Advances and Challenges in Wireless Power Transfer for Modern Applications

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Abstract. Based on seven specified documents, this paper systematically summarizes the core classification, applications, performance, and safety of Wireless Power Transfer (WPT) technology. WPT is categorized into near-field (non-radiative) and far-field (radiative) technologies according to energy transfer mechanisms. Near-field technologies, including inductive coupling and magnetic resonance coupling, are suitable for short-distance and high-efficiency scenarios, with inductive coupling efficiency reaching 80% to 90%. In contrast, far-field technologies, such as microwave and laser transmission, are mainly used for long-distance scenarios, though microwave-based transmission typically exhibits efficiency below 10%. In typical applications, the Qi-standard system for consumer electronics achieves an efficiency of around 85%, the static charging system for electric vehicles reaches approximately 89%, and the Wireless Capsule Endoscopy system can transmit 310 mW of power. These systems generally comply with the safety guidelines set by the International Commission on Non-Ionizing Radiation Protection. Currently, WPT faces challenges such as the trade-off between efficiency and transmission distance, as well as a lack of unified international standards. Future development should focus on advancing medium- and long-distance transmission technologies and promoting integration across diverse application scenarios.

Keywords: Wireless Power Transfer (WPT), Near-field WPT, Far-field WPT, Electric Vehicle Charging.

1. Introduction

As a technology that breaks the limitations of traditional wired transmission, Wireless Power Transfer (WPT) has evolved from theory to practical application since Nikola Tesla conducted resonance experiments [1, 2]. Traditional power grids rely on cables and substations, with significant shortcomings: high transmission losses (the global average loss is 15%-20%, and the loss in India's power grid even reaches 26%-40%), resulting in substantial waste of electrical energy; high maintenance costs for infrastructure; and vulnerability to natural disasters such as floods and earthquakes, leading to frequent power outages [3, 4]. In contrast, WPT enables contactless energy transfer through electromagnetic induction, magnetic resonance, etc. It not only effectively reduces line losses and improves device portability but also integrates communication and power transmission onto a single platform, providing innovative solutions for smart grids, consumer electronics, medical devices, and other fields [4, 5].

In recent years, the demand for WPT has surged with the development of technologies in multiple fields: the popularization of electric vehicles (EVs) has spurred the need for dynamic charging, requiring solutions for efficient energy supplementation during driving; wireless sensor network (WSN) nodes consume large amounts of power due to data transmission, and frequent battery replacement leads to high operation and maintenance costs, necessitating WPT to extend their lifespan; wireless capsule endoscopy (WCE) requires miniaturized and stable power supply, while traditional batteries can only provide 25 mW of power, which is insufficient for high-resolution imaging and robotic movement [3, 6, 7]. For example, power consumed by data transmission accounts for over 60% of the total energy consumption of WSN nodes and combining WPT with data aggregation algorithms can significantly reduce energy consumption [3]. Based on seven specified documents, this paper systematically expounds on the classification principles, performance characteristics, application practices, and core challenges of WPT technology, providing clear references for relevant research and engineering practices.

2. Methods

2.1. Classification and Core Principles of WPT Technologies

As shown in Fig. 1, all the studies we looked at splitting Wireless Power Transfer (WPT) into two main types, near-field (non-radiative) and far-field (radiative) based on how they transfer energy. These two types differ a lot in how far they can send power, how energy spreads out, and what scenarios they work for [5, 8]. Near-field WPT usually works over distances shorter than the wavelength (λ) of electromagnetic waves, with energy staying close to the transmitter and receiver, so there is not much energy lost as radiation. Its key technologies are Inductive Coupling (IPT) and Magnetically Coupled Resonance WPT (MCRWPT). Far-field WPT, on the other hand, works over distances longer than λ, with energy traveling as electromagnetic waves. Its main technologies are Microwave Power Transfer (MPT) and Laser Power Transfer (LPT), which are good for long distances but can be messed up by things like weather or obstacles.

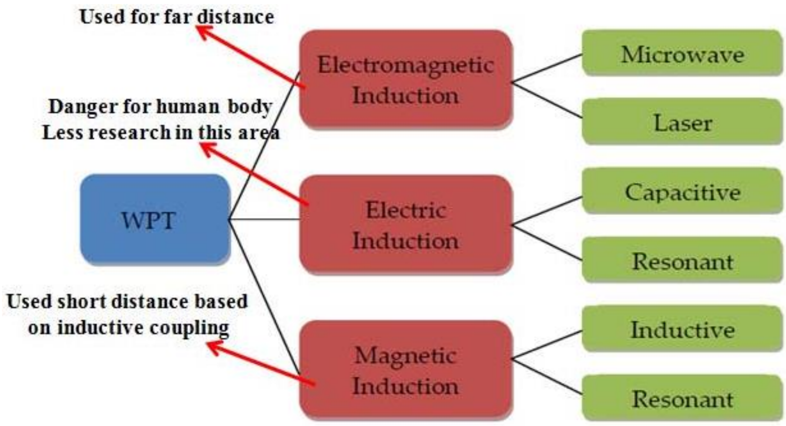

Figure 1. Classification of wireless power transmission [1]

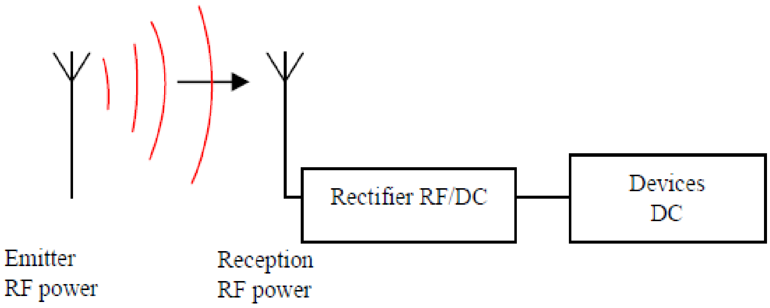

Figure 2. Schematic view of the WPT system [1]

Inductive coupling relies on Faraday's law of electromagnetic induction. Here's how it works: when you run an alternating current through the primary coil (the one sending power), it creates a magnetic field that changes over time. When this magnetic field passes through the secondary coil (the one receiving power), it induces an alternating voltage in the secondary coil. As shown in Fig. 2, after this voltage goes through circuits that turn it into direct current (DC) and stabilize it, it can power the device you're using [5, 8]. A key measure of how well it works is the coupling coefficient (k), which drops a lot as the distance between the two coils increases. For example, if the distance goes from 20 mm to 100 mm, k falls from 0.6 to 0.1, and the efficiency of power transfer drops from 80% to 40% too. A full IPT system has two parts: a transmitter and a receiver. The transmitter has a rectifier (to convert AC to DC), a DC/AC inverter (to turn DC back to high-frequency AC), a transmitting coil, and a compensation capacitor (to fix energy loss from the coil's leakage). The receiver has a receiving coil, an AC/DC rectifier, and a voltage stabilizer. Among different designs for balancing the system, the series-series (SS) setup is widely used for fast charging electric vehicles (EVs) because it works well with high power.

Magnetic resonance coupling lets power travel 1 to 10 times the size of the coils by making the transmitting and receiving coils vibrate at the same frequency. This strengthens the magnetic connection between them [2, 5]. Back in 2007, a team from MIT tested this tech by lighting a 60 W light bulb from 2 meters away, and it worked with about 40% efficiency. To measure how well it works, researchers use two main methods: coupled mode theory and circuit theory. Coupled mode theory uses equations to describe how energy moves, looking at things like the strength of the magnetic field, the natural frequency of the coils, and how well they're connected. Circuit theory uses Kirchhoff's Voltage Law (KVL) to calculate power and efficiency. You can make the system more stable by adding an extra "relay" coil. For example, if the receiving coil tilts 30 degrees, this relay coil can boost power stability from 41% to 65%.

Microwave power transfer uses microwave signals (with frequencies between 1 and 1000 GHz) to send energy. The system has a transmitter and a receiver: the transmitter has a microwave power source and an antenna (like a slotted waveguide or parabolic antenna) that sends the microwaves out into space. The receiver's main part is a "rectenna". A mix of a dipole antenna and a radio frequency (RF) diode. The diode turns the alternating current picked up by the antenna into DC power to run the device [1, 5]. This tech can send power far, but it's not very efficient and usually less than 10%. Using better antennas (like high-gain ones) and beamforming (which focuses on the microwaves) can help a bit. For example, a parabolic antenna might only work at 5% efficiency from 1 km away, but beamforming can bump that up to 8%.

Laser power transfer uses high-power laser beams to move energy. The system has a transmitter and a receiver: the transmitter has a laser source and a lens that focuses on the laser. The receiver uses an array of solar-like cells (photovoltaic cells) to turn the laser's light into electricity, which then goes through a voltage stabilizer to power the device [2, 8]. It works well over short distances (less than 1 km). Efficiency can be 50% to 70%. On a clear day, it might hit 65% efficiency from 100 meters away, but rain scatters and soaks up the laser, dropping efficiency to 40%. You also need a complex system to keep the laser pointed at the receiver. Otherwise, it won't work.

2.2. Performance Evaluation Indicators and Experimental Design

To judge how well a WPT system works, we look at four key things: how efficient it is, how far it can send power, how much power it can send, and how safe it is [6, 7]. Efficiency is just the ratio of the power the receiver gets to the power the transmitter sends. It's the main way to tell if the system is good. How far and how much power it can handle depends on what you're using it for. For example, charging a phone only needs short distances (less than 1 meter) and low power (less than 15 W), but charging an EV needs medium distances (less than 0.5 meters) and high power (in the kilowatt range). Safety checks include looking at the Specific Absorption Rate (SAR). How much energy the body absorbs from the system and current density (how much electric current flows through body tissues), and the temperature of the device's parts. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) says that for frequencies between 100 kHz and 10 MHz, the local SAR (around the head and torso) should be less than 10 W/kg, the average SAR less than 0.4 W/kg, and current density less than f(Hz)/100 A/m^2. The Japan Society of Medical Electronics and Biological Engineering (JSMEBE) adds that the coil in a wireless capsule endoscope (WCE) shouldn't get hotter than 42.5℃. Otherwise, it could damage body tissues.

As shown in Fig. 3, to test WPT systems in different situations, the studies used a mix of computer simulations and real-world experiments [3, 7]. For wireless sensor network (WSN) research, scientists used MATLAB to create two test scenarios: one with 100 sensors spread over a 100 x 100-meter area, and another with 500 sensors over 1000 x 1000 meters. They used these to see how much power the Power Level-Based Data Aggregation (PLBDA) algorithm saved. For WCE power systems, they used a detailed computer model of the human body (with 56 different types of tissue) to check SAR values and current density. They also did real experiments to test how hot the receiving coil got and how stable the power transfer was. For EV wireless charging, they built a physical test setup: they buried a transmitting coil (1 meter wide, 30 turns of wire) in the ground and attached a receiving coil

(0.8 meters wide, 25 turns) to an EV's chassis. They set the system to work at 85 kHz and tested how efficient and stable it was by changing the distance between the coils and the power the EV used.

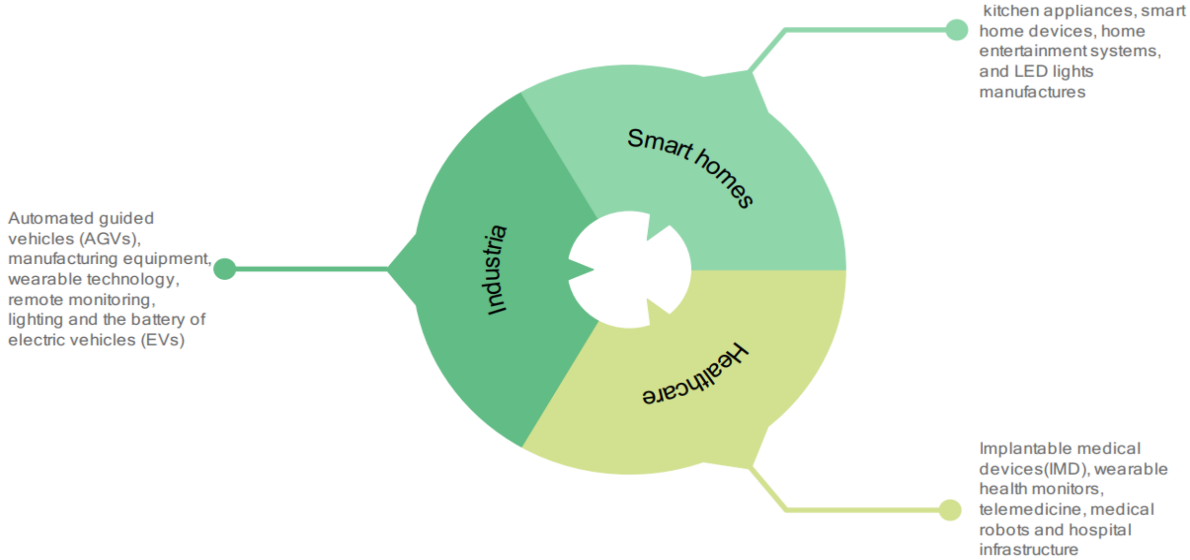

Figure 3. Applications for WPT [6]

3. Results

3.1. Performance Comparison of Different WPT Technologies

When it comes to near-field WPT, inductive coupling (IPT) works best over short distances. If the coils are less than 0.1 meters apart, it can transfer power with 80% to 90% efficiency, but as the distance gets longer, efficiency drops fast. For example, at 100 mm apart, it only works at 40% efficiency [8]. Magnetic resonance coupling (MCRWPT) is better for medium distances (0.1 to 2 meters). MIT's tests showed it works at about 40% efficiency from 2 meters away, and that goes up to 60% when the distance is 1 meter. The shape of the coils and the material inside them (the core) also make a big difference. A pentagonal coil connects better than square or oval ones. Its coupling coefficient is 30% higher. From 10 to 20 mm away, it's 30% more efficient than an oval coil. Using a ferrite core (with a relative permeability of μi=10000) makes the system 10 times more efficient than using an iron dust core.

For far-field WPT, microwave power transfer (MPT) can send power the farthest, theoretically up to tens of thousands of kilometers. But it's the least efficient. Over long distances (more than 1 km), it usually works at less than 10% efficiency. A system with a parabolic antenna might only hit 5% efficiency from 1 km away, but beamforming can push that to 8% [1]. Laser power transfer (LPT) is more efficient than MPT over short distances (less than 1 km). It can work at 50% to 70% efficiency. On a clear day, it might reach 65% efficiency from 100 meters away. But weather messes with it a lot and rain drop efficiently to 40%. You also need a system to keep the laser pointed at the receiver, which adds complexity. Both far-field technologies need a clear line of sight (no obstacles between transmitter and receiver), and their high-frequency signals can be harmful to people. So, you need shielding or power controls to keep users safe.

3.2. Performance of WPT Systems in Typical Application Scenarios

In consumer electronics charging, WPT has two main industry standards: Qi and AirFuel [6]. The Qi standard (made by the Wireless Power Consortium) uses IPT. It can handle 5 to 15 W of power at 5 W, it works at 85% efficiency when the device is 5 mm away from the charger, and 70% when it's 10 mm away. The AirFuel standard (from the AirFuel Alliance) uses MCRWPT. It works at 6.78 MHz and can handle 15 to 100 W. At 15 W, it's 60% efficient when the device is 50 mm away, and it can charge 3 phones at the same time. Apple's iPhone 12 uses MagSafe, which is based on MCRWPT. By designing the coil better and focusing on the magnetic field, it's 15% more efficient than traditional IPT. Its SAR value is less than 0.4 W/kg, which meets ICNIRP's safety rules.

For EV wireless charging, both static (when the car is parked) and dynamic (when the car is moving) systems mostly use IPT [8]. Static systems have the transmitting coil buried in parking lots, with the receiving coil on the EV's chassis. At 3.3 kW of power, it works at 89% efficiency when the coils are 0.2 meters apart. Dynamic systems use a row of coils under the road to charge the car while it's driving. At 2 kW, it's 75% efficient when the car is going 60 km/h, and it can make the EV's range 30% longer. These systems use an SS compensation setup and a ferrite core to reduce energy loss. They also have an aluminum shield to keep the magnetic field near the car below 27 μT. The SAR value is 0.15 W/kg, and current density is 1.8 A/m². Within ICNIRP's safety limits.

In wireless sensor networks (WSNs), combining WPT with the PLBDA algorithm makes the sensors last much longer [3]. The PLBDA algorithm sorts of sensors into areas with high, medium, and low power loss based on how strong the radio signal is (RSSI). This helps optimize the path data takes, saving power. MATLAB simulations showed that in the 100-sensor scenario, PLBDA saved 16.5 to 20.13 dBm of power and way more than traditional methods (tree-based: 4.1 dBm, cluster-based: 4.8 dBm, chain-based: 2.9 dBm, grid-based: 3.5 dBm). In the 500-sensor scenario, PLBDA saved 3.85 to 5.71 dBm, while traditional methods only saved 1.12 to 4.23 dBm. Using a Mobile Charging Vehicle (MCV) to recharge the sensors made their lifespan go from 6 months to 18 months.

For wireless capsule endoscopes (WCEs), WPT systems need to be small, stable, and safe [7]. The system uses IPT: the transmitting coil is a Helmholtz coil (64 cm wide, 26 turns), and the receiving coil is a 3D coil (9.6 mm wide, 130 to 150 turns, with a ferrite core). It works at 400 kHz. Tests showed it can send 310 mW of power from 32 cm away, with 1.24% efficiency. If the capsule shifts 15 cm along the coil's axis, power drops to 250 mW (still 80.6% stable). If it tilts 30 degrees, power drops to 127 mW (41.0% stable). But that's still enough for the WCE to take high-resolution (1080P, 30 frames per second) videos and move like a small robot.

3.3. Safety Verification Results of WPT Systems

When it comes to SAR values, all WPT systems in different uses meet ICNIRP's standards [6, 7, 8]. For WCEs, the local SAR around the head and torso is 0.392 W/kg, around the limbs it's 0.8 W/kg, and the average SAR is 0.2 W/kg. For static EV charging, the SAR near the car (0.1 meters away) is 0.15 W/kg. For consumer electronics using Qi or AirFuel, SAR is less than 0.4 W/kg. So, there's no risk of too much radiation.

For current density, the WCE system has 3.82 A/m²at 400 kHz, the EV system has 1.8 A/m²at 85 kHz, and the 125 kHz IPT system has 1.2 A/m²when 1 A of current is input. All of these are below ICNIRP's limit of f(Hz)/100 A/m², so they won't irritate or damage body tissues [1, 7].

For device temperature, the WCE's receiving coil uses 16 strands of enameled wire, and it stays at a steady 38.2°C. The EV's receiving coil (made of 2 mm copper wire) gets to 40 °C at 3.3 kW, but adding a heat dissipation system can cool it down to 35°C. Both are below JSMEBE's 42.5°C limit, so they won't burn or harm the body [7, 8].

4. Discussion

4.1. Advantages and Core Challenges of WPT Technology

Compared to traditional wired power transfer, WPT has three big pluses. First, it wastes less energy. Near-field WPT works at 80% to 90% efficiency, which is way better than traditional power grids. Those lose 15% to 40% of energy. This makes WPT great for places with little energy or weak grid systems, since it doesn't waste as much electricity [1, 5]. Second, it makes devices easier to use and more flexible. EVs can charge while driving, so you don't have to stop; WSN sensors don't need their batteries to change all the time, which cuts down on maintenance costs; WCEs don't need surgery to replace their power source, which is safer for patients. All of this means WPT can be used in more situations [6, 7]. Third, it combines power transfer and communication. For example, EV wireless charging systems can "talk" to the grid. They charge when there's less demand for electricity and send power back when demand is high, which helps balance the grid. It also avoids power outages caused by broken cables or natural disasters, making the power system more reliable [5].

But WPT still has three big problems to solve. First, there's a trade-off between efficiency and distance. Magnetic resonance coupling works at 40% efficiency from 2 meters away, but if you want to charge multiple devices from 10 meters away (like in a home), you need to make the coils work better (improve their Quality Factor, Q), add relay coils, or adjust the frequency automatically to get efficiency above 50%. Also, when multiple devices charge at the same time, the coils interfere with each other, making efficiency drop 10% to 15%. We need to create new algorithms to fix this interference [8]. Second, there's no single set of rules for WPT across the industry. The Qi standard (which works at 100-205 kHz and handles 5-15 W) is for things like phones and smartwatches. The AirFuel standard (6.78 MHz, 15-100 W) is for EVs and factory equipment. These two standards don't work with each other. They use different ways to transfer power and different frequencies. This makes things more expensive for both people buying devices and companies making them. We need to make unify rules (like the IEEE 802.11be standard that's being worked on) that combine WPT and communication, so different devices can work together [6]. Third, it's hard to balance cost and safety. The equipment for far-field WPT, like high-power antennas and lasers, is expensive. For example, a parabolic antenna for microwave transfer costs five times more than regular cables. Plus, high-frequency signals can be bad for people, so we need things like shielding materials, power controls, and real-time monitoring to keep users safe. All of this makes it harder to turn WPT into a product people can buy [1, 2].

4.2. Technology Selection Strategies for Application Scenarios and Future Directions

Picking the right WPT technology depends on what you're using it for. You have to match the tech to what the scenario needs [6, 8, 9]. For charging things like phones or smartwatches, you need short distances, low power, and high safety. So, Qi-standard IPT is good for charging one device at a time, and AirFuel-standard MCRWPT works if you want to charge multiple devices or need a little more distance. The Qi option is efficient and cheap, while AirFuel can handle more devices and slightly longer distances. For EV charging, you need medium distances, high power, and reliability. Static charging (when the car is parked) uses IPT with an SS compensation setup, and dynamic charging (when the car is moving) uses IPT with a row of coils under the road. You also need to make sure the coils switch fast enough and stay aligned so efficiency doesn't drop. For WSNs, you need low power, long sensor life, and wide coverage. So, you pair IPT with a Mobile Charging Vehicle (MCV) and the PLBDA data aggregation algorithm. The MCV recharges the sensors, and the algorithm finds the best way to send data so less power is used. For medical devices like WCEs or pacemakers, you need small size and high safety. IPT with a 3D receiving coil and ferrite core works here. The 3D coil keeps power steady even if the device moves, the ferrite core helps transfer power better, and keeping the frequency between 100-400 kHz keeps SAR values low. For space and drone tech, you need long distances and resistance to interference. Microwave transfer (MPT) is good for satellites because it can handle bad weather, and laser transfer (LPT) works for short-distance drone charging since it's efficient [10].

In the future, WPT should focus on four areas. First, making it work efficiently over medium and long distances. Metamaterial coils have special properties (negative permittivity and negative permeability) that help focus on the magnetic field and stop energy from leaking. Tests show MCRWPT with metamaterial coils works at 55% efficiency from 10 meters. 25% better than regular coils. We need to make metamaterials cheaper and easier to make so they can be used in real products. Second, fixing interference when multiple devices charge at once. Using orthogonal coils (coils that don't overlap) and Time Division Multiple Access (TDMA), which lets devices charge one after another instead of all at once and can cut efficiency loss from 15% to 5%. We also need to make algorithms that let the system change frequencies automatically to avoid interference. Third, making

WPT safer. We need systems that check SAR values in real time and adjust power if needed, so SAR stays within safety rules even when power is high. We should also use new shielding materials like nanocomposites. They stop magnetic field leakage without making efficiency drop too much [6, 7]. Fourth, combining WPT with other tech and making unify rules. We should blend WPT with 6G, the Internet of Things (IoT), and artificial intelligence (AI). 6G's millimeter-wave tech can make MPT more efficient and cover more area; IoT devices can get power nonstop from WPT; AI can adjust the system's frequency, power, and path in real time to work better in changing environments. At the same time, groups like IEEE and IEC should make unified standards that take the best parts of Qi and AirFuel, so different WPT devices can work together [6].

5. Conclusion

Based on the analysis of seven specified documents, WPT technology is clearly classified into near-field (short-distance, high-efficiency) and far-field (long-distance) categories. Near-field inductive coupling has the highest efficiency, while far-field microwave transmission has the longest distance. In typical applications, WPT has achieved feasible power supply in consumer electronics, EVs, WSNs, and WCE, and all scenarios comply with ICNIRP safety standards. Currently, WPT faces challenges such as the trade-off between efficiency and distance, lack of unified standards, and high costs. In the future, efforts should be made to develop medium- and long-distance high-efficiency technologies and promote multi-technology integration and standard unification. As an innovative technology that breaks the limitations of traditional wired transmission, WPT is expected to become a core support for future smart energy transmission.

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