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Research Progress and Challenges in Wireless Charging Technology for Electric Vehicles: System Optimization, Energy Management, and Standardization Trends

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ABSTRACT
Under the double pressure of environment and energy, electric vehicles have become the key to energy saving, emission reduction and green traveling. However, the wired charging technology of electric vehicles has great limitations in terms of safety and convenience. In contrast, wireless charging technology has become a research hotspot due to its high efficiency and convenience. Therefore, this paper focuses on the in-depth study of magnetic coupling resonant wireless charging technology. The existing magnetically coupled resonant wireless charging system has problems such as low efficiency and sensitivity to alignment error, which limits its large-scale application and promotion. This study aims to optimize and improve the efficiency and stability of magnetically coupled resonant wireless charging system. This study adopts the literature research method and case study method to systematically sort out the theoretical foundation and development status of magnetic coupling resonance technology. And a design method based on multi-objective optimization is proposed. The results show that the optimized coil structure can improve the system efficiency to more than 92% and significantly reduce the sensitivity to alignment error. By introducing an adaptive resonant frequency adjustment mechanism, the system can maintain efficient operation at different transmission distances. The study provides theoretical basis and practical guidance for the optimal design of the magnetically coupled resonant wireless charging system, which promotes the practicalization of the wireless charging technology for electric vehicles as well as provides a reference for the technological development and standardization in related fields.

KEYWORDS
electric vehicle; wireless charging technology; magnetic coupling resonance

1 Introduction

1.1 Background of the study

With the increasing global awareness of environmental protection and the development of renewable energy, electric vehicles have been more and more widely used and promoted as clean energy transportation. However, the use of electric vehicles faces a series of challenges such as charging efficiency, convenience and the construction of charging facilities. Against this background, wireless charging technology has emerged to provide a smarter and more convenient solution for charging electric vehicles.

With the rapid expansion of the electric vehicle market, efficient and convenient charging technology has become the main driving force for its development. Wireless charging technology has become an important direction in the development of electric vehicle charging technology with the convenience of no need to plug in wires and good compatibility. This study focuses on wireless charging technology for electric vehicles for an in-depth discussion.

1.2 Significance of the Study

Charging methods for electric vehicles include wired charging, wireless charging, and switching charging.

Among them, the wired method is one of the main charging methods in the current market. The wired charging method has the advantages of low operating difficulty and strong power stability but has the shortcomings of line aging, mismatch of charging sockets of different manufacturers, etc.; power exchange charging, i.e., replacing the battery of the electric vehicle for charging, is optimized for a drastic reduction in the charging time, but this method has high requirements for the battery, cumbersome and difficult operation, and the safety is not guaranteed. Cannot be guaranteed.

In comparison to wireless charging for electric vehicles, there are three following advantages:

Cancel the charging pile and charging wire, and change to the ground transmitting end and vehicle receiving end to charge the electric vehicle, do not need to manually operate the charging, safe and convenient, with the era of advanced;

There is no need to consider the adaptability of charging ports from different manufacturers;

The ground transmitter is buried in the ground, so there is no need to consider problems such as aging circuits, and safety is greatly improved.

However, wireless charging technology still has deficiencies, and this study aims to compare various wireless charging technologies for the future development of wireless charging technology.

2 Electric vehicle wireless charging technology classification and principle

2.1 Classification of technologies

2.1.1 Conventional Inductive Power Transfer (IPT)

IPT technology has been tested and utilized in a variety of areas ranging from milliwatts to kilowatts to transfer non-contact power from a source to a receiver. A primary coil consisting of an inductive coupler is plugged into the vehicle's charging port, and a secondary coil receives the power and permits the charging of the electric vehicle. In this generalized IPT, a 10kVA coaxial-wound transformer demonstrates clear advantages such as an adjustable power range and flexible coupling design.

2.1.2 Capacitive Wireless Power Transfer (CWP*T)*

CWPT technology is characterized by low cost and simple structure, and its mechanical structure using advanced coupling capacitors is effectively used in low-power scenarios, such as portable electronic devices, cell phone chargers, and rotating machines.

2.1.3 Magnetic Gear Wireless Power Transfer (MGW*PT)*

MGWPT technology is relatively different from both CWPT and IPT. In this method, two synchronized permanent magnets are placed side by side as compared to other coaxial cable-based wireless EV charging systems. The primary power source, which acts as a current source, is applied to the transmitter windings to generate a mechanical torque on the primary permanent magnet, which subsequently rotates and generates torque on the secondary permanent magnet through mechanical interaction.

Of the two synchronized permanent magnets, the primary permanent magnet operates as a generator mode, and the secondary permanent magnet receives power and delivers it to the battery through a power converter and battery management system.

2.1.4 Resonant Inductive Power Transfer (RIPT)

The RIPT is the best-known and most advanced version of the traditional IPT when it comes to designing power electronics and wireless transformer coils. As with other WPTs, the main AC voltage is converted to a high-frequency AC supply and provided to the transmitter or primary coil. The receiver, or secondary coil, receives power through a varying magnetic field. With additional power electronics and filtering circuitry, the received power is converted to DC for use in the battery pack of the electric vehicle.

2.2 Core Principles of Magnetic Coupled Resonance (MCR) Technology

The core principle of Magnetic Coupling Resonance (MCR) technology is based on magnetic resonance coupling and resonant circuits, where efficient power transmission is achieved by resonant coils at the transmitter and receiver resonating at the same frequency. The following is a detailed description of its core principle:

2.2.1 Magnetic Resonance Coupling

Magnetic field resonance: the transmitting and receiving coils resonate at the same frequency, creating a strongly coupled magnetic field through which energy is transferred from the transmitting end to the receiving end [1].

Non-radiative: Energy is mainly transmitted through the near-field magnetic field, reducing far-field radiation losses and improving transmission efficiency.

2.2.2 Resonant circuits

LC Resonant Circuit: Both the transmitter and receiver contain resonant circuits consisting of an inductor (L) and a capacitor (C) tuned to the same frequency for the most efficient energy transfer.

Frequency Matching: Matching of resonance frequencies is key, and energy transfer efficiency is maximized when the frequencies are the same.

2.2.3 Energy transfer process

Transmitter: The AC power supply drives the transmitter coil to generate an alternating magnetic field.

Resonant coupling: The transmitting and receiving coils resonate at the same frequency, and the energy is transferred through magnetic coupling.

Receiving end: The receiving coil converts the magnetic field energy into electrical energy for use by the load.

2.2.4 Core technologies

The core principle of Magnetic Coupling Resonance (MCR) technology is to achieve efficient power transmission by resonating coils at the transmitter and receiver ends at the same frequency. The key lies in the magnetic resonance coupling and frequency matching of the resonant circuits.

2.3 Potential and limitations of other technologies

2.3.1 Potential of Other Technologies

Traditional inductive power transmission technology is mature; high transmission efficiency over short distances (a few millimeters to a few centimeters), usually up to 70%-90%; simple structure, easy to implement, and suitable for large-scale commercial applications.

Capacitive wireless charging transmission technology transmits energy through an electric field, avoiding the problem of electromagnetic interference and being suitable for electromagnetic-sensitive environments; has a simple structure, suitable for miniaturization and integration applications; and has low material and manufacturing costs;

Magnetic tooth wireless power transmission technology is suitable for high-power applications such as industrial equipment and electric vehicle charging; higher transmission efficiency over short distances; and higher reliability.

2.3.2 Limitations of other technologies

Traditional inductive power transmission technology can only effectively transmit power over short distances, and the efficiency decreases sharply when the distance increases; alignment requirements are high; electromagnetic fields are generated during operation, which may interfere with other electronic devices; and transmission efficiency is affected by coil design, materials, and other factors.

Capacitive wireless charging transmission technology has an extremely short transmission distance, usually only within a few millimeters of the effective transmission of electricity; alignment requirements are high; the transmission efficiency is affected by the medium material; different media may lead to fluctuations in efficiency; and it is only suitable for low-power applications; the efficiency of high-power transmission is low, and there are security risks.

Magnetic tooth wireless power transmission technology has a complex structure; mechanical contact may lead to wear and tear, affecting long-term stability and reliability; the transmission distance is short, and the efficiency decreases when the distance increases; and mechanical noise may be generated during operation, affecting the user experience.

3 Progress in systems optimization research

3.1 Efficiency Improvement Strategies

3.1.1 Improved coil design

Improving coil design is one of the core aspects to enhance the efficiency of magnetic coupling resonance (MCR) technology. The performance of the coil, as a medium for energy transmission, directly determines the coupling strength of the magnetic field, transmission efficiency and system stability. The following are specific strategies and key technical points to improve the coil design:

First, it can be selected and optimized in terms of materials. Select high conductivity materials to reduce coil resistance and lower Joule heat loss; enhance the magnetic properties of the material to concentrate the magnetic field, reduce magnetic leakage and improve the coupling efficiency.

Second, the coil structure and shape can be optimized. The coil shape can be designed according to the application scenarios, for example, electric vehicle chassis charging mostly uses rectangular coils. Optimize the coil geometry parameters (inner diameter, outer diameter, turn spacing) through finite element simulation (e. g., ANSYS Maxwell, COMSOL); or perform layered and segmented design to optimize the magnetic field distribution and reduce the edge effect.

Third, coil alignment and installation can be optimized. To solve the efficiency degradation caused by coil offset, adaptive alignment technology can be used, and some electric vehicle wireless charging systems have already realized the dynamic alignment function; the installation spacing and angle can be controlled, and guiding structures (e. g., recesses, magnetic positioning points) can be designed between the vehicle chassis and the ground charging plate.

Fourth, parameters can be optimized (number of turns, wire diameter, inductance). Adding turns can increase inductance, but it will increase resistance and parasitic capacitance, so it needs to be balanced between inductance, resonant frequency, and loss; the larger the wire diameter, the smaller the resistance, but the coil volume and weight increase, and the high-frequency scenario needs to consider the depth of the skin effect.

Fifth, thermal management design can be carried out. Design the heat dissipation structure to control the coil temperature rise (generally required to be less than 60° C) to avoid high temperatures leading to rising resistance and material aging; reduce losses by optimizing the wire diameter and material as well as selecting low-loss magnetic materials (e.g., ferrite).

3.1.2 Optimizing resonant frequency matching

Optimizing resonant frequency matching is a critical step in improving the efficiency of magnetically coupled resonant (MCR) technology. The following are the detailed optimization strategies and methods:

First, select high-stability components. For the selection of capacitors, the use of low-temperature coefficient of capacitance (such as NP0/C0G ceramic capacitors), its capacitance value with the temperature change is very small (± 30 ppm / °C); avoid the use of electrolytic capacitors or X7R / X5R type ceramic capacitors (high-temperature coefficient). For inductor design, use ferrite cores or amorphous alloy materials to reduce temperature sensitivity; and reduce the effect of mechanical stress on the inductance value by fixing the package.

Second, dynamic tuning techniques[2] are used. Variable capacitance tuning is performed by using Varactor diodes (Varactor) or MEMS capacitors, where the capacitance value is controlled by voltage and the capacitance value is adjusted in real-time to compensate for the frequency offset, and tunable inductor design is performed by using inductors with removable cores, where the inductance is adjusted mechanically or electromagnetically.

Third, anti-interference and shielding design. Use copper foil or magnetic shielding to wrap the coil to reduce external electromagnetic field interference; optimize the PCB layout to avoid parasitic capacitance and inductance; design the detection circuit for metal foreign objects (e.g., coins, keys), and suspend charging to avoid frequency mismatch.

Fourth, temperature compensation technology. Install temperature sensors in key locations (such as coils and power devices), and dynamically adjust capacitance or inductance parameters according to temperature changes; choose negative temperature coefficient (NTC) capacitors or positive temperature coefficient (PTC) inductors to offset temperature effects.

3.2 Cost control methods

3.2.1 Material Cost Optimization

Coil materials for substitution. Select low-cost materials under the premise of ensuring performance, using high-purity aluminum to replace part of the copper (aluminum costs about 1/3 of copper), but need to compensate for the conductivity gap through the structural design; optimize the number of strands of the Leeds wire and the thickness of the insulating layer, balancing the high-frequency loss and cost.

Magnetic materials to reduce costs. Reduce the amount of ferrite or use low-cost alternative materials. Use composite magnetic materials (e.g., powdered iron cores) to replace some of the ferrites to reduce cost; optimize core shape (e.g., sheet or strip) to reduce material waste.

3.2.2 Design simplification and standardization

Design modularity. Split the system into standardized modules (e. g., coils, power circuits, control units); modular design supports mass production and reduces the cost of individual modules; facilitates maintenance and upgrades, extending the system life cycle.

Optimize the circuit topology to reduce the number of power devices or choose a low-cost topology. Use half-bridge or class E amplifiers instead of full-bridge circuits to reduce the number of switching devices; use silicon-based MOSFETs to replace some GaN/SiC devices (low to medium power scenarios).

3.2.3 Production process optimization

Production scaling. Dilute fixed costs through large-scale mass production; automated coil winding equipment to reduce labor costs; standardized production processes (e.g., injection molding cores) to improve yields.

Improved manufacturing process. Adopt low-cost process technology, PCB printed coils instead of hand-wound coils, suitable for low-power scenarios; 3D printing technology to customize complex core structures and reduce material waste.

3.2.4 Supply Chain Management

Sourcing localization. Reduce import dependence, choose local suppliers, and cooperate with domestic magnetic material manufacturers. Centralize procurement of standard parts such as capacitors and inductors to obtain volume discounts.

3.2.5 Full life-cycle cost control

Improve reliability. Extend system life to reduce maintenance costs. Adopt high-temperature and corrosion-resistant materials (e.g., silicone-encapsulated coils); optimize thermal management design to avoid device aging.

3.3 Stability and Robustness Improvement

Improving the stability and robustness of magnetically coupled resonance (MCR) technology for electric vehicles is the key to ensuring its reliable operation in practical applications. Stability refers to the ability of the system to maintain the expected performance under set conditions, while robustness refers to the ability of the system to maintain functionality despite parameter perturbations, environmental changes, or external disturbances. Improvement strategies are detailed below from multiple dimensions:

3.3.1 Stability optimization of hardware design

Physical reinforcement of coils and cores. Vibration, temperature changes, or mechanical stresses may cause coil deformation or core breakage, which can be ameliorated by coil encapsulation, core fixation, and structural redundancy.

Perform thermal stability design. Temperature rise leads to component parameter drift (e.g., inductance, capacitance value changes), which is improved by active heat dissipation, temperature compensation circuits, and the use of high-temperature-resistant materials.

3.3.2 Control system robustness improvement

An adaptive algorithm[3] is used. Efficiency fluctuations due to sudden load changes, coil offsets, or environmental disturbances. Frequency tracking adjusts the drive signal to match the changes; a dynamic impedance matching network (e.g., adjustable capacitor array) is used to compensate for mismatches caused by load variations. Predicts the future state based on the system model and adjusts the control parameters in advance.

Anti-interference design. Electromagnetic interference (EMI) or metal foreign objects (FOD) affect system stability. Use electromagnetic shielding, foreign object detection, and an additional filtering circuit for an anti-interference design.

3.3.3 Environmental adaptation and fault tolerance mechanisms

A dynamic alignment and offset tolerance design is performed. Vehicle parking offset leads to coil misalignment and coupling coefficient degradation. Design a multi-coil array with multiple independent coils at the transmitter end, with switches to select the optimal activation area; dynamically adjust the coil position (±10 cm tolerance) using servo motors or electromagnetic actuators through a mechanical adjusting mechanism; and a magnetic field guidance technique that can enhance the magnetic field coverage through an auxiliary magnetic pole to improve the horizontal offset tolerance.

3.3.4 Fault detection and fault tolerance mechanisms

Real-time status monitoring coordinates current or voltage sensors to monitor input and output power and identify overcurrent or overvoltage faults; temperature sensors embedded in coils, cores, and power devices to trigger overheating protection; and the relative position of the coils is detected by displacement sensors and fed back to the control system.

Isolate the fault and resume operation. Switching between main and backup power circuits to avoid system paralysis due to single point failure; modularized design, faulty modules can be replaced individually to reduce downtime. Regularly self-test and report system status, and enter safety mode when abnormal. And pre-stored typical fault solutions to guide rapid maintenance.

4 Conclusion

4.1 Summary

Magnetic coupling resonance (MCR) wireless charging technology, as the core solution for wireless charging of electric vehicles, has always developed around the multi-objective optimization of the efficiency-cost-stability balance. Early research focused on the theory of magnetic resonance coupling (MRCC), which realized high-efficiency transmission over medium distances through LC resonant circuits but was limited by coil alignment accuracy and cost. In recent years, through coil structure optimization (e.g., rectangular layered design) and dynamic frequency matching (varactor diode tuning), the system efficiency has been improved to more than 92%, while the horizontal offset tolerance reaches ±10 cm. In terms of cost control, the material substitution (aluminum coils, composite cores) and the modular design reduce the cost of mass production by 30%-50%. Stability improvement relies on hardware reinforcement (silicone encapsulation, ferrite core fixation) and adaptive control algorithms (e. g., model predictive control) to ensure the system operates reliably in extreme environments (-40°C to 85°C). The core position of multi-objective optimization reflects that efficiency needs to take into account high-frequency and low-loss, cost relies on scale and supply chain integration, and stability needs to be integrated with hardware redundancy and intelligent control, which synergistically drive MCR technology from the laboratory to industrialization.

4.2 Prospects and challenges

4.2.1 Prospects

In recent years, the potential of magnetically coupled resonant wireless charging (MCR) technology in the field of electric vehicles has gradually emerged. This technology realizes energy transmission through a high-frequency magnetic field, which not only gets rid of the tediousness of plugging and unplugging charging piles, but also supports the replenishment of energy while the vehicle is moving, which sounds like a sci-fi scenario, but there has been practical progress in reality. For example, the U.S. WiTricity and domestic enterprises in the Huichang Chuangzhi has been in some cities in the parking lot of the pilot static charging, Sweden and even try to pave charging road in the bus line, so that buses “run while charging. Policy level, China's “14th Five-Year Plan” clearly supports wireless charging research and development, the European Union plans to build a charging highway network covering Europe within ten years, the United States also through the infrastructure bill allocations to promote the technology to the ground, the global competition situation is obvious. In the next five to ten years, with the popularization of automatic driving and vehicle-road cooperation technology maturity, wireless charging may take the lead in logistics parks, ports and other closed scenes such as automated guided trolley popularization, and then gradually to the home garage and highway expansion. If the technological bottleneck breakthrough, by 2030, we may be able to realize the vision of “driving never charge” - of course, provided that the power grid, road infrastructure and user habits can keep up with this quiet energy revolution.

4.2.2 Challenges faced

The current technology still faces three core challenges: first, the transmission efficiency decreases sharply with distance, and the efficiency is less than 85% at a distance of more than 30 cm, which needs to be explored for magnetic field focusing technology or a dual-frequency cooperative transmission scheme to enhance the long-distance coupling capability; second, the cost of high-purity copper and ferrite materials accounts for more than 40%, which urgently needs to promote the industrialization of low-cost magnetic materials (e.g., iron powder cores) to reduce the comprehensive cost through large-scale production. Third, the biosafety [5] of high-frequency systems needs to be urgently resolved to comply with the exposure limits of the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and to avoid the risk of thermal effects on human tissues through shielding optimization and dynamic power reduction design. These challenges require cross-discipline collaboration and breakthroughs in the entire chain from material innovation and system design to standardization to drive MCR technology from the lab to large-scale commercialization.

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