Performance And Application Scenarios Comparison of Wireless Charging Technologies

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Abstract. With the proliferation of portable electronic devices, wearable devices, and electric vehicles, energy supply methods are facing new demands for convenience and reliability. Traditional wired charging methods increasingly reveal issues such as connector wear, lack of flexibility, and safety hazards, making wireless charging a widely focused research direction in both academia and industry. In recent years, related research has continuously broken through bottlenecks in transmission efficiency, stability, and spatial flexibility, laying the foundation for building more efficient energy networks in the future. This paper reviews and analyzes three mainstream wireless charging technologies: inductive power transfer (IPT), magnetic resonance coupling (MRC), and radio frequency (RF) energy transfer. IPT utilizes transmitting coils to generate alternating magnetic fields for efficient power transfer within a few centimeters; MRC achieves medium-distance energy transfer through resonant coupling between transmitter and receiver coils, supporting multi-device sharing; RF technology utilizes far-field radio frequency waves to achieve meter-level energy coverage, though with relatively low overall efficiency. This paper compares the performance differences of these three methods in terms of frequency, transmission distance, efficiency, and multi-device support, and analyzes their applicability in typical scenarios such as consumer electronics, electric vehicles, and medical devices. The research results help clarify the current development context of wireless charging technology and provide reference value for the design and optimization of future novel wireless power supply systems.

Keywords: Wireless Charging; Inductive Power Transfer; Magnetic Resonance Coupling; Radio Frequency Energy Transfer; Electric Vehicles.

1. Introduction

With the continuous development of portable electronic devices and the rapid growth of the electric vehicle market, traditional wired power supply methods have gradually exposed problems such as connector wear, inconvenience of use, and insufficient safety. Wireless charging technology, as an emerging means of energy transmission, is rapidly penetrating various electronic systems due to its non-contact power supply characteristics, becoming a research hotspot widely concerned by both academia and industry [1]. The current mainstream wireless charging technologies include three types: inductive, magnetic resonance, and radio frequency, which are based on different energy coupling mechanisms and possess different transmission distances, efficiencies, and application scenarios [2].

In recent years, wireless charging technology has been in a stage of rapid development, with academic research continuously making breakthroughs in system efficiency, stability, and flexibility. Hu Wei-Kang et al. proposed a method to optimize system operation at "exceptional points," enabling high-efficiency and high-stability transmission without relying on real-time parameter measurements, providing a new theoretical basis and design thought for wireless power transfer in complex environments [3]. Meanwhile, Professor Sekiya Hiroo's team utilized machine learning to build a load-independent wireless power transfer system, effectively reducing voltage fluctuations and maintaining high efficiency, significantly improving system stability and applicability, and providing important support for the subsequent development of miniaturized and low-cost wireless charging devices [4]. Furthermore, Wang Hanwei et al. proposed a metasurface-based free-positioning and multi-device wireless power supply scheme, which not only improved system efficiency and coverage but also realized power distribution and compensation for multiple receivers, enhancing the flexibility and user experience of wireless charging [5]. These research achievements collectively reflect the latest progress in enhancing the performance of wireless charging systems and expanding application scenarios, also laying a solid academic foundation for future industry standards and application implementation.

This paper will systematically review the principles of the three main types of wireless charging technologies. At the same time, it will summarize their architectures, advantages, and disadvantages. On this basis, this paper will conduct targeted performance comparison analysis and, combined with typical application scenarios, further explore their adaptability. Ultimately, this paper aims to clarify the current development status of wireless charging technology and provide theoretical support and practical reference for the research and design of future novel wireless power supply systems.

2. Classification and Working Principles of Wireless Charging Technologies

2.1. Inductive Power Transfer (IPT)

2.1.1 Basic Principles

Inductive power transfer (IPT) wireless charging is based on Faraday's law of electromagnetic induction. An alternating magnetic field is generated by the transmitter coil, and the receiver coil induces a current at the corresponding frequency, which is then rectified to supply power.

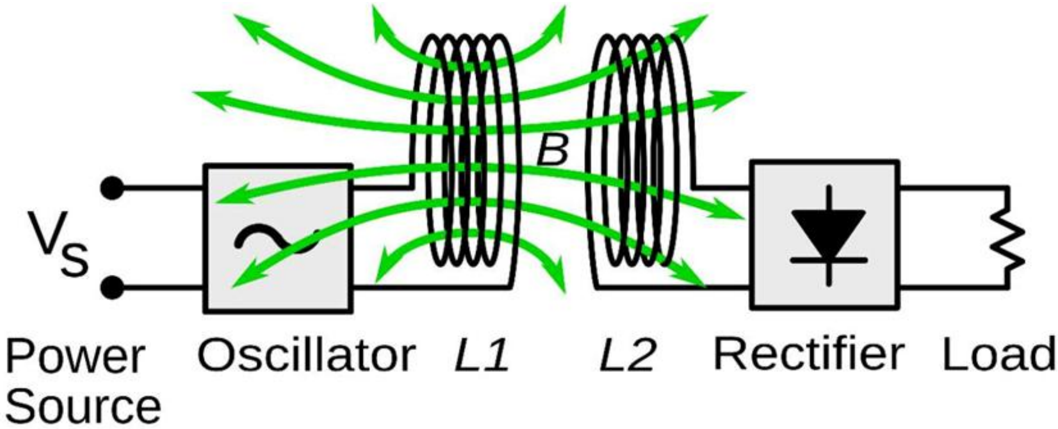

Fig. 1 Basic structure of an inductive wireless charging system

Fig. 1 shows the basic structure of an inductive wireless charging system: the high-frequency oscillating circuit on the transmitter side drives the transmitting coil to produce an alternating magnetic field; the receiving coil on the receiver side then induces an alternating current from this magnetic field, which is rectified and regulated to power the load. Its technical principle is mature, the structure is simple, and the manufacturing cost is relatively low. It is widely used in consumer electronics (such as mobile phones, electric toothbrushes) and medium-to-high power scenarios (such as static charging for electric vehicles) [6]. Its operating frequency is mostly in the range of 87 kHz to 205 kHz, which is also the frequency band adopted by the Qi standard to ensure high efficiency and safety.

2.1.2 Typical Cases

In the field of inductive wireless charging, several representative studies in recent years have promoted the technology towards higher power, broad load compatibility, and higher efficiency. Ahmed A. Shaier et al. designed a "Double D" magnetic coupler that supports efficient transmission of 200 kW at 91.88% efficiency even while the vehicle is in motion, significantly enhancing the feasibility and power capacity of inductive charging for electric vehicles [7]. Meanwhile, Wang Hanzheng designed and implemented a transmitter for a Qi standard-compliant wireless charging system. This transmitter can achieve a maximum charging efficiency of 85%, a maximum load capacity of 15W, and possesses various practical functions such as foreign object detection, providing a reference for the design of wireless charging devices [8]. The research on metamaterial configurations by Wandee Onreabroy et al. further improved charging efficiency over short distances by optimizing electromagnetic flux distribution and provided innovative directions for the structural optimization of inductive systems [9]. The aforementioned cases collectively constitute recent core breakthroughs in inductive wireless charging technology from basic theory to engineering implementation, laying a solid foundation for its widespread adoption in electric vehicles and other high-power application scenarios.

2.1.3 Advantages and Limitations

The main advantages of inductive technology lie in its simple structure, high efficiency (can reach 80%-90% or more under close-range conditions), minimal radiation impact on the human body, high level of device integration, and controllable cost, making it one of the most mature wireless charging solutions on the market.

However, this technology also has obvious limitations. Firstly, its transmission distance is very short, generally only a few millimeters to a few centimeters. As the distance between the transmitting and receiving coils increases, the coupling coefficient decreases significantly, efficiency drops rapidly, and it requires extremely high alignment accuracy between the coils; any misalignment can severely affect the charging effect [10]. Secondly, in high-power systems, to meet large energy demands, the system still faces electromagnetic compatibility issues and thermal management challenges, especially for applications like electric vehicles, where factors such as device alignment deviation, chassis height differences, and electromagnetic leakage need to be carefully considered and controlled.

2.2. Magnetic Resonance Coupling (MRC)

2.2.1 Basic Principles

Magnetic resonance wireless charging (MR-WPT or MCR-WPT) utilizes the resonant coupling of transmitter and receiver resonant circuits. By tuning capacitors and coils to form a high-quality factor resonant system, it achieves efficient energy transfer at a shared frequency.

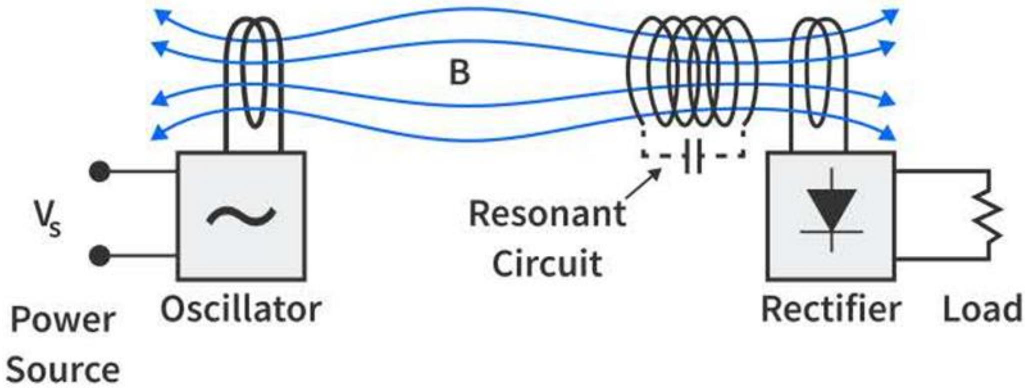

Fig. 2 Typical structure of an LC resonant system for magnetic resonance coupling

Figure 2 shows the typical structure of an LC resonant system for magnetic resonance coupling: both the transmitter and receiver form resonant circuits through coils and capacitors, tuned to the same resonant frequency, achieving magnetic field resonance coupling for energy transfer, significantly improving energy transfer efficiency and distance coverage, while also possessing the potential for multi-receiver energy sharing.

2.2.2 Typical Cases

In the field of magnetic resonance wireless charging, recent research has made significant progress in intelligence, environmental adaptability, and high-power reception capability. Tang Jianlin et al. developed a wireless charging system for electric vehicles that can maintain high-efficiency transmission without precise coil alignment by introducing a PT-symmetric mechanism, reducing alignment accuracy requirements and improving user experience [11]. Pham Thanh Son et al. studied the matching of MR-WPT performance and resonant frequency in conductive media environments, clearly indicating that using 20 MHz or 10 MHz under different conductivity conditions is more conducive to efficiency improvement, providing theoretical guidance for application design in complex media [12]. Furthermore, Liu Ching-Yao et al. proposed a design for a passive receiving unit (PRU) that does not require an external power supply, capable of stably receiving high power over practical distances, supporting efficient wireless charging for electric vehicles for the first time [13]. These three typical achievements collectively promote the academic and engineering development of magnetic resonance wireless charging technology in terms of high efficiency, high reliability, and application diversity.

2.2.3 Advantages and Limitations

In terms of advantages and limitations, the significant advantages of magnetic resonance technology lie in its larger transmission distance and multi-device sharing capability, along with good tolerance to alignment errors, making it suitable for dynamic or semi-dynamic environment applications. However, its limitations are also apparent, mainly including high system complexity, strict requirements for precise control of the magnetic resonance frequency, and sensitivity to environmental disturbances.

In recent years, by adopting new magnetic materials, optimizing coil parameter design, introducing self-adjusting compensation circuits and topologies, and utilizing machine learning to optimize system dynamic performance, the robustness and efficiency of MR-WPT have been significantly improved. In a typical study, Wang L et al. constructed an SSH-chain structure based on topological physics and machine learning algorithms, which, after optimization, exhibited excellent transmission efficiency and system stability in changing environments, demonstrating the importance of intelligent design in future magnetic resonance systems [14].

2.3. Radio Frequency (RF) Wireless Power Transfer

2.3.1 Basic Principles

Radio frequency wireless charging (RF-WPT) is a type of technology that achieves long-distance energy transfer based on electromagnetic wave radiation (mainly in the radio frequency or microwave frequency bands). It typically involves transmitting multiple antennas to form directional RF radiation, and the receiver then uses an integrated antenna array or rectenna to convert the RF energy into DC electrical energy.

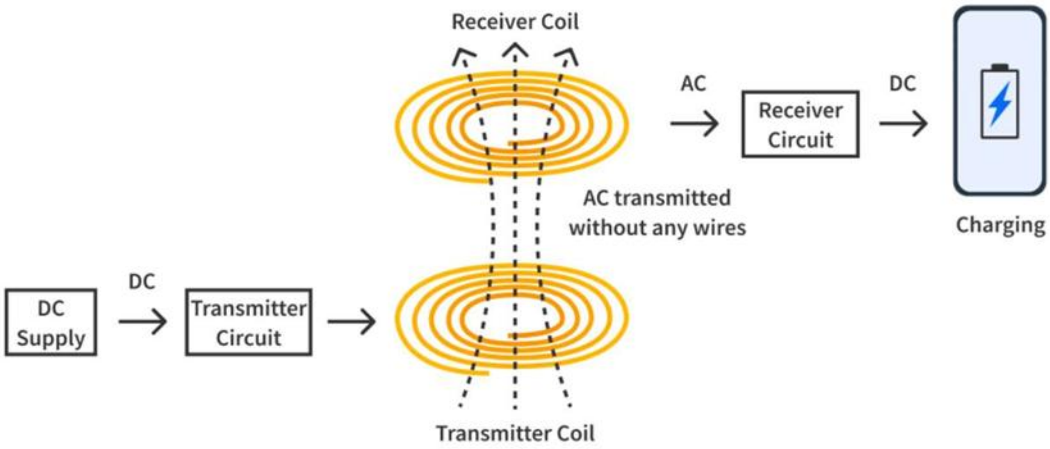

Fig. 3 System block diagram of RF far-field wireless power supply

Figure 3 shows the system block diagram of RF far-field wireless power supply: the transmitter uses an RF or microwave signal source to drive an antenna array, emitting energy in the form of electromagnetic waves through directional radiation; the receiver uses a rectenna to receive RF energy, which is then rectified and regulated to output DC power for the load.

2.3.2 Typical Cases

In the research of RF wireless charging technology, three typical recent advances have significantly enhanced the practicality and flexibility of the technology. Prominent scholar Kyriaki Niotaki et al. systematically reviewed the technological trends in RF energy harvesting and transmission, including millimeter waves, flexible rectennas, and SWIPT (Simultaneous Wireless Information and Power Transfer), simultaneously promoting systems towards higher efficiency and integration [15]. Meanwhile, Onel L. A. López et al. proposed a system architecture and deployment strategy for high-power RF wireless transmission that balances efficiency and EMF (Electromagnetic Field) safety, laying a normative foundation for practical applications [16]. Furthermore, experimental proof by Gilles Callebaut et al. showed that in multi-antenna near-field RF-WPT systems, even with small phase errors, high power efficiency can be maintained, introducing flexibility into system design and reducing synchronization requirements [17]. These research achievements collectively promote the in-depth development of RF wireless charging technology in terms of efficiency, safety, and scalability, and have important guiding significance for future IoT device and Internet of Things power supply systems.

2.3.3 Advantages and Limitations

This method is suitable for low-power terminals such as IoT devices and sensor networks. Its main advantages are long transmission distance (can reach meter level or beyond), no need for strict alignment, support for multiple devices to share resources, and suitability for environmental perception or spatially scattered deployment scenarios [18].

Despite its long-distance power supply capability, RF charging still faces many challenges in performance, especially its overall low transmission efficiency. In RF-WPT, losses from multiple stages including RF power generation, spatial propagation loss, and receiving rectification conversion accumulate, often resulting in actual efficiency below 20%, particularly evident under far-field conditions. Additionally, high-power systems impose strict requirements on electromagnetic radiation safety (EMF), necessitating compliance with prescribed exposure limits and the adoption of near-field restriction strategies to reduce human impact [19].

3. Core Performance Comparison

A simple comparison of the three different transmission methods—Inductive, Magnetic Resonance, and Radio Frequency—is shown in Table 1.

Table 1. Simple comparison of Inductive, Magnetic Resonance, and Radio Frequency wireless charging methods

Method	Inductive Power Transfer	Magnetic Resonance Coupling	Radio Frequency Transfer
Typical Frequency	85–205 kHz	Hundreds kHz – Several MHz	MHz – GHz level
Transmission Distance	1–5 cm	5–50 cm	1–15 m
System Efficiency	High (up to 80–90%)	Medium-High (60–80%)	Low (5–30%, decreases significantly over distance)
Multi-device Capability	Weak (requires multi-coil structure for multiple devices)	Strong (can resonate with multiple receivers)	Strong (supports broadcast coverage)
Safety	High (very low radiation, localized magnetic field)	Relatively High (limited by frequency and power)	Relatively Low (requires strict radiation exposure control)

4. Application Scenario Analysis

4.1. Consumer Electronics Products

The demand for charging convenience in consumer electronics continues to rise, with the three technologies each showing their strengths. Inductive technology dominates the mainstream market due to its low cost and mature solutions. ESSAGER's developed 3-in-1 foldable inductive charging station, compatible with the Qi standard, can simultaneously provide up to 15W charging power for iPhone, Apple Watch, and AirPods [20].

Magnetic resonance technology excels in spatial freedom. The charging dock for smart watches developed by Qingdao Luyu Energy Technology utilizes a 6.78MHz resonant frequency to achieve ≥85% power transfer efficiency within a 5cm distance, allowing users to charge without precise device placement [21]. This technology is particularly suitable for miniaturized products like wearable devices.

RF technology focuses on medium-distance energy replenishment for low-power devices. The microwave wireless charging system developed by Jiangnan University, based on a Gallium Nitride (GaN) Schottky diode rectenna operating in the 5.8GHz band, can provide 200mW of power to multiple devices within a 20cm distance. Its rectification efficiency broke through 90% and has been successfully applied to enhance the continuous battery life of TWS earphones and smart mice [22]. This technology provides a new approach for wireless charging of consumer electronics products.

4.2. Electric Vehicles

In the field of electric vehicles, both inductive and magnetic resonance technologies have practical applications. Plugless Power uses inductive coupling, embedding transmitting coils in ground parking pads that pair with receiving units on the EV chassis to achieve cable-free charging while stationary, with tested efficiency reaching 84%-90% [23].

WiTricity (an MIT spin-off) employs magnetic resonance coupling technology to provide wireless charging systems for electric vehicles ranging from 3.6 kW to 11 kW, achieving end-to-end efficiency exceeding 90%. It has been commercially promoted and signed licensing agreements with multiple automakers [24].

4.3. Inductive Power Transfer (IPT)

The medical and health field imposes higher requirements for reliability and safety on wireless power supply, where wireless charging technologies show significant advantages. Both inductive and magnetic resonance technologies are being researched for use in implantable or wearable medical devices.

Hu Jiankun's research improved the traditional planar spiral coil of inductive wireless charging into an arc-shaped structure that fits the curvature of the human chest. This system can provide stable power transmission for artificial hearts within a 20mm gap, significantly reducing the risk of infection caused by percutaneous wires while improving patient wearing comfort [25].

Magnetic resonance technology is widely used in external medical devices. Sprouthing's adaptive matching system uses AI algorithms to adjust the resonant frequency and impedance in real-time, providing 5-30W wireless power for portable ventilators and infusion pumps. Its patented technology solves the problem of efficiency decay caused by device displacement, controlling efficiency fluctuation within ±2% [26].

5. Conclusion

This paper has reviewed and analyzed three mainstream wireless charging technologies: inductive power transfer (IPT), magnetic resonance coupling (MRC), and radio frequency (RF) energy transfer. IPT wireless charging features a simple structure and high near-field efficiency, finding widespread application in mobile phones and static charging for electric vehicles; however, its transmission distance is short (only a few centimeters) and it requires strict alignment. MRC offers a larger transmission distance and supports multi-device sharing; its disadvantages include system complexity and high requirements for resonant matching. RF technology covers long distances (meter-level) and requires no alignment, making it suitable for powering distributed terminals; however, there remains room for improvement in its efficiency (often <20% under far-field conditions) and electromagnetic radiation safety. In the future, wireless charging systems will develop towards integration, intelligence, and long-distance power supply. For example, multi-mode compatibility and unified standards will enhance system interoperability, intelligent technologies like machine learning will optimize performance, and methods such as RF far-field and laser power transmission will be developed to expand the scope of wireless power supply. It is anticipated that wireless power supply will penetrate deeply into fields such as the Internet of Things (IoT), intelligent transportation, and wearable devices, providing more flexible and efficient electrical energy support for diversified applications.

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