Journal of Harbin Engineering University
ISSN: 1006-7043

Vol 46 No. 6
June 2025

Wireless Power Transfer: Technologies and Future Prospects

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Abstract

Introduction: Wireless Power Transfer (WPT) is an emerging technology enabling the transmission of electrical energy without physical connectors, using electromagnetic fields such as magnetic, electrostatic, or optical. Originating from Nikola Tesla's early experiments, WPT has gained momentum due to advancements in materials, power electronics, and electromagnetic theory. Key methods include inductive, resonant inductive, capacitive, microwave, and laser-based transfer, with applications ranging from consumer electronics and EVs to aerospace and medical implants. Despite its potential, WPT faces challenges like limited range, reduced efficiency over distance, and safety concerns from high-power radiation. On-going research focuses on improving efficiency, range, and safety through innovations in resonant circuits, superconductors, and rectennas. This review highlights the current state, challenges, and future trends—such as dynamic EV charging, space-based solar power, and integration with smart grids and IoT—emphasizing WPT's transformative potential in modern energy systems.

Objectives: The objective of this review paper is to provide a comprehensive analysis of Wireless Power Transfer (WPT) technologies, exploring their underlying principles, current advancements, and practical applications. It aims to critically examine the existing methods—such as inductive coupling, resonant inductive coupling, and microwave/radioactive transfer—highlighting their advantages, limitations, and areas of application. Furthermore, the paper seeks to identify the key challenges impeding widespread adoption and to evaluate emerging trends and research directions that are shaping the future prospects of WPT systems in various sectors, including consumer electronics, electric vehicles, biomedical devices, and industrial automation.

Methods: The methodology of this review paper is based on a systematic analysis of existing literature to explore the current technologies, challenges, and future prospects of Wireless Power Transfer (WPT). Relevant information was gathered from peer-reviewed journals, conference papers, technical reports, and industry publications using databases such as IEEE Xplore, Science Direct, Springer Link, and Google Scholar. The collected literature was categorized according to different WPT techniques, including inductive coupling, resonant coupling, capacitive coupling, microwave transmission, and laser-based transfer. Each method was compared using key performance indicators such as efficiency, range, alignment sensitivity, safety, and scalability. Common challenges and limitations were identified, along with recent advancements and potential solutions. Finally, the review highlights emerging trends and future applications of WPT in areas like electric vehicles, biomedical devices, consumer electronics, and IoT, providing a comprehensive outlook on the evolution of this transformative technology.

Results: The review reveals that Wireless Power Transfer (WPT) has made significant technological progress, with inductive and resonant coupling being the most mature and widely adopted methods, especially in consumer electronics and electric vehicles. While each technology offers unique advantages, challenges such as limited range, alignment issues, energy loss, and safety concerns remain key barriers. However, on-going research and innovation—such as adaptive control systems, improved materials, and hybrid techniques—are addressing these limitations. The findings suggest that WPT holds strong potential for transformative applications across multiple sectors, with promising future developments expected to enhance efficiency, flexibility, and integration into smart systems.

Conclusions: In conclusion, Wireless Power Transfer (WPT) represents a promising shift in how electrical energy can be delivered, offering convenience, flexibility, and new design possibilities across various applications. While current technologies like inductive and resonant coupling have shown practical success, challenges related to efficiency, range, and safety still need to be fully addressed. Continued advancements in materials, system design, and regulatory standards are essential for broader adoption. With sustained research and innovation, WPT is poised to play a crucial role in the future of energy transfer, particularly in smart devices, electric mobility, and biomedical systems.

Keywords: Wireless Power Transfer (WPT), Inductive Coupling, Resonant Coupling, Efficiency, Electric Vehicles (EVs), Biomedical Devices, Smart Grids, Internet of Things (IoT)

1. Introduction

Wireless Power Transfer (WPT) is an innovative approach to electric energy transfers that eliminates physical cables, and thereby plug connections, between power sources and loads. The fundamental principle behind WPT involves the transfer of electrical energy through various types of electromagnetic fields, including magnetic, electric, and radioactive fields. By enabling remote and contactless energy delivery, WPT introduces a paradigm shift in how we power electronic devices, from small consumer gadgets to large-scale infrastructure like electric vehicles and satellites.

Wireless Power Transfer (WPT) is the transmission of electrical energy from a power source to an electrical device without connecting the source to a receiver by electrical conductor or cable. WPT eliminates the physical barriers posed by wires, enabling power transfer in environments where traditional connections are not feasible. This technology is becoming increasingly vital across multiple industries, including consumer electronics, healthcare, electric vehicles (EVs), and more, as it reduces the wear and tear of physical connectors, enhances the mobility of devices, and eliminates safety risks associated with electrical wiring.

In recent years, WPT has gained significant attention, driven by advancements in electromagnetic theory, material science, and power electronics. These developments promise to unlock new possibilities in energy transfer systems, providing wireless energy solutions for everyday devices as well as larger, more complex systems.

The increasing proliferation of portable electronics, wearable devices, electric vehicles, and implantable medical systems has intensified the demand for safe, efficient, and flexible power delivery solutions. Traditional wired systems pose limitations in terms of mobility, safety (e.g., electric shock or fire risk), maintenance, and mechanical wear and tear. These limitations become even more pronounced in environments that are hazardous, sterile (such as operating rooms), or require motion (such as rotating machinery or autonomous vehicles).

WPT offers numerous advantages in this context:

- Convenience: Enables seamless charging without connectors.
- Safety: Reduces risks of sparks, corrosion, and electric shocks.
- Durability: Eliminates wear-prone mechanical contacts.
- Flexibility: Facilitates mobility in dynamic or remote environments.

Additionally, WPT is a key technology in the development of future scenarios, e.g., the Internet of Things (IoT), Industry 4.0, and smart cities, in which a network of pervasively deployed devices is required to function without frequent human assistance for battery recharging and cabling duties.

This review considers various WPT techniques for an in-depth analysis, developing current, and future perspectives on the subject, including the working principles, applications, restrictions, and the state-of-the-art progresses. The scope of the review includes:

- Inductive Coupling: Widely used for short range power transfer.
- Resonant Inductive Coupling: Used for medium range and higher power transfer efficiency.
- Capacitive Coupling: For low power, short-range applications.
- Microwave Power Transfer (MPT): Used for long range power transfer.
- Laser Power Transfer: For high efficiency, long-distance transmission.

2. Objectives

Wireless Power Transfer (WPT) systems have evolved into diverse categories based on the nature of the energy transmission medium and the range of transfer. Each technology offers unique benefits and is suited for specific applications, but also presents technical and practical challenges. In this section, we critically examine the theoretical foundations, implementation strategies, and recent research associated with the main WPT technologies.

3. Methods

Wireless Power Transfer (WPT) systems have evolved into diverse categories based on the nature of the energy transmission medium and the range of transfer. Each technology offers unique benefits and is suited for specific applications, but also presents technical and practical challenges. In this section, we critically examine the theoretical foundations, implementation strategies, and recent research associated with the main WPT technologies.

3.1 Inductive Coupling

The most accepted and commercially utilized method of WPT (wireless power transmission) technology is inductive coupling. This technology relies on Faraday's Law of Electromagnetic Induction which states that a current flow through an electric wire generates a magnetic field that induces voltage in a nearby wire that is placed at distance.

- Advantages: This method is simple, reliable, and efficient for short-range power transfer (typically under 5 cm). Examples of WPT techniques employing this method: Qi telecom mobile device wireless charger.
- Applications: Mobile phone chargers, electric toothbrushes, RFID systems, and biomedical implants. In industrial settings, it is used in contactless power supply systems for rotating parts or hazardous environments (Sample et al., 2011).
- Limitations: Efficiency drops sharply with misalignment or increased distance between coils. Magnetic field leakage can interfere with other electronic devices, and large coils may be required for higher power applications.

Recent research has aimed to improve power density and alignment tolerance. For example, Zhang et al. (2020) proposed a multi-coil structure with adaptive tuning circuits to maintain efficiency under misalignment.

3.2 Resonant Inductive Coupling

Category of resonant inductive couplers: sophisticated inductive couplers as they integrate both transmitter and receiver circuits to a single resonate frequency, allowing increased energy transmission (up to several meters).

- Advantages: Improved range and power transfer efficiency without the need for perfect alignment. This method allows for the dynamic charging of electric vehicles and power charging in robotics.
- Applications: Wireless EV charging stations, drones, and humanoid robots. The SAE J2954 standard defines specifications for resonant WPT systems in EVs.
- Limitations: Complex tuning and higher cost due to additional components like matching networks and frequency control units. Also, interference with nearby resonant systems can be a concern.

Research by Kurs et al. (2007) demonstrated efficient power transfer over a 2-meter range using resonant coupling with over 40% efficiency. More recently, Dai et al. (2021) developed resonant systems with automatic frequency tracking to counteract environmental shifts.

3.3 Capacitive Coupling

Capacitive wireless power transfer (CWT) is based on the induction of the electric field between two plates that act as electrodes. Unlike magnetic-based methods, CPT uses displacement current through the air (or dielectric medium) to transfer energy.

- Advantages: CPT systems are smaller, lighter, and potentially cheaper than inductive systems. They exhibit less sensitivity to metal interference, making them suitable for embedded electronics.
- Applications: Biomedical sensors, wearable electronics, and touch less user interfaces. Some research explores CPT in vehicular systems, where plates are embedded in roads (Lu et al., 2016).
- Limitations: Low power capacity (typically <100 W), very short range (millimetres), and significant power loss due to parasitic capacitance and dielectric heating. Safety concerns also exist due to electric field exposure.

Recent efforts focus on improving shielding and using metamaterials to enhance the capacitance effect (Wang et al., 2020). Despite limitations, CPT remains attractive for compact and low-power applications.

3.4 Microwave Power Transfer (MPT)

Energy that is transmitted with use of electromagnetic waves in the GHz frequency band and delivered through empty space is defined as microwave powered energy transmission. The energy is directed using antennas and captured by rectennas (rectifying antennas) at the receiver end, which convert RF energy into DC power.

- Advantages: Enables long-distance transmission (tens to hundreds of kilometers). Highly directional beams reduce energy dispersion, making MPT suitable for remote power delivery.
- Applications: Satellite power transmission, powering remote sensors, and proposed space-based solar power (SBSP) systems. NASA and JAXA have both conducted trials for beaming solar energy from space to Earth.
- Limitations: Low conversion efficiency (typically 30–50%), significant safety risks due to radiation exposure, and regulatory issues concerning electromagnetic spectrum usage.

Brown (1984) pioneered the MPT field with ground-to-air power beaming experiments. More recently, Takahashi et al. (2015) achieved successful atmospheric power transmission over 500 meters with improved beam accuracy and safety controls.

3.5 Laser-Based Wireless Power Transfer

Laser power transfer (LPT) is a method that involves transforming electricity to a laser light then focusing it on a photovoltaic (PV) light receiver which transforms the light back to electric energy. It is especially suited for highly targeted, long-distance energy delivery.

- Advantages: High precision and long-range capabilities (up to several kilometers). LPT can deliver power to moving targets such as drones or rovers and has high energy density.
- Applications: Military surveillance drones, deep-space communication systems, and medical implants. Some research also explores laser power transfer for autonomous charging of aerial vehicles.
- Limitations: Line-of-sight requirements, atmospheric interference (fog, rain), and serious eye/skin safety concerns limit its widespread use. Moreover, the conversion efficiency of PV cells under laser illumination remains a bottleneck.

Hirose et al. (2017) developed a free-space optical power system that demonstrated 1 kW power delivery with 40% PV conversion efficiency under controlled conditions. Emerging efforts include using adaptive beam steering and high-band gap PV materials to mitigate beam loss and improve receiver response.

3.6 Comparative Overview

4. Results

Significant improvements in WPT efficiency have been observed with the introduction of advanced materials such as superconductors and metamaterials. These innovations have helped enhance the power transfer range and reduce energy loss. For example, the use of resonant circuits in inductive coupling has enabled energy transfer over longer distances with higher efficiency (Liu et al., 2014). Furthermore, new developments in power rectifiers and wireless charging systems have made it possible to charge EVs more efficiently.

Technology	Range	Efficiency	Power Level	Safety	Applications
Inductive Coupling	<10 cm	High (80–95%)	Low to Medium	High	Mobile devices, wearables
Resonant Inductive	~0.1–2 m	Medium-High	Medium to High	Moderate	EVs, robotics
Capacitive Coupling	<10 cm	Low to Medium	Low	Moderate	Medical sensors, IoT
Microwave Transfer	>10 m	Medium (30–50%)	High	Low	Satellites, remote areas
Laser Transfer	>1 km	Low to Medium	Medium to High	Low	Drones, space systems

4.1 Emerging applications

- Space-Based Solar Power: There is active research into the use microwave power transfer for space solar systems aimed at beaming power from solar stations to locations on Earth (Takahashi et al., 2013).

- Dynamic EV Charging: On-going studies have shown that dynamic wireless charging for EVs while driving is becoming feasible, with preliminary tests being conducted in test environments (Zhao et al., 2020).

Researchers are working on improving the efficiency of WPT systems by using more efficient resonant systems, optimizing coil designs, and enhancing energy conversion technologies. The development of universal charging standards and regulatory frameworks has also begun to address interoperability and safety issues (Bakker et al., 2017).

5. Discussion

In multiple sectors, the potential of Wireless Power Transfer to revolutionize energy distribution systems is immense. Current WPT technologies including inductive and resonant inductive coupling, as well as microwave power transfer, show great promise. However, major concerns that must be tackled include the efficiency, range, and cost. Innovations in materials, new circuit designs, and integration with smart grids and IoT are expected to overcome these barriers. The future of WPT is promising, with significant potential for powering consumer electronics, electric vehicles, medical devices, and even space-based systems. To realize this potential, further research and collaboration between academia, industry, and regulatory bodies are necessary to overcome the technical and economic challenges.

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