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Wireless Power Transfer Technology Based on Magnetic Coupling Resonance

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Abstract. With the rapid development of modern technology, smart wireless devices have been widely used in daily life and industrial production, putting forward a clear demand for reliable wireless power supply solutions. Among existing technologies, magnetic coupling resonance has become an important choice for low-to-medium power applications because it achieves a good balance between transmission distance and efficiency. This paper presents a systematic review of magnetic coupling resonant wireless power transfer technology, covering the basic working principles, current research status, existing limitations and future development directions. First, the basic principles of magnetic resonant coupling wireless power transfer are introduced. Then, discussions are carried out from three core research directions: coupling mechanism design, mutual inductance calculation methods and parameter optimization techniques, and representative works on closed, open and semi-open coil structures, analytical mutual inductance models and intelligent optimization algorithms are reviewed in turn. The paper points out two main shortcomings of current research: the lack of studies on multi-coil relay systems and the insufficient analysis of actual operating conditions. Finally, this paper sorts out future research directions worth paying attention to, in order to promote the technology from laboratory environments to practical industrial applications and provide a clear framework for the development of higher-performance and more robust wireless charging technologies.

Keywords: Wireless power transfer, Magnetic coupling resonance, Inductive power transmission

1. Introduction

Today, modern science and technology are developing rapidly, and various intelligent wireless device products have already been widely applied in daily life and industrial production. In civilian life, wireless charging and smart homes are popularized on a large scale, and manufacturing demand has greatly increased; in industrial production, wireless sensors, movable intelligent humanoid machines and so on all need to rely on wireless power transfer technology. Wireless power transfer is mainly divided into three types: magnetic coupling resonance, electromagnetic induction and microwave radiation [1]. Microwave radiation can achieve long-distance power transmission, but the required energy loss is large, the transmission efficiency is low, and the electromagnetic radiation problem is relatively serious, so it is not very suitable for medium- and small-power daily

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and industrial scenarios. Electromagnetic induction transmission technology is mature in development and has relatively high transmission efficiency, but the transmission distance is short and the spatial degree of freedom is poor. Magnetic coupling resonance is based on magnetic field resonance to realize energy transfer, taking into account a certain transmission distance and relatively high transmission efficiency, and the transmission efficiency in relay scenarios is optimal [2].

Magnetic coupling resonance technology solves the pain points of many mobile phones and smart home devices, frequent plugging and unplugging of cables, messy wiring and interface loss in home life, achieves simultaneous charging of multiple devices with wireless intelligent devices, breaks the material and principle barriers of traditional equipment, and is deployed in devices such as smart bands and wireless earphones. This technology also solves the difficulties of cable wear or even breakage caused by frequent movement, rotation and pulling of mobile equipment and distributed industrial sensors in industrial automation scenarios, as well as the extremely high cost of wiring and maintenance. It perfectly adapts to relay scenario transmission and has strong anti-offset capability, so it is applied in devices such as unmanned forklifts and assembly-line detection sensors. This technology also has applications in specific precision scenarios, solving the drawbacks of medical implant devices and outdoor base stations that cannot open holes for wiring and cannot frequently replace batteries. This technology completely isolates electrical appliances, has good sealing performance, and is suitable for long-term unattended operation and power supply, such as outdoor communication micro base stations, small implantable medical auxiliary devices and other precision scenarios.

With the continuous improvement and enhancement of key technologies such as coupled coil structures and relay resonant units, although the theory and applications of magnetic coupling resonance technology have gradually become mature and perfect, there are still problems such as immature research on relay coil technology and insufficient analysis of actual conditions. Therefore, this paper conducts a comprehensive review of magnetic coupling resonance technology, including basic principles, research status, faced limitations and future directions, so as to provide development ideas for higher-performance wireless charging technologies in the future. The arrangement of this paper is as follows: Section 2 is the basic principles, Section 3 is the research status, Section 4 is the limitations of current research and future prospects, and the last is the conclusion.

2. Principal of magnetic coupling resonance technology

A wireless power transfer system consists of a transmitter, a transmission link and a receiver. The starting point of the system is the transmitter, which mainly consists of four parts: the power supply provides the original electrical energy; the high-frequency inverter or power amplifier circuit converts the electrical energy into high-frequency alternating current; the impedance matching network allows as much energy as possible to be sent out and reduces reflection; the transmitting coil converts the electrical energy into an alternating electromagnetic field. In the transmission link, energy goes through a transmission process from the transmitter to the receiver. According to different distances, there are mainly two methods: near-field and far-field. Near-field coupling is carried out through alternating magnetic or electric fields, such as common magnetic induction and magnetic resonance; far-field coupling is carried out through electromagnetic wave radiation, such as microwaves. The receiver converts the received electromagnetic energy back into direct current and delivers it to the load. It usually includes: a receiving coil used to induce electromagnetic energy and generate high-frequency alternating current; a matching network to improve receiving

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efficiency; a rectifier circuit to convert alternating current into direct current; a voltage stabilizing or power regulating circuit to adjust the voltage and current to the range required by the load; and the load, such as a mobile phone battery, an electric vehicle, etc.

Magnetic coupling resonance technology uses two coils with the same resonant frequency and high quality factor to realize wireless power transfer through near-field magnetic coupling. Both the transmitting coil and the receiving coil form an LC resonant circuit tuned to the same frequency. When a high-frequency power supply drives the transmitting coil at this frequency, an alternating magnetic field is generated. According to resonance theory, two objects with equal natural frequencies can transfer energy efficiently when they resonate, while non-resonant objects will not produce any effect; at the same time, energy conversion only occurs within the closed system and has no obvious impact on the outside of the system. Therefore, when the natural frequency of the receiving coil matches the frequency of the transmitting field, the system reaches resonance and the transmission efficiency reaches the maximum, and relatively high efficiency can still be achieved even when the coupling is weak [3].

3. Research status of magnetic coupling resonance wireless power transfer technology

3.1. Coupling mechanism

The magnetic coupling mechanism is the core of contactless energy transfer in wireless power transfer systems. It mainly consists of a transmitting coil and a receiving coil. Geometry, magnetic field distribution and coupling coefficient directly affect the system's transmission efficiency, output power, and adaptability to positional offset and angular changes. Once relative displacement or angular deflection occurs between the transmitting and receiving coils, mutual inductance often drops rapidly and transmission efficiency deteriorates noticeably. Therefore, how to improve the anti-offset performance of the coupling mechanism has always been a key issue in omnidirectional wireless power transfer research.

These mechanisms are currently mainly used in consumer electronics, drones, implantable medical devices and mobile robots. Guo et al. systematically reviewed the research and application of spatial omnidirectional wireless power transfer technology in 2022 [3]. Liu et al. proposed a wireless energy router with omnidirectional power transmission for home energy management in 2022 [4]. Ha-Van et al. developed a cylindrical transmitting coil for two-dimensional omnidirectional transfer in 2022 [5], and Qi et al. proposed an omnidirectional system based on three-phase frustum-shaped coils in the same year [6]. Li et al. further realized free-positioning and omnidirectional transfer using self-decoupled planar transmitter coils in 2023 [7]. Chen et al. optimized a multi-receiver system based on spherical coil structures in 2022 [8].

In open structures, existing work has attempted to generate a rotating magnetic field in the target area by modulating the excitation current, so as to improve adaptability to planar receiving coils and free-positioning capability of devices. However, closed structures generally suffer from low magnetic field utilization and complex multi-source excitation control; open structures often have larger volumes, more dispersed magnetic fields and higher manufacturing difficulty.

3.2. Mutual inductance calculation

Mutual inductance is a key parameter that quantitatively describes the magnetic coupling strength between the transmitting and receiving coils. Its magnitude directly determines the system's transmission efficiency and output power. When the relative position or angle of the transmitting and

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receiving coils changes, the mutual inductance value also changes. Therefore, whether mutual inductance can be calculated quickly and accurately is crucial for system analysis and subsequent optimization design.

For planar coils and arbitrary positions, Lin et al. proposed a mutual inductance calculation method for circular coils with a convex annular bounded magnetic shield at arbitrary positions in 2024 [9]. Zhang et al. gave a calculation method for mutual inductance between polygonal coils under arbitrary poses in 2022 [10]. Dehui and Hao proposed a new method for calculating mutual inductance between two perpendicular coils in 2023 [11].

For three-dimensional structures, existing work has provided a general algorithm for mutual inductance and self-inductance of coaxial and non-coaxial cylindrical coils based on Bessel functions, and has also made certain optimizations on numerical implementation. These studies have enriched the theory of mutual inductance calculation, but the accuracy is often not ideal when the distance is large or when facing curved structures such as hemispheres, and it is also difficult to uniformly handle arbitrary postures.

3.3. Parameter optimization

The geometric parameters of the coupling mechanism (number of turns, radius, wire diameter, turn spacing, etc.) directly determine mutual inductance, internal resistance and resonance characteristics, thereby affecting the transmission performance of the entire system. Optimizing these parameters within a limited volume can simultaneously improve efficiency and anti-offset capability, which is an important step in enhancing the practicality of wireless power transfer.

Early optimizations mostly relied on electromagnetic simulation and numerical calculation. Yu et al. proposed an optimization method for coil structure parameters of magnetically coupled resonant wireless power transfer systems in 2023 [12]. He et al. carried out multi-coil structure parameter optimization design in 2021 [13]. Wen et al. optimized receiving coil parameters based on an improved BP neural network in the same year [14]. Luo et al. performed multi-objective optimization of inductive power transfer double-D pads in 2021 [15]. In terms of multi-objective optimization, existing work has attempted to simultaneously maximize the coupling coefficient and minimize the leakage magnetic field, or used Pareto optimization to improve the average mutual inductance while suppressing mutual inductance fluctuations, thereby further enhancing anti-offset capability. However, multi-objective problems are usually highly nonlinear and the computational burden increases significantly. Therefore, using relatively accurate mutual inductance formulas for parameter co-optimization currently appears to be an effective way to improve system performance.

4. Limitations and outlook

4.1. Lack of research on multi-coil relay systems

Most related studies on model optimization, parameter tuning and adaptive control of magnetic coupling resonance take the traditional two-coil wireless power transfer system as the main research object. Existing parameter optimization methods, frequency regulation schemes and adaptive control strategies can effectively solve the performance degradation problems caused by parameter fluctuations and air-gap changes under two-coil working conditions. When the above methods are directly transferred to a three-coil system with a relay, the introduction of the relay coil brings additional coupling relationships, making the system mutual inductance and other conditions more

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complex. Currently, there is little specialized analysis corresponding to the relay coil; in particular, there is a lack of systematic research under actual working conditions such as coil offset.

Subsequent research should correspond, combine and complement the existing parameter optimization, frequency tuning and adaptive control technologies with the three-coil relay topology. It is necessary to improve and establish a system equivalent model adapted to the relay structure, analyze the influence of position and coil offset on the system transmission performance; improve the parameter optimization algorithm to make it adapt to the relay scenario, and enhance the efficiency and output stability of the multi-coil system under non-ideal conditions.

4.2. Insufficient analysis of actual working conditions

In the currently published related literature, most verification work is completed under ideal conditions where the coils are strictly aligned, the load conditions are fixed, and environmental interference is small. Although some literature has studied the influence of air-gap changes, parameter disturbances, mutual inductance fluctuations and single variables, in real engineering practice, these three types of variables usually occur simultaneously as multiple disturbances. Existing technologies lack analysis of comprehensive performance under the superposition of multiple disturbances, and there are still corresponding shortcomings in the landing adaptability in complex actual scenarios such as distributed sensors and industrial sites.

Therefore, research needs to become closer to real engineering application scenarios. In the future, the situation of multiple interference coupling such as coil offset and transmission distance changes should be considered simultaneously. This can not only improve the theoretical analysis of system transmission performance under multi-disturbance conditions, but also verify the actual effect of parameter optimization and control schemes under disturbances, and promote the magnetic coupling resonance relay system from the ideal environment to the actual application in industrial sites.

5. Conclusion

This paper presents a systematic review of magnetic resonant coupling wireless power transfer technology. First, the basic framework of the wireless power transfer system and the basic principles of magnetic coupling resonance technology are elaborated. Then, the research progress of this technology is reviewed from three dimensions: magnetic coupling mechanism, system parameter optimization and control technology. Existing research has established equivalent models of multi-coil mutual inductance and frequency splitting, proposed parameter iterative optimization methods based on model correction and communication-free frequency tuning schemes, and developed adaptive control strategies for air-gap and load disturbances. However, most of the current research results are concentrated on two-coil systems, and the system analysis and experimental verification of the three-coil relay topology under conditions such as coil offset, cross-coupling and superposition of multiple interferences are still insufficient. In addition, most existing work is carried out under ideal alignment and single-variable conditions, making it difficult to be directly applied to actual engineering scenarios such as distributed sensors, unmanned forklifts and implantable medical devices. Looking to the future, it is necessary to deeply integrate the existing parameter optimization, frequency tuning and adaptive control methods with the multi-coil relay structure, construct equivalent models and multi-objective optimization algorithms that can adapt to offset and multiple interferences, so as to promote the system from the ideal environment to industrial applications. This paper provides a clear research framework and development path for the

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application of magnetic coupling resonance technology in the field of high-performance and high-robustness wireless charging, which is helpful to accelerate the transformation of related achievements into practical applications.

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