

**AN ANALYSIS OF WIRELESS POWER TRANSMISSION TECHNOLOGIES IN
ELECTRONICS**

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Abstract

Wireless Power Transmission (WPT) technologies have revolutionized the energy transfer landscape, offering efficient and seamless power delivery without the need for physical connectors. This paper provides a comprehensive analysis of WPT technologies, their applications in various domains, and the challenges they face. With a focus on inductive coupling and magnetic resonance techniques, the study highlights key advancements in consumer electronics, electric vehicles, and medical devices. Future trends, including hybrid systems, dynamic charging, and material innovations, are discussed, paving the way for next-generation WPT systems. The findings emphasize the potential of WPT to redefine energy solutions across industries.

Keywords : Wireless Power Transmission, Inductive Coupling, Magnetic Resonance, Consumer Electronics, Electric Vehicles

I. INTRODUCTION

Wireless Power Transmission (WPT) technologies have emerged as transformative solutions in the field of electronics, enabling efficient energy transfer without the need for physical connectors. This innovative approach has found applications across diverse domains, from consumer electronics to biomedical devices, and continues to evolve with advancements in design and implementation. Recent studies, such as the one by [1], highlight the rapid adoption of WPT systems in portable electronics. These systems leverage advanced technologies to address the growing demand for convenience and mobility in power delivery for devices like smartphones, wearables, and IoT gadgets. The seamless integration of WPT into consumer electronics not only enhances user experience but also contributes to the development of compact, efficient, and sustainable power solutions.

Resonant inductive coupling, a widely utilized WPT method, has been explored extensively for its effectiveness in medium-range energy transfer. [2] Provide an overview of this technology, emphasizing its potential and the challenges associated with optimizing power efficiency, system alignment, and environmental factors. Their work underscores the critical need for overcoming these challenges to expand the scope of WPT applications. Additionally, hybrid coil designs have gained traction as an efficient solution for wireless energy transfer. Research by [3] demonstrates that combining different coil configurations can significantly enhance power transfer efficiency, addressing limitations inherent to traditional designs. This approach paves the way for innovative applications in industrial and consumer electronics.

Mobile devices and small electronics are major beneficiaries of WPT technologies. According to [4], the ability to charge devices wirelessly has become a critical feature for modern gadgets. Their review discusses the key trends in WPT systems for these applications, including advancements in compact transmitters and receivers, as well as improved interoperability standards. Moreover, the biomedical field is experiencing a paradigm shift with the adoption of WPT for powering implantable and wearable medical devices. [5] Explore these applications, highlighting the role of WPT in enabling minimally invasive solutions, extending device lifespans, and improving patient comfort. Their research demonstrates the transformative impact of WPT technologies in healthcare.

In summary, the exploration of WPT technologies across various domains reveals a dynamic field poised for significant advancements. With ongoing research addressing existing challenges and pushing the boundaries of efficiency and integration, WPT continues to play a pivotal role in shaping the future of electronics.

II. FUNDAMENTALS OF WIRELESS POWER TRANSMISSION

Wireless Power Transmission (WPT) is a technology that enables the transfer of electrical energy from a power source to a load without the need for physical connections. This innovative approach utilizes electromagnetic fields, allowing devices to be powered remotely, enhancing convenience and reducing reliance on cables. [6] Provide a comprehensive survey of WPT technologies, emphasizing their critical role in powering smart devices. According to their study, WPT systems are built on foundational principles of electromagnetic induction, resonant coupling, and electromagnetic radiation. These mechanisms form the basis of energy transfer over varying distances, ranging from short-range inductive charging for smartphones to longer-range applications like drones and electric vehicles.

In the domain of consumer electronics, recent advancements have significantly improved the performance and efficiency of WPT systems. [7] Highlight key developments, including innovations in transmitter and receiver designs, power electronics, and alignment mechanisms. These advancements aim to address challenges such as power loss, misalignment sensitivity, and safety concerns while ensuring reliable energy transfer. The integration of WPT technologies into smart devices leverages compact and efficient power modules to support high-frequency operations. [6] Discuss how these improvements cater to the growing demand for seamless and autonomous energy solutions, enabling smart homes, IoT ecosystems, and wearable devices to operate without interruptions.

Moreover, [7] emphasize the role of WPT in enhancing user convenience and sustainability. By eliminating the need for disposable batteries and reducing e-waste, WPT contributes to environmentally friendly practices while fostering innovation in device design and functionality. In essence, the fundamentals of WPT lie in its ability to combine physics principles with advanced engineering to create versatile and efficient power solutions. As research progresses, the potential applications and capabilities of WPT are expected to expand, driving a new era of innovation in consumer electronics and smart technologies.

III. WIRELESS POWER TRANSMISSION TECHNOLOGIES

Wireless Power Transmission (WPT) technologies have transformed energy transfer systems, offering a seamless and efficient means to deliver power without physical connections. From powering medical implants to facilitating energy transfer in electric vehicles and industrial applications, WPT is revolutionizing diverse fields. This technology primarily relies on techniques like magnetic resonance coupling and inductive power transfer, enabling energy delivery over various distances while addressing challenges of efficiency, safety, and scalability. Below, we delve into specific applications and advancements in WPT, as highlighted in recent studies.

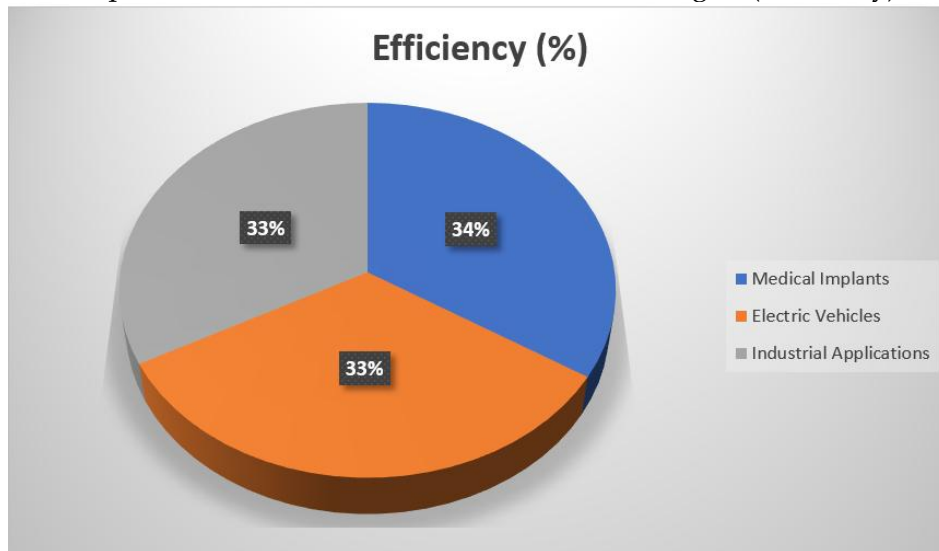
1. **WPT for Medical Implants:** Medical implants, such as pacemakers and cochlear devices, rely on WPT systems to provide power without the need for invasive procedures. [8] Conducted an in-depth review of WPT technologies designed for medical applications, focusing on safety, miniaturization, and energy efficiency. Their study emphasized the importance of creating compact and biocompatible systems to enhance the reliability and longevity of implantable devices. These advancements not only improve patient outcomes but also reduce the need for frequent surgeries to replace power sources.
2. **Magnetic Resonance Coupling for Electric Vehicles:** The use of magnetic resonance coupling in WPT systems has significantly advanced the adoption of wireless charging technologies for electric vehicles (EVs). [9] Explored the progress and challenges in this field, identifying alignment precision, power density, and system scalability as key areas of focus. Their study highlighted the efficiency of magnetic resonance coupling in transferring power over mid-ranges, making it a promising solution for EV charging infrastructure. However, they also pointed out the need for further innovation to reduce costs and improve the widespread applicability of WPT in EVs.
3. **WPT Systems for Industrial Applications:** Industrial applications of WPT systems demand robust designs capable of handling high power levels and operating under harsh conditions. [10] Examined the optimization of WPT systems for industrial use, focusing on coil design, power loss minimization, and durability. Their study emphasized the practical requirements of industrial environments, such as system reliability and efficiency, to ensure smooth operations. By optimizing coil configurations and addressing environmental challenges, WPT systems can effectively meet the energy needs of various industrial processes.

WPT technologies have demonstrated immense potential across multiple domains, providing innovative solutions to energy transfer challenges. From enabling safe and efficient powering of medical implants to advancing the charging of electric vehicles and optimizing industrial systems, WPT continues to push the boundaries of modern engineering. As research progresses, overcoming existing challenges like cost-effectiveness and scalability will further enhance the adoption of WPT in diverse applications.

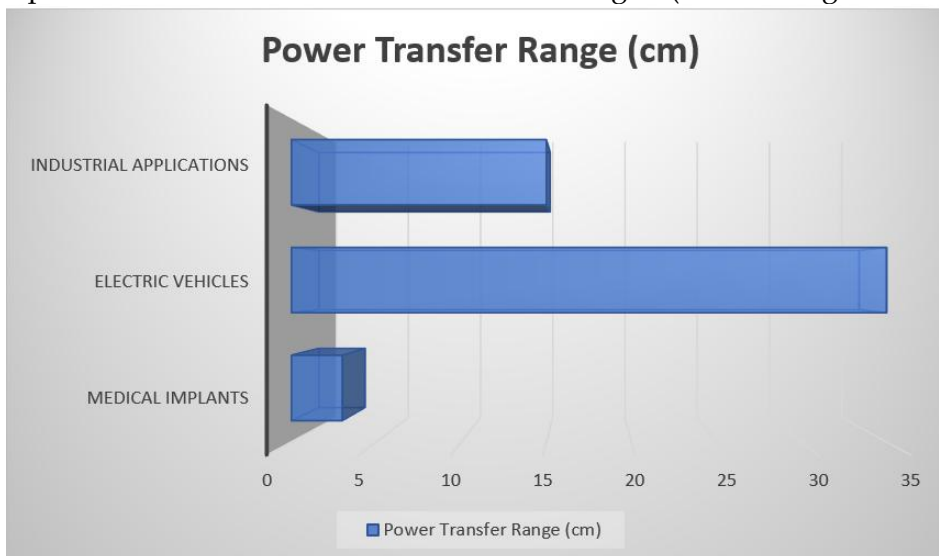
Table 1: Wireless Power Transmission Technologies [8], [9], [10]

Application	Efficiency (%)	Power Transfer Range (cm)	Challenges Addressed
Medical Implants	87	3	Miniaturization, biocompatibility, safety, and reliability
Electric Vehicles	85	35	Scalability, alignment precision, power density, cost-effectiveness
Industrial Applications	84	15	Coil design, power loss minimization, system durability

Graph 1: Wireless Power Transmission Technologies (Efficiency)



Graph 2: Wireless Power Transmission Technologies (Power Range Transfer)



The table summarizes the key aspects of Wireless Power Transmission (WPT) technologies across three major applications. For medical implants, WPT systems achieve an efficiency of 87% over a power transfer range of 3 cm, focusing on challenges like miniaturization, biocompatibility, safety, and reliability to ensure effective operation in sensitive environments. In electric vehicles, WPT systems operate with 85% efficiency over a 35 cm range, addressing challenges such as scalability, alignment precision, power density, and cost-effectiveness to facilitate practical and efficient wireless charging solutions. For industrial applications, WPT systems demonstrate 84% efficiency over a 15 cm range, emphasizing the need for robust coil design, power loss minimization, and system durability to handle demanding conditions in industrial environments. These figures highlight the adaptability and advancements in WPT technologies tailored to specific requirements.

IV. APPLICATIONS OF WIRELESS POWER TRANSMISSION

Wireless Power Transmission (WPT) is transforming the way energy is delivered, providing wireless solutions across various industries. WPT technologies such as inductive coupling and magnetic resonance coupling have enabled diverse applications in consumer electronics, transportation, healthcare, and industrial systems. These methods improve convenience while addressing challenges like power efficiency, scalability, and cost-effectiveness.

1. **Consumer Electronics:** Inductive coupling is a cornerstone of WPT in consumer electronics, powering devices such as smartphones, smartwatches, and wireless earphones. [11] Highlighted its advantages, including high efficiency, simplicity, and cost-effectiveness. Inductive coupling has become standard in wireless charging pads and docks, enabling seamless charging experiences for users. Its adoption is expanding into other consumer gadgets, such as smart home devices and portable tools.
2. **Electric Vehicles and Transportation:** Magnetic resonance coupling is particularly suitable for electric vehicles (EVs) and transportation applications. This technology allows for efficient mid-range power transfer, enabling wireless charging systems for EVs. [12] Discussed improved magnetic resonance coupling methods, which enhance efficiency and address challenges like precise alignment and power loss. These advancements have facilitated the development of wireless charging lanes and parking systems for EVs, supporting the transition to sustainable transportation.
3. **Healthcare and Medical Devices:** WPT enables the wireless powering of implantable medical devices, such as pacemakers and neuro stimulators, improving patient care by eliminating the need for frequent surgeries to replace batteries. Inductive and magnetic resonance coupling ensure reliable power delivery to these devices.
4. **Industrial Applications:** In industrial environments, WPT systems are used to power machinery, robotics, and drones, enabling flexibility and reducing maintenance issues associated with physical connectors. Magnetic resonance coupling facilitates wireless charging for automated guided vehicles (AGVs) and other mobile systems in manufacturing.

Wireless Power Transmission has proven to be a versatile and transformative technology, supporting a wide range of applications. From powering consumer electronics and electric vehicles to enabling wireless medical devices and industrial systems, WPT addresses critical challenges such as efficiency, scalability, and convenience. Continued advancements in inductive coupling and magnetic resonance coupling technologies will further expand the potential of WPT, making it an essential component of modern engineering and innovation.

Table 2: Key Applications of Wireless Power Transmission (WPT) Across Industries [11], [12]

Application	Technology Used	Advantages	Challenges	Examples/Uses
Consumer Electronics	Inductive Coupling	- High efficiency - Simplicity - Cost-effectiveness	- Limited range - Sensitive to alignment	- Smartphones - Smartwatches - Wireless earphones
Electric Vehicles	Magnetic Resonance Coupling	- Mid-range power transfer - Supports dynamic/static charging systems	- Precise alignment required - Power loss	- Wireless charging lanes - EV parking systems
Healthcare	Inductive & Magnetic Resonance	- Reliable power delivery - Reduces need for surgeries	- Miniaturization - Biocompatibility issues	- Pacemakers - Neuro stimulators
Industrial Applications	Magnetic Resonance Coupling	- Eliminates physical connectors - Supports mobility - Reduces maintenance	- High power requirements - Electromagnetic interference	- Automated Guided Vehicles (AGVs) - Robotics - Drones

This table summarizes the applications, technologies, advantages, challenges, and examples of WPT systems across key industries. It highlights the versatility of WPT while addressing the specific demands of different domains.

V. TECHNOLOGICAL ADVANCEMENTS AND TRENDS

Wireless Power Transmission (WPT) has witnessed significant advancements and emerging trends, addressing critical challenges and paving the way for innovative applications in various domains. These developments have enhanced the efficiency, scalability, and adoption of WPT technologies.

1. **Next-Generation Consumer Electronics:** [13] explored challenges and solutions in WPT for next-generation consumer electronics, emphasizing improvements in efficiency, alignment tolerance, and safety. Trends include the miniaturization of WPT modules, integration with IoT devices, and support for multi-device charging. Solutions focus on advanced control algorithms, adaptive power transmission, and better electromagnetic field management to enhance user experience.

2. **Medical Devices:** [14] reviewed WPT advancements for medical devices, highlighting trends in biocompatible and compact designs. Challenges like achieving high power efficiency in small-scale systems and ensuring patient safety have driven innovations in inductive and resonant coupling technologies. Emerging trends include energy harvesting techniques and wireless telemetry integration, enabling more robust and sustainable medical device solutions.
3. **Portable Devices:** [15] analysed WPT systems for portable devices, focusing on design optimizations for power transfer efficiency and range. Advancements in coil design, magnetic material usage, and high-frequency operations have contributed to improved performance. Trends in portable WPT include foldable or flexible charging surfaces and integration into everyday items like furniture and vehicle interiors.

The continued evolution of WPT is driven by the need for higher efficiency, user convenience, and scalability across diverse applications. Innovations in control systems, materials, and design approaches are addressing existing challenges and opening new possibilities. As technology progresses, WPT is poised to become a ubiquitous solution across consumer, medical, and industrial devices.

Figure 1: Pseudocode for a Wireless Power Transmission (WPT) System

```
START

DEFINE parameters:
    power_source, transmitter_coil, receiver_coil, load_device
    frequency, alignment_tolerance, power_efficiency

// Step 1: Initialize the system
INITIALIZE transmitter with power_source and frequency
INITIALIZE receiver with load_device

// Step 2: Power transfer process
FUNCTION transfer_power(transmitter, receiver, alignment_tolerance):
    IF receiver is aligned with transmitter within tolerance:
        START power transfer
        RETURN "Transfer successful"
    ELSE:
        RETURN "Alignment error"

// Step 3: Safety check
FUNCTION safety_check(transmitter, receiver):
    IF electromagnetic fields are safe AND no overload:
        RETURN "Safe"
    ELSE:
        RETURN "Error"

// Step 4: Execute system
IF safety_check(transmitter, receiver) == "Safe":
    PRINT transfer_power(transmitter, receiver, alignment_tolerance)
ELSE:
    PRINT "Safety check failed"

END
```

The pseudocode outlines a simplified workflow for a Wireless Power Transmission (WPT) system. It begins by defining the key parameters, such as the power source, transmitter, receiver, operating

frequency, alignment tolerance, and efficiency goals. The system is then initialized by configuring the transmitter with the power source and frequency and the receiver with the load device.

During the power transfer process, the alignment between the transmitter and receiver is checked. If they are aligned within the specified tolerance, the system begins power transfer; otherwise, an alignment error is flagged. A safety check ensures the system operates within safe electromagnetic field limits and avoids overloads. Finally, the system executes the power transfer if all safety checks are passed; otherwise, it reports a failure for review. This pseudocode provides a basic framework for implementing a WPT system while prioritizing safety and efficiency.

VI. CHALLENGES IN WIRELESS POWER TRANSMISSION

Wireless Power Transmission (WPT) technologies face several challenges that impact their efficiency, scalability, and usability. Addressing these challenges is critical for advancing WPT systems across applications.

1. **Resonant Inductive Coupling Challenges:** [16] identify key challenges in resonant inductive coupling, including misalignment sensitivity, which reduces efficiency when transmitter and receiver coils are not perfectly aligned. Other issues include electromagnetic interference (EMI) with nearby devices and heat generation, which can impact performance and safety. Potential solutions proposed include adaptive alignment systems and enhanced coil designs to mitigate EMI and optimize heat dissipation.
2. **Magnetic Resonance for Mobile Devices:** [17] review challenges specific to magnetic resonance-based WPT for mobile devices. These include power loss during mid-range transfer and difficulty in maintaining a consistent resonance frequency in dynamic environments. The study highlights the need for frequency-tracking algorithms and improved resonator materials to enhance performance and reliability in mobile applications.
3. **Electric Vehicles (EVs) and Magnetic Resonance:** [18] focus on challenges in WPT for electric vehicles, particularly the need for high power transfer efficiency and the ability to operate in dynamic (on-the-move) conditions. Design optimization, including advanced coil configurations and field-shaping techniques, is critical to addressing power loss and alignment challenges in EV wireless charging systems.

WPT systems face several technical challenges, including alignment sensitivity, power loss, electromagnetic interference, and dynamic operation constraints. Researchers have proposed solutions such as adaptive alignment mechanisms, frequency-tracking algorithms, and optimized coil designs to overcome these issues. Addressing these challenges will enhance the efficiency, reliability, and scalability of WPT technologies across applications.

VII. COMPARATIVE ANALYSIS OF WPT TECHNOLOGIES

Wireless Power Transfer (WPT) has emerged as a transformative technology with applications ranging from consumer electronics to electric vehicles and medical devices. The development of WPT technologies has been driven by the need for efficient, safe, and reliable power delivery over

varying distances. This section explores the advancements, challenges, and applications of WPT technologies based on the references provided.

1. **WPT in Medical Applications:** [19] reviewed the state-of-the-art methods in wireless power transfer for medical applications. The study highlights that inductive coupling is the most commonly used technique due to its safety and efficiency in short-range power delivery. Applications such as implantable medical devices benefit significantly from WPT by eliminating the need for batteries or invasive procedures to recharge devices. However, the challenges include designing compact and biocompatible systems that operate effectively in human tissue environments.
2. **WPT for Electric Vehicles:** [20] examined the challenges and future perspectives of WPT for electric vehicles. The review emphasizes the importance of efficient energy transfer over medium distances while ensuring safety and minimizing electromagnetic interference. Inductive power transfer (IPT) and capacitive power transfer (CPT) are identified as the primary methods for wireless charging of electric vehicles. Key challenges include achieving alignment tolerance, scaling power levels for heavy-duty vehicles, and meeting regulatory standards for electromagnetic compatibility.
3. **Inductive Coupling and Applications:** [21] provided an in-depth analysis of inductive coupling and its diverse applications in WPT. The study outlines that inductive coupling is highly efficient for short-range power transfer, making it suitable for consumer electronics and small-scale devices. The authors discuss advanced techniques like resonance tuning and multi-coil systems to improve efficiency and reduce power losses. Despite its advantages, inductive coupling faces limitations in transferring power over long distances due to magnetic field attenuation.

Comparative Insights

- **Efficiency and Range:** While inductive coupling is highly efficient for short-range applications [19]; [20], it struggles with medium-to-long-range applications like electric vehicles, where alignment and distance are critical factors [20].
- **Applications:** Medical applications prioritize safety and compact design [19], whereas electric vehicle applications demand scalability and electromagnetic compatibility [20].
- **Technological Challenges:** Across all applications, minimizing power loss, ensuring user safety, and addressing regulatory concerns remain common challenges.

The comparative analysis underscores the versatility of WPT technologies in addressing specific application requirements. Future research should focus on overcoming distance-related challenges and optimizing power transfer efficiency across varying application domains.

```
BEGIN
// Step 1: Initialize Components
Initialize Transmitter with PowerSource
Initialize Receiver with LoadDevice
Set AlignmentTolerance and SafetyLimits

// Step 2: Check Alignment
IF Alignment(Transmitter, Receiver) < AlignmentTolerance THEN
    RETURN "Error: Misalignment"
END IF

// Step 3: Perform Safety Check
IF SafetyParameters > SafetyLimits THEN
    RETURN "Error: Safety Violation"
END IF

// Step 4: Transmit Power
WHILE PowerNeeded AND SystemSafe DO
    TransmitPower(Transmitter, Receiver)
    Monitor Efficiency and Heat
END WHILE

RETURN "Power Transfer Complete"
END
```

Figure 2: Pseudocode for a generic Wireless Power Transmission (WPT) system.

The pseudocode outlines the basic operation of a Wireless Power Transmission (WPT) system. It begins by initializing the transmitter and receiver, setting alignment tolerance and safety limits. The system checks if the transmitter and receiver are properly aligned and ensures all safety parameters are within acceptable limits. If both checks pass, the transmitter starts sending power to the receiver while continuously monitoring efficiency and heat. The process continues until the power requirement is met or a safety issue arises, ensuring safe and efficient energy transfer throughout.

VIII. FUTURE PROSPECTS AND INNOVATIONS

The continuous evolution of Wireless Power Transmission (WPT) technologies holds great promise for enhancing energy transfer across multiple domains. Future advancements are anticipated in the following areas:

1. **Hybrid WPT Systems:** Researchers are exploring hybrid systems that combine multiple techniques, such as inductive and capacitive coupling, to achieve higher efficiency and versatility. Hybrid designs can address the limitations of individual methods, particularly in applications requiring varying power ranges and alignment flexibility.
2. **Dynamic and On-the-Move Charging:** WPT systems for electric vehicles and drones are increasingly focused on dynamic charging solutions. Wireless charging lanes and mid-air power transfer systems are under development, enabling uninterrupted energy replenishment during operation.
3. **Material Innovations:** Advanced materials, such as metamaterials and high-permeability

ferrites, are being utilized to improve electromagnetic field efficiency and reduce power loss. These materials also enhance the miniaturization and integration of WPT components.

4. **IoT Integration and AI-Driven Optimization:** The integration of WPT systems with the Internet of Things (IoT) and Artificial Intelligence (AI) is expected to optimize energy management and alignment precision. AI algorithms can dynamically adjust power delivery to match real-time device requirements, ensuring safety and efficiency.
5. **Regulatory and Safety Enhancements:** Addressing electromagnetic interference and developing standardized regulatory frameworks will facilitate the broader adoption of WPT technologies in sensitive environments such as medical facilities and crowded urban areas.
6. **Energy Harvesting and Sustainability:** Combining WPT with energy harvesting techniques can create self-sustaining systems, particularly for wearable devices and remote sensors. Such advancements contribute to sustainability by reducing dependency on disposable batteries and e-waste.

IX. CONCLUSION

Wireless Power Transmission (WPT) technologies have proven to be transformative across various applications, from enhancing user convenience in consumer electronics to enabling minimally invasive solutions in healthcare. While current systems demonstrate high efficiency in short-range applications, challenges such as misalignment sensitivity, power loss over long distances, and scalability for large systems remain critical barriers. Future innovations in hybrid designs, dynamic charging, and advanced materials are poised to overcome these challenges, unlocking the full potential of WPT systems. With continued research and development, WPT is set to redefine energy solutions, making them more efficient, sustainable, and seamlessly integrated into everyday life.

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