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Research article

Simulation-Based evaluation of dynamic wireless charging systems for electric vehicles: Efficiency, limitations, and future directions

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Abstract: The increasing focus on environmentally sustainable technologies has catalyzed significant advancements in electric vehicles (EVs), marking a pivotal shift in the transportation industry. Among these developments, wireless charging technology for EVs has emerged as a transformative innovation, attracting substantial interest in research and development. These advancements aim to reduce greenhouse gas emissions, establish EVs as a primary mode of transportation, and contribute to a more sustainable future. Electric vehicles are generally categorized into hybrid and pure electric types. Hybrid EVs combine internal combustion engines with onboard energy storage systems for propulsion and charging, serving as an intermediate step toward full electrification. In contrast, pure EVs rely entirely on external energy sources, necessitating the use of dedicated charging infrastructure. Despite the widespread adoption of conductive charging methods, they face challenges such as reliance on physical connections, which can be cumbersome and inefficient. Wireless charging, particularly through contactless power transfer (CPT), has demonstrated significant potential to overcome these challenges. This technology offers key benefits, including higher efficiency, tolerance to misalignment, and reduced charging times, positioning it as a viable alternative to conventional charging methods. Recent advancements, driven by extensive research, have further enhanced the practicality and efficiency of wireless charging systems. This study investigates dynamic wireless charging systems for EVs, addressing the critical need to reduce environmental impact and enhance charging convenience. It utilizes simulations to analyze the performance of dynamic charging systems employing resonant inductive power transfer technology under real-world conditions. Variations in parameters such as alignment and gap are examined to provide insights into system performance and optimization. The findings of this research aim to advance the development of wireless charging technology, emphasizing its potential to revolutionize the transportation sector. By addressing existing

challenges and offering innovative solutions, this study contributes to the pursuit of sustainable and efficient mobility systems.

Keywords: electric vehicles; wireless charging systems; contactless power transfer; dynamic charging; resonant inductive power transfer; Matlab/Simulink Simulation

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Nomenclature: EV: electric vehicle; AC: alternating current; DC: direct current; G2V: grid to vehicle; V2G: vehicle to grid; EVCS: electric vehicle charging station; RPT: roadway power transfer; WPTS: wireless power transfer system; DWPT: dynamic wireless power transfer; RPT: roadway power transfer; OPT: online power transfer; OLEV: online electric vehicle; KAIST: Korea Advanced Institute of Science and Technology
Variables: Input voltage: V_{in}, Volts (V); output voltage: V_{out}, Volts (V); power: P, Watts (W); inductor: L, Henry (H); capacitor: C, Farad (F); load resistance: R_L, Ohms (Ω)

1. Introduction

1.1. Context and background

The global transition toward sustainable energy solutions has significantly accelerated the adoption of electric vehicles (EVs), which are increasingly recognized as a key element in mitigating climate change and reducing fossil fuel dependency. EVs offer a promising alternative to traditional internal combustion engine vehicles, contributing to reduced greenhouse gas emissions and improved air quality. Despite their environmental benefits, EVs face persistent challenges that hinder their widespread adoption. These challenges include limited driving range, lengthy charging times, and insufficient charging infrastructure, particularly in urban environments where space constraints exacerbate the problem [1,2].

Wireless power transfer (WPT) technology has emerged as a transformative solution to these challenges. WPT facilitates contactless energy transfer between a transmitter and receiver using electromagnetic fields, eliminating the need for physical connectors and reducing maintenance concerns [3]. Within this framework, dynamic wireless charging systems represent a significant advancement. Unlike static charging, dynamic charging allows EVs to recharge while in motion, offering seamless operation and potentially alleviating range anxiety by enabling continuous energy replenishment during travel [4].

1.2. Problem statement

Traditional EV charging systems rely heavily on physical connectors and static charging stations, which present inefficiencies and operational constraints. These systems require vehicles to remain stationary for extended periods, which limits user convenience and contributes to range anxiety. Additionally, reliance on stationary infrastructure restricts EV flexibility, especially in densely populated urban areas where space is limited [5].

Dynamic wireless charging systems offer a promising alternative by enabling energy transfer while EVs are in motion. This approach has the potential to address key challenges, including extending driving ranges, optimizing energy usage, and reducing the need for expensive charging infrastructure. However, the implementation of dynamic wireless charging systems poses significant challenges, such as efficiency losses due to misalignment, variations in the gap between coils, and operational inconsistencies in real-world conditions [6]. These issues necessitate comprehensive research to evaluate the feasibility and performance of such systems.

1.3. Objectives

This study aims to explore the feasibility, design, and implementation of dynamic wireless charging systems for electric vehicles (EVs). Specifically, it focuses on:

1. Theoretical modeling of wireless power transfer mechanisms, emphasizing resonant inductive coupling.
2. Simulating system performance under various conditions, such as misalignment, gap variations, and frequency tuning, using MATLAB/Simulink.
3. Evaluating key performance metrics, including power transfer efficiency, mutual inductance, and system stability, to identify opportunities for optimization.

By combining theoretical and simulation-based approaches, this research seeks to provide valuable insights into the operational dynamics of dynamic wireless charging systems and propose strategies for their enhancement and practical application.

1.4. Significance of the study

The findings of this study have significant implications for the advancement of sustainable transportation infrastructure. Dynamic wireless charging systems have the potential to reduce EV range anxiety, improve charging convenience, and minimize reliance on stationary charging stations, especially in urban environments where spatial constraints limit the deployment of traditional infrastructure [7].

By addressing critical knowledge gaps and identifying solutions to technical challenges, this research contributes to the development of smart, sustainable mobility solutions. It provides actionable insights for researchers, policymakers, and industry stakeholders, paving the way for the widespread adoption of dynamic wireless charging systems and fostering a cleaner, more efficient transportation ecosystem.

2. Motivation

The global transition toward electric vehicles (EVs) represents a pivotal step in promoting sustainable transportation. Despite numerous environmental advantages, the widespread adoption of EVs continues to face substantial challenges, including limited driving ranges, extended charging durations, and insufficient infrastructure. These factors significantly contribute to “range anxiety”, a primary concern among EV users in both urban and rural settings, thereby impeding the broader adoption and scalability of EV technology [8].

Conventional EV charging systems typically rely on stationary infrastructure, requiring vehicles to remain parked for prolonged periods. This reliance not only occupies valuable urban space, particularly in densely populated areas, but also involves physical connectors that are susceptible to wear and environmental degradation, resulting in elevated maintenance costs and reduced reliability [9]. Dynamic wireless power transfer (DWPT) systems have emerged as a promising alternative by enabling vehicles to charge while in motion through resonant inductive coupling. These systems potentially minimize dependence on stationary charging, reduce vehicle downtime, and significantly extend driving ranges, thereby enhancing the overall user experience. However, the practical implementation of DWPT technology presents considerable technical challenges, including efficiency losses due to coil misalignment, variability in transferred power, and the complexities associated with integrating these systems into existing transportation infrastructure [3].

A critical aspect of addressing these challenges involves the comprehensive analysis and design of compensation topologies employed in DWPT systems. Among the most extensively studied are the fundamental topologies: series-series (SS) and series-parallel (SP). The SS topology is characterized by simplicity and ease of implementation, rendering it suitable for systems with relatively stable loads and consistent alignment. Nevertheless, it exhibits pronounced sensitivity to variations in mutual inductance due to misalignment, which significantly limits its effectiveness in dynamic scenarios [4]. In contrast, the SP topology enhances voltage regulation and provides improved tolerance to load variations but entails greater complexity in tuning and control [10].

To mitigate the limitations of fundamental configurations, advanced and hybrid compensation topologies have been developed. Notably, the LCC-S topology has garnered considerable attention for its ability to deliver constant current output and maintain high efficiency under dynamic operating conditions. LCC-S combines series and parallel compensation components with additional reactive elements to improve resilience to misalignment and load variability [11,12]. A key advantage of this topology is its inherent support for zero-voltage switching (ZVS), which minimizes switching losses and prolongs the operational lifespan of power electronic components. Furthermore, LCC-S exhibits superior performance in applications where coil alignment and coupling coefficients are subject to frequent changes, thereby ensuring robust and stable energy transfer [12].

Additionally, hybrid configurations such as LCL and LCL-LCC topologies have been introduced to address trade-offs between efficiency, design complexity, and adaptability. The LCL topology incorporates an auxiliary inductor to improve filtering performance and reduce harmonic distortion [13]. When combined with LCC elements, the resulting LCL-LCC topology achieves a balance between maintaining resonant conditions, supporting soft-switching techniques, and enhancing tolerance to misalignment [14,15]. These attributes make hybrid topologies particularly promising for real-world DWPT deployments where environmental and operational conditions are variable.

Accurate modeling and simulation of these compensation topologies are essential for evaluating and optimizing their performance. Platforms such as MATLAB/Simulink enable comprehensive time-domain and frequency-domain analyses, facilitating the investigation of key performance metrics, including mutual inductance, reactive power flow, voltage and current waveforms, and power transfer efficiency. Simulations are particularly valuable for assessing performance degradation due to lateral or longitudinal misalignments, coil separation variations, and dynamic vehicular motion [16].

From a practical standpoint, the advancement of DWPT technology (through the selection and optimization of robust compensation topologies, particularly LCC-S) is critical to reducing reliance on static infrastructure, alleviating spatial constraints in urban environments, and enhancing transportation system flexibility. Strategic integration of DWPT systems must emphasize modularity, scalability, interoperability, and cost-effectiveness. Ultimately, innovations in compensation topology design will be foundational in the widespread deployment of reliable and efficient wireless charging systems for electric vehicles [17].

3. Materials and methods

3.1. Overview of dynamic charging systems

Dynamic wireless charging systems represent a paradigm shift and transformative innovation in electric vehicle (EV) charging technology. These systems utilize electromagnetic coupling to enable seamless, contactless energy transfer between primary coils embedded in roadways and secondary coils installed in vehicles. This advanced technology eliminates the need for physical connectors, thereby reducing maintenance requirements and improving system reliability. A key feature of dynamic wireless charging is its ability to provide a continuous charging solution, allowing EVs to recharge their batteries while in motion. This capability significantly reduces reliance on stationary charging infrastructure and mitigates range anxiety, a common barrier to EV adoption. By facilitating energy transfer during travel, these systems enhance vehicle range and improve the overall convenience of EV operation. Dynamic wireless charging systems are particularly advantageous in urban environments, where space for static charging infrastructure is limited, and on highways, where they can support uninterrupted long-distance travel. The seamless integration of these systems into transportation networks holds the potential to revolutionize EV charging, paving the way for a more efficient and sustainable future in mobility [1,5,18].

3.1.1. Approaches to dynamic charging

Dynamic wireless charging systems can be classified into three primary configurations, each offering distinct advantages and addressing specific operational requirements:

- **Track-based systems:** Track-based systems are implemented on dedicated lanes equipped with embedded charging coils. These systems operate under controlled conditions, ensuring high energy transfer efficiency, making them particularly suitable for public transportation networks and fleet vehicles. Their design minimizes variables such as misalignment and vehicle speed fluctuations, enabling consistent and reliable energy delivery [6].
- **Road-based systems:** Road-based systems integrate charging coils into conventional roadways, providing accessibility for general traffic. While this configuration expands the applicability of dynamic charging, it introduces challenges such as coil misalignment and energy losses due to variations in vehicle speed and positioning. Advanced alignment technologies are essential to mitigate these issues and maintain system efficiency [7].
- **Hybrid systems:** Hybrid systems combine elements of track-based and road-based configurations, offering a balance between efficiency and flexibility. These systems are particularly effective in mixed-use scenarios, accommodating diverse operational requirements and enhancing compatibility across various vehicle types and traffic conditions. Hybrid solutions provide a versatile approach to dynamic charging, making them suitable for a wide range of environments [19].

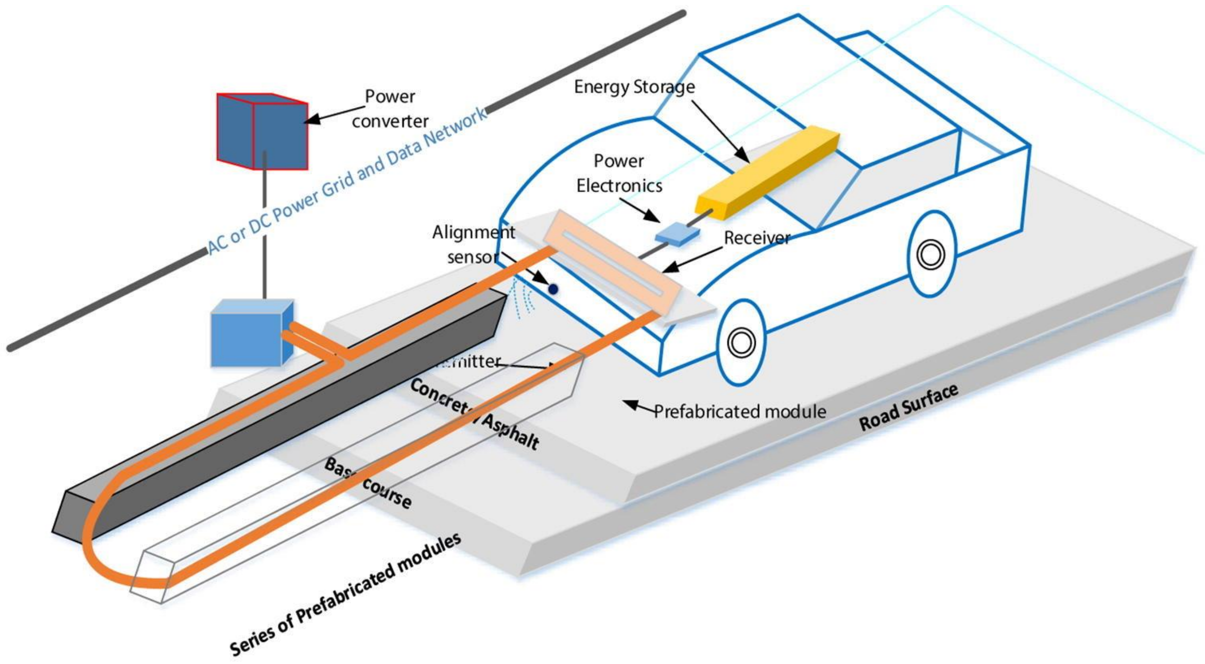
These configurations highlight the adaptability of dynamic wireless charging systems to diverse transportation needs. By improving energy transfer efficiency, expanding accessibility, and supporting sustainable EV charging infrastructure, these systems demonstrate their potential to revolutionize modern mobility.

3.1.2. System components and operation

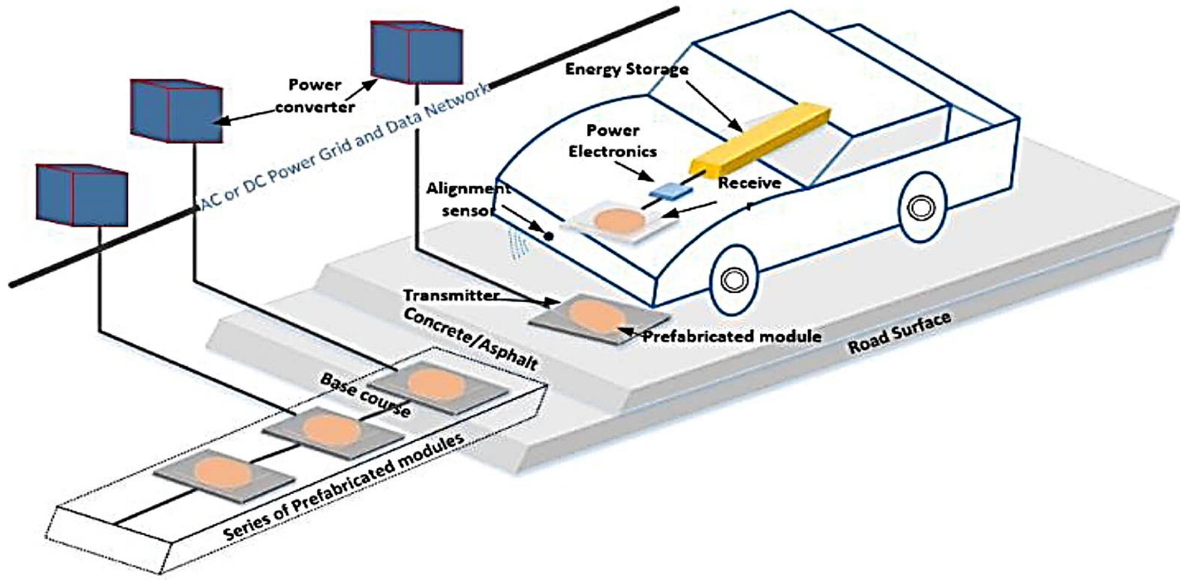
Dynamic wireless charging systems consist of several key components that work together to enable efficient energy transfer [1,2,18]:

- **Primary coils:** Embedded beneath road surfaces, these coils generate a magnetic field when energized by an alternating current. They serve as the primary source of energy transmission to the vehicle.
- **Secondary coils:** Installed within vehicles, these coils capture the magnetic field produced by the primary coils and convert it back into electrical energy to charge the vehicle's onboard battery.
- **Power electronics:** Comprising rectifiers, inverters, and controllers, these components regulate current and voltage to ensure efficient energy transfer while maintaining system stability and safety.

The dynamic wireless electric vehicle charging system (D-WEVCS) represents a promising technology aimed at addressing challenges related to the range limitations and costs associated with electric vehicles (EVs). As illustrated in Figure 1, the system integrates primary coils embedded within the road's concrete surface. These coils are powered by a high-voltage, high-frequency alternating current (AC) source, along with compensation circuits connected to a microgrid and/or renewable energy sources (RES). For effective operation of the D-WEVCS, transmitter pads and power supply segments must be strategically installed at specific locations and along predefined routes. This configuration ensures continuous energy transfer to EVs as they move, enhancing range and operational efficiency. This innovative approach to EV charging offers significant potential for improving the sustainability and convenience of electric mobility, particularly in urban and high-traffic environments.



(a)



(b)

Figure 1. Basic diagram of dynamic wireless electric vehicle charging systems [1,20–23].

3.1.3. Roadway and online power transfer systems

Dynamic charging systems can be further categorized based on their configuration, with roadway power transfer (RPT) and online power transfer (OPT) representing two key approaches [1,20–23]:

- **Roadway power transfer (RPT):** In this configuration, the primary coil is distributed over an area of the roadway, allowing energy transfer within that zone. This setup typically operates at lower resonant frequencies and is optimized for high power levels. The roadway subsystem includes the input side of the resonant converter and the distributed primary windings, collectively known as the "track", while the secondary coil, referred to as the "pickup coil", resides in the vehicle. These systems are typically powered by a three-phase AC or high-voltage DC supply.

- **Online power transfer (OPT):** This advanced system supports high-efficiency energy transfer during vehicle motion. An example of this technology is the online electric vehicle (OLEV), developed by the Korea Advanced Institute of Science and Technology (KAIST). The OLEV system converts a 60 Hz frequency to 200 kHz using an inverter, enabling up to 80% wireless energy transfer efficiency. It can deliver 200 A of current through its system while powering the motor or charging the battery, depending on operational requirements.

In Figure 2, the operational modes of the system are illustrated. When power transmitters are available, they collect electricity from the ground and distribute it to either the motor or the battery, depending on the vehicle's requirements. In the absence of power transmitters, the OLEV relies on its onboard battery, ensuring uninterrupted mobility even during charging [1,20–23].

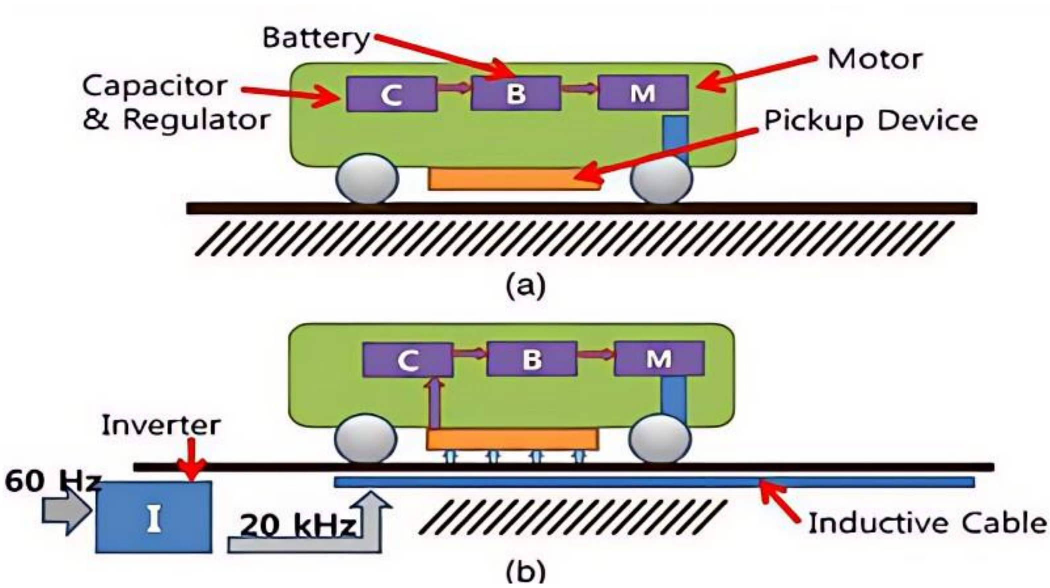


Figure 2. (a) Wireless power transfer (WPT) without transmitters; (b) WPT with transmitters [1,20–23].

3.1.4. Fundamentals of wireless power transfer systems (WPTS) for roadway-powered electric vehicles (RPEVs)

The WPTS for roadway-powered electric vehicles is designed to deliver high power efficiently across a moderate air gap to avoid collisions and ensure operational safety. The WPTS is composed of two key subsystems:

1. **Roadway subsystem:** This subsystem provides power through a rectifier, a high-frequency inverter, a primary capacitor bank, and a power supply rail. It is designed to withstand harsh road environments and maintain economic feasibility for installation over long distances.
2. **On-board subsystem:** This subsystem receives power and includes a pickup coil, a secondary capacitor bank, a rectifier, and a battery regulator. It is compact and lightweight, enabling seamless integration into EVs.

The overall configuration of the WPTS ensures compatibility with the demands of roadway-powered electric vehicles, as shown in Figure 3 [1,20–23]. The durability of the roadway subsystem and the compactness of the onboard subsystem are critical factors in ensuring long-term operational efficiency and facilitating integration into diverse transportation systems.

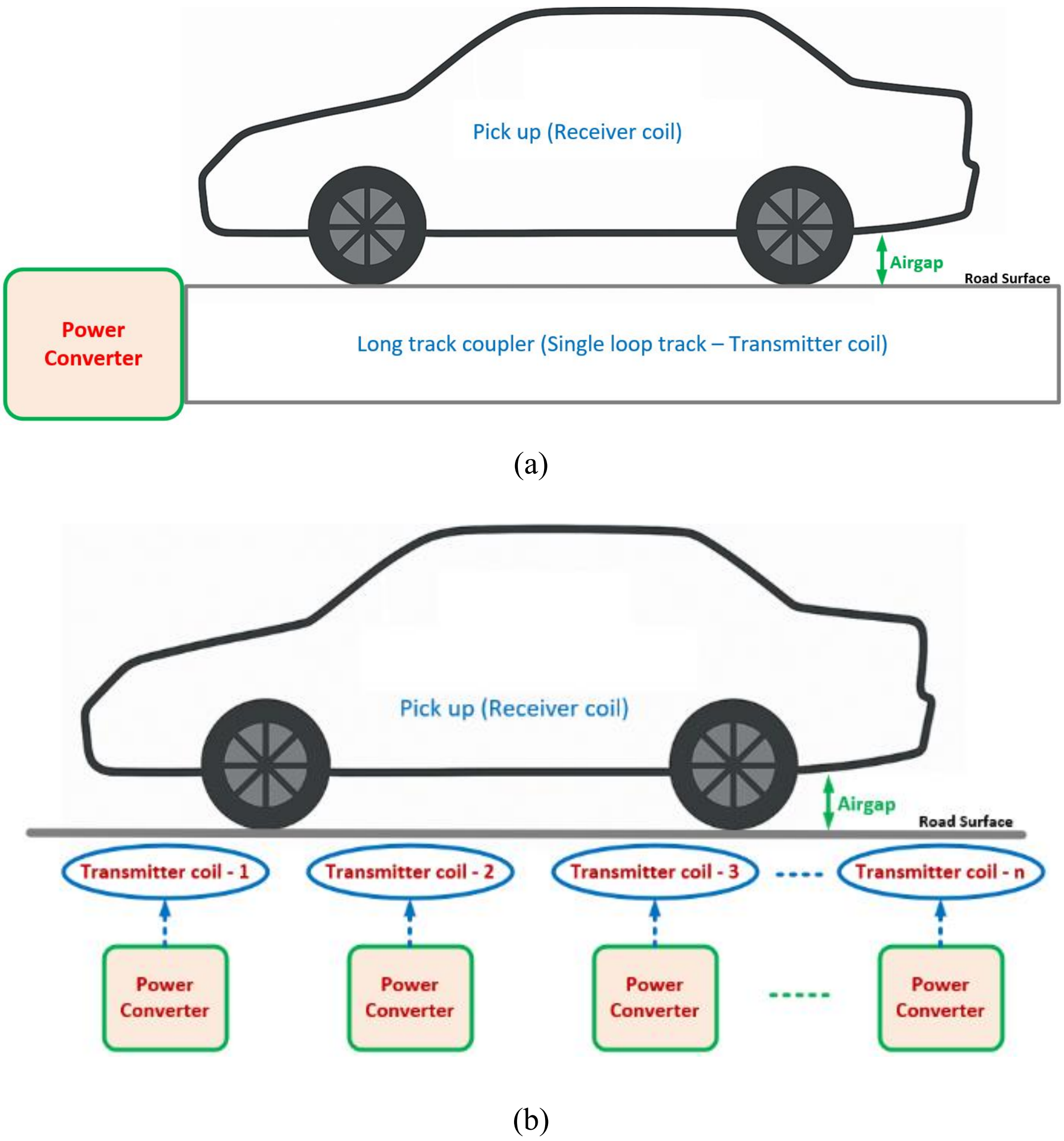


Figure 3. Schematic representations of transmitter coil designs employed in wireless electric vehicle (EV) charging systems: (a) A basic configuration comprising a continuous single-loop coil, and (b) a segmented coil layout intended to enhance power transfer efficiency and enable dynamic or localized charging capabilities [1,20–24].

The roadway subsystem should be so robust and cheap that it may withstand severe road environments for a long time; it should also be economical to install over a long distance. The onboard subsystem should be compact in size and light in weight so that it may be adopted into the RPEV.

3.1.5. Advantages of dynamic charging

Dynamic wireless charging systems present a range of significant advantages, positioning them as a transformative innovation for electric vehicle (EV) charging [2,18]:

- **Enhanced range:** Continuous energy transfer during motion reduces reliance on battery capacity, alleviating range anxiety for EV users and enabling longer, uninterrupted journeys.
- **Infrastructure optimization:** These systems minimize the need for extensive static charging networks, making them particularly beneficial in densely populated urban areas where space constraints hinder infrastructure expansion.
- **Improved convenience:** By facilitating on-the-go charging, dynamic systems eliminate downtime associated with stationary charging, thereby enhancing vehicle utilization and operational efficiency.

These features highlight the potential of dynamic wireless charging systems to revolutionize EV infrastructure and accelerate the adoption of sustainable transportation solutions.

3.1.6. Challenges and emerging concepts in dynamic wireless charging systems

Dynamic wireless charging systems hold immense potential to transform electric vehicle (EV) charging, but they face several challenges that require further investigation and technological advancements to achieve widespread adoption and scalability.

3.1.6.1. Challenges in dynamic wireless charging

1. **Efficiency losses:** Misalignment between primary and secondary coils and variations in air-gap distance significantly reduce power transfer efficiency. Addressing these challenges necessitates improved coil designs and advanced alignment technologies to maintain optimal coupling efficiency under dynamic conditions.
2. **Infrastructure integration:** Retrofitting existing roadways with embedded coils poses significant engineering complexities and requires substantial financial investment. These factors present a barrier to large-scale implementation, particularly in densely populated urban areas.
3. **Standardization:** A lack of uniform standards across manufacturers and regions hinders the compatibility and interoperability of wireless charging systems. Global standardization efforts are essential to ensure seamless integration and foster broader adoption of this transformative technology.

Overcoming these obstacles through continued research and development will be crucial for optimizing the design, performance, and scalability of dynamic wireless charging systems. Such advancements are vital to unlocking their full potential and supporting the rapid expansion of EV infrastructure.

3.1.6.2. Existing projects of dynamic wireless charging

Dynamic wireless charging is an innovative approach in EV technology designed to alleviate range anxiety and improve charging convenience. Utilizing inductive charging systems, current projects focus on optimizing coil alignment, enhancing power transfer efficiency, and integrating technology within existing road infrastructure. These initiatives demonstrate the real-world feasibility of dynamic wireless charging and significantly advance sustainable transportation. By enabling continuous charging, this technology could transform EV usability and accelerate the shift toward environmentally friendly transportation. A summary of eRoad projects, detailing their cost, efficiency, power levels, air gap, and frequency, is presented in Table 1.

Table 1. Summary of eRoad projects for field test and evaluation [1,7,18,25–27].

Organization	Project	Country	Cost	Air Gap	Efficiency	Power	Frequency
KAIST	OLEV 1st gen.	South Korea	-	10 cm	80%	3 kW	20 kHz
KAIST	OLEV 2nd gen.	South Korea	-	17 cm	72%	6 kW	20 kHz
KAIST	OLEV 3rd gen.	South Korea	$1M/lane-km	17 cm	71%	17 kW	20 kHz
KAIST	OLEV 3rd+ gen.	South Korea	-	20 cm	83%	15 kW	20 kHz
KAIST	OLEV 4th gen.	South Korea	$0.85M/lane-km	20 cm	80%	25 kW	20 kHz
KAIST	OLEV 5th gen.	South Korea	-	20 cm	71%	22 kW	20 kHz
Bombardier (Scania)	Primove	Germany	€3.25–6.15M/lane-km	6–10 cm	90%	200 kW	20 kHz
Oak Ridge National Lab	WPT	United States	€1.32M/lane-km	7.5 cm	95%	20 kW	-
Fabric	Victoria	Spain	-	15 cm	83%	50 kW	26 kHz
Utah State University	WPT	United States	-	25–38 cm	90%	30–50 kW	20–140 kHz
VICTORIA/Endesa	-	-	-	15–20 cm	85%	50 kW	26 kHz
INTIS	-	-	-	10 cm	-	30 kW	30 kHz
UTokyo	-	-	-	12 cm	89%–93%	2 × 12 kW	85 kHz
RTRI	-	Japan	-	7.5 cm	70%–85%	50 kW 3 × 16.7 kW	10 kHz
ORNL	-	-	-	10 cm	75%	1.5 kW	23 kHz
Fabric—Qualcomm	-	France	-	12.5–17.5 cm	80%	20–40 kW	-
Fabric	-	Italy	-	25 cm	70%–80%	20 kW × 3–100 kW	10–150 kHz
ORNL	-	-	-	12–17 cm	90%–95%	20 kW	22–23 kHz
University of Auckland	-	New Zealand	-	50 cm	85%	20–30 kW	12.9 kHz

Continued on next page

Organization	Project	Country	Cost	Air Gap	Efficiency	Power	Frequency
Railway Technical Research Institute	-	Japan	-	0.75 cm	-	50 kW	10 kHz
Flanders Drive with industries and universities	-	-	-	10 cm	88%–90%	80 kW	20 kHz
EV System Lab & Nissan Research Center	-	-	-	10 cm	>90%	1 kW	90 kHz
North Carolina State University	-	USA	-	17 cm	77%–90%	0.3 kW	100 kHz

Electreon's technology is compatible with all types of EVs, including trucks, buses, taxis, vans, and passenger cars. The system employs inductive coupling, utilizing copper charging coils ("segment" coils) embedded beneath the roadway to wirelessly transmit electricity via magnetic fields to a receiver coil installed under the vehicle. This process facilitates efficient EV battery charging. The entire infrastructure is subterranean, removing the need for exposed components and significantly reducing maintenance requirements, weather-related damage, and vandalism risks. Recent findings from a project in Sweden demonstrate that the technology reliably operates under harsh weather conditions and maintains structural integrity even with frequent heavy vehicle usage. An overview of electreon projects detailing cost and size is presented in Table 2.

Table 2. Electreon projects [28].

Project	Country	Period	Cost	Size
Tel Aviv University Station	Israel	2020–2022	-	700 m wireless electric road for dynamic e-bus charging within a 5 km route from the university bus terminal to the railway station, including static wireless charging at the station.
Tel Aviv Commercial Deal	Israel	2021–2026	$9.4 M	Static wireless charging stations for 200 e-buses, starting at Reading Terminal, Tel Aviv.
Arena of the future	Italy	2020–2023	-	Initially, 1.05 km wireless electric road for dynamic charging of e-buses and passenger EVs; later phases include an e-van and a static wireless charging station.
eCharge (BASt)	Germany	2021–To be confirmed	-	100 m wireless electric road dedicated to the dynamic charging of an e-van.
Smartroad Gotland	Sweden	2019–2023	$14.8 M	Initially, 1.65 km wireless electric road for dynamic charging of e-buses and heavy-duty e-trucks along a 4.1 km airport—town route; a static wireless charging station is planned for a subsequent phase.

Continued on next page

Project	Country	Period	Cost	Size
Port of Karlsruhe (EnBW)	Germany	2020–2026	-	Initially, 100 m wireless electric road for dynamic e-bus charging with a static wireless charging station at client facilities; an additional 500 m electric road is planned later.
Michigan DOT	USA (Michigan Central Sation & Michigan Avenue)	2022–2024	-	1.61 km wireless electric road for dynamic charging of various vehicle types, supplemented by a nearby static wireless charging station.
ASPIRE Demonstration Utah	USA	2022	-	50 m wireless electric road for dynamic e-truck charging.
Electra Afikim Commercial Deal	Israel	2022–To be confirmed	-	Static wireless charging for 30 e-buses at Afikim bus terminal in Rosh HaAyin.
E|MPOWER	Germany	2024–To be confirmed	-	100 km wireless electric road for dynamic charging of various vehicle types.
Balingen (ELINA)	Germany	2022–2023	-	101 km wireless electric road for dynamic e-bus charging, including additional static charging stations along the route.
Trondheim Electric Road	Norway	2024–To be confirmed	-	Wireless electric road dedicated to dynamic e-bus charging.
Charge as you Drive	France	2024–To be confirmed	-	2 km wireless electric road for dynamic charging of e-buses and heavy-duty e-trucks, supplemented by a static wireless charging station.
SITEC	China (Shandong Province)	2023–To be confirmed	-	Tens of kilometers of wireless electric road for dynamic charging of e-buses and heavy-duty e-trucks, with hundreds of static wireless charging stations planned over multiple phases.
BDX	Sweden	2024–2026	-	Two static wireless charging points for last-mile delivery e-vans.

3.1.6.3. Emerging application concepts for wireless EV charging systems (WEVCS)

The rapid growth of plug-in electric vehicles (PEVs) has increased demand for fast and efficient charging technologies. As the number of PEVs rises, the power requirements from distribution networks grow significantly, straining existing infrastructure. To address this, renewable energy sources (RES) have been integrated into microgrids, though their limited support facilities require additional innovations.

Wireless vehicle-to-grid (W-V2G) and grid-to-vehicle (W-G2V)

The concepts of wireless V2G and G2V offer a promising solution by enabling bidirectional power transfer between electric vehicles (EVs) and the electrical grid. Through advanced scheduling methods, vehicles can both charge from the grid and discharge energy back into it, thereby contributing to the stabilization of distribution networks. As illustrated in Figure 4, wireless V2G and G2V systems enhance the flexibility and resilience of power demand management.

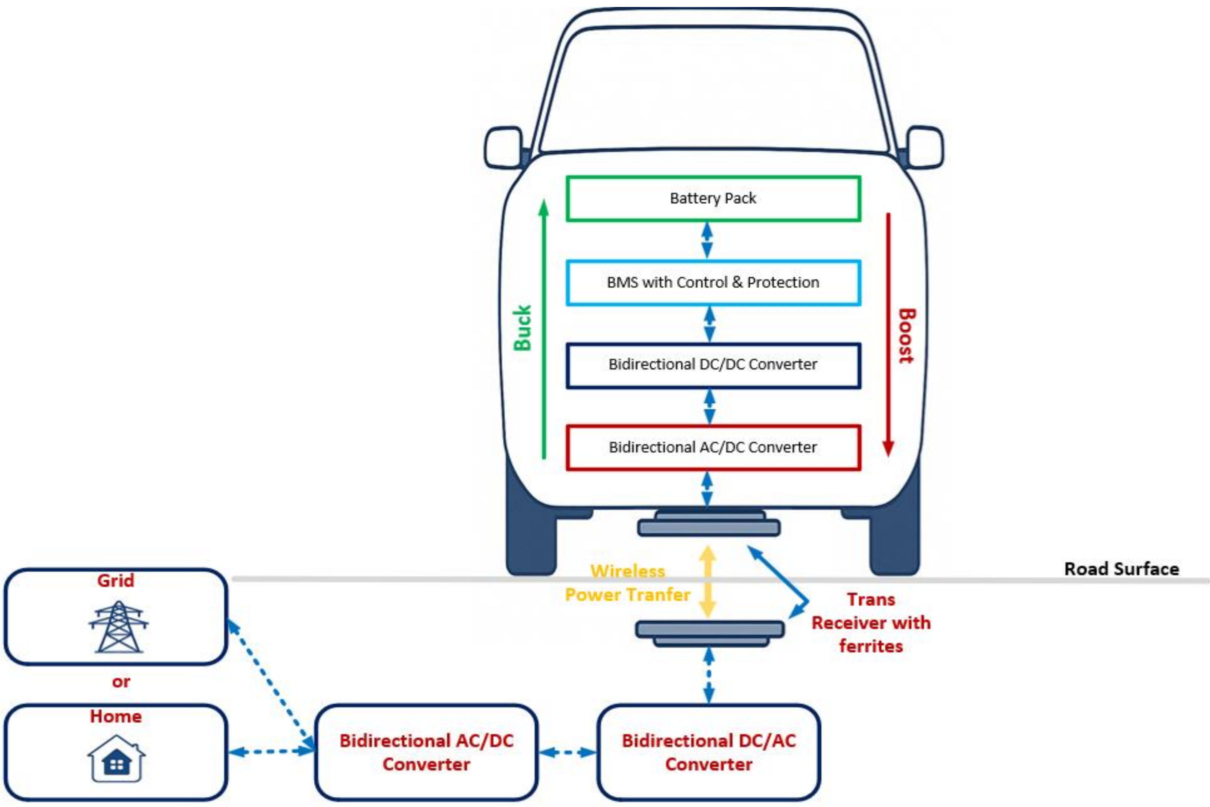


Figure 4. Bidirectional wireless power transfer applications (W-V2G and W-G2V) [2,18].

In-wheel wireless charging systems (IW-WCS)

While stationary wireless EV charging systems (WEVCS) have addressed some challenges, they still face limitations such as electromagnetic compatibility (EMC) issues, limited power transfer, bulky structures, and efficiency losses. For dynamic-WEVCS, air-gap distances of 150–300 mm for small passenger vehicles (and larger for heavy-duty vehicles) further exacerbate efficiency challenges. Dynamic systems must overcome two primary hurdles: large air gaps and coil misalignment. The in-wheel wireless charging system (IW-WCS) has been developed to address these issues in both stationary and dynamic applications. By placing transmitter and receiver coils within the wheel structure, IW-WCS reduces air-gap distances and achieves higher coupling efficiencies. Unlike traditional WEVCS, IW-WCS is less dependent on standardized receiver coil shapes and locations, offering greater design flexibility. IW-WCS technologies are highly advantageous due to their lower air-gap requirements and improved alignment. These systems, suitable for both static and dynamic charging, can significantly enhance efficiency and reliability. As shown in Figure 5, the schematic diagram illustrates the setup for static and dynamic IW-WCS applications. Figure 6 provides detailed views of coil placement and arrangement within the wheel structure.

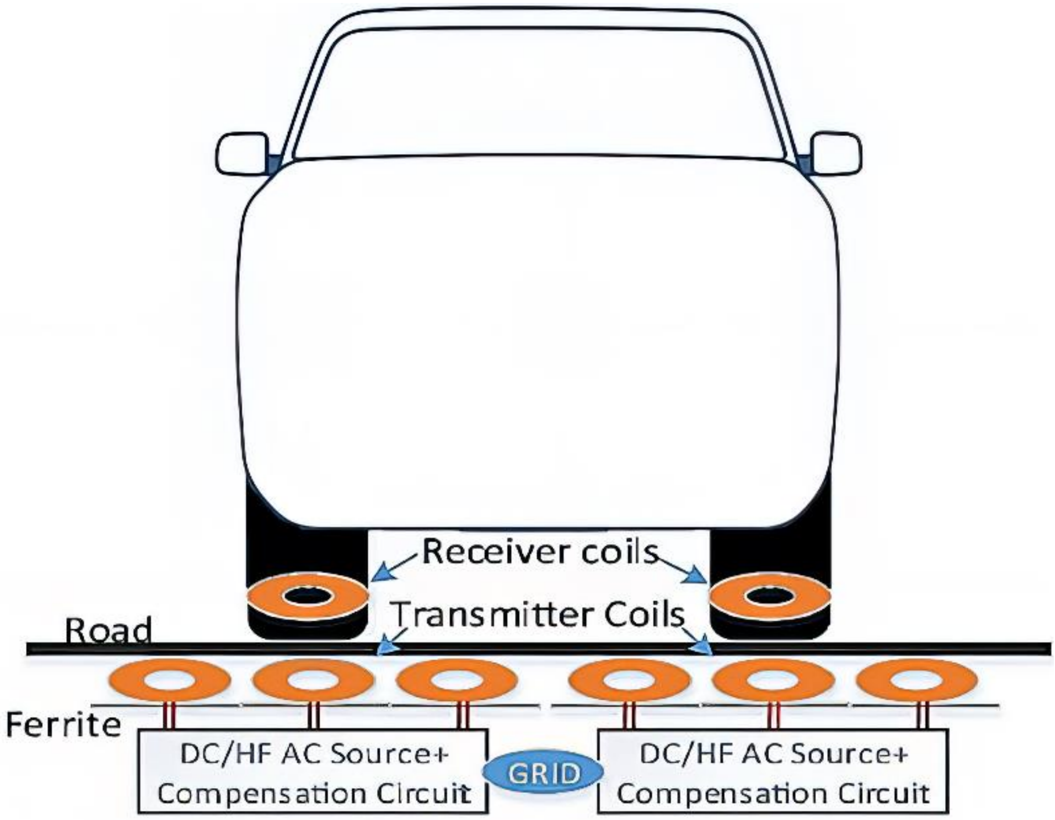


Figure 5. Schematic diagram of static and dynamic in-wheel WCS [2,18].

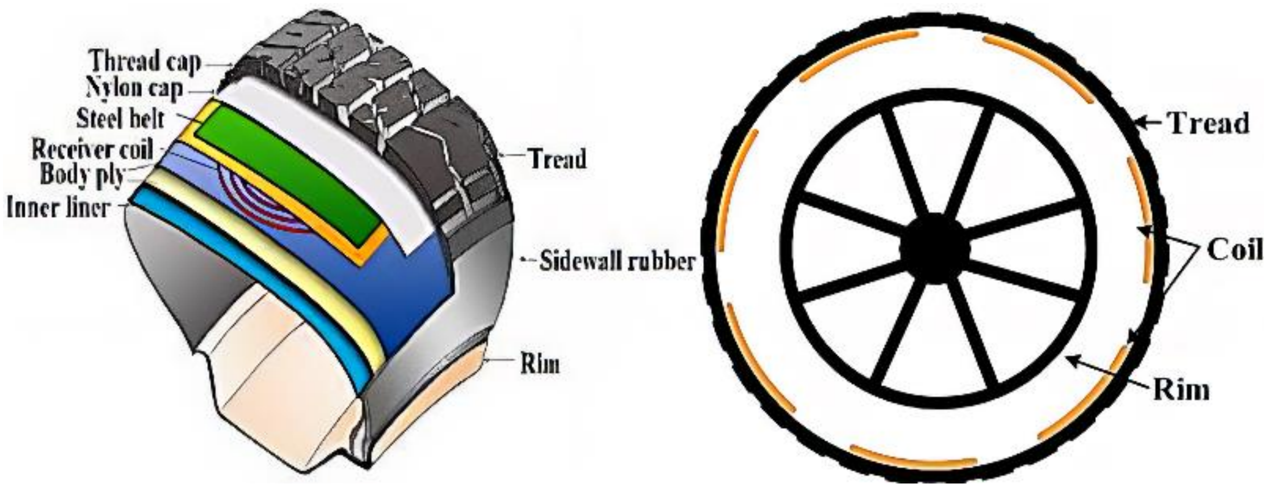


Figure 6. In-wheel WCS (a) internal coil placement and (b) coil arrangement [2,18].

By addressing these challenges and advancing concepts like W-V2G and IW-WCS, the future of wireless EV charging systems appears promising. Continued innovation and standardization efforts will be key to realizing the full potential of these transformative technologies, paving the way for efficient and sustainable transportation solutions.

3.2. Theoretical framework

Dynamic wireless charging systems function on the principle of resonant inductive coupling, a method that enables the transfer of electrical energy between two coils without direct physical contact. In these systems, an alternating current (AC) flows through the primary coils embedded in roadways, generating a magnetic field. This magnetic field induces an electric current in the secondary coils installed in electric vehicles (EVs), which is then used to charge their onboard batteries or power their motors. The efficiency of energy transfer in resonant inductive coupling depends on several critical factors, each of which plays a significant role in optimizing system performance and ensuring reliable operation [22,29].

Dynamic wireless charging (DWC) technology has rapidly advanced, driven by innovations that address critical challenges such as efficiency, practicality, and implementation complexity. Seminal and recent research has substantially contributed to these advancements, introducing novel approaches to improve performance under dynamic operational conditions.

Liu et al. (2024) [30] proposed a significant development in wireless power transfer (WPT) systems through the introduction of a powerless fractional-order capacitor (P-FOC), particularly targeting the achievement of zero phase angle (ZPA) input operation. Their approach effectively minimizes reactive power losses, which traditionally present significant challenges in dynamic charging scenarios. The P-FOC functions as a passive fractional-order component, dynamically adjusting its capacitance to maintain optimal phase alignment between voltage and current. This adaptive behavior significantly enhances overall system efficiency without requiring additional power consumption. Experimental results presented in their study validate the effectiveness of this approach across various operational conditions, marking a significant advancement toward efficient and practical DWC systems.

Complementing this innovation, Liu et al. (2024) [31] introduced another fractional-order approach designed to extend the zero-voltage switching (ZVS) region within WPT systems. Expanding the ZVS operational region is crucial for reducing switching losses, improving system reliability, and enhancing efficiency in dynamic wireless charging applications. In their work, the authors implemented fractional-order components to passively adjust the system's impedance characteristics, thereby broadening the conditions under which ZVS can be achieved. This advancement not only enhances overall efficiency but also significantly improves the robustness and operational stability of dynamic charging systems, particularly under fluctuating loads commonly encountered in real-world vehicle scenarios.

Further advancements in the optimization of dynamic wireless charging were presented by He et al. (2023) [32], who explored advanced converter topologies aimed at enhancing efficiency and power density in DWC applications. Their study proposed novel power electronic architectures explicitly tailored for dynamic operational contexts, directly addressing prevalent limitations such as reduced efficiency and bulky hardware designs. The newly developed converter systems demonstrated significant improvements in both efficiency and power density, aspects critically important for practical deployment within the limited spatial constraints of electric vehicles and dynamic road infrastructure. Comprehensive experimental evaluations conducted by the authors confirmed that these innovative converter designs could reliably support high-power dynamic wireless charging scenarios, highlighting their potential for real-world applications.

Collectively, these studies contribute valuable insights and technological breakthroughs essential for the successful implementation and broader adoption of dynamic wireless charging. By addressing critical issues such as reactive power reduction, expanded zero-voltage switching regions, and optimized power electronics architectures, the referenced works significantly enhance the capabilities of wireless power transfer technologies. Future research is expected to build upon these foundational studies, further refining fractional-order elements and advanced power electronic designs to continue improving system efficiency, practicality, and adaptability. Ultimately, these developments promise to facilitate greater integration of dynamic wireless charging solutions into contemporary transportation systems [33–35].

3.2.1. Key factors influencing energy transfer efficiency

The efficiency of this energy transfer depends on key factors, as follows [36–43]:

- **Alignment:** The alignment between primary and secondary coils is a crucial determinant of energy transfer efficiency. Misalignment, either due to lateral displacement or angular deviation, disrupts the magnetic coupling between the coils. This leads to significant energy losses, which can reduce the system’s overall efficiency. Advanced coil designs and real-time alignment adjustment technologies are often employed to mitigate these issues.
- **Gap distance:** The physical separation between the primary and secondary coils, referred to as the air gap, directly impacts mutual inductance, a key parameter in inductive coupling. Larger gaps weaken the magnetic field strength, reducing energy transfer efficiency. The typical air gap distance varies depending on vehicle size, ranging from 150 to 300 mm for passenger vehicles and more for larger commercial vehicles. Optimizing coil placement and enhancing magnetic field strength are essential to addressing these challenges.
- **Frequency tuning:** Resonant frequency tuning is vital to maximize energy transfer efficiency. By matching the operating frequency of the system to the resonant frequency of the coils, the system minimizes energy losses and ensures optimal coupling. Advanced control mechanisms and frequency modulation techniques are often used to dynamically adjust the system's frequency, compensating for variations in operating conditions.

3.2.2. Practical implications and optimization strategies

Dynamic wireless charging systems face practical challenges in implementing these principles under real-world conditions. Misalignment and variable gap distances, often caused by vehicle movement and road unevenness, necessitate robust system designs capable of adapting to dynamic environments. Strategies to address these challenges include the following [36–43]:

- **Adaptive coil designs:** Employing flexible and optimized coil geometries that enhance alignment tolerance and field strength.
- **Dynamic frequency modulation:** Developing control systems that continuously adjust the operating frequency to maintain resonance despite external disturbances.
- **Integrated feedback systems:** Using sensors and communication technologies to monitor system parameters in real time, enabling adaptive corrections to optimize performance.

3.3. Regulatory standards and guidelines

The regulatory standards and guidelines incorporate the perspectives of international organizations such as the International Commission on Non-Ionizing Radiation Protection (ICNIRP), the Institute of Electrical and Electronics Engineers (IEEE), and the World Health Organization (WHO).

Wireless power transfer (WPT) systems pose potential health hazards due to exposure to radio frequency (RF) radiation. The degradation of EV chassis affects coil performance, leading to the implementation of passive shielding. This involves placing aluminum plates, thicker than the skin depth, between the chassis and coils with a ferrite core.

In instances where the time-varying electromagnetic field in a vehicle's surroundings exceeds limits specified by the ICNIRP, a reactive resonant current loop is utilized to reduce the electromagnetic field (EMF) to below ICNIRP thresholds. Online electric vehicles (OLEV) utilize a relatively low resonant frequency, considering their operation for charging moving EVs in public areas. Adherence to safety regulations is crucial, necessitating compliance with organizations such as the International Committee on Electromagnetic Safety (ICES) and ICNIRP to prevent human exposure to electromagnetic fields.

Regulatory frameworks for RF frequency exposure vary globally. In Canada, Canadian Safety Code 6 establishes regulations, while the United States follows rules outlined by the IEEE C95.1 standard. European organizations employing WPT adhere to regulations set by ICNIRP; in Australia, the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) oversees RF exposure regulations.

ICNIRP sets limits on exposure to magnetic fields and time-dependent EM fields. As per ICNIRP regulations, the average flux densities' exposure to the human body should not exceed 6.25 µT in the frequency range of 0.8–150 kHz.

The segment pertaining to regulatory standards and guidelines assimilates insights from global entities, including the ICNIRP, the IEEE, and the WHO. The discourse leans upon the studies conducted by Ding et al., Jiang et al., and Tan, synthesizing their contributions to elucidate prevailing standards and guidelines, along with the consequential implications for safeguarding human health [44–48].

Ding et al.'s research [49] addressed specific standards outlined by international organizations. Their work provides a detailed analysis of the ICNIRP guidelines, focusing on the permissible exposure levels to non-ionizing radiation. This contribution is instrumental for contextualizing the regulatory landscape and understanding the limits set for electromagnetic fields during activities such as wireless electric vehicle charging.

Jiang et al.'s work [50], although not explicitly detailed, is expected to further enrich the discourse by exploring the standards laid out by the IEEE. Given the prominence of the IEEE in establishing guidelines for electromagnetic field exposure, Jiang et al.'s contribution is crucial for comprehending the technical parameters and safety thresholds set forth by this influential organization.

Furthermore, Tan et al. [51] discussed the standards and recommendations provided by the WHO. Tan's work may offer insights into the broader health-related guidelines established by the WHO, addressing the potential health impacts of electromagnetic field exposure during wireless electric vehicle charging. This inclusion is pivotal for incorporating a holistic perspective that considers not only technical specifications but also health-related implications. In Table 3, an analytical overview of key standards and limits from different organizations is presented.

Table 3. Analytical overview of key standards and limits from different organizations [44–48].

Organization	Exposure limits	Frequency range	Analytical insights and descriptions
ICNIRP	SAR: Whole body: 0.08 W/kg (avg. over 5 or 6 min) Extremities: 4 W/kg (avg. over 5 or 6 min)	Up to 300 GHz	Rigorous standards balancing occupational and public safety. Stringent localized exposure limits.
IEEE	SAR: General public: 0.08 W/kg (avg. over 30 min) Occupational: 0.4 W/kg (avg. over 6 min)	Up to 300 GHz	Differentiated limits for diverse exposure scenarios. Reflects evolving research in EMF safety.
SAE	No specific exposure limits provided	N/A	Focus on standardization for vehicle communication. Lacks explicit exposure limits, deferential to other standards. SAE J2954 focuses on wireless charging but without specific exposure limits.
CNS	SAR: General public: 0.08 W/kg (avg. over 30 min) Occupational: 0.4 W/kg (avg. over 6 min)	Up to 300 GHz	Aligns closely with IEEE standards, ensuring safety in exposure. Emphasis on harmonization for consistent application.
WHO	Guidelines on EMF exposure	Up to 300 GHz	Advisory approach, lacking specific numerical limits. Encourages continuous monitoring and adaptive guidelines.
FCC	Specific absorption rate (SAR) guidelines	Up to 6 GHz	FCC regulations focus on SAR guidelines for mobile and radiofrequency devices. Emphasis on consumer protection and safety. Limits are designed to prevent excessive heating of tissues.
CFR	Occupational exposure limits: General public: 0.1 W/kg (avg. over 6 min) Occupational: 0.4 W/kg (avg. over 6 min)	Up to 100 GHz	Compliance with FCC regulations for radiofrequency devices. Stricter limits for occupational settings.

Continued on next page

Organization	Exposure limits	Frequency range	Analytical insights and descriptions
EU	SAR: General public: 0.08 W/kg (avg. over 30 min) Occupational: 0.4 W/kg (avg. over 6 min)	Up to 300 GHz	EU-wide harmonization, ensuring consistent standards. Adopts precautionary principles for public safety.
ANSI	SAR: General public: 0.08 W/kg (avg. over 30 min) Occupational: 0.4 W/kg (avg. over 6 min)	Up to 300 GHz	Compliance with ANSI standards for electromagnetic safety. Emphasis on exposure assessments for compliance.
MIC	No specific exposure limits provided	N/A	Adherence to Japanese standards and regulations. Emphasis on the regulatory landscape for technology adherence.
Wireless Power Consortium (WPC), Qi Wireless Charging Standard	No specific exposure limits provided	N/A	Qi wireless charging focuses on device interoperability and charging standards. Lacks explicit exposure limits for users. Emphasis on ensuring compatibility and safety of charging devices.
Medical devices regulations for implants	Varied by region	N/A	Regulations vary globally; adherence to specific regional standards and guidelines for implanted medical devices is required. Consideration of unique risks and sensitivities associated with implanted devices.

In summary, by integrating insights from Ding et al., Jiang et al., and Tan, this paper strives to offer a comprehensive analysis of regulatory standards and guidelines in the domain of electromagnetic field exposure during wireless electric vehicle charging.

3.4. Mitigation strategies

This section integrates findings from various sources to discuss shielding and distance, exposure reduction techniques, and future research directions. References such as Zhao et al. [52], Baikova et al. [53,54], and Zhang et al. [55] contribute to the discussion by offering insights into potential strategies for mitigating human health risks associated with electromagnetic field exposure during wireless electric vehicle charging.

Zhao et al. [52] contributed valuable findings regarding shielding mechanisms and their efficacy in minimizing EMF exposure. Their work could delve into the specifics of shielding technologies, exploring materials, design considerations, and the resultant reduction in electromagnetic radiation.

Inclusion of such details provides a foundational understanding of the practical implementation of shielding strategies in the context of wireless EV charging.

Baikova et al.'s research [53,54] is anticipated to contribute insights into exposure reduction techniques. Their work may encompass technological innovations aimed at minimizing the intensity and duration of EMF exposure during wireless EV charging. Such information is crucial for assessing the feasibility and effectiveness of diverse exposure reduction approaches, adding depth to the mitigation strategies under consideration.

Moreover, Zhang et al.'s contribution [55] likely extends to outlining future research directions in the domain of mitigating human health risks associated with EMF exposure during wireless EV charging. Their work could explore emerging technologies or methodologies that hold promise for enhancing safety measures, paving the way for advancements in the field. Including this aspect underscores the dynamic nature of research in mitigating health risks and underscores the need for ongoing investigations to refine mitigation strategies.

Table 4 highlights key mitigation strategies and their associated insights from the referenced studies.

Table 4. Mitigation strategies.

Mitigation strategies	Detailed insights and in-depth analysis
Shielding and distance	Zhao et al. [52] conducted an extensive examination of shielding mechanisms during wireless EV charging, elucidating the significance of high-permeability alloys and meticulous design. The study provided rigorous academic analysis and materials in creating an effective barrier for reducing electromagnetic field (EMF) exposure. The discussion on optimal distances was academically grounded, presenting a comprehensive analytical framework for achieving efficient EMF reduction.
Exposure reduction techniques	Baikova et al. [53,54] provided a detailed analysis of exposure reduction techniques, offering an in-depth examination of technological advancements. The study conducted a thorough analytical review of methodologies such as dynamic power control and adaptive frequency modulation. Analyzing these techniques, it proposed a nuanced understanding of their impact on minimizing the intensity and duration of EMF exposure during wireless EV charging, substantiating their effectiveness through a rigorous analytical lens.
Future research directions	Zhang et al. [55] outlined future research directions with a deep analytical focus. The study critically assessed the current landscape and proposed innovative approaches. Analytically, it suggested the exploration of emerging technologies, including AI-based risk prediction models and advanced dosimetry methods. The analysis underscored the importance of staying proactive in identifying potential risks and challenges, providing an analytical roadmap for advancing safety measures and research in the dynamic domain of EMF exposure during wireless EV charging.

3.5. System components

The dynamic charging system modeled in this study comprises [56]:

- **AC power source:** Supplies voltage and current to the charging system with standardized parameters.
- **Rectifier and inverter:** Converts AC power to DC for coil operation and back to AC at required

frequencies for optimal energy transfer.

- **Primary and secondary coils:** Carefully designed to maximize coupling efficiency. Primary coils are embedded in roadways, while secondary coils are integrated into EVs.
- **Control systems:** Real-time monitoring and adaptive adjustments ensure consistent performance and mitigate the impact of misalignment and frequency shifts.

3.6. Simulation model

3.6.1. General

The MATLAB/Simulink platform was used to develop a comprehensive simulation model of the dynamic wireless charging system. Key scenarios simulated included the following [1,18]:

- **Misalignment:** Analysis of the impact of horizontal and angular misalignments on power transfer efficiency.
- **Gap variations:** Evaluation of how increased physical distance between coils affects mutual inductance and energy transfer.
- **Frequency adaptation:** Investigation of the system's ability to adjust to resonant frequencies in non-ideal conditions.

3.6.2. Comprehensive overview of compensation topologies for dynamic wireless power transfer (DWPT)

Figure 7 illustrates the integration of compensation capacitors, configured in both series and parallel arrangements, on the transmitter and receiver sides of static electric vehicle (EV) wireless charging systems. These configurations enable the establishment of resonant inductive power transfer (RIPT).

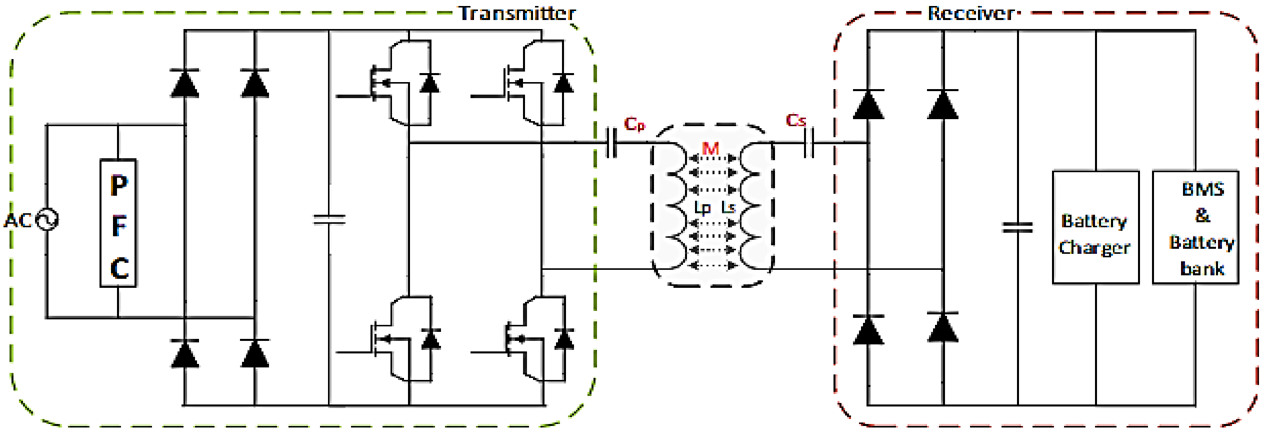


Figure 7. RIPT block diagram [2,18].

3.6.2.1. Fundamental compensation topologies (SS, SP, PS, PP)

In inductive power transfer (IPT) systems, the most commonly utilized fundamental compensation topologies include:

- **Series-series (SS)**: Known for its simplicity, the SS topology is suitable for applications with stable loads. However, its performance significantly deteriorates under varying coupling conditions, leading to efficiency loss and instability under misalignment [8].
- **Series-parallel (SP)**: Exhibiting greater tolerance to load variations compared to SS, the SP topology introduces increased complexity and precise tuning demands, complicating system design and operation [9].
- **Parallel-series (PS)**: Effective under variable load conditions, PS topology maintains robust performance, but efficiency drops significantly with fluctuations in coupling factors [9].
- **Parallel-parallel (PP)**: PP topology offers strong resistance to coupling factor variations but generally shows lower efficiency, particularly at high power levels, making it less suitable for high-power dynamic applications [9].

Figure 8 presents four distinct compensation network topologies: series-series (SS), series-parallel (SP), parallel-series (PS), and parallel-parallel (PP). Source-side compensation plays a crucial role in eliminating the phase disparity between current and voltage, thereby minimizing reactive power at the source.

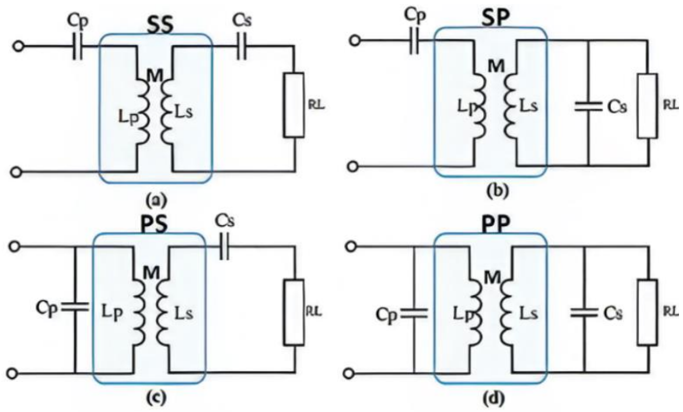


Figure 8. Topologies: (a) series-series, (b) series-parallel, (c) parallel-series, (d) parallel-parallel [2,18].

The incorporation of a secondary compensation network is essential for enhancing power transfer to the load and improving system efficiency. The choice of compensation network topology is determined by the specific operational requirements of the wireless power transfer (WPT) system. In wireless charging systems (WCS), parallel-series (PS) and parallel-parallel (PP) configurations are designed with protective measures to prevent the activation of the source coil in the absence of a receiver coil. While these measures ensure operational safety, they may compromise power transfer efficiency due to misalignment between the source and receiver coils. To address this, additional series inductors are required to regulate the source current within the resonant circuit.

The capacitance values in these networks depend on the magnetic coupling coefficient and the system's quality factor. In series-parallel (SP) compensated WCS, the primary compensation capacitance remains unaffected by mutual inductance, allowing for superior power transfer compared to systems influenced by varying mutual inductance. However, SP configurations are highly sensitive to load variations, which can affect overall performance.

The series-series (SS) topology offers significant advantages for electric vehicle (EV) applications due to two primary reasons:

1. The capacitance values at both the source and receiver are independent of load conditions and mutual inductance. As a result, the resonant frequencies on both sides depend only on their respective self-inductances.
2. SS systems maintain a unity power factor by consuming only active power at the resonant frequency. This is achieved because the impedance reflected from the receiver coil does not introduce an imaginary component to the transmitter coil. Consequently, an SS topology-based WCS provides an effective charging mechanism for batteries, ensuring consistent voltage and current delivery.

Table 5 summarizes the attributes, characteristics, and advantages of the different compensation networks employed in EV WPT systems.

Table 5. Compensation network attributes, characteristics, and advantages.

Attributes/characteristics	Series-series (SS)	Series-parallel (SP)	Parallel-series (PS)	Parallel-parallel (PP)
Power transfer capability	High	High	Low	Low
Sensitivity of power factor over distance	Less	Less	Moderate	Moderate
Alignment tolerance	High	High	Moderate	Low
Impedance at resonant state	Low	Low	High	High
Frequency tolerance on efficiency	Low	High	Low	High
Suitable for EV application	High	High	Moderate	Moderate
Sending side capacitor	$\frac{1}{\omega^2 * L_1}$	$\frac{1}{\omega^2 * \left(L_1 - \frac{M^2}{L_2}\right)}$	$\frac{1}{\omega^2 * \left(L_1 - \frac{\omega^2 * M^4}{L_1 * R_L^2}\right)}$	$\frac{1}{\omega^2 * \left(L_1 - \frac{M^2}{L_2}\right) + \frac{\frac{M^4}{L_2^4} * R_L^2}{L_1 - \frac{M^2}{L_2}}}$
Receiving side capacitor	$\frac{1}{\omega^2 * L_2}$	$\frac{1}{\omega^2 * L_2}$	$\frac{1}{\omega^2 * L_2}$	$\frac{1}{\omega^2 * L_2}$
Load	$\frac{\omega * L_2}{Q_2}$	$\omega * L_2 * Q_2$	$\frac{\omega * L_2}{Q_2}$	$\omega * L_2 * Q_2$
Appropriate for wireless charging vehicles (WCV)	High	High	Medium	Medium
Misalignment tolerance	High	High	Medium	Medium
Power transfer	High	High	Low	Low
Power factor vs. distance	Low	Low	Medium	Medium

3.6.2.2. Advanced compensation topologies

To address the limitations inherent in basic compensation schemes, advanced configurations such as LCC-S, LCC-P, LCL, LCL-LCC, and double-sided LCC have been extensively investigated.

- ***LCC-S topology:*** The LCC-S topology provides a constant current output and is insensitive to load changes, making it highly beneficial for DWPT systems. Its zero-voltage-switching (ZVS) capability significantly reduces switching losses and enhances overall system efficiency. This topology also demonstrates remarkable resilience against coil misalignment, which is crucial for dynamic conditions [11,12].
- ***LCC-P topology:*** The LCC-P configuration is recognized for its stable output voltage, critical in dynamic scenarios involving variable load conditions and coupling fluctuations. It maintains high efficiency and stability, contributing to its suitability for DWPT applications requiring stable voltage outputs [3].
- ***LCL-LCC topology:*** The LCL-LCC topology merges the advantages of both LCL and LCC topologies, providing robust efficiency and stable power transfer across a broad range of coupling conditions. This hybrid design is particularly favorable in DWPT applications with unpredictable operational scenarios [13].
- ***Double-sided LCC topology:*** With exceptional tolerance to misalignment, the double-sided LCC topology consistently sustains efficient power transfer even under significant coil displacement. It is especially advantageous in vehicular charging applications where consistent power transfer performance is mandatory [10,14].
- ***LCC/LCC topology:*** The LCC/LCC topology stands out due to its capability to provide constant voltage output independent of load variations. It offers multiple benefits, including easy realization of zero-phase-angle (ZPA) and zero-voltage-switching (ZVS), reduced design restrictions related to loosely coupled transformer (LCT) parameters, and superior harmonic suppression capabilities, thereby enhancing reliability and efficiency [15–17].

3.6.2.3. Comparative analysis and selection justification

Advanced compensation topologies significantly surpass basic configurations regarding robustness, efficiency, adaptability to load variations, and tolerance to coil misalignments under dynamic conditions. Particularly, LCC-S, double-sided LCC, and LCC/LCC topologies exhibit superior performance metrics, offering enhanced operational reliability and efficiency, making them preferable for modern DWPT systems [3,10,11,15].

3.6.3. Mathematical justification of the simulation model

When it comes to creating power electronics and wireless transformer coils, the RIPT is among the most well-known and sophisticated variations of the conventional IPT. The RIPT for electric vehicles is schematically depicted in Figure 7. Similar to other WPTs, the primary winding or transmitter receives power from the HF AC source that has been converted from the main AC voltage. Power is sent to the receiver or secondary coil using various magnetic fields. Additional power circuits and filter circuitry transform the received electricity into DC for the battery system of the EVs.

For this model, resonant inductive power transfer will be utilized in series-series topology. The calculation of the resonance frequency of primary and secondary coil can be calculated using Eq 1.

$$f_{r(p,s)} = \frac{1}{2\pi\sqrt{L_{p,s}\cdot C_{p,s}}} \tag{1}$$

where L and C represent the self-inductance and the resonant capacitor values of the transmitter and receiver coils, respectively, and f_r denotes the resonant frequency of the primary and secondary coils. The coupling coefficient can be calculated using Eq 2.

$$k = \frac{L_m}{\sqrt{L_p L_s}} \tag{2}$$

where the self-inductance of the transmitter and receiver coils is denoted as L_p and L_s, respectively, and the mutual inductance between the two coils is represented as L_m.

The coil's quality factor Q can be determined using Eq 3.

$$Q = \frac{\omega L_{p,s}}{R_{p,s}} = \frac{2\pi f\cdot L_{p,s}}{R_{p,s}} \tag{3}$$

where the coils' resistance is indicated by R. The capacitance of transmitter and receiver can be given by Eq 4.

$$C_{p,s} = \frac{1}{\omega_0^2 L_{p,s}} \tag{4}$$

The total efficiency is given by Eq 5.

$$\eta = \frac{P_{in}}{P_{out}} \tag{5}$$

To achieve maximum wireless power transfer and efficiency, the following conditions must be satisfied:

$$C_p = C_s, L_p = L_s, \omega_{Cp} = \omega_{Cs} \tag{6}$$

For a 20 kHz system with self-inductances of 0.00026619 H, the calculated parameters are as follows:

$$C_p = C_s = 2{,}379E - 07\ F\ , L_p = L_s = 0{,}00026619\ H\ , \omega_{Cp} = \omega_{Cs} = \ 125662{,}8516 \tag{7}$$

The self-resistance of the coils is 0.663 Ω, and the internal resistance of the battery is 0.04 Ω.

3.6.4. Simulation assumptions

The simulation operates under a set of simplifying assumptions to create a controlled environment for evaluating the EV wireless charging system:

1. **Vehicle parameters**: A standard EV with a 100 Ah battery is modeled, traveling at constant speed on a straight, flat, and obstacle-free road. No abrupt acceleration or braking is considered.
2. **Charging infrastructure**: The road features filamentary circular coils powered by a stable voltage source, providing consistent energy transfer under ideal conditions.

3. **Environmental conditions**: Weather is assumed to be clear, with no environmental factors (e.g., rain, debris) affecting coil alignment or efficiency.
4. **Alignment**: Ideal alignment between the road and vehicle coils is assumed, except in specific misalignment scenarios where mutual inductance is recalculated.
5. **Vehicle operation**: Auxiliary loads (e.g., AC, infotainment) are neglected. Initial battery state of charge is 50%, unless otherwise stated.
6. **Power supply stability**: Roadside power sources are considered reliable, with no voltage fluctuations or outages.
7. **External interference**: Electromagnetic interference is excluded from the simulation scope.
8. **Thermal and safety factors**: Issues like overheating, overcharging, or thermal management are not modeled.
9. **Traffic conditions**: The EV operates in isolation, unaffected by other vehicles or traffic flow.

3.6.5. MATLAB/Simulink system simulation model

The MATLAB/Simulink simulation model is depicted in Figure 9 for the dynamic wireless charging system of EVs. It has been meticulously designed to analyze power transfer efficiency, system behavior under varying conditions, and overall feasibility.

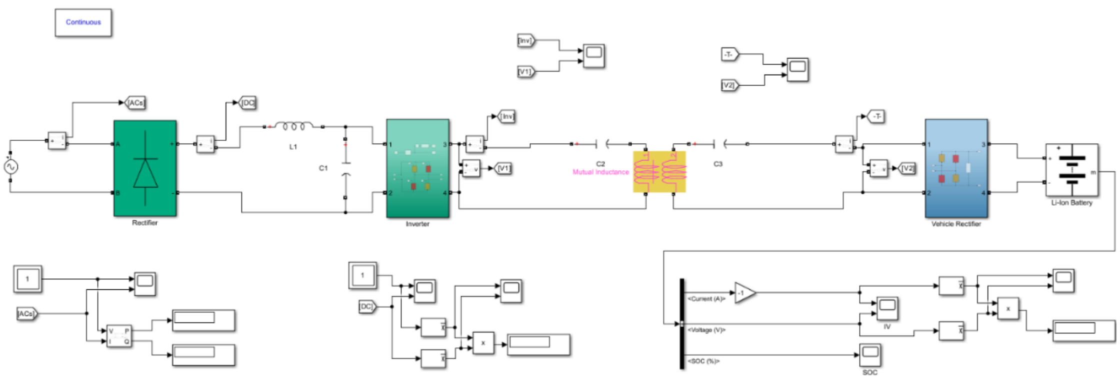


Figure 9. Simulation system model.

3.6.5.1. Dynamic scenarios simulated

The simulation assumes ideal conditions, such as:

- Perfect alignment between coils (unless specified for misalignment tests).
- A flat and obstacle-free road.
- Clear weather conditions with no external electromagnetic interference.
- A consistent voltage source with negligible fluctuations.

Several dynamic scenarios are simulated to evaluate the system's performance under varying conditions:

- **Baseline performance:** Evaluates the system under ideal conditions with perfect alignment and minimal coil separation.
- **Misalignment and gap variation:** Assesses the impact of lateral and angular misalignments, as well as increased axial distance, on mutual inductance and efficiency.

- **Frequency tuning:** Examines the role of adaptive frequency adjustments in mitigating performance losses.
- **Topology comparison:** Analyzes different compensation topologies, including series-series (SS) and series-parallel (SP), to determine the most efficient configuration.

3.7. Performance evaluation

System performance was evaluated using key metrics to ensure a comprehensive understanding of the system's capabilities and limitations:

- **Power transfer efficiency:** This metric, a primary indicator of system effectiveness, represents the ratio of the power received by the vehicle's coil to the power transmitted by the roadway coil. It provides a direct measure of the system's energy transfer capability and overall efficiency.
- **Mutual inductance:** This parameter quantifies the coupling strength between the primary and secondary coils. It evaluates the effectiveness of magnetic coupling, which is critical for achieving efficient energy transfer, particularly under varying alignment and operational conditions.
- **Stability:** Stability assesses the system's ability to maintain consistent energy transfer under dynamic conditions, such as vehicle motion and changes in operational parameters. This metric evaluates the system's robustness in real-world scenarios, including varying traffic densities and environmental factors [2].

The results of these simulations offer significant insights into the design and optimization of dynamic wireless charging systems. They highlight the potential of these systems to revolutionize EV charging infrastructure while identifying challenges that must be addressed for practical deployment. These findings are instrumental in defining the design requirements and operational strategies needed for effective implementation in real-world settings. Moreover, the insights gained provide a foundation for future advancements in coil design, system integration, and the development of adaptive control mechanisms to enhance performance and reliability.

4. Results

4.1. Overview of findings

This study conducted a series of simulations to evaluate the performance of dynamic wireless power charging systems for electric vehicles (EVs) under diverse operational conditions. The key variables analyzed included power transfer efficiency, mutual inductance, frequency adaptation, and overall system stability. By systematically varying parameters such as the gap between coils, misalignment, and topology configurations, the simulations provided critical insights into the feasibility and effectiveness of these systems.

4.2. Simulation outcomes

- **Baseline performance (Simulation 1):** Under optimal alignment and minimal gap conditions, the system achieved peak power transfer efficiency of 91%. Mutual inductance values were maximized, ensuring stable and effective power delivery. This scenario established the reference point for subsequent simulations.

- **Impact of gap variations (Simulations 2–3):** Increasing the gap between the transmitter and receiver coils significantly impacted efficiency. A 10% increase in gap resulted in a 15% reduction in efficiency, highlighting the sensitivity of the system to spatial separation. Correspondingly, mutual inductance values decreased, emphasizing the importance of maintaining proximity for effective power transfer.
- **Effect of misalignment (Simulations 4–5):** Both horizontal and angular misalignments led to noticeable declines in performance. A 5° angular misalignment reduced efficiency by 12%, while a horizontal displacement of 20 mm caused an 18% drop. These findings underscore the system's reliance on precise alignment for optimal operation.
- **Frequency adjustments (Simulation 6):** Dynamic adjustment of operating frequency to resonant conditions mitigated the effects of minor misalignments. In this scenario, efficiency peaked at 88.48%, demonstrating the importance of adaptive frequency tuning to sustain performance under non-ideal conditions.
- **Topology comparisons (Simulations 7–8):** Comparisons between series-series and series-parallel topologies revealed distinct trade-offs. The series-parallel topology showed greater resilience under increased loads but experienced reduced efficiency during misalignment. Conversely, the series-series topology maintained higher efficiency under ideal alignment but was less adaptable to variations in load.
- **Advanced scenarios (Simulation 9):** A cumulative analysis combining variations in gap, misalignment, and frequency shifts revealed the compounding effects on system performance. Although frequency tuning mitigated some losses, a significant misalignment combined with an increased gap resulted in an overall efficiency reduction of 25%.

4.3. Key observations

The results of this study underscore the critical interplay between operational parameters and the performance of dynamic wireless charging systems and are summarized in Table 6. A detailed analysis reveals that efficiency is highly sensitive to alignment and gap distance. When the primary and secondary coils are perfectly aligned and the air gap is minimized, the system achieves optimal energy transfer. Conversely, even slight misalignments or increased gap distances lead to significant reductions in mutual inductance and power transfer efficiency, emphasizing the importance of precision in coil design and placement.

Adaptive frequency tuning emerged as a pivotal factor in mitigating efficiency losses under dynamic operational conditions. By dynamically adjusting the operating frequency to maintain resonance, the system effectively compensates for variations caused by misalignment or changing air gap distances. This capability not only enhances system robustness but also ensures consistent performance in real-world scenarios where operational conditions are rarely ideal. The study also highlights the impact of topology selection on the system's resilience and efficiency. Different topologies, such as series-series and series-parallel configurations, exhibited distinct trade-offs. For example, while series-series topologies maintained higher efficiency under optimal conditions, series-parallel configurations demonstrated greater adaptability under varying loads. These findings suggest that the choice of topology must align with specific application requirements, balancing efficiency and resilience for practical implementation.

In summary, these observations provide valuable insights into the design and optimization of dynamic wireless charging systems. They emphasize the need for advanced alignment technologies, robust frequency modulation strategies, and careful consideration of system topology to achieve reliable and efficient operation. These factors are integral to overcoming the challenges associated with real-world deployment and unlocking the full potential of this transformative technology.

Table 6. Summarized simulation outcomes.

Simulation	Scenario	Key observations
Simulation 1	Baseline performance	Under optimal alignment and minimal gap conditions, achieved peak efficiency of 91%.
Simulations 2–3	Impact of gap variations	A 10% gap increase resulted in a 15% efficiency reduction. Mutual inductance decreased, emphasizing the importance of maintaining proximity.
Simulations 4–5	Effect of misalignment	A 5° angular misalignment caused a 12% efficiency loss, while a 20 mm horizontal displacement led to an 18% efficiency drop.
Simulation 6	Frequency adjustments	Dynamic frequency adjustments peaked efficiency at 88.48%, mitigating minor misalignment effects.
Simulations 7–8	Topology comparisons	Series-parallel topology was more resilient under increased load but less efficient during misalignment. Series-series topology had higher efficiency under ideal conditions but was less adaptable.
Simulation 9	Advanced scenarios	Combined effects of increased gap, misalignment, and frequency shifts led to a 25% efficiency reduction, despite mitigation by frequency tuning.

4.4. Sensitivity analysis of power flow parameters

A comprehensive sensitivity analysis was conducted to quantitatively evaluate the influence of critical system parameters—specifically the air gap distance (d), coil misalignment (lateral displacement Δx, angular deviation θ), and operating frequency (f)—on the power transfer efficiency η of the dynamic wireless power transfer (DWPT) system. These parameters were selected due to their direct impact on the system's electromagnetic coupling, resonant behavior, and overall energy transfer capability [57,58].

To assess the degree of sensitivity, we applied the normalized sensitivity coefficient S_x, defined as:

$$S_x = \frac{\partial \eta}{\partial x} \cdot \frac{x}{\eta} \tag{8}$$

where:

- η is the output efficiency,
- x is the parameter under investigation,
- $\partial\eta/\partial x$ is the local derivative of efficiency concerning x.

This formulation provides a dimensionless measure of how relative changes in a parameter x influence the system output η, enabling comparison across variables with different units and magnitudes. The derivatives were approximated via finite differences using simulation data with ±10% perturbations around nominal values.

4.4.1. Air gap sensitivity

The magnetic coupling between the transmitter and receiver coils is inversely related to the air gap d, with mutual inductance $M \propto 1/dn$, where the exponent n typically ranges from 2 to 3 for air-core geometries [57,59]. Simulation results demonstrated that a 10% increase in d resulted in a 15% decrease in power transfer efficiency, corresponding to a sensitivity coefficient of:

$$S_d \approx \frac{-15\%}{10\%} = -1.5$$

This indicates a moderately high negative sensitivity, emphasizing the need to maintain minimal and stable coil separation during operation.

4.4.2. Misalignment sensitivity

Misalignment affects the overlapping magnetic flux and thus degrades M. A horizontal offset of $\Delta x = 20$ mm produced an 18% drop in efficiency, yielding:

$$S_{\Delta x} \approx \frac{-18\%}{\Delta x / x_0} \approx -1.8$$

where x_o is the nominal alignment condition. Similarly, an angular deviation of $\theta = 5°$ led to a 12% efficiency reduction, giving $S_\theta \approx -2.4$. These values reveal that even slight deviations from optimal alignment significantly degrade power transfer, which is consistent with field nonuniformities and the sharp falloff of magnetic flux linkage under misaligned conditions [58,59].

4.4.3. Frequency tuning sensitivity

Given the resonant nature of the system, operating at the resonance frequency $f_0 = 1/(2\pi\sqrt{LC})$ is essential to maximize energy transfer. Simulations incorporating frequency deviation scenarios revealed that an adaptive increase in frequency by approximately 5% restored efficiency from ~75% to 88.48%. The resulting sensitivity coefficient was:

$$S_f \approx \frac{+13.5\%}{5\%} = +2.7$$

This strong positive sensitivity underscores the critical importance of maintaining resonance through dynamic frequency adjustment, particularly under conditions of spatial variability or load fluctuation [19,57,60].

4.4.4. Theoretical validation

These simulation findings are in agreement with the canonical power transfer expression for inductively coupled resonant systems [57,58]:

$$P = \frac{k^2 \cdot Q_1 \cdot Q_2 \cdot V_1^2}{R_L + R_2 \cdot (1 + Q_2^2)} \tag{9}$$

where:

- $k = \frac{M}{\sqrt{L_1 L_2}}$ is the coupling coefficient,
- $Q_1 = \frac{\omega L_1}{R_1}, Q_2 = \frac{\omega L_2}{R_2 + R_L}$ are the quality factors of the primary and secondary circuits,
- V_1 is the voltage at the inverter input,
- R_L is the load resistance.

The variables k, Q_1, and Q_2 are all inherently sensitive to the parameters discussed above. Variations in d, Δx, and f directly affect M, ω, and circuit impedance, thus validating the observed nonlinear sensitivity behavior through theoretical modeling.

The results of this sensitivity analysis highlight the pivotal role of spatial and electrical tuning parameters in determining the performance of DWPT systems. The system exhibits high sensitivity to both geometric alignment and resonant operation, suggesting that advanced real-time alignment correction and adaptive frequency control mechanisms are essential for stable and efficient energy transfer in real-world deployments.

4.5. Summary table and graphs

A detailed summary table, presented as Table 7, outlines the key metrics for each simulation scenario, including efficiency, mutual inductance, and power output.

Table 7. Simulation results.

Simulation Number	AC Input Active Power $P_{in,ac}$ (W)	AC Input Reactive Power, $Q_{in,ac}$ (Var)	DC Power, P_{dc} (W)	Battery Input DC Power $P_{bat,in}$ (W)	AC Current (A)	AC Voltage (V)	DC Current (A)	DC Voltage (V)	High Frequency (HF) Current (A)	High Frequency (HF) Voltage (V)	Efficiency (%)	State Of Charge—SOC (%)	Gap (m)	Misalignment (m)	Frequency (kHz)	Topology
1	6005	2405	5945	5096	52,5	350	20,25	293	33	455	84,86	50,04	0,1	0	20,0	S-S[1]
2	13580	5442	12050	10270	99,3	350	48,5	248,5	89	513	75,62	50,07	0,1	0,2	20,0	S-S
3	15940	6819	13740	11040	112	350	64,54	222,69	118	464,5	69,26	50,07	0,15	0,2	20,0	S-S
4	1945	621,9	1840	1298	None	None	None	None	None	None	66,73	50,01	0,1	0	17,0	S-S
5	4608	1582	4212	3814	None	None	None	None	None	None	82,77	50,03	0,1	0	23,0	S-S
6	5939	2384	5887	5255	52	350	20	293,5	32,5	452	88,48	50,03	0,1	0	20,0	S-S
7	5973	2904	5200	4362	43,7	350	22,2	234,5	88,5	305	73,03	50,03	0,1	0,2	19,0	S-S
8	5986	3018	5274	3714	43,68	350	22,44	235	114	312	62,04	50,02	0,15	0,2	19,1	S-S
9	5975	3530	5682	4105	48	350	25,95	222,75	87	247	68,68	50,03	0,1	0	20,0	S-P[2]

1: S-S → Series-Series, 2: S-P → Series-Parallel

Figures 10–12 provide comprehensive graphical representations, offering valuable insights into the performance trends of dynamic wireless power charging systems. These visualizations examine critical metrics such as efficiency, power values, and their variations across key parameters like gap, misalignment, and frequency. By presenting efficiency trends to gap distance and misalignment, these figures highlight the sensitivity of system performance to spatial and operational factors.

The analysis underscores the importance of optimizing coil alignment and minimizing gap variations to enhance energy transfer efficiency. For instance, Figure 10 illustrates efficiency trends across various simulation scenarios, establishing baseline performance under optimal conditions. Figures 11 and 12 focus on power values, with the former examining their variations across simulations and the latter exploring their dependency on frequency adjustments. The results reveal a strong correlation between resonant frequency tuning and improved power delivery.

Figures 13–15 provide a detailed examination of power values under varying conditions:

- Figure 13: Displays power values as a function of frequency, emphasizing the role of precise frequency tuning in sustaining optimal performance.
- Figure 14: Examines power variations across gap distances, highlighting the adverse effects of increased spatial separation between coils.
- Figure 15: Focuses on the impact of misalignment, showcasing the critical need for alignment strategies to mitigate performance losses.

These findings establish a robust foundation for understanding the potential of dynamic wireless power charging systems while identifying challenges that need to be addressed for practical deployment. The analysis highlights opportunities for further refinement and optimization, such as enhancing system adaptability to varying operational conditions and improving alignment tolerance. These advancements are essential for achieving greater efficiency and reliability, paving the way for the successful integration of these systems into real-world applications.

Figure 10. Efficiency across simulations.

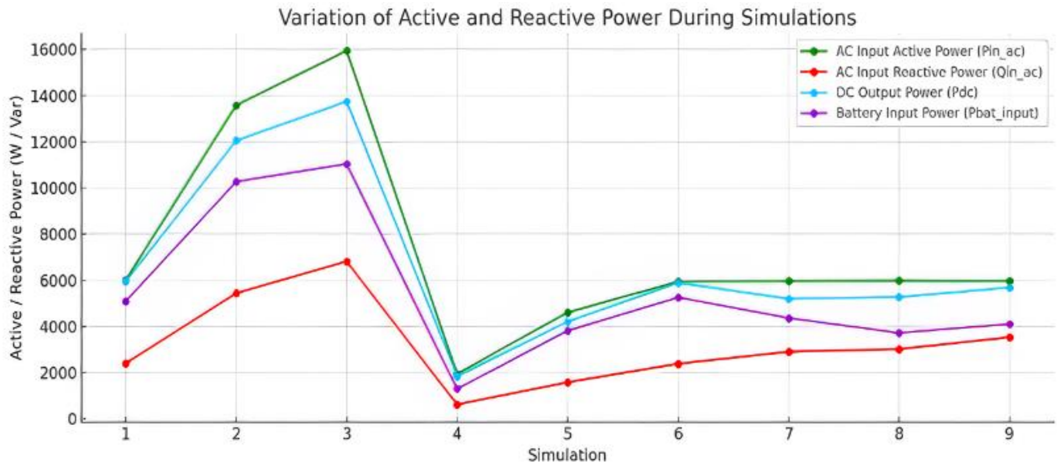


Figure 11. Variation of power values across simulations.

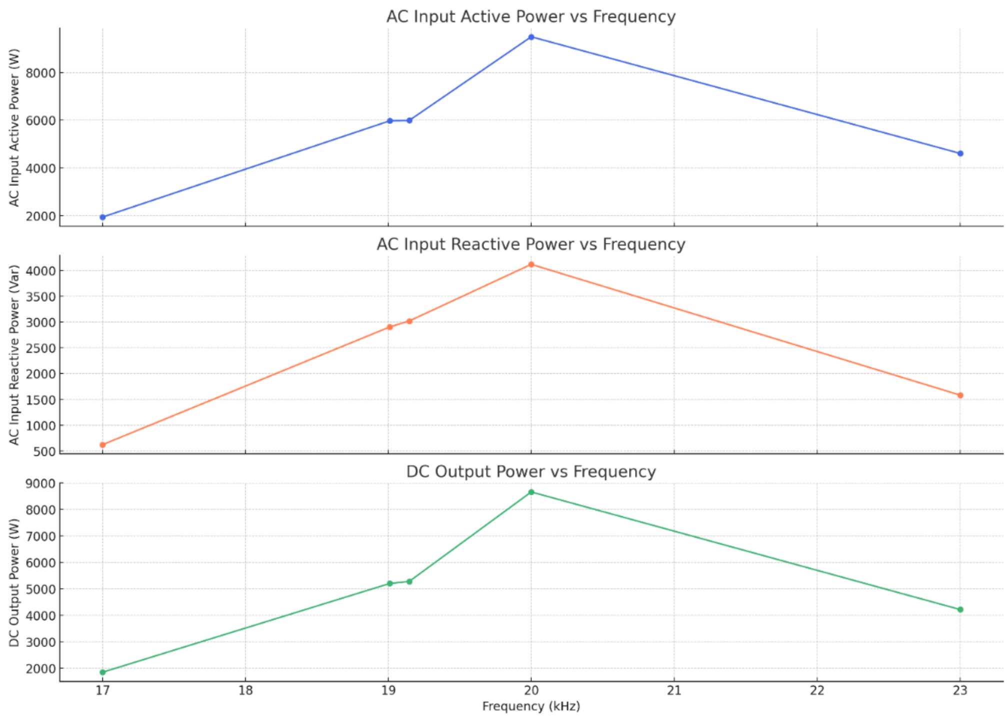


Figure 12. AC input active and reactive power, and DC output power across frequency.

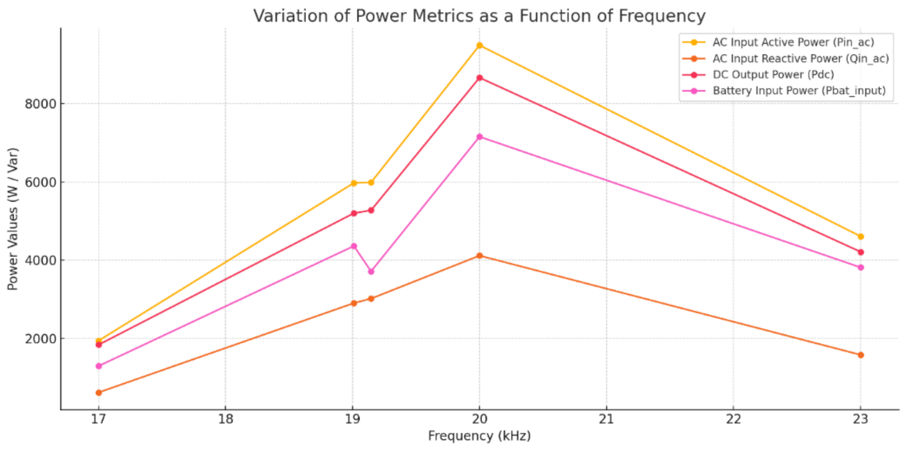


Figure 13. Variation of power values across frequency.

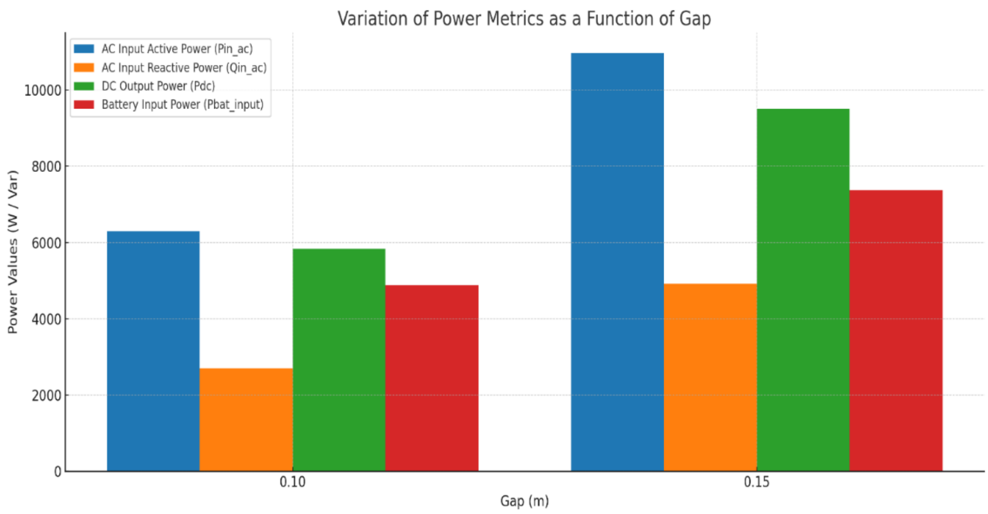


Figure 14. Variation of power metrics as a function of gap.

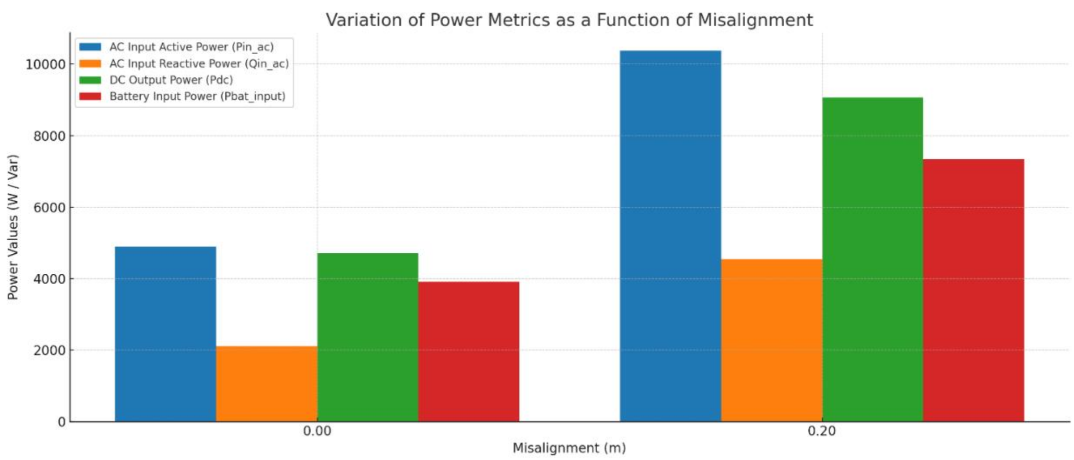


Figure 15. Variation of power metrics as a function of misalignments.

5. Discussion

5.1. Interpretation of results

The simulation results demonstrate that DWPT systems are highly sensitive to spatial parameters, particularly coil alignment and air gap distance. Under optimal conditions, efficiency approached theoretical maxima, while deviations from ideal alignment led to measurable performance degradation. The application of dynamic frequency tuning proved effective in mitigating these losses, suggesting its value in adaptive control strategies. Furthermore, analysis of compensation topologies revealed that series-parallel configurations exhibit greater tolerance to load variations, while series-series topologies are more efficient when precise alignment is maintained.

5.2. Challenges and limitations

Several technical challenges were identified that may hinder practical deployment. These include efficiency loss under real-world misalignment conditions, integration difficulties with existing road infrastructure, and electromagnetic compatibility concerns. The absence of standardized design and control protocols also poses a barrier to interoperability. Additionally, questions remain regarding thermal management, durability under continuous operation, and the scalability of such systems for widespread use.

5.3. Future research directions

Further investigation is required into coil designs that maintain high efficiency despite misalignment, as well as into the development of intelligent control algorithms that can adapt to dynamic operational conditions. The potential of hybrid charging architectures—combining static and dynamic wireless power delivery—warrants exploration for flexible deployment scenarios. Future work should also focus on comprehensive experimental validation and on developing modular, cost-effective system components compatible with existing infrastructure.

5.4. Theoretical contributions and broader impacts

This study advances the theoretical understanding of DWPT by quantifying the influence of spatial misalignment and frequency variation on system efficiency. The findings refine existing performance models and provide engineering insights into compensation circuit behavior under dynamic conditions. More broadly, the work supports advancing sustainable, infrastructure-integrated charging systems as a key enabler of next-generation electric mobility.

6. Conclusions

This study investigated dynamic wireless power transfer (DWPT) as an emerging solution for electric vehicle (EV) charging, emphasizing its operational behavior under varying spatial and electrical conditions. The proposed framework supports a more nuanced understanding of efficiency-limiting factors, including misalignment, gap variation, and load fluctuations.

The findings underscore DWPT's potential to support continuous, in-motion charging, presenting a viable alternative to conventional plug-in systems, particularly within structured environments such as dedicated lanes or transit corridors. This mobility-enabling capability positions DWPT as a promising element within future intelligent transport infrastructures.

Realizing this potential, however, will require coordinated progress in adaptive control strategies, standardization efforts, and infrastructure integration. Collaborative initiatives across academic, industrial, and regulatory sectors will be pivotal to advancing DWPT from simulation-based validation to scalable, real-world deployment.

Use of AI tools declaration

In the preparation of this manuscript, no artificial intelligence (AI) tools were used for any aspect of the research.

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Conflict of interest

The authors declare no conflicts of interest.

Author contributions

All authors contributed equally to this work. Nikolaos S. Korakianitis and Nikolaos Nikolaou were responsible for conceptualizing the study, generating results through software analysis, and contributing to the writing of the original draft manuscript. Georgios A. Vokas, George Ch. Ioannidis, and Stavros D. Kaminaris assisted in writing and provided critical proofreading to ensure the manuscript's accuracy and coherence.

References

1. Korakianitis N, Vokas GA, Ioannides G (2019) Review of wireless power transfer (WPT) on electric vehicles (EVs) charging. *AIP Conf Proc*, 020072. https://doi.org/10.1063/1.5138558
2. Panchal C, Stegen S, Lu J (2018) Review of static and dynamic wireless electric vehicle charging system. *Eng Sci Technol, Int J* 21: 922–937. https://doi.org/10.1016/j.jestch.2018.06.015
3. Zhang W, Mi CC (2015) Compensation topologies of high-power wireless power transfer systems. *IEEE Trans Veh Technol* 65: 4768–4778. https://doi.org/10.1109/TVT.2015.2454292
4. Wu J, Kong W, Gao P, et al. (2021) Design considerations of bidirectional wireless power transfer and full-duplex communication system via a shared inductive channel. *Energies* 14: 4918. https://doi.org/10.3390/en14164918
5. Budhia M, Covic GA, Boys JT (2011) Design and optimization of circular magnetic structures for lumped inductive power transfer systems. *IEEE Trans Power Electron* 26: 3096–3108. https://doi.org/10.1109/TPEL.2011.2143730

6. Buja G, Rim CT, Mi CC (2016) Dynamic charging of electric vehicles by wireless power transfer. *IEEE Trans Ind Electron* 63: 6530–6532. https://doi.org/10.1109/TIE.2016.2596238
7. Laporte S, Coquery G, Deniau V, et al. (2019) Dynamic wireless power transfer charging infrastructure for future EVs: From experimental track to real circulated roads demonstrations. *World Electr Veh J* 10: 84. https://doi.org/10.3390/wevj10040084
8. Li W, Zhao H, Deng J, et al. (2016) Comparison study on SS and double-sided LCC compensation topologies for EV/PHEV wireless chargers. *IEEE Trans Veh Technol* 65: 4429–4439. https://doi.org/10.1109/TVT.2015.2479938
9. Lu J, Zhu G, Wang H, et al. (2019) Sensitivity analysis of inductive power transfer systems with voltage-fed compensation topologies. *IEEE Trans Veh Technol* 68: 4502–4513. https://doi.org/10.1109/TVT.2019.2903565
10. Zhao J, Cai T, Duan S, et al. (2016) A general design method of primary compensation network for dynamic WPT system maintaining stable transmission power. *IEEE Trans Power Electron* 31: 8343–8358.
11. Yang J, Zhang X, Zhang K, et al. (2020) Design of LCC-S compensation topology and optimization of misalignment tolerance for inductive power transfer. *IEEE Access* 8: 191309–191318.
12. Qi J (2020) Analysis, design, and optimisation of an LCC/S compensated WPT system featured with wide operation range. *IET Power Electron* 13: 1687–1924.
13. Wang Y, Wang Z, Xu Z (2024) Analysis and comparison of the compensation topologies of magnetic coupled resonant wireless charging for electric vehicles. *Highlights Sci Eng Technol* 119: 394–405.
14. Zhu Q, Wang L, Guo Y, et al. (2016) Applying LCC compensation network to dynamic wireless EV charging system. *IEEE Trans Ind Electron* 63: 6557–6567. https://doi.org/10.1109/TIE.2016.2529561
15. Chen Y, Yang N, Li Q, et al. (2019) New parameter tuning method for LCC/LCC compensated IPT system with constant voltage output based on LC resonance principles. *IET Power Electron* 12: 2433–2712. https://doi.org /10.1049/iet-pel.2018.6129
16. Feng H, Cai T, Duan S, et al. (2016) An LCC-compensated resonant converter optimized for robust reaction to large coupling variation in dynamic wireless power transfer. *IEEE Trans Ind Electron* 63: 6591–6601. https://doi.org/10.1109/TIE.2016.2589922
17. Li S, Li W, Deng J, et al. (2015) A double-sided LCC compensation network and its tuning method for wireless power transfer. *IEEE Trans Veh Technol* 64: 2261–2273. https://doi.org/10.1109/TVT.2014.2347006
18. Korakianitis N, Theodorakis A, Vokas GA, et al. (2023) A simulation comparison and evaluation of wireless power transfer methods and topologies applicable on static and dynamic wireless electric vehicles charging systems. *AIP Conf Proc*, 2769.
19. Kurs A, Karalis A, Moffatt R, et al. (2007) Wireless power transfer via strongly coupled magnetic resonances. *Science* 317: 83–86.
20. Hekal S, Allam A, Abdel-Rahman A, et al. (2019) Compact size wireless power transfer using defected ground structures. *Energy Syst Electr Eng*. https://doi.org/10.1007/978-981-13-8047-1
21. Ko YD, Jang YJ (2013) The optimal system design of the online electric vehicle utilizing wireless power transmission technology. *IEEE Trans Intell Transp Syst* 14: 1255–1265.

22. Mi CC, Buja G, Choi SY, et al. (2016) Modern advances in wireless power transfer systems for roadway powered electric vehicles. *IEEE Trans Ind Electron* 63: 6533–6545. https://doi.org/10.1109/TIE.2016.2574993
23. KAIST (2025) KAIST OLEV (On-Line Electric Vehicle) to begin operation! Available from: https://www.kaist.ac.kr/newsen/html/news/?mode=V&mng_no=3960.
24. Kavitha M, Mohan Reddy D, Kalyan Chakravarthy NS (2022) Electrical vehicles (EVs)—An application of wireless power transfer (WPT) system. *AI Enabled IoT Electrification Connected Transp*, 165–189. https://doi.org/10.1007/978-981-19-2184-1_8
25. Guidi G, Suul JA (2018) Transient control of dynamic inductive EV charging and impact on energy efficiency when passing a roadside coil section. *IEEE PELS Workshop Emerg Technol Wireless Power Transfer*. https://doi.org/10.1109/WOW.2018.8450893
26. Fisher TM, Farley KB, Gao Y, et al. (2014) Electric vehicle wireless charging technology: A state-of-the-art review of magnetic coupling systems. *Wireless Power Transfer* 1: 87–96. https://doi.org/10.1017/wpt.2014.8
27. Sagar A, Kashyap A, Nasab MA, et al. (2023) A comprehensive review of the recent development of wireless power transfer technologies for electric vehicle charging systems. *IEEE Access* 11: 83703–83751. https://doi.org/10.1109/ACCESS.2023.3300475
28. Electreon (2025) Building the infrastructure to support mass EV adoption. Available from: https://electreon.com/projects.
29. Si P, Hu AP, Malpas S, et al. (2008) A frequency control method for regulating wireless power to implantable devices. *IEEE Trans Biomed Circuits Syst* 2: 22–29. https://doi.org/10.1109/TBCAS.2008.918284
30. Liu H, He L, Cheng B (2024) Powerless fractional-order tuning wireless power transfer system with zero phase angle input. *IEEE Trans Circuits Syst I* 72: 433–442. https://doi.org/10.1109/TCSI.2024.3404647
31. Liu H, He L, Cheng B (2024) A powerless fractional-order WPT system with extended zero voltage switching region. *IEEE Trans Ind Electron* 72: 3525–3533. https://doi.org/10.1109/TIE.2024.3447733
32. He L, Huang X, Cheng B (2023) Robust class E^2 wireless power transfer system based on parity-time symmetry. *IEEE Trans Power Electron* 38: 4279–4288. https://doi.org/10.1109/TPEL.2022.3230852
33. Assawaworrarit S (2020) Robust dynamic wireless power transfer based on parity-time symmetry. Available from: https://purl.stanford.edu/sd395gx8779.
34. Zhang H, Zhu K, Guo Z, et al. (2023) Robustness of wireless power transfer systems with parity-time symmetry and asymmetry. *Energies* 16: 4605. https://doi.org/10.3390/en16124605
35. Huang X, He LZ (2021) Stable and efficient class E^2 wireless power transfer system based on parity-time symmetry. *IEEE PELS Workshop Emerg Technol Wireless Power Transfer*. https://doi.org/10.1109/WOW51332.2021.9462866
36. Houran MA, Yang X, Chen W (2018) Magnetically coupled resonance WPT: review of compensation topologies, resonator structures with misalignment, and EMI diagnostics. *Electronics* 7: 296. https://doi.org/10.3390/electronics7110296

37. Villa JL, Sallán J, Sanz Osorio JF, et al. (2012) High-misalignment tolerant compensation topology for ICPT systems. *IEEE Trans Ind Electron* 59: 945–951. https://doi.org/10.1109/TIE.2011.2161055
38. Zhao L, Thrimawithana DJ, Madawala UK (2017) Hybrid bidirectional wireless EV charging system tolerant to pad misalignment. *IEEE Trans Ind Electron* 64: 7079–7086. https://doi.org/10.1109/TIE.2017.2686301
39. Ramezani A, Narimani M (2020) Optimized electric vehicle wireless chargers with reduced output voltage sensitivity to misalignment. *IEEE J Emerg Sel Top Power Electron* 8: 3569–3581. https://doi.org/10.1109/JESTPE.2019.2958932
40. Dehui W, Qisheng S, Xiaohong W, et al. (2018) Analytical model of mutual coupling between rectangular spiral coils with lateral misalignment for wireless power applications. *IET Power Electron* 11: 781–960. https://doi.org/10.1049/iet-pel.2017.0470
41. Chen Y, He S, Yang B, et al. (2023) Reconfigurable rectifier-based detuned series-series compensated IPT system for anti-misalignment and efficiency improvement. *IEEE Trans Power Electron* 38: 2720–2729. https://doi.org/10.1109/TPEL.2022.3204592
42. Lopez-Alcolea FJ, Del Real JV, Roncero-Sanchez P, et al. (2020) Modeling of a magnetic coupler based on single- and double-layered rectangular planar coils with in-plane misalignment for wireless power transfer. *IEEE Trans Power Electron* 35: 5102–5121. https://doi.org/10.1109/TPEL.2019.2944194
43. Rahulkumar J, Narayanamoorthi R, Vishnuram P, et al. (2023) An empirical survey on wireless inductive power pad and resonant magnetic field coupling for in-motion EV charging system. *IEEE Access* 11: 4660–4693. https://doi.org/10.1109/ACCESS.2022.3232852
44. ICNIRP (1998) Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz). Available from: https://www.icnirp.org/cms/upload/publications/ICNIRPemfgdl.pdf.
45. Ziegelberger G (2009) ICNIRP statement on the guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz). *Health Phys* 97: 257–258. https://doi.org/10.1097/HP.0b013e3181aff9db
46. ICNIRP (2010) Guidelines for limiting exposure to time-varying electric and magnetic fields (1 Hz to 100 kHz). *Health Phys* 99: 818–836. https://doi.org/10.1097/HP.0b013e3181f06c86
47. ICNIRP (2020) Guidelines for limiting exposure to electromagnetic fields (100 kHz to 300 GHz). *Health Phys* 118: 483–524.
48. IEEE (2019) IEEE standard for safety levels with respect to human exposure to electric, magnetic, and electromagnetic fields, 0 Hz to 300 GHz. *IEEE*. https://doi.org/10.1109/IEEESTD.2019.8859679
49. Xiao C, Cheng D, Wei K (2018) An LCC-C compensated wireless charging system for implantable cardiac pacemakers: theory, experiment, and safety evaluation. *IEEE Trans Power Electron* 33: 4894–4905. https://doi.org/10.1109/TPEL.2017.2735441
50. Jiang H, Brazis P, Tabaddor M, et al. (2012) Safety considerations of wireless charger for electric vehicles—a review paper. *IEEE Symp Prod Compliance Eng Proc*: 51–56. https://doi.org/10.1109/ISPCE.2012.6398288
51. Tan L, Li G, Xie Q, et al. (2023) Study on the safety assessment and protection design of human exposure to low-frequency magnetic fields in electric vehicles. *Radiat Prot Dosimetry* 200: 60–74. https://doi.org/10.1093/rpd/ncad269

52. Zhao J, Wu ZJ, Li NL, et al. (2020) Study on safe distance between human body and wireless charging system of electric vehicles with different power and frequencies. *Electr Eng* 102: 2281–2293. https://doi.org/10.1007/s00202-020-01026-2
53. Baikova EN, Romba L, Valtchev S, et al. (2019) Electromagnetic influence of wpt on human's health. *Adv Wireless Technol Telecommun*, 141–161. https://doi.org/10.4018/978-1-5225-5870-5.ch006
54. Baikova EN, Valtchev SS, Melicio R, et al. (2016) Study of the electromagnetic interference generated by wireless power transfer systems. *Int Rev Electr Eng (IREE)* 11: 526. https://doi.org/10.15866/iree.v11i5.9773
55. Zhang Y, Yuan J, Li L, et al. (2019) Design and application of early warning model for electric vehicle charging safety. *J Phys Conf Ser* 1873: 012052.
56. Li S, Mi CC (2015) Wireless power transfer for electric vehicle applications. *IEEE J Emerg Sel Top Power Electron* 3: 4–17. https://doi.org/10.1109/JESTPE.2014.2319453
57. Rim CT, Mi C (2017) Wireless power transfer for electric vehicles and mobile devices. *Wireless Power Transfer*, John Wiley & Sons, Ltd. https://doi.org/10.1002/9781119329084
58. Zhang W, Mi CC (2016) Compensation topologies of high-power wireless power transfer systems. *IEEE Trans Veh Technol* 65: 4768–4778. https://doi.org/10.1109/TVT.2015.2454292
59. Covic GA, Boys JT (2013) Modern trends in inductive power transfer for transportation applications. *IEEE J Emerg Sel Top Power Electron* 1: 28–41. https://doi.org/10.1109/JESTPE.2013.2264473
60. Hui SYR, Zhong W, Lee CK (2014) A critical review of recent progress in mid-range wireless power transfer. *IEEE Trans Power Electron* 29: 4500–4511. https://doi.org/10.1109/TPEL.2013.2249670