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Principles and Optimization of Wireless Energy Transmission Technology

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Abstract: Wireless energy transmission technology through the transmitter will be converted into microwave, laser or electromagnetic field and other energy carriers to realize the transmission of space, and the receiver will be captured back to the energy conversion of electrical energy, the whole process can be completed without physical contact energy transfer. The core mechanism is to build the energy coupling channel of the transmitter-receiver system, and realize the spatial power transmission through electromagnetic field interaction. In the electromagnetic induction coupled transmission system, the industrial frequency alternating current is converted into direct current by rectification and filtering, and then converted into high-frequency alternating current by high-frequency inverter. This current excites the primary side transmitting winding to generate a time-varying magnetic field, and through magnetic coupling in the secondary side receiving winding inductance electromotive force, and ultimately through the high-frequency rectifier and power regulation circuit to the load power supply. The essence of the process is to establish a transceiver double-ended resonant network, through the magnetic field resonance to achieve efficient energy exchange, and its transmission characteristics follow the laws of electromagnetic induction and the circuit resonance principle of double constraints.

Keywords: Wireless energy; Transmission technology; Internet

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1. Introduction

With the exponential growth of smart devices and the deep penetration of Internet of Things (IoT) technology, the traditional wired charging method gradually exposes the adaptability defects in the scenarios of enhanced mobility demand, device miniaturization evolution, and harsh environment applications. Wireless Power Transfer (WPT) technology provides a revolutionary solution to the above problems by realizing contactless transmission of electrical energy through an electromagnetic field coupling mechanism [1]. This technology shows unique advantages in the fields of continuous power supply for medical implantable devices (e.g., pacemakers), industrial IoT sensor network construction, and dynamic charging of electric vehicles, etc. According to MarketsandMarkets, the global WPT market size will reach $13.5 billion in 2026, with a compound annual growth rate of 22.7%.

The current technology evolution is facing three core contradictions: (1) the negative correlation between transmission efficiency and distance (typical system efficiency >90% at a distance of 10cm, plummeting to <30% at 1m); (2) the balance between electromagnetic radiation safety and transmission power; (3) the dynamic stability control of multi-physical field coupling. Breaking through these bottlenecks is of strategic significance for realizing the goal of an all-weather autonomous power supply for intelligent equipment proposed in Made in China 2025.

2. Principle of wireless energy transmission technology

2.1. Electromagnetic induction principle

The principle of electromagnetic induction, as the physical cornerstone of wireless energy transfer (WPT) technology, is derived from the theoretical system of electromagnetism constructed by Michael Faraday in the 19th century. Its physical nature follows Faraday's Law of Electromagnetic Induction: when the transmitting end (Tx) coil is fed with high-frequency alternating current, according to the Ampere's Loop Law, the time-varying current will stimulate the alternating magnetic field in space; the magnetic field passes through the receiving end (Rx) coil, and according to Faraday's Law, the induced electromotive force will be generated in the closed conductor loop, which will be converted to direct current through rectifier and filter circuits to supply power to the loads. This energy transfer mechanism based on magnetic field coupling can realize high-efficiency power transmission in the near-field region (usually $\leq \lambda/2\pi$) [10,11].

The technology system has three significant advantages: first, the circuit topology is simple, only the primary-secondary coil and compensation network can build the transmission channel; second, the manufacturing cost advantage is significant, the scale application of mature inductors and power electronics reduces the complexity of the system; third, in the centimeter pitch can achieve 80–90% transmission efficiency, perfect fit for the wireless charging base of smart phones, electric toothbrush confined power supply, implantable pacemakers and other short-distance application scenarios [10–13].

However, the physical constraints of electromagnetic induction WPT are also prominent: its energy transmission characteristics strictly follow the inverse cubic law of distance, when the transmission distance exceeds 10cm, the power density is exponentially decaying; the system is sensitive to the relative spatial attitude, the transverse offset of more than 30% of the radius of the coil may trigger a sudden change in the coupling coefficient; high-frequency magnetic fields in the conductor generated by the eddy current effect leads to additional heat loss, the need to use nanocrystalline magnetic cores or ferrite shielding. The eddy current effect in the conductor due to the high-frequency magnetic field leads to additional thermal loss, which requires the use of nanocrystalline cores or ferrite shielding to suppress electromagnetic radiation (EMI), which increases the weight and cost of the system to a certain extent.

Current research focuses on topology innovation and intelligent control: the expansion of the effective coupling region through helical-planar hybrid coil arrays, combined with adaptive impedance matching networks realized by digital signal processors (DSPs) to dynamically compensate for parameter shifts; and the application of new lithium-based composite magnetic materials is expected to break through the frequency-loss bottleneck of traditional soft magnetic materials. Nevertheless, the application scenarios are still limited by near-field constraints.

2.2. Magnetic resonance principle

Magnetic resonance wireless energy transfer technology breaks through the distance limitation of traditional inductive coupling, and its prototype technology originates from the concept of "strong coupling magnetic resonance" proposed by the MIT research team in the cover paper of Science in 2007. The technology is based on the concept of "strong coupling magnetic resonance" proposed by the MIT research team in the cover paper of Science in 2007. The technology is based on the construction of a high-quality factor (Q) resonant circuit between the transmitter (Tx) and the receiver (Rx), so that both of them can form a strong coupling mode at a specific frequency point (usually at the MHz level). When the resonant frequency of the system satisfies $\omega=1/\sqrt{(LC)}$, the energy is no longer leaked through near-field radiation, but is transmitted directionally between the resonators through the swift wave tunneling effect, and the theoretical transmission distance can be on the order of several meters [10–13].

Compared with electromagnetic induction, magnetic resonance technology has three major technological breakthroughs: first, the transmission distance is significantly improved, in maintaining more than 50% efficiency can be achieved when the degree of freedom of 0.5–2m; second, the spatial tolerance ability to enhance, allowing ± 15° tilt angle and 50% coil area offset; third, through the design of multi-mode resonant cavity can be realized through the directional distribution of power for multi-load power supply system to provide technical support. The MIT prototype system realizes 60W power transmission at a distance of 2m with an efficiency of 40%, which verifies the feasibility of medium-distance WPT [13].

However, this technology route still faces multiple challenges: first, the system efficiency is sensitive to frequency offset, environmental temperature drift or component parameter changes may lead to resonance mismatch; second, the detection of metal foreign objects and thermal management problems in the strong magnetic field environment, the need to integrate infrared arrays and temperature sensors to build a safety protection mechanism; third, in complex electromagnetic environments, the cross-coupling between multiple devices may cause interference, the need to develop cognitive radio Third, in complex electromagnetic environments, cross-coupled interference may occur between multiple devices, requiring the development of cognitive radio-style dynamic spectrum management strategies.

The current research frontiers focus on the cross-innovation of material science and control theory: the use of high-temperature superconducting (HTS) coils to increase the Q value to the order of 10^5, combined with deep reinforcement learning algorithms to achieve millisecond dynamic tuning; the application of new electromagnetic metamaterials to reshape the spatial field distribution through the structure of the artificial magnetic conductor (AMC), which provides a possibility of constructing a standardized WPT infrastructure. Possibility. These advances indicate that the magnetic resonance technology is developing in the direction of high power density and strong environmental adaptability [10,11,13].

3. Wireless energy transmission efficiency study

3.1. Analysis of transmission efficiency influencing factors

Wireless energy transfer (WPT) efficiency is a key indicator of system performance, and its core influencing factors include transmission distance, operating frequency, coupling mechanism design, load matching, and environmental interference.

(1) Transmission distance:

Electromagnetic induction WPT efficiency decays exponentially with distance (e.g., >90% at 10 cm, <20%

at 50 cm), whereas magnetic resonance maintains 60% to 80% efficiency over resonant distances (e.g., 1 m) [2].

Mechanism: magnetic field strength decreases inversely with distance squared, and resonant coupling slows the decay through high Q [3].

(2) Operating frequency:

High frequency (MHz class) can improve the efficiency of the magnetic resonance system, but is limited by switching device loss and electromagnetic radiation safety.

Low frequencies (kHz class) are suitable for high power scenarios (e.g., electric vehicle charging), but require larger coil sizes [4].

(3) Coupling method:

Coil structure (e.g., planar helical coils, DD coils) affects the coupling coefficient (*k*), multi-coil arrays can extend the transmission range. Angular offsets lead to asymmetric coupling, and magnetic resonance type is more tolerant (±30° efficiency degradation <15%) [5,9,12].

3.2. Methods to improve transmission efficiency

Strategies and methods are proposed to optimize the transmission efficiency, such as improving the coupling method and using electromagnetic metamaterials. In order to break through the efficiency bottleneck, the current research mainly focuses on three aspects: coupling optimization, circuit regulation, and new material application.

(1) Coupling mechanism improvement:

Dynamic tuning: impedance matching network based on real-time load detection (e.g., LCC compensation topology) to solve the detuning problem [6].

(2) Electromagnetic metamaterials:

Negative permeability metamaterials can focus the magnetic field and increase the efficiency by 2 to 3 times [7].

(3) Control algorithm optimization:

Machine learning can predict the optimal operating frequency (e.g., neural networks to optimize resonance points) and adapt to dynamic environments [8].

4. Application scenarios of wireless energy transfer technology

4.1. Wireless power supply for consumer electronics

The industrialization of wireless energy transfer (WPT) technology in the field of consumer electronics has entered an explosive growth stage, and its technology penetration is reshaping the energy supply paradigm of terminal equipment. Typical application scenarios cover three major dimensions:

Qi standard-based 15W fast charging solution realizes the interactive experience of “instant charging,” and the magnetic alignment mechanism (e.g. Apple’s MagSafe) enhances the charging efficiency to 82%, which reduces the energy conversion rate by about 8% compared with the traditional contact charging. Smart watches, wireless headphones, and electric toothbrushes are IP68 waterproof through the fully-enclosed design, completely eliminating the problem of oxidized metal contacts. Experimental data shows that the interface failure rate of devices adopting WPT technology drops to less than 0.3% over a 5-year lifecycle. By integrating a bi-directional WPT module, flagship smartphones (such as the Huawei Mate 60 Pro) can provide a 5W reverse power supply to low-power devices, such as TWS headphone boxes, to build an energy-sharing ecosystem among mobile devices [14,15].

The technological advantages in this field are centered on a triple value leap: interaction revolution: eliminating the mechanical wear and tear of the physical interface, the USB-C interface plug life (about 10,000 times) is no longer a bottleneck in the life of the device; safety upgrade: the design of no exposed conductor reduces the risk of short-circuit of splashing liquids by 90%, which is particularly suitable for applications in wet environments; ecological convergence: synergy with the smart home system (e.g., Xiaomi's wireless charging coffee table), realizing a 30cm range for multiple devices. It can realize automatic charging of multiple devices within a 30cm range and build a spatial energy field. However, the standardization process is lagging behind, restricting the development of the industry: the current private fast charging protocols (such as OPPO AirVOOC, Huawei SuperCharge) and the coexistence of universal Qi standards, resulting in cross-brand devices being able to maintain only the basic power transmission of 5W [14,15].

4.2. Wireless evolution of smart devices

WPT technology is driving smart devices to the "zero-wire" form of in-depth evolution, its technology spillover effect in three major areas of revolutionary impact: biomedical electronics: implantable neurostimulators (such as MIT's research and development of the "electronic pill") through the percutaneous transmission of energy, to achieve 10 years of continuous operation, to avoid the replacement of the surgical battery once every five years. Clinical data show that this technology reduces postoperative infection rates from 2.3% to 0.15%. Industrial IoT: Passive Wireless Sensor Networks (WSNs) use energy harvesting technology to capture μW-level energy from industrial electromagnetic fields to enable real-time condition monitoring of rotating machinery (e.g., wind turbine gearboxes). In petrochemical industry applications, the technology enables a 40% increase in equipment predictive maintenance efficiency. Smart Home: Wall-embedded WPT modules (e.g. IKEA launch series) provide continuous power to IoT devices through 30mm pitch, completely eliminating the need for battery replacement. Tests have shown that a single transmitter can support 10 devices to work stably, with a combined system efficiency of 72%.

Technological innovation has triggered three major paradigm shifts, design freedom to eliminate the battery compartment and interface area, and device volume reduction of more than 40% (e.g., the thickness of a pacemaker has been reduced from 12mm to 6mm); and a manufacturing revolution in which the SMT placement process has been simplified by 30%, and assembly yields have been increased to 99.5%. The radiation-resistant WPT module enables nuclear industry robots to work continuously for 1,000 hours in a strong electromagnetic environment [14,15].

4.3. Technological breakthroughs in specific scenarios

In extreme application scenarios, WPT technology shows irreplaceable strategic value. Typical cases include: a dynamic power transmission system: the online electric vehicle (OLEV) system developed by the Republic of Korea's KAIST, with a 20kHz transmitting coil array pre-buried in the road surface, realizes continuous power supply for buses while driving. Data from the Seoul Demonstration Line show that at 30km/h vehicle speed, the system has a transmission efficiency of 85%, and the weight of the on-board batteries has been reduced by 60%. However, the cost per kilometer of road modification is up to $500,000, and electromagnetic radiation safety (ICNIRP standards compliance) and metal foreign object detection challenges need to be addressed. UAV Continuous Operation Platform: DJI and WiBotic jointly developed a 300W-class magnetic resonance charging station, which adopts a dual alignment mechanism of visual guidance + electromagnetic localization, and can maintain ±2mm docking accuracy even at wind speeds of level 5. Tests have shown that the system extends the endurance of logistics UAVs to 12 hours, but it needs to break through the technical bottleneck of dynamic coupling stability under turbulent conditions. Space Energy Transmission: NASA promotes the "Space Solar Power Station" (SSPS) project, which plans to transmit 100kW-class electricity to near-Earth orbit satellites through 2.45GHz microwave beams. Ground verification experiments (10kW level) show that the rectifier antenna array can increase the receiving efficiency to 83%, but need to solve the atmospheric attenuation (30% efficiency drop in rainy and foggy weather) and RF safety protection, and other challenges. The evolution from consumer-grade convenient power supply to industrial-grade continuous energy supply finally realizes the ultimate goal of space-scale energy transmission [15].

5. Conclusion

Wireless energy transfer (WPT) technology reconfigures the energy transfer paradigm through the electromagnetic field coupling mechanism, and its core value lies in breaking through the constraints of the physical medium, providing a disruptive solution for the energy supply in the intelligent society. Studies have shown that electromagnetic induction and magnetic resonance technologies exhibit unique advantages in short-range high-power (<10cm, efficiency >90%) and medium-range dynamic scenarios (0.5–2m, efficiency >50%), respectively, and efficiency optimization requires a combination of coupling design, material innovation, and control algorithms in three dimensions. At the application level, WPT has realized the leapfrog penetration from consumer electronics to industrial Internet of Things - Qi standard pushes the wireless charging efficiency of smartphones to break through 82%, the Republic of Korea's OLEV system verifies the transmission efficiency of 85% under dynamic charging, and NASA's space solar power plant project foretells the potential of microwave energy transmission for space applications. The NASA space solar power station project has demonstrated the potential of microwave energy transmission for space applications. However, the technology evolution is still constrained by bottlenecks such as the physical limit of efficiency-distance, electromagnetic safety threshold (ICNIRP standard), and complex environment coupling instability. The future breakthrough direction should focus on multidisciplinary cross-innovation: enhancing the resonance quality factor ($Q>10^5$) through high-temperature superconducting materials, realizing μs-level dynamic tuning based on deep reinforcement learning, and building a standardized EMC framework to support scale deployment. With the integration of new electromagnetic metamaterials and adaptive control algorithms, WPT technology is expected to lead to revolutionary applications in the fields of long-term power supply for medical implantable devices, autonomous energy replenishment for unmanned systems, and energy network for deep-space exploration, and ultimately to realize the ultimate vision of "Energy Transmission without Boundaries."

Disclosure statement

The author declares no conflict of interest.

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