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Comparison and Application Analysis of Three Wireless Charging Methods

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Abstract: With the rapid development of the electronics industry, increasingly stringent requirements have been placed on battery endurance and power transfer efficiency (PTE). To meet the demands of modern high-technology society, numerous research teams have invested substantial efforts in wireless charging technologies. At present, wireless charging mainly includes electromagnetic induction-based wireless charging, magnetic resonant coupling-based wireless charging, and microwave-based wireless charging. By comparatively analyzing the operating principles of these three approaches, this paper summarizes their respective advantages and disadvantages. Electromagnetic induction-based wireless charging is highly constrained by transmission distance and is therefore suitable only for short-range power transfer. Magnetic resonant coupling-based wireless charging enables relatively longer transmission distances; however, it poses potential safety risks, as resonance may occur between the charging equipment and conductive objects in the surrounding environment under certain conditions. Microwave-based wireless charging is well-suited for radio-frequency wireless power transfer (WPT) in the microwave band. Through frequency-band adjustments, it can be extended to long-distance wireless power transfer across multiple bands. In the future, improvements in coil stability, transmitter frequency tuning, and bandwidth expansion may further enhance the power transfer efficiency and application potential of wireless charging technologies.

Keywords: Wireless charging; Electromagnetic induction; Magnetic coupling; Electromagnetic microwave

1. Introduction

With the increasing societal dependence on electronic devices and more stringent performance requirements, wireless charging technology, also known as wireless power transfer (WPT), has attracted extensive attention and research in recent years, achieving notable developments and applications across multiple fields. Traditional wired charging methods are gradually being replaced by emerging wireless approaches. Wireless charging eliminates spatial constraints, significantly reduces transmission losses along cables, and better satisfies expectations for high-efficiency modern devices. Currently, wireless charging technologies mainly include electromagnetic induction-based wireless charging, magnetic resonant coupling-based wireless charging, and microwave-based wireless charging. The most fundamental approach is electromagnetic induction-based wireless charging, which transfers power based on the principle of electromagnetic induction; however, it is strongly limited by transmission distance. Magnetic resonant coupling-based wireless charging also employs electromagnetic induction, but differs in that a resonant compensation circuit is used to adjust the coils to the same resonant frequency [1]. In contrast, microwave-based wireless charging utilizes electromagnetic wave radiation and achieves power transfer through mutual conversion between electrical energy and microwave energy, although it is more susceptible to environmental influences. Although both domestic and international research teams have conducted in-depth studies on wireless charging, challenges such as energy losses during power transfer and relatively low power transfer efficiency persists.

This paper comparatively analyzes the technical principles, characteristics, and applications of the three wireless charging methods to identify approaches with superior performance and strategies to overcome inherent limitations. Furthermore, the practical value of these technologies is evaluated to provide clear objectives and directions for future development of wireless power transfer technology.

2. Fundamental theories of the technologies

2.1. Wireless charging based on electromagnetic induction

When an alternating current is supplied to the transmitting coil, an alternating magnetic field is generated around the coil. If the receiving coil is located within this magnetic field, according to the principle of electromagnetic induction, a current will be induced in the closed circuit whenever the magnetic flux through the loop changes. Consequently, the magnetic field and magnetic flux of the receiving coil also vary, thereby generating an induced electromotive force and induced current. By appropriately regulating the induced electromotive force, power can ultimately be delivered to electronic components [1]. **Figure 1** shows the simplified circuit of the electromagnetic induction technique. To reduce magnetic flux loss, this method is significantly constrained by transmission distance and is therefore suitable only for short-range power transfer. Wang *et al.* reported that ion-optimized substitution achieved by co-doping Nb_2O_5 and Li_2CO_3 into NiCuZn ferrite not only promotes uniform densification of the material microstructure but also significantly enhances its electromagnetic properties, including permeability and saturation magnetic induction, while reducing power loss [2]. Owing to its excellent electromagnetic performance, this material is suitable as a magnetic isolator for wireless charging transmitters, enabling efficient energy transfer and rapid long-distance charging performance. This also demonstrates that electromagnetic induction wireless charging may suffer from considerable energy losses compared with wired charging and impose stringent requirements on material properties and performance.

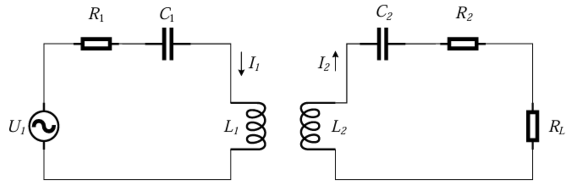

Figure 1. Simplified circuit of the electromagnetic induction technique.

2.2. Magnetic resonant coupling-based wireless charging

This wireless charging method is based on the phenomenon of magnetic resonant coupling. Its fundamental principle is essentially similar to that of electromagnetic induction-based wireless charging. However, resonant compensation circuits with specific resonant frequencies are additionally introduced to both the transmitting and receiving coils. When the resonant frequencies of the two coils are matched, magnetic resonance occurs at the receiving side, thereby achieving higher power transfer efficiency (PTE) and enhanced energy delivery capability. **Figure 2** illustrates the simplified schematic circuit of the wireless charging system for electric vehicles. The primary advantage of this method is that the distance requirement between the two coils is less restrictive than that of electromagnetic induction-based wireless charging, enabling relatively longer-distance power transfer. Nevertheless, potential safety risks exist, since the charging equipment may form an unintended resonant system with metallic objects in the surrounding environment under certain conditions [3]. To further improve energy harvesting efficiency, researchers have investigated various hybrid structures that enhance performance through combined piezoelectric and electromagnetic transduction. To realize continuous self-powered operation in complex environments, Yu *et al.* proposed a multidirectional piezoelectric-electromagnetic vibration energy harvester (MD-PEVEH), which enables efficient multidirectional energy collection [4]. The MD-PEVEH adopts a pendulum-based structure. A magnet located at the bottom of the pendulum interacts with a fixed coil to generate electricity through electromagnetic induction, while an integrated piezoelectric cantilever converts mechanical strain into electrical energy. The multidirectional adaptability of the pendulum significantly enhances energy capture capability in dynamic environments, making the device particularly suitable for applications such as wireless sensor networks, structural health monitoring, and Internet of Things devices. Experimental results demonstrate stable performance under different excitation angles. At an excitation frequency of 8.5 Hz, the rectified harvester achieved a maximum output power of 6.99 mW, and power fluctuations were limited within 5%, confirming its multidirectional coherence and stability. Capacitor charging tests further verified its effective energy storage capability. These results indicate that magnetic resonant coupling-based wireless charging features relatively high efficiency and long-distance capability, although limitations remain in terms of long-term durability.

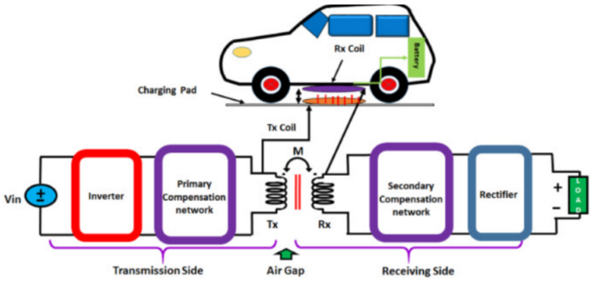

Figure 2. Main circuit of the resonant coupling wireless charging system for vehicle charging.

2.3. Microwave-based wireless charging

Microwave-based wireless charging is founded on the principle of electromagnetic wave radiation [3]. In this method, electrical energy and microwave energy are continuously converted into each other. First, a microwave conversion device converts the input alternating current into microwaves, which are then transmitted through the air over long distances. After being received at the receiving terminal, the microwaves are converted back into electric current by a rectification and conversion circuit. Following appropriate regulation, electrical power is supplied to electronic components. **Figure 3** shows the architecture of the microwave wireless charging system. Although this method enables long-distance power transfer, it is strongly affected by environmental factors as well as the reflection and refraction characteristics of electromagnetic waves, resulting in considerable propagation losses [5]at the beginning of each time slot, the SU should make the decision to harvest RF energy or to transmit a packet. The mode decision depends on the channel state and the available energy in the energy queue. We formulate the mode management problem of the SU as a Markov decision process (MDP. Yan *et al*. proposed the world's first watt-level radio-frequency wireless power transfer (RF-WPT) system with intelligent continuous tracking and obstruction detection [6]. The system operates in the 5.8 GHz band and integrates advanced technologies such as millimeter-precision LiDAR, multi-object image recognition algorithms, and a rectification efficiency of 66.8%. Chen *et al.* introduced a capacitor-free four-layer coil pad using flexible printed circuits and polyimide substrates for medium-power operation at low resonant frequencies [7]. Nanocrystalline ribbon cores were also explored, exhibiting higher magnetic saturation and lower core loss compared with conventional MnZn ferrites. Experimental results demonstrated a power density of up to 29.9 W/cm^3 and an efficiency of 92%. Li proposed a laser-guided strategy to construct hierarchical carbon structures for ultra-broadband microwave absorption [8]. These improvements partially overcome the limitations of microwave-based wireless charging, including relatively low efficiency and narrow operating frequency bands.

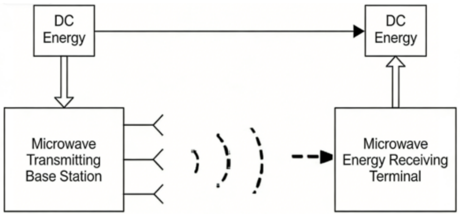

Figure 3. Architecture of the microwave wireless charging system.

3. Comparison of advantages and disadvantages of different technologies

3.1. Electromagnetic induction-based wireless charging

Electromagnetic induction-based wireless charging transfers electrical energy over short distances using a loosely coupled transformer structure with separated primary and secondary coils. This technology is relatively mature and has already been applied in many practical scenarios. For example, wireless charging systems have been deployed for airport shuttle buses at Haneda Airport, as well as non-contact charging pads developed by Splashpower and non-contact charging systems produced by Showa Aircraft Industry. However, this method is strongly limited by transmission distance, and the power transfer efficiency (PTE) decreases significantly as the distance increases. Moreover, the relative positions of the separated primary and secondary coils must be precisely aligned; otherwise, the PTE will deteriorate markedly [9]. Therefore, conventional electromagnetic induction-based wireless charging is subject to considerable constraints, including limited transfer distance, strict alignment requirements, and high material performance demands. Its application range is consequently restricted. Many companies attempt to improve its performance by incorporating additional components or compensation structures based on this technology.

3.2. Magnetic resonant coupling-based wireless charging (MRC-WPT)

To satisfy the requirements of constant-voltage and constant-current charging for electrical devices, various research teams have successively proposed compensation structures and topologies, including basic compensation networks, LCL-S topologies, S/LCL-compensated constant-voltage and constant-current WPT systems, and S-LCC/LCL resonant wireless power transfer systems [10]. These approaches gradually optimize magnetic resonant coupling technology. Under zero-phase-angle (ZPA) conditions, constant-voltage and constant-current power transfer can be achieved. System stability can also be maintained during frequency switching, thereby reducing system cost and the complexity of resonant parameter adjustment [11]. Compared with conventional electromagnetic induction–based wireless charging, this method not only overcomes the distance limitations of the former but also improves transfer capability. It exhibits lower propagation losses, enables constant-voltage and constant-current output, and provides a more stable WPT system. However, its overall PTE is still lower than that of traditional wired charging methods, and further optimization is required. Consequently, magnetic resonant coupling-based wireless charging demonstrates significant development potential. This approach also has broad market prospects. Owing to its relatively high PTE and stable system performance, it is suitable for short- to medium-range power transfer applications in practical production. It not only reduces material costs but also lowers the maintenance costs associated with traditional wired charging.

3.3. Microwave-based wireless charging

Microwave-based wireless charging extends wireless power transfer to the microwave frequency band. As electromagnetic waves at specific microwave frequencies experience relatively low attenuation in air, this method substantially overcomes the distance limitations of both electromagnetic induction-based and magnetic resonant coupling-based wireless charging, making it applicable to a wider range of scenarios. With the advancement of microwave WPT research, various groups have proposed high-performance microwave energy harvesting antennas, high-efficiency broadband rectifier circuits, and hybrid solutions combining resonant coupling technology with microwave techniques [12]. Compared with the previous two methods, microwave-based wireless charging exhibits smaller propagation losses and can achieve transmission distances on the order of kilometers. However, broadband rectifier circuits, which constitute one of its core components, remain insufficiently mature. Further research is required in bandwidth expansion and efficiency optimization. Microwave-based wireless charging is therefore suitable for large-scale applications in microwave-band wireless power transfer, particularly for enterprises requiring long-distance power transfer. With appropriate frequency-band adjustments, it can also be extended to remote WPT applications across multiple bands.

3.4. Comparative analysis of the three technologies

Based on the principle analysis above, the similarities and differences among electromagnetic induction-based, magnetic resonant coupling-based, and microwave-based wireless charging technologies are summarized in **Table 1**.

Table 1. Comparative analysis of the three wireless charging methods

Wireless charging method	Principle	Advantages	Disadvantages
Electromagnetic induction-based	Electromagnetic induction	Reduces losses associated with traditional wired transmission media	Strongly distance-limited; suitable only for short-range power transfer
Magnetic resonant coupling-based	Electromagnetic induction and magnetic coupling	Relatively high PTE and stable WPT system; suitable for short range transfer	Overall efficiency still lower than wired charging
Microwave-based	Electromagnetic wave radiation	Applicable to microwave bands; supports long-distance and multi-band WPT after frequency adjustment	Highly affected by environmental metallic objects and other uncertainties

4. Challenges and future development of wireless charging technology

In recent years, wireless charging has achieved encouraging progress. However, several critical bottlenecks remain, including short charging distance, limited flexibility, and low power transfer efficiency (PTE) [13]. Electromagnetic induction-based wireless charging suffers from issues such as large transmission delay, instability, and possible connection interruptions during the communication process. Magnetic resonant coupling-based wireless charging faces challenges related to coil performance, including the quality factor of the coils, the relative position and distance between coupled coils, winding resistance, and load resistance matching. All these factors can significantly affect the power transfer efficiency of the WPT system as well as the durability of the device. Microwave-based wireless charging, on the other hand, must address challenges such as expanding the usable microwave frequency band and mitigating the influence of conductive objects and environmental factors along the propagation path. In future work, substantial research efforts are required to further improve wireless charging technologies to enable their large-scale application in production and daily life. To enhance system stability, electromagnetic induction-based and magnetic resonant coupling–based wireless charging methods can improve coil performance and adopt various compensation structures to achieve constant-voltage and constant-current power transfer, thereby stabilizing the WPT system. In contrast, microwave-based wireless charging is more susceptible to uncontrollable environmental factors; therefore, additional components or shielding structures may be introduced at both the transmitting and receiving sides to stabilize the output voltage and current. In terms of power transfer performance, electromagnetic induction-based and magnetic resonant coupling-based methods can reduce propagation losses by controlling the transmitter operating frequency, thereby improving efficiency. For microwave-based wireless charging, bandwidth expansion, optimization of microwave signal sources and power amplifiers, and integration with conventional communication systems can help reduce losses and further enhance power transfer efficiency.

5. Conclusion

Wireless charging is expected to become a core technology for future wireless power transfer (WPT). This paper introduces three wireless charging methods: electromagnetic induction-based, magnetic resonant coupling-based, and microwave-based wireless charging. Through an analysis of their operating principles and a comparison of their respective advantages and disadvantages, it is found that conventional electromagnetic induction-based wireless charging is strongly limited by transfer distance and requires strict alignment of transformer components as well as high material performance. On this basis, magnetic resonant coupling-based wireless charging improves performance through coupling optimization. It provides relatively high power transfer efficiency and a more stable WPT system, making it suitable for short- to medium-range power transfer, although energy losses during propagation still exist. Microwave-based wireless charging is suitable for long-distance power transfer in the microwave frequency band but is more susceptible to environmental influences. The comparative analysis provides guidance for selecting the most appropriate wireless charging method under specific application scenarios. For example, magnetic resonant coupling-based methods are preferable for medium-range applications, whereas microwave-based methods are more suitable for long-distance power transfer. By examining the limitations of each technology, targeted improvements and hybrid integration of multiple approaches can be developed to overcome the performance bottlenecks of individual methods and promote the integrated advancement of wireless charging technologies. At present, various technical routes with different parameters coexist in the market. Summarizing these wireless charging methods helps identify common performance indicators, improve compatibility among different devices, reduce industrial adaptation costs, and support sustainable development. Driven by continuous technological optimization and expanding application scenarios, the wireless power transfer industry is entering a period of rapid growth. Nevertheless, challenges such as propagation losses, lower efficiency compared with conventional wired methods, cost control, and electromagnetic radiation safety must still be addressed through further research and technological advancements.

Disclosure statement

The authors declare no conflict of interest.

References

[1] Yuan Z, 2020, Transmission Characteristic Analysis of Wireless Charging System Based on Magnetic Resonance, thesis, Hebei University of Technology.

[2] Wang P, Wang P, Wang J, et al., 2024, Enhancing Electromagnetic Properties of NiCuZn Ferrites through Nb and Li Co-Doping for Wireless Power Transfer. Ceramics International, 50(24, Part C): 54966–54975.

[3] Lin S, Mo X, 2025, Research on Wireless Charging Technology for Power Batteries of New Energy Vehicles on Highways. Popular Science & Technology, 27(4): 92–95.

[4] Yu Y, Zhou J, Tang C, et al., 2025, A Multidirectional Piezoelectric-Electromagnetic Vibration Energy Harvester for Sustainable Power Generation in Dynamic Environments. ACS Applied Materials & Interfaces, 17(28): 40539–40545.

[5] Zhao J, Wei Y, Song M, et al., 2015, Dynamic Mode Management in Cognitive Radio Networks with RF Energy Harvesting, In 11th International Conference on Wireless Communications, Networking and Mobile Computing (WiCOM 2015), 156–158.

[6] Yan Z, Hu C, Hou B, et al., 2025, A Watt-Level RF Wireless Power Transfer System with Intelligent Auto-Tracking Function. Electronics, 14(7): 1259.

[7] Chen L, Yu B, Fu Y, et al., 2024, Pushing Wireless Charging from Station to Travel, In Proceedings of the 30th Annual International Conference on Mobile Computing and Networking, 46–61.

[8] Li Z, Li N, Song Y, et al., 2025, Laser-Engineered Carbon Hierarchies with Multiscale Attenuation Mechanisms for Ultrabroadband Microwave Absorption. Chemical Engineering Journal, 2025(522): 168152.

[9] Yang Z, 2022, Design and Implementation of an Electromagnetic Induction Wireless Charging Receiver System, thesis, Southeast University.

[10] Kurs A, Karalis A, Moffatt R, et al., 2007, Wireless Power Transfer via Strongly Coupled Magnetic Resonances. Science, 317(5834): 83–86.

[11] Li G, Wang Z, Wang G, 2026, Design of S-LCC/LCL Resonant Radio Energy Transmission System. Journal of Tianjin University of Technology, 2026: 1–8.

[12] Xu B, 2019, Research on Technology of Microwave Wireless Charging Circuit, thesis, University of Electronic Science and Technology of China.

[13] Bobba P, Anwar M, Bhupathi H, et al., 2024, Simultaneous Wireless Power and Data Transfer in Different Applications, In E3S Web of Conferences, 01147.