This indicates that there are actually two operating frequencies where the output voltage or the voltage gain is independent of load resistance R_L . These frequencies are:

$$\omega_{cv,L} = \frac{\omega_o}{\sqrt{1 + k}} \quad (3)$$

$$\omega_{cv,R} = \frac{\omega_o}{\sqrt{1 - k}} \quad (4)$$

Typically, $\omega_{cv,R}$ is preferred for CV operation as it is higher than the resonant frequency, resulting in the inverter switches undergoing ZVS at turn-on.

- (ii) **Maximum Efficiency operation:** For the given coupling conditions and for a given coil geometry, the expression for efficiency (η) of an SS-WPT system is given by

$$\eta = \frac{1}{1 + \frac{R_R}{R_L} + \frac{R_T}{R_L} \left\{ \frac{[R_L + R_R]^2}{M^2 \omega^2} + \left(\frac{L_R}{M} \right)^2 \frac{\left(\left(\frac{\omega}{\omega_R} \right)^2 - 1 \right)^2}{\left(\frac{\omega}{\omega_R} \right)^4} \right\}} \quad (5)$$

where, ω_R is the Rx-side resonant frequency and R_R and R_T are the Rx and Tx coil resistances, respectively. The frequency ω_{max} at which the maximum efficiency occurs can be obtained by solving: $\left. \frac{d\eta}{d\omega} \right|_{@constant R_L, M} = 0$. This results into $\omega_{max} = \frac{\omega_R}{\sqrt{1 - \frac{1}{2Q_{R,r}^2}}}$, where, $Q_{R,r} = \frac{\omega_R L_R}{R_L + R_R}$ and $\omega_R = \frac{1}{\sqrt{L_R C_R}}$. Therefore, the expression for maximum efficiency (η_{max}) becomes:

$$\eta_{max} = \frac{1}{1 + \frac{R_R}{R_L} + \frac{R_T}{M^2 \omega_R^2} \frac{[R_L + R_R]^2}{R_L} \left\{ 1 - \frac{[R_L + R_R]^2}{4(\omega_R L_R)^2} \right\}} \quad (6)$$

To obtain this peak value of η_{max} , the following condition needs to be satisfied.

$$\left. \frac{d\eta_{max}}{dR_L} \right|_{@constant M} = 0$$

This results in: $R_L \approx \sqrt{R_R^2 + M^2 \omega_R^2 \frac{R_R}{R_T}}$; at which η_{max} is maximum. In most of the applications, the values of R_R and R_L are less than 1 and $R_L \gg R_R$. Therefore, $R_L \approx M \omega_R \sqrt{\frac{R_R}{R_T}}$. If $\omega_R = \omega_0$, then the value of R_L at which efficiency of SS-WPT system becomes maximum is:

$$R_L \approx M \omega_0 \sqrt{\frac{R_R}{R_T}} \quad (7)$$

(iii) Condition for Operating at Maximum Power: The expression for input power of an SS-WPT system is given by:

$$P_{in} = V_{in}^2 \frac{R_L [R_T R_L + (\omega M)^2]}{[R_T R_L + (\omega M)^2]^2 + \left[R_L \left(\omega L_T - \frac{1}{\omega C_T} \right) \right]^2} \quad (8)$$

It can be observed from (8) that there is always a unique value of R_L that corresponds to the maximum value of P_{in} occurs. The condition for maximum power as R_L is varied can be determined by solving: $\frac{dP_{in}}{dR_L} = 0$, which leads to:

$$R_{L,max} = \frac{(\omega M)^2}{(\omega L_T - \frac{1}{\omega C_T})} - \left(\omega L_R - \frac{1}{\omega C_R} \right); \text{ for max. } \bar{P}_s$$

$$R_{L,max} = \frac{\omega C_T (\omega M)^2}{\left(\frac{\omega}{\omega_T} \right)^2 - 1} - \frac{\left(\frac{\omega}{\omega_R} \right)^2 - 1}{\omega C_R} \quad (9)$$

Let $\omega_R = \omega_T = \omega_0$, then

$$R_{L,max} = \frac{\left(\frac{\omega}{\omega_0} \right)^4 k^2 - \left[\left(\frac{\omega}{\omega_0} \right)^2 - 1 \right]^2}{\omega_0 C_R \left(\frac{\omega}{\omega_0} \right) \left[\left(\frac{\omega}{\omega_0} \right)^2 - 1 \right]} \quad (10)$$

- (iv) Choice of Frequency for ZVS: The plots of $\frac{\omega}{\omega_0}$ versus R_L for which $P_{in,max}$ and η_{max} occur are shown in Figure 17. This can be used as a criterion for choosing ω for ZVS. The value of R_L at which both plots meet can be selected as the critical value for achieving $P_{in,max}$ and η_{max} .
- (v) Zero Phase Angle Operation: Zero Phase Angle (ZPA) operation is an important condition in WPT systems, where the input voltage and current are in phase. Under ZPA operation, the input impedance is purely resistive, minimizing reactive power and reducing switching losses. Therefore, proper tuning of the compensation network to achieve ZPA is essential for improving power transfer capability and overall system efficiency.
- (vi) Bifurcation Free Operation: Systems employing variable frequency control (VFC) [131] to regulate variables like output voltage V_L , output current I_L and output power P_0 and intended to achieve zero phase angle

(ZPA) have to restrict their operating region to avoid the bifurcation phenomenon (BFP) [132]. BFP is the phenomenon during which the system exhibits multiple ZPA frequencies. This causes difficulty in identifying the ideal ZPA frequency and may lead to an inefficient or unstable operation of the VFC systems. To prevent this, it is important to ensure that ω_0 is the only ZPA frequency. The following condition is being extensively used for avoiding BFP [132].

$$k < \frac{1}{Q_0} \sqrt{1 - \frac{1}{4Q_0^2}} \quad (10)$$

Equation (10) gives the maximum operating value for to avoid BFP.

(vii) Design Methodology for achieving Maximum Efficiency and avoiding bifurcation: The step-by-step design procedure of an SS-WPT system is in the flow chart shown in Figure 18.

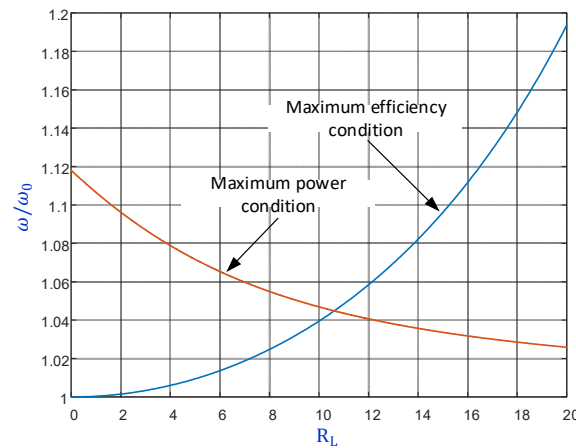


Figure 17. The plots of $\frac{\omega}{\omega_0}$ versus R_L for which $P_{in,max}$ and η_{max} occurs.

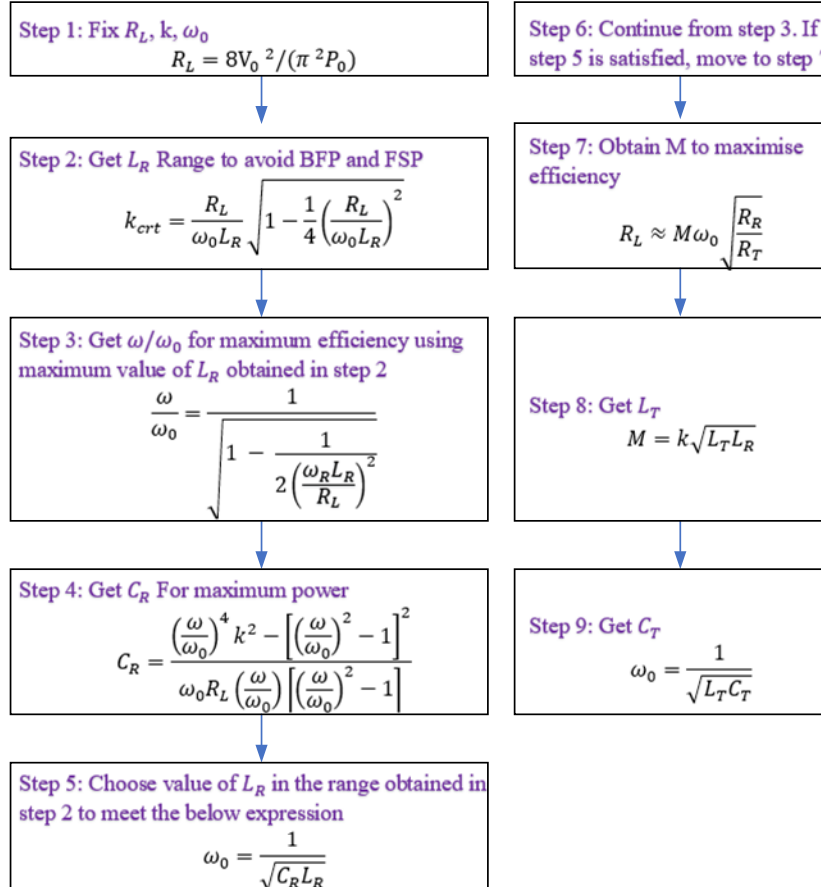


Figure 18. Flow chart of the design procedure of an SS-WPT system.

5. Challenges and Future Research Directions in EV Wireless Charging

The practical deployment of WPT, particularly at high charging power and in dynamic wireless power transfer (DWC) applications, still faces several technical, economic, safety, and infrastructure-related challenges. At the same time, developments in power electronics, sensors, artificial intelligence, communication, and smart-grid technologies are creating new opportunities for improving the performance and functionality of wireless charging systems.

5.1. Challenges in EV Wireless Charging

Despite the remarkable progress in EV WPT technology, its transition from laboratory-scale development to reliable, economical, and large-scale deployment remains constrained by several technical, economic, safety, and infrastructure-related challenges. Practical operating conditions such as coil misalignment, variable coupling, changing air gaps, and dynamic vehicle motion can adversely affect power transfer efficiency and system stability. In addition, the high cost and complexity of power electronic converters, compensation networks, and charging infrastructure remain important barriers to its widespread adoption. One such challenge in WPT is the presence of metal objects or living beings within the air gap or in close proximity to the transmitter and receiver coils, which can pose safety risks during operation. To mitigate these risks, WPT systems employ foreign object detection (FOD) schemes.

Foreign Object Detection (FOD)

Metallic objects such as coins, bolts, nails and tools can generate intense eddy currents when exposed to the alternating magnetic field, resulting in excessive heating, reduced power transfer efficiency, and potential fire hazards. Similarly, living objects, including humans and animals, must be detected to prevent exposure to high magnetic fields. The mechanism of FOD is depicted in Figure 19. As wireless charging systems move toward higher power levels, autonomous operation, and dynamic wireless charging, conventional FOD techniques are no longer sufficient. Consequently, recent research shown in Table 7 has focused on developing intelligent, fast, and highly reliable detection methods that combine multiple sensing technologies with artificial intelligence.

Table 7. Foreign object detection techniques used in WPT system. Prepared by the author; based on Reference [133].

Technique	Principle	Major Advantages	Major Limitations
Magnetic field-based	Magnetic-field disturbance using sensing coils	High sensitivity; good spatial resolution; detects small metallic objects	Mainly metallic objects; sensor placement critical
Vision-based	RGB/IR image processing	Object size, shape, and location identification	Lighting, weather, blocking
Thermal sensing	Infrared temperature monitoring	Direct detection of heating hazards	Requires detectable thermal signature; ambient-temperature dependence
Capacitive	Electric-field/capacitance variation	Effective for humans and non-metallic objects	Environmental and sensitive to geometry of the foreign object
Ultrasonic	Acoustic time-of-flight	Distance and object detection; EM-interference immunity	Affected by object orientation and environment
Hybrid sensor fusion	Multiple sensing modalities	High reliability; reduced false alarms	Higher cost and complexity
FEA-based	Mutual inductance, field, and eddy-current analysis	Material-specific characterization; supports algorithm design	Computationally intensive; model dependent
AI/ML	Data-driven classification of sensor measurements	High accuracy; reduced false positives; real-time classification	Requires representative datasets and computation
Electrical parameter-based	Impedance, inductance, voltage/current variations	Simple and low-cost implementation	Sensitive to misalignment and load variations
Standards-oriented protection	Continuous monitoring, shutdown, power reduction, restart	Enhanced safety and standard compliance	Requires reliable operation across conditions

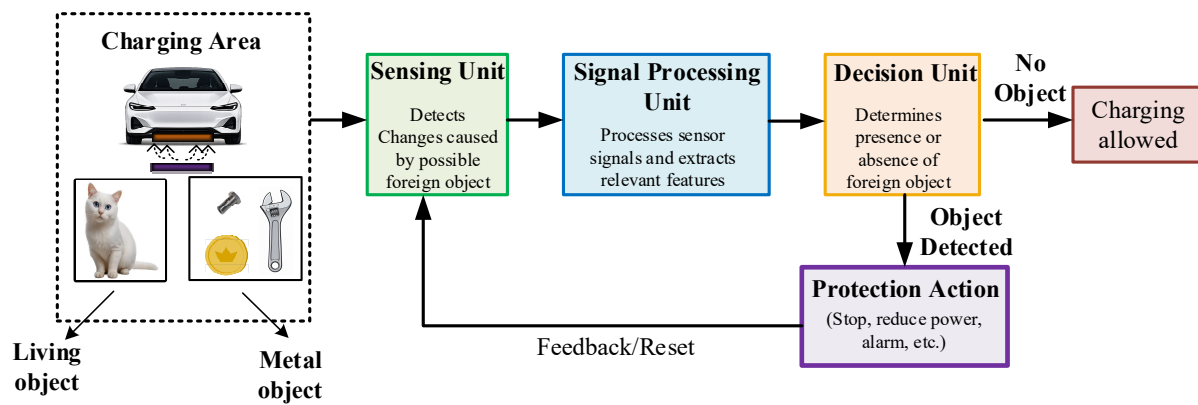


Figure 19. Foreign object detection mechanism in WPT.

The other major challenges associated with EV-WPT systems are briefly summarized in Table 8.

Table 8. Summary of Major Challenges in EV Wireless Charging.

Major Challenge	Main Causes	Possible Improvement
Efficiency reduction	Misalignment, increased air gap, leakage flux, switching losses	Adaptive compensation, self-tuning, improved magnetic design
High infrastructure cost	Coils, converters, shielding, road installation and maintenance	Modular design, standardization, low-cost materials
Electromagnetic safety	Magnetic-field leakage and high-power operation	Improved shielding, field confinement, real-time monitoring
Standardization	Different coil structures, compensation methods and communication protocols	Common charging, safety and communication standards
Grid integration	Simultaneous charging and rapidly varying loads	Smart charging, energy management and V2G
Infrastructure reliability	Mechanical loads, vibration, corrosion and road deformation	Durable materials, condition monitoring and predictive maintenance

5.2. Standards

Standards are required to ensure safe, interoperable, reliable, and efficient operation of wireless charging systems across various vehicles and charging infrastructure. They establish common requirements for power levels, alignment, EMF (Electromagnetic field) exposure, electromagnetic compatibility (EMC), communication, safety, and testing.

5.2.1. Electromagnetic Compatibility (EMC)

Conducted (common mode and differential mode) and radiated Electromagnetic interference (EMI) are the major concerns in any power electronic system, especially high frequency systems. In addition to conventional radiated EMI present in power electronic systems, the high energy stray (leakage) electromagnetic field (EMF) induced in the airgap is another form of radiated EMI, which is also a major concern in WPT systems. This stray EMF is particularly important when the performance of other electrical gadgets in the vicinity of EV is concerned. For example, this may interfere with implanted medical gadgets like pacemakers by inducing unwanted signals and disrupting the pacing activity. Moreover, as EVs are becoming smarter, the number of electrical components used in an EV is also increasing significantly. Therefore, EV WPT systems must comply with electromagnetic compatibility (EMC) requirements to avoid interference with vehicle electronics, communication systems, and nearby equipment. SAE J2954 specifies assessment of radiated emissions, conducted emissions, radiated immunity, conducted immunity, electrostatic discharge (ESD), and magnetic-field immunity for EVs. For vehicle-level WPT operation, the system operates in the 79–90 kHz frequency range, and SAE J2954 recommends a maximum radiated emission level of 82.8 dB μ A/m at the operating frequency. For WPT installations located within 10 m of known sensitive equipment in public spaces, the recommended limit is reduced by 15 dB to 67.8 dB μ A/m. Conducted emissions associated with the WPT function are required to meet applicable FCC (Federal Communications Commission) Part 18 requirements, while other electronic equipment and communication devices inside EV are subject to FCC Part 15 requirements [9].

5.2.2. Human Exposure and ICNIRP Limits

Human exposure to electromagnetic fields is a key constraint for EV WPT because high-frequency magnetic fields are generated across the air gap between the ground assembly (GA) and vehicle assembly (VA). SAE J2954 bases its human EMF exposure requirements on ICNIRP (International Commission on Non-Ionizing Radiation Protection) 2010 for the 79–90 kHz WPT operating range. For the general public, the ICNIRP reference levels specified by SAE J2954 are 27 μT (or 21.5 A/m) for magnetic field strength and 83 V/m for electric field strength. The corresponding basic restriction is an internal electric field of 11.475 V/m at 85 kHz. These limits apply particularly to regions 2 and 3, representing areas outside and inside the vehicle, respectively [9].

5.2.3. Interoperability Limits and Requirements

Interoperability ensures that different manufacturers' ground assemblies and vehicle assemblies can operate together safely and effectively (i.e., they are compatible). SAE J2954 defines three principal WPT power classes: WPT1 (0–3.7 kVA); WPT2 (0–7.7 kVA); and WPT3 (0–11.1 kVA). It also defines Z-classes based on the VA coil ground-clearance range: Z1 = 100–150 mm; Z2 = 140–210 mm; and Z3 = 170–250 mm for the VA. SAE J2954 establishes performance-based interoperability criteria between the Vehicle Assembly (VA) and Ground Assembly (GA) of an EV WPT system. It uses standardized J2954 Test Stations and test procedures to evaluate whether VAs and GAs meet specified power-transfer and safety requirements, including testing with normative Test Station VAs for WPT1, WPT2, and WPT3. The standard also defines WPT power classes and Z-classes to evaluate interoperability under different operating conditions and ground-clearance ranges. In addition, Interoperability Class I and Class II are defined for GAs, with Class I providing broader interoperability for public applications. Thus, interoperability is demonstrated through standardized performance testing rather than requiring every VA to operate with every GA [9].

The summary of existing standards for WPT systems is provided in Table 9.

Table 9. Summary of the popular standards for WPT systems.

Standard	Main Scope/Relevance
SAE J2954:2024 [9]	Light-duty EV stationary WPT; interoperability, safety, EMF, EMC, performance, and alignment; up to 11 kVA.
SAE J2954/2:2022 [134]	Higher-power WPT for heavy-duty EVs, including stationary and some dynamic applications.
IEC 61980-1:2020 [135]	General requirements for EV wireless power transfer systems.
IEC 61980-2:2023 [136]	Communication and positioning requirements for magnetic-field WPT.
IEC 61980-3:2022 [137]	Specific requirements for stationary magnetic-field WPT systems.
IEC PAS 61980-5:2024 [138]	Dynamic WPT interoperability, power transfer, safety, and EMC for moving EVs.
ISO 5474-4:2025 [139]	On-board MF-WPT requirements for passenger and light commercial EVs; safety, efficiency, interoperability, and testing.
ISO 5474-6:2025 [140]	MF-WPT requirements for heavy-duty vehicles, including static and dynamic applications.
ICNIRP 2010 [141]	Human exposure limits for time-varying electric and magnetic fields (1 Hz–100 kHz).
IEEE C95.1-2019 [142]	Human exposure limits for electric, magnetic, and electromagnetic fields (0 Hz–300 GHz).
ISO 15118-1:2019 [143]	Vehicle-to-grid communication framework, including communication relevant to wireless charging.

5.3. Future Research Directions

Future research is expected to focus on improving charging capability, system integration, automation, intelligent control, and large-scale infrastructure. Key research areas include high-power wireless charging, unified wired and wireless charging, autonomous charging, dynamic wireless charging highways, simultaneous power and data transfer, and AI-based WPT systems. These developments aim to improve efficiency, reliability, user convenience, scalability, and economic feasibility. The major future research directions of WPT systems are briefly summarized in Table 10.

Table 10. Advanced technical trends in next-generation WPT. Prepared by the author; based on Reference [144].

Research Trend	Technical Concept	Key Parameters/Control Variables	Expected Technical Improvement
Misalignment-tolerant couplers	Uses optimized or multi-coil magnetic structures	Coupling coefficient, coil displacement, leakage flux	Maintains power transfer under lateral and angular displacement
Segmented DWPT	Energizes only the Tx segment located near the moving vehicle	Vehicle position, speed, segment activation, transferred power	Reduces standby losses and unnecessary magnetic-field exposure
AI-assisted control	Data-driven estimation and optimization of system operation	Coupling, load, temperature, battery state, power demand	Adaptive power regulation and improved efficiency
Bidirectional WPT	Allows power flow from grid to EV and EV to grid	DC-link voltage, power direction, battery SOC, grid demand	Enables V2G/V2H and grid-support functions
Power–data integration	Uses the wireless interface for charging and communication functions	Authentication, alignment, billing, battery data	Reduced communication hardware and improved automation
Digital-twin-based WPT	Real-time virtual representation of the physical charging system	Electrical, thermal and operational states	Online diagnosis, optimization and predictive maintenance
Predictive maintenance	Uses measured degradation indicators to predict failures	Temperature, impedance, losses, insulation and converter parameters	Increased infrastructure availability and reduced maintenance cost

6. Conclusions

This paper has discussed the current trends in coil design, compensation networks and power converters, highlighting their contributions to improving misalignment tolerance, system performance and efficiency. A step by step design methodology for designing an SS-WPT system is provided. This methodology accounts for the critical aspects like frequency bifurcation, zero voltage switching, maximum efficiency, and maximum power transfer, thereby supporting optimal design and operation of WPT systems. Despite this progress, several challenges, including foreign object detection, infrastructure cost, interoperability, standardization hinder the adoption of WPT systems. Future research is expected to focus on hybrid and adaptive compensation networks, control techniques, AI-assisted optimization, advanced magnetic materials, etc. Continued efforts in these areas are essential to develop reliable, safe and efficient interoperable WPT systems.

7. Biographies of the Authors



Vivek Agarwal (Fellow, IEEE) received his Ph.D. in Electrical Engineering from the University of Victoria, Victoria, BC, Canada, in 1994. After a brief tenure as a Research Engineer at Statpower Technologies, Burnaby, BC, Canada (1994–1995), he joined the Department of Electrical Engineering at Indian Institute of Technology Bombay, Mumbai, India, where he is currently a Professor. His research interests are in power electronics, with a focus on transportation electrification, inductive resonant wireless power transfer, power quality, MMCs, renewable energy conversion, and microgrids. He serves on the editorial boards of IEEE Transactions on Power Electronics and IEEE Transactions on Industry Applications.



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