Difference Analysis Between Electromagnetic Induction and Resonant Wireless Charging

Yanxu Lu *

Shenghua Zizhu Academy, Shanghai, 200241, China

* Corresponding Author Email: jimmy_lu07@outlook.com

Abstract. This paper presents a comparative analysis of two mainstream wireless charging technologies: electromagnetic induction and magnetic resonance. It systematically analyzes their working principles, charging efficiency, implementation methods, advantages and disadvantages, as well as typical applications in different scenarios. Through a detailed comparison of experimental data with existing literature, this study reveals that electromagnetic induction technology excels in charging efficiency but is limited by its short operating distance. In contrast, magnetic resonance technology offers greater spatial flexibility, albeit with a slight compromise in efficiency. These findings help readers to comprehensively understand the applicability of these two technologies in key application scenarios such as smartphones, electric vehicles, and implantable medical devices. In addition, this article also explores the optimization of multi-mode fusion, intelligent tuning, and new material heat dissipation. This study offers valuable insights for decision-making, standards development, and user experience enhancement. It thereby contributes to the advancement and adoption of wireless charging technology, paving the way for more convenient and efficient power solutions in the future.

Keywords: Electromagnetic wireless charging, Resonant wireless charging, Charging efficiency.

1. Introduction

Electronic devices, ranging from smartphones to electric vehicles, have become deeply integrated into modern society. However, with the increase in the number of devices, charging issues have gradually become prominent, and the limitations of traditional wired charging methods are becoming increasingly apparent. For example, the mechanical lifespan of traditional charging interfaces is limited, and the charging interface standards between different devices are not unified (such as Apple and Android devices), which brings many inconveniences to users. Driven by progress in materials science and power electronics, wireless charging technology has become a promising solution to these problems.

The emergence of wireless charging technology not only improves the convenience of charging, but also brings many benefits to the use and maintenance of devices. At present, there are two mainstream methods for wireless charging technology: electromagnetic induction wireless charging and magnetic resonance wireless charging. There are significant differences between these two methods in terms of charging efficiency and application scenarios. Electromagnetic induction wireless charging technology has high efficiency in close range charging, but the charging distance is limited; Magnetic resonance wireless charging technology has more advantages in flexibility, but its efficiency is relatively low. Each technology has distinct strengths and weaknesses, making them suitable for different applications, such as electric vehicles and smartphones. Although these two technologies have significant differences in their basic working principles, this difference leads to complex trade-offs in key performance indicators such as efficiency, spatial freedom, cost, and complexity. This complexity poses a huge challenge for system designers and product engineers, making it difficult for them to select the most suitable technology for specific application scenarios without a clear and detailed comparison framework. This study systematically evaluates these two technologies in depth, aiming to overcome this challenge and construct a clear and practical technology selection guide based on application requirements.

This article aims to explore in depth the two mainstream technologies of electromagnetic induction wireless charging and magnetic resonance wireless charging. By detailing their working principles, strengths, limitations, and application scenarios, this article provides a clear delineation of the capabilities and limitations of each technology. The insights derived from this analysis aim to provide information for future development, standardization efforts, and the adoption of wireless charging in different fields, ultimately helping it develop into a more universal and integrated energy solution. Achieving this vision will require not only technological breakthroughs but also supportive policies and market promotion.

Interdisciplinary collaboration, integrating knowledge from materials science and electromagnetics, is key to its progress. Wireless charging is anticipated to see widespread application in smart homes, electric vehicles, and medical devices. This adoption will bring considerable convenience to daily life and industrial production, promoting a transformation in energy transmission.

2. Fundamental Energy Transmission Mechanisms

2.1. Magnetic Induction Coupling

Electromagnetic induction wireless charging operates on the principle of Faraday's law of induction. When a high-frequency alternating current is applied to the transmitter coil, it generates an alternating magnetic field within a short range (typically millimeters to centimeters). This changing magnetic field induces an electromotive force (EMF) in the receiver coil, as described by:

$$E = \frac{d\Phi}{dt} \tag{1}$$

Where E is the EMF and dΦ/dt is the rate of change of magnetic flux. This process directly converts energy from electrical to magnetic and back to electrical form in a single step. The coupling coefficient is highly sensitive to the axial distance and lateral alignment between the coils. While efficiencies can reach 80-85% under optimal conditions (e.g., very close coupling), the tolerance for lateral offset is typically less than 3 mm, beyond which efficiency drops sharply. In 2007, Marin Soljacic, an assistant professor of physics at MIT, and his research team used magnetic resonance to successfully light a 60W light bulb from 1.9 meters away by constructing two transmitting and receiving resonator coils with a radius of 30cm [1]. Germany is achieving systematic breakthroughs in high-power fast charging technology for new energy vehicles, including architecture optimization and material innovation. At present, technological development mainly focuses on the deep coupling between the 800V high-voltage platform and third-generation semiconductor devices, replacing traditional insulated gate bipolar transistors with silicon carbide power modules to achieve energy efficiency improvement At present, technological development mainly focuses on deep coupling between 800V high-voltage platforms and third-generation semiconductor devices, using SiC power modules instead of traditional IGBTs to achieve energy efficiency improvement [2].

2.2. Magnetic Resonance Coupling

Magnetic resonance introduces resonant capacitors based on electromagnetic induction, tuning the transmitting coil and receiving coil to the same frequency, and forming a strongly coupled evanescent wave channel in the near-field region through a high quality factor resonator; Even if the air gap expands to several tens of centimeters or the lateral displacement exceeds 10 centimeters, the system can still maintain a transmission efficiency of 50% -70% with the help of coupling mode theory and support one to many power supply. The performance of the resonator coils is primarily determined by their energy conversion capability, for which a high quality factor (Q) is the key parameter. The performance of the resonator coils is primarily determined by their energy conversion capability, for which a high quality factor (Q) is the key parameter. For a simple inductor, the quality factor is defined by its inductive reactance (ωL) divided by its parasitic resistance (R), i.e., Q = ωL/R [3]. In a practical MR-WPT system, the effective Q-factor is influenced by the overall circuit impedance at the resonant frequency.

This scheme selects a multi node charging method based on node density and improves energy efficiency through centralized charging. To solve the problem of insufficient charging efficiency in traditional charging schemes, an efficient multi node directional charging scheme (MNDCS) is proposed. This scheme selects a multi node charging method based on node density and improves energy efficiency through centralized charging [4]. As noted by Wang et al. (2024), while magnetic resonance significantly relaxes alignment requirements through the "resonance tunneling" effect, it introduces greater control complexity, necessitating real-time impedance matching and frequency stability measures.

3. Performance analysis

Building on the fundamental principles outlined in the previous section, this chapter presents a systematic comparison between Inductive Wireless Power Transfer (IPT) and Magnetic Resonance Wireless Power Transfer (MR-WPT). The evaluation revolves around three core indicators that are crucial for technology selection in practical applications: transmission efficiency, spatial degrees of freedom (including transmission distance and offset tolerance), and system complexity and cost. This analysis combines experimental data with recent literature research results, providing a clear framework for understanding the inherent trade-off between the two technologies.

3.1. Transmission Efficiency

Efficiency is defined as the ratio of the output power obtained by the load to the input power at the transmitting end, and is the primary indicator of concern for all energy transmission systems.

This section aims to comprehensively compare the charging efficiency of two well-known wireless charging technologies. The data derived from both experiments and reviews reveal distinct characteristics of these two technologies. Electromagnetic induction wireless charging is capable of achieving an end-to-end efficiency that exceeds 85% under optimal conditions, where the air gaps are maintained at the millimeter level and the coupling coefficients are high. This high efficiency makes IPT highly suitable for applications that require close proximity between the transmitter and receiver, such as charging small consumer electronics. However, this technology has notable limitations. If the center deviation of the coil surpasses 3 millimeters or the spacing between the coils increases to the centimeter level, the efficiency plummets below 60%. Moreover, IPT is extremely sensitive to the presence of foreign objects in the vicinity of the charging field, which can further degrade its performance. On the contrary, magnetic resonance wireless charging presents a different profile. It can sustain a transmission efficiency ranging from 50% to 70% over a considerably longer distance of 3 to 30 centimeters. This is made possible by employing a high-quality factor resonator that operates at a frequency of 6.78 megahertz. The ability to maintain relatively high efficiency over such distances makes MR-WPT a more flexible solution, especially for applications where spatial freedom is crucial, such as in the automotive sector. In fact, the latest in-car prototype has demonstrated even greater potential. By utilizing multi-module parallel connections and dynamic tuning, the efficiency has been enhanced to 95%, nearly matching the efficiency of wired charging solutions. This advancement significantly narrows the gap between wireless and wired charging in terms of performance. Additionally, the introduction of a relay resonator into the MR-WPT system to form a TX-relay-RX structure has proven to be a game-changer. It not only extends the power transmission distance but also ensures that the energy transmission efficiency of the system remains robust, thereby expanding the applicability and feasibility of magnetic resonance wireless charging in various scenarios [5].

3.2. Spatial Freedom

The spatial degree of freedom refers to the system's tolerance for distance variations and alignment deviations, which is the main difference between the two technologies and the core factor determining their applicability in different scenarios.

When it comes to transmission distance and tolerance, electromagnetic induction wireless charging is highly demanding in terms of alignment precision. Specifically, it requires that the lateral offset be kept under 5 millimeters. This stringent requirement means that devices must be placed with great accuracy to ensure effective charging, which can be a significant inconvenience for users. On the other hand, magnetic resonance wireless charging exhibits much greater flexibility. It can accommodate radial offsets exceeding 10 centimeters and angular deviations up to 20 degrees. This substantial leeway greatly reduces the precision needed for parking or placing the devices, making the charging process much more user-friendly and practical in real-world scenarios. Building on these advantages, Jadidian and others have introduced a groundbreaking magnetic beamforming technique for magnetic resonance wireless power transfer (MR-WPT) systems. Their approach involves integrating wireless energy transmission with wireless communication technologies. Drawing inspiration from the MIMO beamforming concept prevalent in wireless communication, they have engineered the Mag MIMO system. This system manipulates the current at the transmitter (TX) end to perform beamforming on the non-radiative magnetic field. The resulting focused magnetic field is then directed towards the receiving device to facilitate wireless charging. The experimental outcomes are quite impressive. Within a close range of 0.5 centimeters, the energy transfer efficiency of this technology can reach as high as 89%. Moreover, the charging range has been successfully extended to 40 centimeters. Another notable feature is that the efficiency remains unaffected by the orientation of the receiving device, which adds to the convenience and versatility of the system. However, it is important to point out that the Mag MIMO system, in its current form, is limited to charging only one device at a time [6].

3.3. System Complexity and Cost

System Complexity and Cost refers to the complexity and cost issues faced by wireless charging technology in implementing its functions.

Magnetic resonance wireless charging, though offering remarkable spatial freedom and medium-range power transfer capabilities, entails a higher degree of system complexity. Specifically, it necessitates real-time frequency tracking to maintain resonance amidst varying conditions, sophisticated impedance matching networks to optimize energy transfer, and advanced electromagnetic interference (EMI) suppression algorithms to ensure reliable operation. These requirements lead to control unit costs that are 30 - 50% higher compared to electromagnetic induction wireless charging. Additionally, the increased complexity heightens the challenges in heat dissipation and shielding design, further complicating the overall system architecture. In contrast, electromagnetic induction wireless charging shines in low-cost, high-efficiency, and close-range applications. It is particularly well-suited for scenarios where devices are frequently charged and require minimal alignment, such as consumer electronics. On the other hand, magnetic resonance wireless charging is more appropriate for situations that demand medium power, spatial freedom, and the ability to charge multiple devices simultaneously, like in the automotive and industrial sectors.

4. Application Scenario Analysis

4.1. Consumer Electronic

Electromagnetic resonance wireless charging technology leverages the electromagnetic coupling characteristics of the near-field to achieve efficient energy transfer. The region within a wavelength range centered on the field source is referred to as the near-field or induction field, whereas the region outside this wavelength range is known as the far-field. In this setup, electromagnetic energy flows periodically between the space surrounding the radiation source and the interior of the radiation source itself. Given that the electric field is predominantly confined within the capacitor, a non-radiative alternating magnetic field is established around the transmitting coil, facilitating the transfer of energy [7]. This principle underpins the widespread adoption of electromagnetic induction in various applications.

At the level of electricity demand, there are significant differences in equipment types: sensors and control units (≤ 100W) require precise voltage stabilization (fluctuation<2%); The information entertainment host (several hundred watt level) requires fast dynamic response (voltage recovery time<10ms); Electric compressors (kilowatt level) must have high efficiency converter carrying capacity (conversion efficiency ≥ 95%) [8]. In the realm of consumer electronics, electromagnetic induction has solidified its position as the mainstream solution for mobile phones and headphones. The Qi standard, which is widely recognized and utilized, has enabled a measured efficiency of 75-85% within a 15 W power range. Despite its high efficiency, the stringent alignment requirement within a 5 mm tolerance somewhat restricts the charging freedom, necessitating precise placement of devices for optimal performance. This technology is well-suited for applications where devices are frequently charged and require high efficiency, but the limited spatial freedom can be a drawback in more dynamic environments.

4.2. Electric Vehicle

The automotive sector has seen remarkable progress in wireless charging technology, particularly with the application of magnetic resonance principles. Companies such as WiTricity and Qualcomm Halo have been at the forefront of this innovation, developing 11 kW wireless charging systems that achieve peak efficiencies of up to 90%. These systems are designed with a significant 3-30 cm air gap and a lateral offset tolerance of 10 cm, making "stop and charge" a practical reality for electric vehicles (EVs). This means that EVs can be charged without the need for precise alignment, significantly enhancing the convenience and feasibility of wireless charging in everyday use. Moreover, dynamic wireless charging has emerged as a sophisticated solution, enabling vehicles to be continuously charged through coil arrays while in operation. This technology allows for seamless power transfer even as the vehicle moves, addressing one of the primary concerns related to charging infrastructure. However, the technical complexity and cost associated with dynamic wireless charging are relatively high, posing challenges for widespread adoption [9]. The flexibility and efficiency offered by magnetic resonance wireless charging are transformative for the EV industry. By reducing the need for precise alignment and increasing tolerance for movement, wireless charging becomes a more viable option for everyday use. This advancement not only enhances user convenience but also paves the way for a future where EVs can be charged effortlessly, without the hassle of plugging in. As the technology continues to evolve, it holds the promise of making wireless charging a standard feature in the automotive industry, further accelerating the transition to sustainable transportation.

4.3. Future trend: Hybrid Ecosystem

For scenarios involving the simultaneous wireless power supply to multiple devices, magnetic resonance technology has proven to be highly effective. It can provide 100 W-500 W of power to laptops, drones, and automated guided vehicles (AGVs) all at once on a single desktop, all through a unified 6.78 MHz resonance frequency. The measured efficiency in these applications ranges from 60-70%, which is commendable given the complexity of powering multiple devices concurrently. This technology has been recognized and listed as a national standard technology route by the China Electricity Council, highlighting its significance and potential for widespread adoption.

Looking ahead, the integration of magnetic attraction alignment and magnetic resonance chip technology into the upcoming Qi2 standard promises to create a hybrid ecosystem. This ecosystem will combine the benefits of "induction close-fitting fast charging" and "resonance space energy replenishment," catering to consumer, automotive, and industrial scenarios alike. The ultimate goal is to achieve a cable-free energy supply across all scenarios, thereby enhancing user convenience and driving the broader adoption of wireless charging technologies. The hybrid approach leverages the strengths of both electromagnetic induction and magnetic resonance, offering a seamless and versatile wireless charging experience that meets the diverse needs of modern applications.

5. Conclusion

Through research, this article found that electromagnetic induction wireless charging technology can achieve 80% -85% high-efficiency energy transmission within millimeter level spacing, but it is extremely sensitive to coil alignment, and the efficiency will sharply decrease when the offset exceeds 3 millimeters. The magnetic resonance wireless charging technology establishes a "resonance tunnel" through a 6.78MHz high-quality factor resonator, which can maintain an efficiency of 50% -70% at a distance of 3-30 centimeters and a lateral offset of 10 centimeters, and supports one to many power supply. Therefore, electromagnetic induction wireless charging is suitable for cost sensitive and distance fixed consumer electronic products, such as mobile phones and headphones, and has formed a Qi standard ecosystem; Magnetic resonance wireless charging is suitable for medium power scenarios that require spatial freedom and multi device charging, such as 11kW electric vehicles and desktop multi device 100-500W scenarios. However, magnetic resonance wireless charging systems require real-time frequency modulation, impedance matching, and electromagnetic interference suppression, which increases control costs by 30-50% and makes design and heat dissipation more complex.

Although the current research has conducted a comprehensive comparative analysis of electromagnetic induction and magnetic resonance wireless charging technologies, the performance of these two technologies may still be affected by more factors in practical applications, such as stability under different environmental conditions and long-term reliability. In addition, with the continuous development of technology, new materials and devices may further enhance the performance of these two technologies. Future research should delve deeper into the impact of these factors on the performance of wireless charging technology, and seek new methods to further improve the efficiency, reduce costs, and complexity of wireless charging, in order to achieve wider applications and more efficient energy transfer. The upcoming Qi2 standard reflects this trend by combining magnetic attraction alignment with resonance principles to create a hybrid ecosystem. This system achieves seamless integration of induction based close range fast charging and resonance based spatial power transmission, providing promising cable free solutions in the consumer, automotive, and industrial fields. These advancements are crucial for making wireless charging a powerful and ubiquitous technology.

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