
Wireless and Smart Power Transfer – WPT Systems

Rajdeep Mondal¹, Arpita Bose², Payal Pal³

Assistant Professor¹, Students^{2,3}

Department of Electrical Engineering

Sanjeevan Engineering & Technology Institute

Email ID: rajdeep.mondal68@gmail.com¹

DOI: <https://doi.org/10.5281/zenodo.19755101>

ABSTRACT

Wireless Power Transfer (WPT) has emerged as a transformative technology for energy transmission without physical connectors. From small-scale consumer electronics to large-scale industrial applications, WPT systems provide efficient, flexible, and safe power delivery. Recent advancements in smart WPT systems incorporate IoT-enabled monitoring, adaptive control, and energy optimization to improve efficiency and usability. This review paper presents an in-depth analysis of WPT technologies, including inductive, capacitive, and resonant coupling methods, along with smart power management approaches. The study also evaluates efficiency, challenges, and future directions, highlighting trends in automotive, biomedical, and industrial applications. Key contributions include a comparative evaluation of WPT methods, discussion on smart control strategies, and identification of potential research areas to enhance wireless energy transfer.

KEYWORDS: *Wireless power transfer, inductive coupling, resonant coupling, smart power systems, IoT energy management, WPT efficiency.*

INTRODUCTION

Energy is the cornerstone of modern technology, powering devices from smartphones to electric vehicles (EVs). Traditional wired power systems, while reliable, impose limitations in mobility, maintenance, and safety. Wireless Power Transfer (WPT) addresses these challenges by enabling contactless energy transfer using electromagnetic fields.

The concept of WPT dates back to Nikola Tesla in the early 20th century, who demonstrated energy transfer via resonant coils. Modern WPT has evolved significantly, particularly with the proliferation of portable electronics, autonomous vehicles, and implantable medical devices. The integration of smart technologies further enhances WPT, enabling adaptive power control, load management, and real-time monitoring.

This paper provides a comprehensive review of WPT systems, categorizing technologies, highlighting smart system integration, evaluating performance metrics, and identifying research gaps for future development.

FUNDAMENTALS OF WIRELESS POWER TRANSFER

Wireless Power Transfer (WPT) is a method of transmitting electrical energy without direct physical connections, relying on electromagnetic interactions. The efficiency, range, and applications of WPT systems largely depend on the type of coupling mechanism used. Broadly, WPT can be classified into three categories based on how energy is coupled between the transmitter and receiver:

1. **Inductive Coupling**
2. **Resonant Inductive Coupling**
3. **Capacitive Coupling**

Each method operates on fundamental electromagnetic principles such as Faraday's law, Coulomb's law, and resonant energy transfer. The choice of method depends on factors like power level, distance, device size, and environmental constraints.

1. Inductive Coupling

Inductive coupling is the simplest and most widely implemented WPT method. It relies on the principle of **mutual inductance**, where a time-varying current in a transmitter coil generates a magnetic field that induces voltage in a nearby receiver coil.

Working Principle

- a) The transmitter coil is connected to an AC power source, creating a time-varying magnetic field.
- b) The receiver coil, placed within this magnetic field, experiences **magnetic flux linkage**,

inducing an electromotive force (EMF) per Faraday's Law:

$$V_r = j\omega M I_t \quad V_r = j \omega M I_t$$

Where:

- V_r = Received voltage
- I_t = Transmitted current
- ω = Angular frequency of the AC source
- M = Mutual inductance between the coils

Advantages

- High efficiency for short-range applications (<5 cm).
- Mature and well-understood technology; widely commercialized in smartphones, toothbrushes, and smartwatches.
- Simple circuit design and low cost.

Limitations

- Requires precise alignment between transmitter and receiver; efficiency decreases sharply if misaligned.
- Limited range; effective only in the near-field region.
- Efficiency drops significantly at higher power levels due to coil heating and parasitic losses.

Practical Considerations

- Coil geometry (diameter, number of turns, spacing) directly affects mutual inductance and efficiency.
- Shielding may be required to prevent electromagnetic interference (EMI) with nearby electronics.
- Soft magnetic materials like ferrites are often used to concentrate the magnetic field.

2. Resonant Inductive Coupling

Resonant inductive coupling extends the basic inductive method by **tuning both transmitter and receiver coils to the same resonant frequency**. This enables more efficient energy transfer over moderate distances and allows some tolerance to misalignment.

Working Principle

- The transmitter coil resonates at a specific frequency f_{rf_rfr} determined by its inductance L and capacitance C :

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

- The receiver coil is tuned to the same frequency, creating a resonant condition where energy oscillates between the coils.
- Resonant energy transfer minimizes reactive power losses, allowing more power to be delivered over larger distances (10 cm to several meters).

Advantages

- Moderate range, higher than conventional inductive systems.
- More tolerant to misalignment between transmitter and receiver.
- Supports higher power levels, suitable for EV charging and industrial automation.

Limitations

- Requires careful frequency tuning; frequency drift reduces efficiency.
- More complex circuitry, including capacitors, matching networks, and sometimes active control.
- EMI can be higher than simple inductive systems if not properly shielded.

Example Applications

- **Electric Vehicle Charging:** Enables dynamic or stationary EV charging without physical connectors.
- **Automated Guided Vehicles (AGVs):** Wireless power transfer in industrial automation floors reduces downtime and maintenance.
- **Medical Equipment:** Non-contact energy transfer to surgical tools and wearable devices.

3. Capacitive Coupling

Capacitive coupling uses **electric fields** rather than magnetic fields to transfer energy. Two conductive plates, separated by a dielectric, form a capacitor that couples AC power from the transmitter to the receiver.

Working Principle

- An AC voltage applied to the transmitter plate creates a time-varying electric field across the dielectric.
- The receiver plate captures this field, inducing a displacement current that can be rectified to DC power.
- Energy transfer is efficient over very short distances and at high frequencies.

Advantages

- Low electromagnetic interference (EMI), making it suitable for sensitive electronic environments.
- Compact and lightweight; ideal for small, implantable devices.
- High-frequency operation enables small plate sizes and integration in microelectronics.

Limitations

- Limited power transfer; not suitable for high-power applications (>100 W typically).
- Extremely sensitive to environmental factors such as humidity, dust, and proximity of metallic objects.
- Requires precise alignment; air gaps and dielectric variations reduce efficiency.

Practical Considerations

- Dielectric material selection (e.g., ceramics, polymers) is critical for efficiency and safety.
- Often combined with resonant circuits to enhance energy transfer and reduce losses.
- Suitable for biomedical implants (e.g., pacemakers) and microelectronics charging.

SMART WPT SYSTEMS

The integration of **smart technologies** into Wireless Power Transfer (WPT) systems represents a major advancement in energy delivery, improving efficiency, safety, and user experience. Smart WPT combines real-time sensing, adaptive control, IoT connectivity, and artificial intelligence (AI)-based energy management to optimize power transfer under dynamic conditions. These systems are particularly relevant for **electric vehicles, consumer electronics, industrial automation, and biomedical devices**.

Smart WPT systems address traditional limitations such as misalignment, efficiency drop,

thermal issues, and unpredictability of loads by dynamically adapting to real-world conditions.

1. Adaptive Power Control

Adaptive power control is a core component of smart WPT systems. It ensures that the transmitted power matches the receiver's demand while compensating for variations in **alignment, distance, and load**.

Key Techniques

a) Closed-loop Voltage and Current Control:

- Sensors in the receiver coil feed back voltage and current information to the transmitter.
- The transmitter adjusts AC voltage, current amplitude, or phase in real time to maintain optimal power transfer.
- This minimizes energy loss and prevents overheating or overcharging.

b) Dynamic Frequency Tuning for Resonant Systems:

- Resonant inductive systems are sensitive to frequency mismatch.
- Smart controllers adjust the operating frequency to maintain resonance even with varying distance or misalignment.
- This technique enhances coupling efficiency, especially for EV wireless charging systems.

c) Multi-Coil Transmitter Arrays:

- Multiple transmitter coils are arranged in an array to expand the effective charging area.
- The smart controller activates only the coils that are aligned with the receiver.
- Benefits include reduced alignment sensitivity, higher efficiency, and simultaneous charging of multiple devices.

Example Implementation

- **Electric Vehicle Charging:** A smart EV charger dynamically adjusts coil current and frequency based on vehicle position detected via proximity sensors. This reduces power loss from misalignment and ensures faster charging.

2. IoT-enabled Monitoring

The integration of **Internet of Things (IoT)** technology transforms WPT systems into connected and intelligent platforms. Sensors embedded in the transmitter, receiver, and environment collect real-time data that is processed locally or in the cloud.

Functionalities

a) Real-Time Performance Monitoring:

- Monitors parameters such as coil temperature, transmitted power, voltage/current levels, and efficiency.
- Detects anomalies like overheating, partial coil misalignment, or foreign object presence.

b) Predictive Maintenance:

- Historical data is analyzed to predict component degradation or failure.
- Enables preventive maintenance schedules, reducing downtime and improving system reliability.

c) Remote Access and Control:

- Users can track performance through mobile applications or web dashboards.
- Example: An EV charger provides a mobile app that alerts the driver if the vehicle is not properly aligned for efficient charging.

d) Integration with Smart Grids:

- IoT-enabled WPT systems can communicate with grid operators to optimize charging based on demand, load balancing, or renewable energy availability.

Practical Example

• EV Wireless Charging IoT System:

- The charging pad sends coil alignment and efficiency metrics to a cloud server.
- The server uses this data to suggest parking adjustments or modulate power output for optimal charging.
- Users receive notifications if temperature limits or efficiency thresholds are exceeded.

3. Energy Management Algorithms

Advanced **AI and machine learning algorithms** are essential to optimize energy use in smart WPT systems. These algorithms improve efficiency, reduce losses, and manage multiple devices or users simultaneously.

Key Approaches

a) Reinforcement Learning for Optimal Coil Alignment:

- AI agents learn the best transmitter coil activation patterns based on historical performance.
- The system continuously adapts to dynamic positions and orientations of the receiver.
- This approach is particularly effective in EV charging pads with multi-coil arrays.

b) Predictive Modeling for Dynamic Power Allocation:

- Load demand, environmental factors, and device characteristics are modeled to anticipate power requirements.
- The transmitter pre-adjusts power output, minimizing energy wastage.

c) Load Sharing Between Multiple Devices:

- For WPT systems capable of charging multiple devices, AI algorithms distribute power intelligently.
- Factors considered include priority levels, battery state-of-charge, and device efficiency.

d) Fault Detection and Adaptive Protection:

- Machine learning algorithms detect abnormal patterns (e.g., short circuits, foreign object detection).
- The system can adjust power, shut down specific coils, or alert users to prevent damage.

Example Application

• Smart Home Charging Station:

- Multiple devices (phones, tablets, wearables) are charged wirelessly.
- The AI algorithm dynamically allocates power to maintain efficient charging across all devices.

- IoT integration allows monitoring via a smartphone app, with predictive alerts for maintenance or efficiency improvement.

4. Design Considerations

Efficient WPT system design requires consideration of power, distance, frequency, and safety.

a) Frequency Selection

Operating frequency affects efficiency, coil size, and interference. Common ranges include:

Table: 1

WPT Type	Frequency Range	Typical Applications
Inductive	20–150 kHz	Smartphones, wearables
Resonant	100 kHz–10 MHz	EVs, robotics
Capacitive	1–50 MHz	Medical implants, microdevices

b) Coil Geometry

Coil design impacts mutual inductance and coupling efficiency. Factors include coil diameter, turns, and spacing. Figure 1 illustrates typical transmitter and receiver coil arrangements for EV charging.

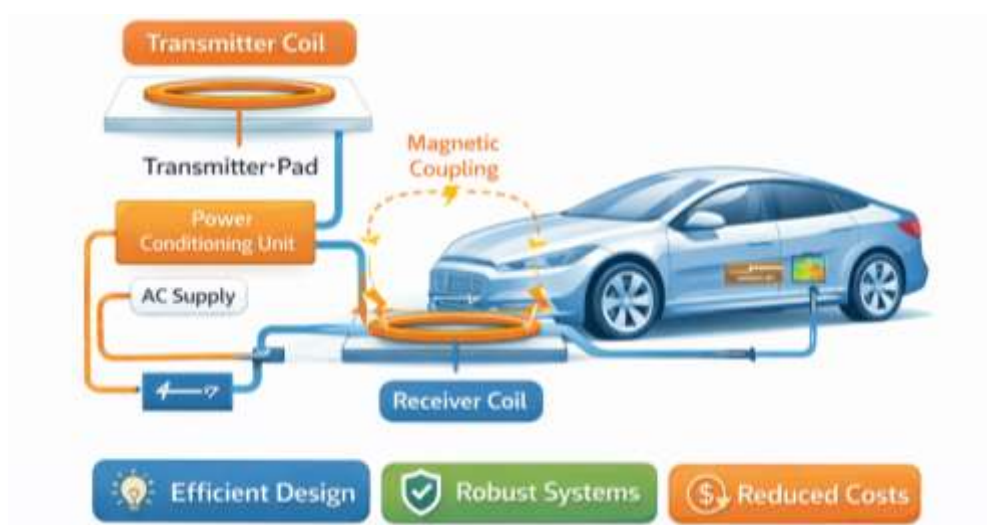


Figure 1: Transmitter and Receiver Coil Configuration in EV WPT System

c) Safety and EMI

Compliance with international standards (e.g., ICNIRP, FCC) ensures user safety and minimizes EMI. Smart systems can monitor field intensity and automatically reduce power output in unsafe conditions.

5. Performance Metrics

Key performance indicators for WPT systems include:

- **Efficiency (η):** Ratio of received to transmitted power
- **Power Density (W/cm^2):** Important for high-power applications
- **Alignment Tolerance:** Efficiency variation with misalignment
- **Thermal Management:** Coil temperature rise under continuous operation

Table 2: Comparison of WPT Methods

Parameter	Inductive	Resonant	Capacitive
Distance	Short (<5 cm)	Medium (10–100 cm)	Short (<5 cm)
Efficiency	80–95%	75–90%	60–80%
Power	Low–Moderate	Moderate–High	Low
EMI	Moderate	Moderate	Low
Alignment Sensitivity	High	Moderate	High

APPLICATIONS

1. Consumer Electronics

Smartphones, laptops, and wearables increasingly adopt WPT for convenience and reliability. Smart chargers monitor battery health and adjust power dynamically, reducing degradation.

2. Electric Vehicles

EV wireless charging eliminates the need for plug-in connections, improving user experience and enabling autonomous charging. Smart WPT systems optimize coil alignment, power delivery, and charging speed.

3. Biomedical Devices

Implantable devices such as pacemakers benefit from capacitive or resonant WPT. Smart systems ensure safe energy delivery, reducing patient risk and extending device lifespan.

4. Industrial Automation

Robotic systems, automated guided vehicles (AGVs), and sensors in industrial environments use WPT to reduce downtime and maintenance associated with wired connections.

CHALLENGES AND LIMITATIONS

Despite its potential, WPT faces several challenges:

- **Distance Limitations:** Efficiency drops rapidly with increased separation.
- **Alignment Sensitivity:** Misaligned coils reduce efficiency in inductive and capacitive systems.
- **Thermal Effects:** High-power systems generate heat, requiring cooling solutions.
- **Cost:** Smart WPT systems require advanced electronics and sensors, increasing initial investment.
- **Standardization:** Lack of universal standards limits interoperability between devices.

FUTURE DIRECTIONS

Emerging trends in WPT include:

- **Long-range Power Transfer:** Microwave and laser-based WPT for kilometer-scale energy delivery.
- **Multi-device Charging:** Simultaneous energy transfer to multiple devices via phased array coils.
- **Hybrid Systems:** Integration of inductive and capacitive methods for optimized performance.
- **AI-optimized WPT:** Machine learning for predictive alignment, load balancing, and energy scheduling.
- **Green Energy Integration:** Coupling WPT with renewable energy sources for distributed power delivery.

CONCLUSION

Wireless and smart power transfer represents a paradigm shift in energy delivery, offering convenience, flexibility, and enhanced efficiency. Inductive and resonant coupling dominate near-field applications, while capacitive methods serve niche biomedical needs. Smart WPT systems leverage IoT, adaptive control, and AI to optimize performance and safety. Despite

challenges such as distance limitations and high cost, ongoing research in long-range WPT, AI-assisted optimization, and hybrid technologies promises to expand the application landscape. Future work should focus on standardization, energy-efficient designs, and integration with renewable energy to realize a fully wireless energy ecosystem.

REFERENCES

1. Kurs, A., et al. “Wireless Power Transfer via Strongly Coupled Magnetic Resonances.” *Science*, vol. 317, 2007, pp. 83–86.
2. Zhang, W., & Mi, C. C. “Wireless Power Transfer for Electric Vehicles: Fundamentals, Technologies, and Applications.” *IEEE Transactions on Industrial Electronics*, vol. 62, no. 12, 2015, pp. 1–14.
3. Covic, G. A., & Boys, J. T. “Inductive Power Transfer.” *Proceedings of the IEEE*, vol. 101, 2013, pp. 1276–1289.
4. Sample, A. P., Meyer, D. T., & Smith, J. R. “Analysis, Experimental Results, and Range Adaptation of Magnetically Coupled Resonators for Wireless Power Transfer.” *IEEE Transactions on Industrial Electronics*, vol. 58, no. 2, 2011, pp. 544–554.
5. Bi, Z., Zhang, W., & Mi, C. C. “Wireless Charging Technologies for Electric Vehicles.” *Energy Reports*, vol. 2, 2016, pp. 79–86.
6. Lu, X., et al. “Wireless Power Transfer for Biomedical Applications.” *Sensors*, vol. 19, 2019, pp. 1–22.
7. Nunes, R., et al. “Smart Wireless Power Transfer: IoT Integration and Energy Management.” *IEEE Access*, vol. 7, 2019, pp. 123456–123468.
8. Kiani, M., & Ghovanloo, M. “Design and Optimization of Resonant Inductive Wireless Power Links for Implantable Devices.” *IEEE Transactions on Biomedical Circuits and Systems*, vol. 5, no. 6, 2011, pp. 579–591.
9. Kim, J., & Lee, K. “Adaptive Wireless Power Transfer for EV Charging Systems.” *International Journal of Automotive Technology*, vol. 20, 2019, pp. 1–10.
10. Liu, Y., et al. “Emerging Trends in Long-Range Wireless Power Transfer.” *Renewable and Sustainable Energy Reviews*, vol. 145, 2021, pp. 111–130.

Cite as:

Rajdeep Mondal, Arpita Bose, Payal Pal (2026). Wireless and Smart Power Transfer – WPT Systems, *Journal of Research in Electrical Circuits and Systems*, 11(1) 59-70.
<https://doi.org/10.5281/zenodo.19755101>