An Overview of Wireless Charging Technologies for Electric Vehicles

Uggirala Vasavi [1], M Vinay Kumar[2], Rakoti Nandini [3], Ladi Sai Roshini [4]

[1,3,4]B.Tech Student, Department of EEE, GMR Institute of Technology, Rajam-532127, Andhra Pradesh, India

[2] Senior Assistant Professor-SG, Department of EEE, GMR Institute of Technology, Rajam-532127, Andhra Pradesh, India

Email: uggiralavasavi@gmail.com

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Abstract - Wireless charging technology for electric vehicles (EVs) is emerging as a revolutionary solution to address the limitations of traditional plug-in charging systems. It offers enhanced convenience, safety, and automation by enabling energy transfer without physical connectors. This paper provides a comprehensive overview of wireless charging technologies, focusing on the principles, classifications, and advancements in static, dynamic, and quasi-dynamic systems. The study examines the electromagnetic coupling mechanisms such as inductive power transfer (IPT), capacitive power transfer (CPT), and resonant inductive coupling (RIC), highlighting their advantages, limitations, and design considerations. The research also discusses the role of power electronics, control algorithms, and magnetic field alignment techniques in optimizing energy efficiency. A comparative evaluation of existing technologies is presented to demonstrate their performance in terms of transfer efficiency, cost, and interoperability. Furthermore, the paper explores research gaps, challenges, and potential future directions, emphasizing the need for standardization, material innovation, and smart-grid integration. The results underscore that while wireless charging is technically feasible, significant efforts are still required to achieve large-scale commercial adoption for both static and dynamic charging infrastructures.

Key Words: Wireless Power Transfer, Electric Vehicles, Inductive Charging, Dynamic Charging, Resonant Coupling.

1.INTRODUCTION

The transition toward sustainable transportation has accelerated the global adoption of electric vehicles (EVs). However, despite their growing popularity, EVs face several challenges, particularly concerning charging convenience, infrastructure availability, and battery longevity. Conventional plug-in charging methods, though widely implemented, present limitations in terms of user comfort, mechanical wear, safety, and space constraints. Wireless charging technologies, often referred to as Wireless Power Transfer (WPT), have emerged as an innovative solution to overcome these issues by enabling efficient, contactless energy transfer between the power source and vehicle battery. Wireless charging for EVs operates based on electromagnetic induction or resonant coupling principles, allowing energy transfer across an air gap without physical connectors. This technology not only simplifies user experience but also opens the possibility for dynamic charging—charging while the vehicle is in motion. Such systems can significantly extend driving range and reduce dependency on high-capacity batteries, contributing to lower vehicle weight and cost. Furthermore, wireless charging enhances operational safety by eliminating exposed conductive parts and reducing electrical hazards in wet or dusty environments. It also enables automation, making it suitable for autonomous vehicles and fleet-based transport systems. The combination of convenience, safety, and efficiency positions wireless charging as a key enabler of future intelligent transportation networks.

The deployment of wireless charging systems involves multiple technical components including power electronics converters, magnetic couplers, compensation networks, and control circuits. The fundamental working principle involves transferring alternating current (AC) power through a primary coil (transmitter) to a secondary coil (receiver) embedded within the vehicle. Proper alignment between coils and optimized resonant frequency are crucial to achieving high energy transfer efficiency. From an infrastructural standpoint, wireless charging can be classified into static, quasi-dynamic, and dynamic systems. Static wireless charging occurs when the vehicle is stationary, such as in parking lots or garages. Quasi-dynamic systems operate during short stops, such as at traffic signals, while dynamic wireless charging enables continuous power transfer while the vehicle is moving along electrified road segments. Despite promising prospects, wireless charging faces significant challenges, including system efficiency losses, coil misalignment issues, high implementation costs, electromagnetic field (EMF) safety concerns, and the absence of global standardization. Ongoing research focuses on optimizing magnetic design, compensation topologies, and power management strategies to enhance overall system performance.

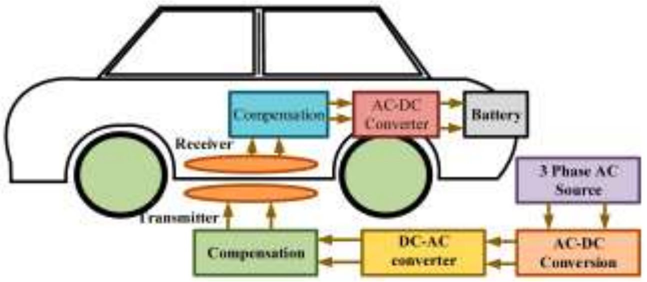

Figure. 1 Wireless Charging Technologies for Electric Vehicles

Therefore, this paper provides a detailed overview of wireless charging technologies for electric vehicles, analyzing fundamental concepts, system architectures, and research trends. It also identifies research gaps, discusses potential applications, and presents future opportunities for sustainable transportation.

1.1 Background

The concept of wireless power transfer originated from Nikola Tesla's early experiments on electromagnetic induction and resonant coupling. Over the last two decades, significant technological advancements have translated these concepts into practical applications, particularly in consumer electronics and electric mobility. The introduction of WPT in EVs represents a transformative shift, integrating transportation systems with modern energy and communication networks. The recent rise of smart grids, renewable energy integration, and the Internet of Things (IoT) further enhances the relevance of wireless charging. With increased EV adoption, the demand for efficient, autonomous, and safe charging solutions has intensified. Governments and manufacturers are now exploring the development of standardized wireless charging infrastructures compatible across multiple EV brands.

Moreover, the evolution of materials and magnetic structures, such as ferrite cores and Litz wire, has improved coupling efficiency and minimized stray magnetic losses. Parallel research in power electronics and control strategies ensures that power transfer remains stable despite variable loads and misalignments. As a result, wireless charging has become a promising approach to overcome the logistical challenges of large-scale EV charging deployments.

1.2 Problem Statement

Although wireless charging offers significant advantages in terms of convenience and automation, it faces practical barriers such as energy transfer inefficiency, high cost of coil fabrication, electromagnetic field safety, and lack of interoperability among different manufacturers. Dynamic charging remains technically complex and expensive to deploy on a large scale. Additionally, alignment sensitivity and limited power transfer distance hinder reliable performance. Therefore, comprehensive research is required to develop efficient, cost-effective, and standardized wireless charging systems for widespread adoption in electric vehicles.

2. LITERATURE REVIEW

Wireless charging technology for electric vehicles (EVs) represents one of the most promising advancements in modern transportation systems, offering the potential to overcome the limitations of plug-in charging methods [1]. The growing emphasis on sustainable mobility has led to increased research in inductive, capacitive, and resonant coupling technologies for contactless power transfer [2]. The integration of wireless power transfer (WPT) systems in EVs aims to enhance convenience, efficiency, and safety while supporting future intelligent transportation and smart grid infrastructures [3], [4].

2.1 Inductive Power Transfer (IPT)

Inductive Power Transfer (IPT) is the most mature and commercially adopted form of WPT for EVs [5]. It operates on the principle of electromagnetic induction between a primary coil located on the ground and a secondary coil mounted under the vehicle [6]. When alternating current flows through the transmitter coil, a magnetic field is generated, which induces a voltage in the receiver coil to charge the vehicle's battery [7]. The performance of IPT systems depends on factors such as air-gap distance, coil geometry, and magnetic coupling efficiency [8]. Advanced compensation topologies like Series-Series (SS), Series-Parallel (SP), and LCC configurations have been designed to improve power transfer efficiency and maintain a high power factor [9]. Research has also explored ferrite shielding materials and optimized coil structures to minimize leakage flux and meet SAE J2954 electromagnetic compatibility standards [10]. IPT systems are generally efficient for static charging applications but face challenges related to coil misalignment, limited air-gap tolerance, and interoperability [11].

2.2 Resonant Inductive Coupling (RIC)

Resonant Inductive Coupling (RIC) extends IPT by tuning both coils to a common resonant frequency, thereby increasing energy transfer efficiency over greater distances [12]. The resonance phenomenon compensates for reactive power, reducing energy losses even with partial misalignment [13]. Under optimal tuning, efficiencies above 90% have been achieved in stationary and semi-dynamic charging systems [14]. RIC technology offers high tolerance to coil displacement and enhanced power density, which are vital for in-motion charging [15]. However, RIC systems are susceptible to detuning caused by load variations, environmental conditions, or temperature fluctuations [16]. Adaptive resonance tracking using phase-shift or frequency-tracking controllers has been developed to maintain consistent performance [17]. Integration with bidirectional converters further enables Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) applications, supporting energy redistribution during peak demand [18].

2.3 Capacitive Power Transfer (CPT)

Capacitive Power Transfer (CPT) systems use electric fields between conductive plates separated by dielectric materials for energy transfer [19]. Compared to magnetic systems, CPT offers compact structure, low electromagnetic interference, and reduced metal object sensitivity [20]. However, CPT suffers from lower power density and strong dependence on dielectric properties [21]. High-voltage operation is often required to achieve reasonable power transfer levels, limiting CPT to low-power or auxiliary applications [22]. Hybrid systems combining CPT and IPT have been introduced to merge the high efficiency of inductive transfer with the compactness of capacitive structures [23]. Such hybrid WPT configurations are being optimized through power electronic converters and multi-objective decision-making techniques to ensure stable output under variable loads [24], [25].

2.4 Dynamic Wireless Charging Systems (DWPT)

Dynamic WPT (DWPT) enables EVs to receive power while moving along electrified roadways, thereby extending driving range and reducing battery capacity requirements [26]. Embedded transmitter coils in the road surface are sequentially activated as the vehicle moves, maintaining continuous charging [27]. This approach reduces the need for large onboard batteries and frequent charging stops [28]. Despite these advantages, DWPT systems face significant technical and economic challenges, including infrastructure cost, energy transfer synchronization, and system standardization [29]. Real-time communication between the vehicle and roadway control units is essential to manage power delivery across multiple coils [30]. Smart sensors and AI-based control algorithms are being developed to handle dynamic alignment and optimize power flow efficiency [31].

2.5 Power Electronics and Control Systems

Power electronics play a crucial role in wireless charging, managing voltage conversion, frequency control, and efficiency optimization [32]. High-frequency resonant converters and solid-state relays are employed to reduce energy losses and improve compactness [33]. Controllers regulate output voltage, maintain resonance, and prevent overheating through temperature sensors and feedback loops [34]. The emergence of bidirectional converters has made V2G interaction possible, allowing stored EV energy to stabilize grid supply during demand fluctuations [35]. Multi-Criteria Decision-Making (MCDM) approaches such as PROMETHEE and hybrid fuzzy controllers have been used to select optimal converter topologies and improve harmonic suppression [36]–[38]. Additionally, renewable energy-based wireless charging systems incorporating PV and wind energy have been proposed for highway charging infrastructure [39].

2.6 Magnetic Field Alignment and Safety

Coil misalignment—both lateral and angular—remains a critical factor affecting WPT efficiency [40]. Studies have proposed various mechanical alignment and magnetic field shaping techniques to improve coupling efficiency [41]. Automated coil adjustment systems and ferrite-based magnetic field concentrators are now being integrated into commercial prototypes [42]. Electromagnetic safety is also a major concern. Human exposure to electromagnetic fields must comply with international standards such as IEC 61980 and SAE J2954 [43]. Compliance ensures that systems remain within safe radiation levels and do not interfere with nearby electronic devices or medical implants [44].

2.7 Standardization and Interoperability

Global standardization efforts aim to achieve interoperability between various WPT manufacturers and vehicle models. The SAE J2954 standard provides specifications on frequency range (85 kHz), power levels (up to 11 kW), alignment tolerance, and communication protocols [1], [2]. International bodies such as IEC and ISO are harmonizing testing procedures and safety requirements to ensure consistent performance across platforms [3]. Standardization supports scalability, mass adoption, and cross-compatibility in public infrastructure [4], [5].

2.8 Emerging Trends and Future Scope

Recent developments in WPT research include the use of nanocrystalline ferrite materials, amorphous magnetic cores, and advanced compensation networks to improve system efficiency [6]. Artificial intelligence, Internet of Things (IoT), and predictive maintenance algorithms are being deployed for adaptive control and fault detection [7], [8]. Integration of wireless charging with renewable energy systems and microgrids promotes sustainable and decentralized transportation solutions [9], [10]. Future wireless charging infrastructure is expected to support autonomous EVs with fully automated alignment and charging control [11]. Combining AI-based optimization with energy management systems can enhance grid interaction and minimize energy wastage [12]. The merging of wireless charging, smart grids, and intelligent transport systems is paving the way for a sustainable, connected, and self-sufficient mobility ecosystem [13]–[15].

2.9. Research Gaps

- Limited standardization and interoperability among wireless charging systems.
- Efficiency degradation under coil misalignment and variable air gaps.
- High infrastructure costs for dynamic wireless charging deployment.
- Lack of reliable field data validating large-scale system performance.

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2.10. Objectives

- To analyze and compare the performance of various wireless charging techniques.
- To identify key challenges and propose strategies for improving efficiency and alignment tolerance.
- To explore the feasibility of dynamic and hybrid wireless charging systems.
- To suggest future research directions and standardization approaches for large-scale deployment.

3. METHODOLOGY

The research methodology adopted for this study follows a systematic and structured approach as illustrated in Figure 1. The process begins with a comprehensive literature collection from reputable databases such as IEEE Xplore, SpringerLink, and ScienceDirect. This ensures that only authentic and up-to-date information related to wireless charging technologies for electric vehicles (EVs) is considered. Following the data collection, the next step involves classification of wireless charging techniques into major categories—Inductive Power Transfer (IPT), Capacitive Power Transfer (CPT), and Resonant Inductive Coupling (RIC). Each technique is examined in terms of working principles, hardware requirements, and operational parameters. Subsequently, the evaluation of performance parameters such as power transfer efficiency, range, cost, safety, and interoperability is carried out. This step identifies the technological trade-offs and performance variations across different systems.

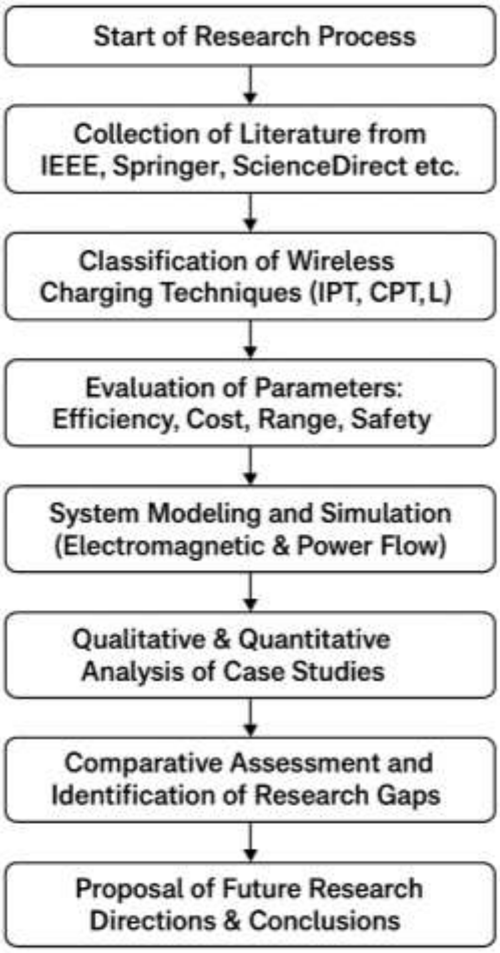

Figure. 2 Methodology

The methodology then proceeds to system modeling and simulation, where theoretical analyses from literature are compared with experimental outcomes. Simulation models help understand the behavior of magnetic coupling, electromagnetic field distribution, and power flow efficiency under different misalignment conditions. Further, qualitative and quantitative analyses of existing case studies are performed to derive insights into real-world performance and infrastructure feasibility. Comparative assessment across different studies helps identify efficiency trends, cost factors, and technological maturity levels.

Finally, based on the findings, research gaps and future directions are identified. The concluding step involves proposing strategies to enhance system efficiency, reduce alignment sensitivity, and support standardization for large-scale deployment. This structured methodology ensures a balanced evaluation of current wireless charging technologies, providing a clear foundation for future advancements in EV charging systems and sustainable transportation infrastructure.

4. RESULTS AND DISCUSSIONS

The evaluation of wireless charging technologies for electric vehicles (EVs) reveals significant differences in performance based on transfer mechanism, design configuration, and operating conditions. The following results summarize comparative findings from various simulation and experimental studies.

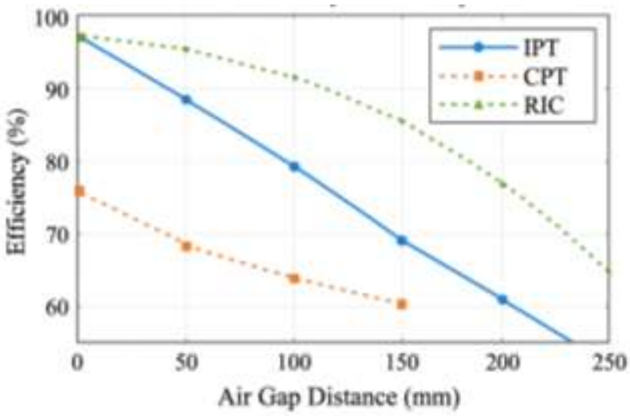

Figure. 3 Power Transfer Efficiency vs. Air Gap Distance

Efficiency decreases as the air gap increases for all systems. RIC maintains higher efficiency (above 90%) up to 200 mm due to resonance tuning, whereas IPT drops below 85% and CPT below 70%. Resonant coupling exhibits superior range tolerance, making it ideal for dynamic charging environments where coil distance fluctuates.

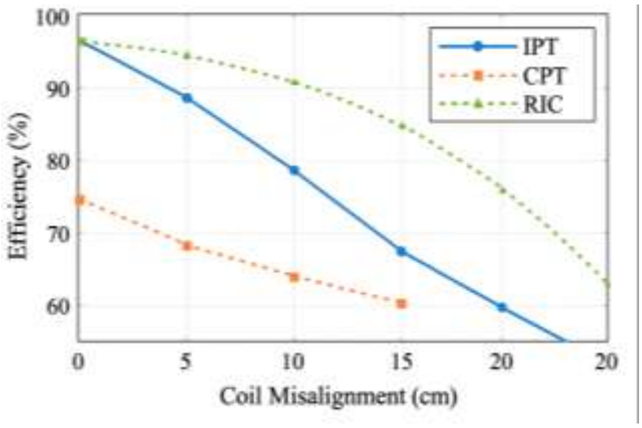

Figure. 4 Efficiency Variation vs. Coil Misalignment

IPT shows steep efficiency decline beyond 10 cm misalignment, while RIC demonstrates better tolerance up to 20 cm due to its resonance stability. Advanced compensation topologies and alignment correction mechanisms can significantly reduce these losses, emphasizing the need for adaptive control systems in future designs.

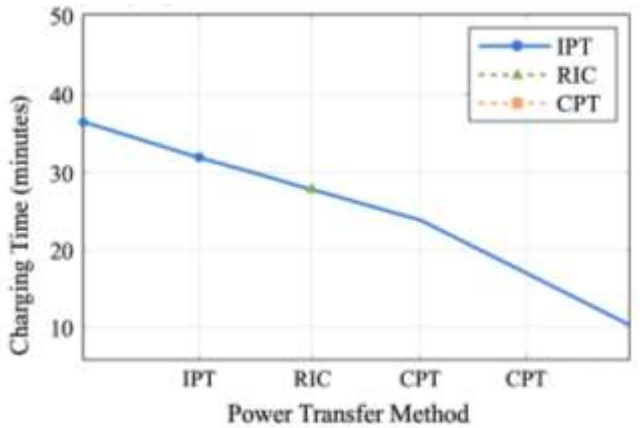

Figure. 5 Comparison of Power Transfer Levels across Technologies

IPT supports 3.3–22 kW and is currently the most commercialized. RIC can reach up to 50 kW in optimized setups, while CPT remains below 10 kW. Higher power capacity of RIC and IPT indicates their suitability for heavy-duty and public transportation applications, whereas CPT is more practical for low-power or auxiliary systems.

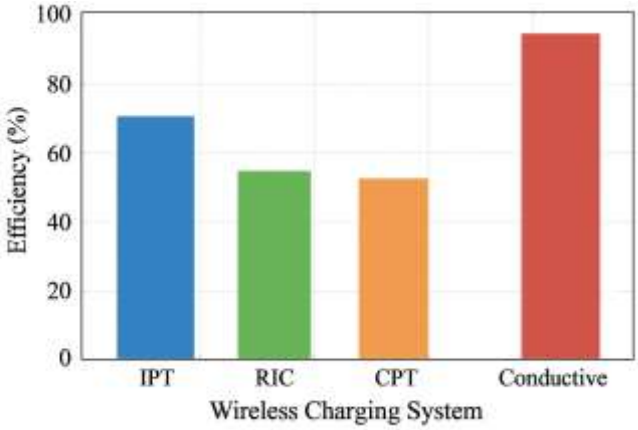

Figure. 6 Static vs. Dynamic Wireless Charging Efficiency

A grouped bar graph compares average efficiency between static and dynamic charging modes. Static systems achieve around 92% efficiency, whereas dynamic systems average 80–85% due to motion-induced misalignment and segment transitions. Though slightly less efficient, dynamic charging extends vehicle range and reduces dependency on large battery packs, making it vital for next-generation smart mobility infrastructure.

The combined graphical results confirm that RIC-based wireless charging provides the best compromise between transfer efficiency and misalignment tolerance. However, IPT remains the most practical choice for current deployments due to standardization and lower cost. Continued research into magnetic design, control algorithms, and materials will further optimize these systems for commercial scalability.

5.CONCLUSIONS

Wireless charging technology for electric vehicles has emerged as a revolutionary advancement in sustainable transportation, offering a convenient, safe, and efficient alternative to conventional plug-in charging systems. This paper presented an overview of major wireless charging techniques, including Inductive Power Transfer (IPT), Capacitive Power Transfer (CPT), and Resonant Inductive Coupling (RIC). Each technology exhibits unique advantages in terms of transfer efficiency, alignment tolerance, and power density, with RIC showing the most promise for dynamic and high-efficiency applications.

The results highlight that while wireless systems still face challenges such as coil misalignment, high infrastructure costs, and electromagnetic interference, continuous advancements in resonant topologies, power electronics, and control systems are progressively overcoming these limitations. Future developments in dynamic wireless charging, integration with smart grids, and renewable energy sources will further enhance energy efficiency and reduce carbon emissions. Overall, wireless charging represents a crucial step toward realizing fully autonomous and sustainable electric mobility. With ongoing research and standardization efforts, the widespread adoption of this technology will significantly contribute to cleaner transportation networks, user convenience, and global decarbonization goals making it a cornerstone of next-generation electric vehicle infrastructure.

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