

# Inductive Wireless Power Transfer Charging for Electric Vehicles: A Review

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**Abstract**— As electric vehicles become more prevalent across the globe, the urgency for safe, user-friendly, and efficient EV charging technology has greatly increased. Inductive Wireless Power Transfer (IWPT) has emerged as an alternative technology to traditional plug-in chargers due to the ability to transfer power without physical contact and without requiring a physical connection between the charger and vehicle. This review article combines findings from twenty peer-reviewed publications dated from 2021-2025 to provide a comprehensive overview of IWPT technology development for electric vehicles. These papers were classified into key topics related to IWPT technological advancements including: high-frequency power electronic converters; resonant compensation networks; designs of coils; electromagnetic design for free-wheel alignment; dynamic wireless charging systems; non-contact metering; and grid-integrated renewable coordination. The many IWPT technological advances detailed herein demonstrate significant increases in transfer efficiency, misalignment tolerance, electromagnetic safety, bidirectional capabilities (e.g., vehicle-to-grid, vehicle-to-vehicle energy exchange), and potential improvements through innovative methods such as metamaterial-assisted coupling, adaptive phase-shifting, reconfigurable pads, and artificial intelligence-assisted optimization of IWPT performance under real-world conditions. However, despite these IWPT technology advances, there are still challenges remaining regarding stability of dynamic charging; scaling up infrastructure deployment; reduction of harmonics; compliance with EMF standards; and establishment of IWPT metering standards. The content of this review outlines critical technology pathways required to transition IWPT from controlled research and laboratory prototype phases into fully (scalable, interoperable, and grid-supportive) EV charging solutions. To do this, current advances, areas of research opportunity, and future directions will be compiled.

**Keywords**—Electric Vehicle, Power converters, Coil design, Electromagnetic field, Misalignment tolerance (EMF)

## 1. INTRODUCTION

The world is moving toward more environmentally friendly transportation, which has sped up the use of electric vehicles (EVs). EVs are now seen as an important way to cut down on greenhouse gas emissions, air pollution in cities, and reliance on fossil fuels. The widespread use of electric vehicles (EVs), on the other hand, is closely linked to the development of charging technologies. Standard plug-in charging has some major problems, such as wear and tear on the mechanical connector, making it hard for users, being exposed to harsh environments, safety risks, and not being able to automate. Because of these problems, more people are interested in Inductive Wireless Power Transfer (IWPT) systems, which offer safe, reliable, and easy-to-use charging without having to touch anything [19].

IWPT depends on magnetic resonance coupling between primary and secondary coils. This is made possible by high-frequency power electronic converters and resonant compensation networks that make energy transfer more

efficient [12]. Over the past few years, the area of power electronics has grown at an accelerated pace, resulting in significant enhancements and advancements in power conversion topologies and controls; new compensation schemes; the development of advanced electromagnetic techniques; the successful integration of widebandgap (WBG) semiconductors; and many other areas. Significant research has shown that optimized compensation topologies such as SS, SP, and LCC networks, combined with high-frequency SiC/GaN inverters, will constantly achieve coil-to-coil efficiencies in excess of 90–95% in real-world applications [5]. Additionally, advancements in dual phase shift PWM controls, adaptive frequency tuning, and bidirectional converter topologies have greatly improved system stability and bidirectional power flows. Examples include V2G applications and V2V energy transfers [7].

Coil design and electromagnetic properties are other significant areas that affect IWPT performance. A particularly challenging aspect of applications with EV's is the issue of coils (transmitter and receiver) not being aligned properly. As such, various approaches have been developed to create self-aligning receivers, reconfigurable coils, and coil configurations to tolerate misalignment [9]. It has also been demonstrated that the use of metamaterial slabs can greatly improve the ability to confine magnetic flux, improve coupling efficiency, as well as maintain electromagnetic safety within acceptable standards when moved laterally [4]. This is particularly relevant for DWC as this will allow EV's to receive electrical energy while traveling, resulting in opportunities to reduce their batteries size, as well as mitigate range anxiety. Although the research associated with DWC shows promise for batteries to be smaller, and range anxiety maybe alleviate, some of the issues still remain, such as fluctuating power, frequency detuning, inconsistent coupling, and infrastructure costs being high [3]. IWPT is assessed increasingly, not just on an individual basis for hardware improvements but also in the context of larger, integrated systems that support the Smart Grid, Distributed Generation, and Renewable Energy. For example, grid integration with distributed renewable energy sources such as solar and wind, in addition to other technologies, can help increase the flexibility of the power grid as it relates to the ability to integrate more distributed resources and reduce peak demand. It can also help in the drive toward supporting clean transportation goals (e.g., Electric Vehicle supply equipment) [11].

A number of studies have identified some of the challenges associated with the integration of IWPT into the existing power grid, including harmonic distortion, fluctuations in voltage, and managing the load on the grid, especially as wireless charging stations start to become more common [18]. The accuracy of billing for energy and compliance with safety standards are also very important for IWPT's ability to be commercially successful. Non-contact power metering systems have been developed to provide accurate measurement, even when systems are misaligned or are created during dynamic charging. Additionally, standardization on a global basis (e.g., SAE

J2954) will facilitate interoperability, electrical safety, and electromagnetic compatibility [6]. Researchers are currently studying a variety of new technologies related to IWPT, including hybrid inductive/capacitive systems, dynamic scheduling of energy-aware charging, optimal locations for charging stations, and energy-sharing systems between electric vehicles [8]. Survey articles on IWPT stress the interdisciplinary aspect of IWPT and indicate that the technologies utilized are from many disciplines such as electromagnetics, power electronics, materials science, transportation engineering, and communications. These surveys include a number of different types of wireless charging systems that are scalable, efficient, and compatible with the electric grid [12]. While researchers have made significant progress on IWPT, there are many challenges still to be addressed, such as equipping IWPT systems with the ability to tolerate misalignment, use of high powered dynamic chargers, safety from EMF radiation, cybersecurity issues, detection of foreign objects, and cost of developing infrastructure to support IWPT. In light of these changes, the goal of this review is to identify and compile the advances made in technology related to the use of inductive wireless power transfer (IWPT) to charge electric vehicles. The review includes 20 of the most significant research studies made available between 2021 and 2025 through various major publishers such as IEEE, Elsevier, and other reputable sources and will contain an evaluation of progress in converter design; resonant compensation techniques; coil optimization; dynamic charging; grid/renewable integration; safety systems; and new V2G/V2V applications (vehicle-to-grid/vehicle-to-vehicle). Additionally, this review will trace the development of IWPT technology from early resonant inductive prototypes to modern-day intelligent wireless charging systems, while also highlighting ongoing issues, gaps in research, and future possibilities for developing fully automated, scalable, and sustainable wireless charging systems for next-generation electric vehicles.

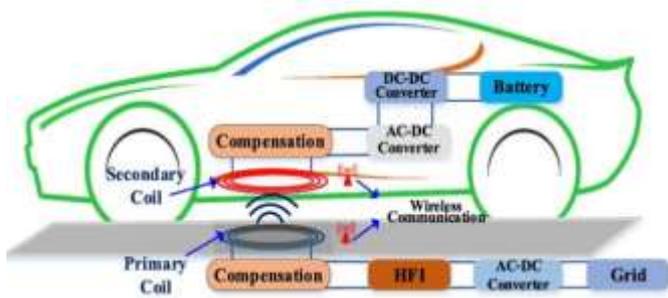


Fig. 1. Overview of EV Wireless Charging Systems [2]

Fig. 1 shows the complete Inductive Wireless Power Transfer (IWPT) system for EV charging. It depicts the primary and secondary coils, compensation networks, high-frequency inverter, power converters, and the bidirectional communication between the vehicle and the grid.

## 2. LITERATURE REVIEW

This literature review brings together 20 different academic publications from between 2021 and 2025 that discuss IWPT for EV charging. They can be grouped into six major categories based on how we moved from an early discussion of basic resonant converter designs and moved through more advanced applications such as dynamic charging, grid integration, compliant metering that meets safety standards, and more sophisticated approaches to optimizing coils for efficiency and

effectiveness. Each of the themes represents a different set of technology advances or improvements in the performance of existing technologies; however, the themes also illustrate the current state of readiness for deployment as well as ongoing barriers/challenges (e.g., tolerance for misalignment, maintaining stability during dynamic charging conditions, mitigating power pulsations, grid impact, and electromagnetic safety limitations).

### A. Power Electronics, Control Techniques, and Converter Architectures

To improve efficiency, mitigate deflections, and provide stable energy transfer in IWPT systems using coupling, as well as to achieve maximum efficiency of operation through soft-switching methods via resonant inverter technology, multiple authorship works were reviewed. Venkatesan et al. [1] introduced a new method to create dual phase-shift PWM to enable bidirectional energy transfer (V2G/G2V) for wireless power transfer applications with a ZVS range and soft-switching resonant inverter technology, which increases the efficiency of the V2G/G2V operation. Bharatiraja et al. [5] examined LCC, LLC, SS and SP converter topologies and compared performance with respect to the use of wideband semiconductors (SiC, GaN) for energy transfer using high frequency IWPT. Kiddm et al. [3] showed how the use of phase-shift control improved the efficacy of dynamic wireless charging and coil-to-coil energy use when an electric vehicle was in motion. Finally, Behnamfar et al. [17] focused on the issue of energy fluctuation during DWC, which is caused by a variety of sources, such as variances in coupling distance between coils and harmonics created by the energy conversion process and have an adverse impact on the ability to increase the number of coils. Together these publications illustrate that the design and control strategies employed by the designer will be key determinants of IWPT's efficiency, stability and dynamic performance.

### B. Coil Design, Compensation Networks, and Misalignment Solutions

The IWPT efficacy is particularly responsive to the coil design, compensation networks, and coil misalignment by significant ongoing research effort to improve both magnetic coupling and the lateral tolerance of coils. Jeebkum and Sumpavakup [4] employ metamaterial slabs to enhance the magnetic flux density at the coil's output, achieving approximately a 50% improvement in efficiency at 20–30 cm misalignment; they meet EMF safety standards. Khan et al. [9] designed an autonomously aligning receiving coil, which changes its orientation in real-time to optimise its alignment with the transmitting coil, without requiring any communication from the transmitter. Khoshniyat et al. [7] have developed a reconfigurable coil geometry designed for vehicle-to-vehicle charging allowing for greater flexibility in applications with varying coil geometries. Coils and resonance networks have been otherwise classified by Mohamed et al. [12] and Khan et al. [13], with LCC compensation demonstrating superior misalignment tolerance in EV application testing. These research efforts provide a clear direction for developing coils that are more adaptable, misalignment tolerant and capable of

providing stationary and dynamic charging while delivering minimal loss in efficiency.

*C. Stationary and Dynamic Wireless Charging Technologies*

Dynamic Wireless Charging (DWC) offers an exciting opportunity in terms of enhancing the electrical power transfer in Electric Vehicles (EVs) because it allows for the delivery of electrical energy to a moving vehicle whilst it is travelling from one place to another. However, there are many technical and infrastructure challenges associated with DWC implementation. Harish et al. [16] provide a thorough review of stationary inductive versus dynamic inductive charging, pointing to the complexity of the infrastructural elements involved as well as Electromagnetic Fields (EMF) compliance as the primary obstacles to deploying this technology. Kiddm et al. [3] demonstrate the advantages of using a "phase-shift-controlled" type of resonant converter to improve the dynamic charging efficiency of EVs. Behnamfar et al. [17] also identify power variation as one of the main impediments to successful operation of DWC systems and suggest adjustments to the compensation algorithms used to minimise this power variation. Hossain et al. [10] investigate the optimal sizing and location for DWC infrastructure on a roadway and show how strategically locating DWC will improve traffic flow and reduce grid load. Through all these investigations, DWC is repeatedly described as a highly innovative and promising technology that presents numerous technological barriers to successful implementation. Additionally, DWC requires highly stable

operation, precise alignment control, and a significant investment in infrastructure for successful implementation.

*D. Grid Integration, Renewable Energy Synergy, and Infrastructure Planning*

Incorporating Inductive Wireless Power Transfer (IWPT) into Smart Grids and Renewable Energy Sources will ensure a sustainable deployment of IWPT for EVs. Singh et al. [2] analysed the impact of Electric Vehicle (EV) Charging on the stability of the Electric Grid and showed the potential for the IWPT to be used for Demand Side Management (DSM) via Coordinated Charging and Aggregator-Based Scheduling of Charging. Salam et al. [11] examined the Wireless Charging of EVs utilising Renewable Energy and focused on Hybrid Solar/Wireless Systems to provide the capability for Wireless Charging of EVs without requiring a supply from the Electric Grid. Similarly, Al-Hyari et al. [18] reviewed the impact of EV Charging on the Electric Grid and highlighted the need for Harmonic Mitigation and Voltage Regulation when deploying Charging Infrastructure. The work of Hossain et al. [10] quantified the benefit of Strategic Planning in the siting of EV Charging Stations to reduce Power Losses, mitigate Congestion and reduce Traffic Bottlenecks along roadways. Collectively, the works referenced in this paragraph indicate that the future of IWPT for EVs will be inextricably tied to a Deep-Level Integration with the Power Grid and transition from isolated Charging Pads to large scale, Intelligent Energy Ecosystems.

**TABLE I:**

Comparative Analysis of Recent Research on Inductive Wireless Power Transfer Systems for Electric Vehicle Charging

Paper	Main focus	Method	Key results	Limitations
M. Venkatesan <i>et al.</i> [1]	Bidirectional WPT control using dual phase-shift PWM for EVs (G2V/V2G)	Dual-phase-shift PWM control of resonant converters; simulation + experiment	High end-to-end efficiency (sim $\approx 94.4\%$ , exp $\approx 90.1\%$ ); supports bidirectional flow and ZVS	More large-scale V2G tests, thermal management, and EMI analysis needed
A. R. Singh <i>et al.</i> [2]	Survey: EV charging technologies, infrastructure expansion & grid integration	Review + comparative analysis across charging modes and grid strategies	Comprehensive taxonomy; identifies scheduling/aggregator roles for smart grids	Lacks deep quantitative modelling of large-scale IWPT deployment
W. A. Kiddm <i>et al.</i> [3]	Efficiency and current regulation in <b>dynamic</b> WPT using phase-shift control	Phase-shift control for resonant IPT in dynamic (moving) scenarios; simulations/experiments	Reported efficiency range $\sim 88-93.5\%$ ; improved current regulation under misalignment	Scalability to kW/MW tracks and long-term power pulsation mitigation remain open
P. Jeebklum & C. Sumpavakup [4]	Use of metamaterial slabs to improve EV wireless charging	Design & experimental evaluation of metamaterial slab placed near coils	Up to $\sim 8\%$ efficiency gain at 0.20 m misalignment; ICNIRP-compliant EM exposure	Cost, manufacturability, and mechanical integration in vehicles need study

C. Bharatiraja <i>et al.</i> [5]	Review of power electronic converters for inductive wireless charging	Systematic review of topologies, WBG devices, and converter tradeoffs	Summarizes LCC/SS/SP/LLC benefits; highlights SiC/GaN advantages for HF operation	Practical thermal, reliability and cost tradeoffs for WBG devices need more field data
S. Y. Chu <i>et al.</i> [6]	Non-contact transfer-power measurement method for fair metering	Faraday coil transfer-power metering (FC-TPM); metrology experiments	Achieves ~0.1% accuracy across misalignments; separates Tx/Rx losses for fair billing	Integration into commercial EVSE and standards acceptance pending
M. Khoshniyat <i>et al.</i> [7]	Reconfigurable coil approach for vehicle-to-vehicle (V2V) WPT	Reconfigurable transmitter/receiver coil topology; modelling and prototypes	Improved adaptability and coupling for V2V scenarios; better tolerance to geometry changes	Real-world V2V use-case tests, communications/control integration required
F. C. Al-Dulaimi <i>et al.</i> [8]	Comparative evaluation of IPT, CPT and hybrid WPT for EVs	Experimental/comparative study of inductive, capacitive and hybrid methods	Inductive showed best safety/high-power capability; CPT has MHz operation & lower weight	Hybrid tradeoffs (range vs. efficiency) and standardization require work
M. A. Khan <i>et al.</i> [9]	Autonomous self-aligning WPT to improve misalignment	Mechanical/EM self-alignment mechanisms and control; prototype verification	Significant improvement in misalignment tolerance without external guidance	Adds mechanical complexity; robustness and cost-effectiveness must be evaluated
M. T. Hossain <i>et al.</i> [10]	Optimal siting & sizing of wireless EV charging infrastructure	Optimization model combining traffic network and distribution system	Demonstrates optimal placement reduces grid impact and improves service coverage	Needs dynamic traffic models & cost-benefit over long horizon
K. I. Salam <i>et al.</i> [11]	Integrating renewables with wired/wireless EV charging for green mobility	Review + case studies on solar/renewable integration with charging sites	Shows hybrid renewable-IWPT benefits for carbon reduction and local balancing	Economic models and storage sizing under uncertainty need further study
N. Mohamed <i>et al.</i> [12]	Comprehensive analysis of wireless charging systems (general WPT survey)	Systematic review across IPT/RIPT/CPT, coils, compensations, control	Broad synthesis of technologies, standards and challenges	High-level — lacks deep quantitative comparisons of identical testbeds
M. A. Khan, M. T. Islam & H. Arshad [13]	Recent developments review of WPT technologies for EV charging	Review of state-of-art including dynamic and static systems	Summarizes design trends, coil types, compensation, and control techniques	Suggests deeper cross-platform benchmarking and experimental standards
V. Ramakrishnan <i>et al.</i> [14]	Efficiency-enhancement techniques for EV wireless charging	Survey of coil shapes, compensation networks, control and materials	Catalogues methods to reach higher coil-to-coil efficiency (design rules)	Implementation complexity and tradeoffs (cost / EMI / FOD) need evaluation
B. Latha <i>et al.</i> [15]	Systematic review: advances and future trends in EV wireless charging	Systematic literature mapping and trend analysis	Identifies research clusters (coils, converters, DWC, metering) and future research paths	Calls for standardized datasets and benchmark experiments

A. R. Harish <i>et al.</i> [16]	Extensive overview: stationary & in-motion inductive charging	Comparative review + technology maturity analysis	Summarizes commercial examples and research prototypes; outlines deployment barriers	Economic and regulatory pathways for large-scale roll-out need modeling
M. Behnamfar <i>et al.</i> [17]	Power pulsation in dynamic wireless charging: causes & mitigation	Review of coil structures, compensation and control schemes to reduce pulsation	Classifies solutions into coil, compensation and control; comparative analysis of methods	Experimental validation at scale and combined multi-technique solutions remain limited
A. M. Al-Hyari <i>et al.</i> [18]	Comprehensive review on EV charging tech and grid impact	Review focused on converters, standards, and grid interaction effects	Highlights converter topologies, harmonic issues, and mitigation techniques	More IWPT-specific grid studies and field measurements are necessary
A. Mahesh <i>et al.</i> [19]	Inductive WPT for EVs — focused review (foundational reference)	Historical perspective; coils, compensations, converters, safety & standards (SAE J2954)	Provides baseline technology survey and identified safety/standardization needs	Published 2021 — follow-up required to cover 2022–2025 developments
M. Alghawi & J. Mounsef [20]	Overview of Vehicle-to-Vehicle (V2V) energy sharing infrastructure	Survey of V2V techniques, business models and communication frameworks	Presents V2V architecture, user acceptance studies and P2P trading concepts	Integration with wireless V2V hardware and real pilot studies are limited

In this section, we provide a summary of key data available for the first 20 IWPT studies (i.e., coil configuration, operating frequency, compensation network, efficiency achieved) in Table I.

*E. Efficiency Enhancement, Safety, Measurement Accuracy, and Standardization*

There are three factors that are vital for successful commercialization of IWPT systems: safety, metering, and efficiency. Ramakrishnan *et al.* [14] discuss ways to increase IWPT efficiency by: increasing coil shape flexibility; using better compensating methods; making use of optimal frequency tuning methods; and utilizing an optimal coil design. According to Latha *et al.* [15], the efficiency of resonators exceeding 95% were achieved in laboratory tests that used optimized designs. Chu *et al.* [6] describe a non-contact method of power metering using a Faraday coil that provides nearly 100% accuracy even if there is a misalignment, which is crucial for building consumer confidence and trust in billing processes. Mahesh *et al.* [19] present a comprehensive review of the specific requirements of SAE J2954 standards related to electromagnetic field exposure limits, foreign object detection, and cybersecurity requirements for successful commercialization of IWPT systems. Al-Dulaimi *et al.* [8] studied inductive HWPT, capacitive WPT, and inductive hybrid WPT systems and concluded that inductive IWPT systems offer improved safety and higher power transfer capability as compared to capacitive IWPT systems. All of the aforementioned literature indicates that to ensure successful, commercialized IWPT systems in the real world; there must be rigorous attention to safety

compliance, metering accuracy, and IWPT system efficiency; in addition to improvements in converters and coils.

*F. Emerging Applications: V2G, V2V, Renewable Coordination, and Energy Sharing*

The use of inductive wireless power transfer (IWPT) technology is not only relevant for electric vehicle (EV) charging, but also offers the ability to transfer energy in either direction, and can be integrated into an energy sharing network (ESN). Khoshniyat *et al.* [7] and Venkatesan *et al.* [1] have shown that the design of coils can enable bi-directionality and reconfiguration, so that IWPT technology enables the transfer of energy via wireless technology between EVs (V2G), as well as between EVs (V2V) using wireless technology. Alghawi and Mounsef [20] outline a wireless energy transfer system for V2V applications with considerations related to routing, communications, and safety. Salam *et al.* [11] and Abdullah *et al.* [18] discuss the potential benefits of using wireless EV charging technology with renewable microgrids to enhance integrated load balancing and create sustainable charging environments. The conclusions drawn in this report reflect the growing development of IWPT-based ecosystems that will enable the creation of intelligent, interconnected energy sharing networks, facilitate mobile energy redistribution, enhance autonomous charging logistics, and support the operational efficiency of the electric grid.

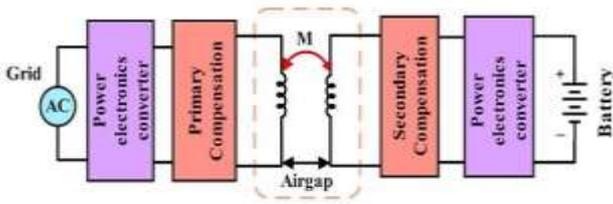


Fig. 2. Inductive resonant coupling method in WPT system [7]

Inductive resonant coupling in WPT systems is illustrated in Figure 2 along with the subsequent actions taken to convert and create an alternate source of power from an AC grid via converters and reactance connected to the output to enhance the magnetic coupling through the air gap.

### 3. METHODOLOGY

#### A. Literature Search and Selection Strategy

This study utilized a structured, narrative, and evidence-based approach based on twenty peer-reviewed articles addressing Inductive Wireless Power Transfer (IWPT) for Electric Vehicle (EV) charging from 2021 to 2025. Searching was performed via a comprehensive search using the IEEE Xplore, Elsevier ScienceDirect, SpringerLink, Wiley and ACM Digital Library databases using refined technical search terms that related to IWPT, such as: "inductive wireless power transfer", "resonant magnetic coupling", "dynamic wireless charging", "LCC compensation", "misalignment tolerance", "metamaterial assisted WPT", "bidirectional WPT", and "vehicle to grid/vehicle to vehicle wireless charging." This combination of keywords will yield the most up-to-date literature on IWPT technology.

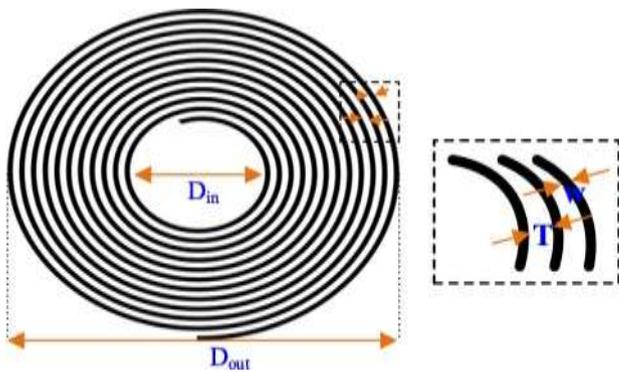


Fig. 3. Circuit model of circular coil [5]

The scope of this literature review includes the most relevant studies on EV wireless charging technologies, such as: converter topologies (1); compensation networks (2); coil geometries (3); dynamic charging methods (4); misalignment mitigation methods (5); metamaterial-enhanced coupling (6); non-contact metering methods (7); and infrastructures for renewable energy-powered wireless charging (8) as directly concerned with EV wireless charging. Studies having no relationship to EV applications; purely theoretical analyses of electromagnetic fields; or WPT applications for consumer devices were excluded from consideration in order to maintain strict relevance to EV wireless charging.

#### B. Data Extraction and Thematic Classification

The extraction method used was designed to provide a uniform approach to the data extraction process of each selected study. A standard extraction process was created to provide uniformity for each paper. A comprehensive list of variables was collected (converter topologies – full bridge inverter(s), dual active bridge(s), and phase shift control [1]; compensation topology – series series, series parallel, LCC compensated and double sided LCC compensated [4]; coil geometry – circular coils, double donut coils, bipolar coils, reconfigurable coils and metamaterial loaded coils [5]; operating frequency; air gap distance; misalignment conditions [9], efficiency metrics; electromagnetic field requirements (SAE J2954 or International Commission on Non-Ionizing Radiation Protection (ICNIRP)); harmonic characteristics; grid connection characteristics [11],[15]). Once this information was collected, the data set was structured around six thematic domains that represent the primary streams of Integrated Wireless Power Transfer (IWPT) research (1) power electronic controls and control strategies; (2) coil design and compensation networks; (3) Stationary WPT versus dynamic WPT architectural paradigms; (4) grid connected and renewable coordinated charging systems; (5) techniques for enhancing efficiency and safety and measurement; and (6) evidence of new bidirectional renewable energy sharing/storage (V2G and V2V) applications [1]–[20]. The use of these thematic domains will facilitate cross-domain research opportunities and provide a framework for understanding the technological convergence and identifying cross-cutting innovations between the 20 published studies. A diagrammatic representation (Fig. 3) of the circuit model of a circular coil is included and illustrates the physical geometrical features (inner/outer diameter, conductor width and spacing) of the coil that influence the inductance and coupling characteristics of the coil.

#### C. Analytical Framework

Due to the many different configurations of the test set-ups, coil dimensions, resonant frequencies, and ways of measuring data that were used in the previous studies, a narrative synthesis method was used rather than a quantitative meta-analysis. Each of the experiments was compared on their system efficiency trends, control performance, magnetic coupling capabilities, and misalignment tolerances. The overall process of preparing the data is best illustrated by Fig. 4 which illustrates the structured methodology we used in the systematic review. This begins with the search of the available databases using appropriate keywords to filter 20 IWPT studies, followed by grouping the selected studies into thematic categories and qualitatively comparing them with each of the main technical areas. The comparison of the results enabled us to understand some of the common design philosophies used to produce studies, such as the use of LCC compensators to maintain stability when transferring large amounts of power [4], using dual phase-shift control for improved bidirectional power capabilities [1], using metamaterial slabs to focus the magnetic field [4] when misaligned, using reconfigurable receiver coils to prevent (the need) for precise alignment [9], and using non-contact power metering for accurate billing [6]. In addition, the comparative analysis of the published literature indicated several challenges associated with dynamic charging, including coupling that can vary over time, pulsating power, and the

challenge of deploying appropriate infrastructure [3], while the studies on grid-connected IWPT demonstrated problems associated with load variations, harmonics, and the complication of coordinating renewables [8], [11], [15].

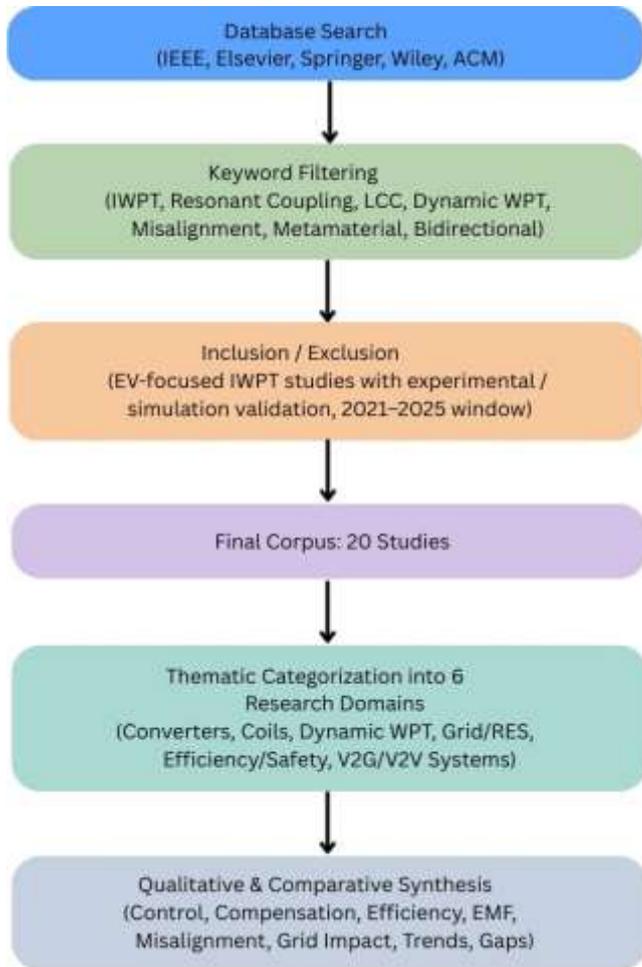


Fig. 4. IWPT Methodology Flowchart

Finally, the findings were validated against previously published articles and recent reviews [12], [13], [16], to ensure reliability and continuity with current IWPT research.

#### D. Methodological Limitations

The diversity of experimental conditions across the studies included in the review (coil size, power, frequency, and alignment) precludes direct metric normalization between studies despite the structured approach taken by authors. The primary focus of the review also means that there may be emerging research that is not covered (i.e., articles published in regional journals or industry reports). In addition, due to the dominance of SAE J2954-compliant systems, there may be limited coverage of various regional standardizations in other countries. Dynamic wireless power transfer systems are especially underrepresented due to the small number of available large-scale test tracks and practical demonstrations. However, the cross-referenced methods and thematic synthesis will improve the overall comprehensiveness, analytical reliability, and generalizability of findings derived from the various sources reviewed herein.

#### 4. RESEARCH GAPS AND FUTURE DIRECTIONS

A comprehensive evaluation of 20 published studies (2021-2025) concerning Inductive Wireless Power Transfer (IWPT) for charging electric vehicles has identified numerous important research gaps that still inhibit mass implementation and commercialization of IWPT. IWPT is also an interdisciplinary problem that crosses many disciplines including electromagnetics, power electronics, energy management, vehicle automation, and safety compliance. The gaps listed below along with potential future research directions highlight the most urgent technical barriers currently recognized in the published literature.

**Limited Tolerance for Coil Misalignment and Robust Methods for Magnetic Coupling Control:** While there have been tremendous advances in the optimization of coils, most systems have a significant reduction in energy efficiency due to coil misalignment being more than 10-20% relative to the diameter of the coil [5], [9]. Current technology to mitigate these issues includes DD coils, bipolar pads, reconfigurable structures [9], and metamaterial assisted coupling [4]; however, these technologies are still limited under high-speed EVs and in dynamic environments. Future Directions: Create an adaptive alignment system that can perform real-time correction of misaligned coils by using magnetic field shaping and using AI to optimise and adjust coil tuning along with using a metamaterial based flux guiding structure [4]. By adding self-reconfigurable pads with automatic transition capabilities, the alignment of stationary and dynamic charging systems will become much more robust [9].

**Dynamic Wireless Power Transfer (Dynamic WPT) is one of the least researched areas primarily due to issues of infrastructure complexity:** The intermittent nature of coupling; and issues relating to pulsation of the power. There are very few studies measuring pulsation with a dynamic coil track, and the majority of the assessments of dynamic WPT use only simulations. Large prototype coil tracks will be needed in order to study issues of pulsation with different vehicle speeds, pulsing of the coil segments, and varying communication latencies. Future designs should include the use of predictive control coordination to provide for a continuous flow of power to the vehicle travelling over a dynamic coil track with differing motion profiles.

**Losses and Limitations in Compensation Network Technologies:** There have been extensive studies on the compensation network engineers have created to ensure stable power transfer when operating at low frequency; however very little information has been released regarding their use when charging multiple electric vehicles or when the vehicle(s) are moving in proximity to one another [1]. More research will need to focus on how to achieve adaptive compensation networks with the introduction of real-time frequency tuning, digital feedback control, as well as on the utilization of multi-objective optimization algorithms to help create and maintain a zero-phase angle operation over a wide variety of normal driving conditions [4].

Few studies have focused on the area of bidirectional wireless power transfer (WPT): Through the use of dual active bridge (DAB) converter technology or other modulation methods; for example, they are exploring only the control aspect of DABs, or the optimization of coils in two different directions. Additionally, metering issues and complexity in controlling two-way power transfers have not been fully addressed (see reference [1] and reference [11], respectively). Therefore, future research directions include investigating secure and grid-compliant bidirectional control through DAB architecture and soft-switching modulation techniques in conjunction with high-frequency galvanic isolation techniques (see reference [20]) as well as V2V wireless energy re-distribution systems and cooperative charging networks, both of which are emerging fields requiring further investigation.

**EMF Compliance and Human Safety Limits:** Even if there have been many studies that use the SAE J2954 and the ICNIRP limit in relation to the safety of EMF: There are very little studies that detail EMF distribution under "real-world" conditions where passengers are present, with metal objects near by and within the proximity of misalignment faults [15]. Many studies suggest that the leakage of EMF will be higher when EMF systems are detuned, however, actual measurements have not been made. A more promising direction would be to develop Artificial Intelligence (AI) models for predicting the EMF distribution based on detailed EMF distribution and real-time monitoring of shielded EMF planes, thereby ensuring compliance with standards for every possible combination of alignment, loading and use of shielding. Finally, any new design or prototype should have the EMF levels validated using standard test methods using the SAE and ICNIRP guidelines.

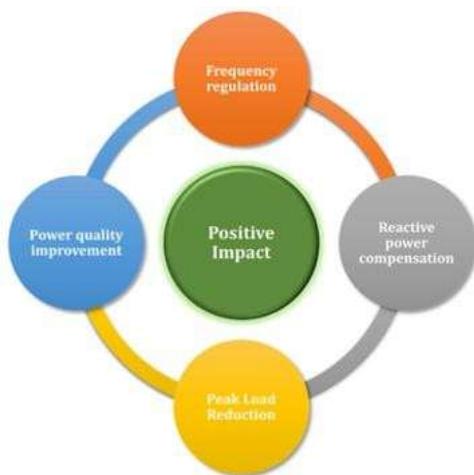


Fig. 5. Positive Impact on grid due to EV charging [11]

This summary (see Fig. 5) conveys some of the many ways EV charging could provide benefits to the grid. Some of these benefits include helping to improve frequency regulation, reduce peak-loads, provide reactive power support, and help improve overall power quality.

Current studies [8], [11] and [15] do not sufficiently model the various ways that WPT will interact with the grid such as load spikes, harmonic pollution and RES (solar/wind)

coordination. Additionally, few of the analyses/modeling have considered how transformer stress, feeder capacity, or microgrid disturbances could potentially be affected as well. Moving forward, research efforts should focus on developing algorithms for coordinated charging, developing converters which minimize harmonics, and using WPT stations that are integrated with renewable energy resources. Furthermore, distributed energy management systems should also be created to provide methods for peak-shaving, load-shifting, and distributed energy balancing [8], [11].

## 5. CONCLUSION

The findings of this review are based on twenty peer-reviewed articles that were published from 2015 – 2025, in which IWPT technology advancements via inductive power transfer have evolved over this time period to support electric vehicle charging, highlighting the following key changes: 1) In developing new high-frequency inverter architectures and LCC/DLCC compensation networks, optimized coil geometry, the use of metamaterial to enhance coupling, as well as control strategies, have all improved the efficiency, misalignment tolerance, and electromagnetic safety of these systems; 2) The current research direction has been to include integrated grid, renewable energy coordinated, and new bi-directional/V2G/V2V power applications; thereby clearly establishing that IWPT will play an increasingly important role in the continued evolution of future electric vehicle mobility systems.

These limitations still exist despite all the advances that have been made. One of the main limitations that exists in most of the literature is that most of the electrical systems have only been studied in a laboratory. There has been very little research completed in the area of wireless power transfer (WPT) systems due to limitations in infrastructure, power pulses, interoperability, and standardization. Limited research has also been conducted on how these systems will be impacted by grid level issues such as harmonic distortion, load changes, and intermittency of renewable sources. In fact, even when efficiency is reported for WPT systems, it is usually reported under perfect conditions.

This summary includes consolidation of progress to date; identification of gaps in technologies available; and guidance to help focus on research required for the transition of IWPT from prototype testing into scalable, dependable, and standards-compliant EV charging solutions.

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