Wireless Power Transfer

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Enhancing wireless charging efficiency: addressing metal interference through advanced electromagnetic analysis and detection techniques

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Abstract

Wireless charging is an emerging technology that is quickly gaining popularity due to the potential to provide wireless power transmission for several gadgets. Nonetheless, the use of metallic objects is capable of greatly disrupting the effectiveness and reliability of wireless charging systems. This advanced technology involves the transmission of electrical energy between a charging station and the target device through the air gap with the help of techniques like magnetic coupling and magnetic resonance. These methods are appropriate for recharging devices with large batteries such as hand-held communication devices and electric vehicles. In the case of wireless charging, the application of metal foreign objects inside the energy transmission field causes complicated electromagnetic coupling because of the high-frequency electromagnetic field. These metallic interferences cause a change in the equivalent impedance of the transmitting coil; thereby, reducing the current at the transmitting end and consequently the charging efficiency. To this end, it is necessary to carry out a detailed investigation of the features of the wireless charging process in cases where metal objects are present. This includes studying the particular electromagnetic processes that take place and finding effective ways of identifying and preventing the effects of the metal foreign objects. This way, it is possible to provide for the maintenance of the required level of energy transmission in the systems of wireless charging.

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Introduction

In the constantly developing area of wireless charging technology, one of the main issues is the existence of metal objects in the charging area[1]. These objects can greatly influence the performance and reliability of wireless charging systems, resulting in overheating, energy dissipation, and even destruction of the charged devices. To this end, several techniques of metal foreign object detection (FOD) have been proposed each of which provides different ways of improving the efficiency of wireless charging. Thus, by analyzing these latest innovations, the goal is to give an overview of the current technologies, their strengths and weaknesses, and their applications. This research will explore a range of metal foreign object detection methodology applications. These methods include, but are not limited to, inductive sensing, capacitive sensing, and advanced imaging techniques. Each method will be examined in detail, focusing on its technical specifications, operational mechanisms, and suitability for different wireless charging scenarios[2,3]. Additionally, the analysis will cover emerging technologies that promise to enhance detection accuracy and system integration. The advantages and disadvantages of each detection method will be critically analyzed. Key factors such as detection sensitivity, response time, cost-effectiveness, ease of integration, and compatibility with existing wireless charging infrastructure will be considered. This comprehensive evaluation will help identify the most effective and practical solutions for enhancing wireless charging efficiency[4,5].

Today's FOD methods can be classified into metal FOD and living organism FOD. Although metal detection has been researched for a long time, research on detecting living organisms is still in its infancy. The majority of the research has been done on additional sensors such as thermal cameras, X-rays, pressure sensors, radars, and heat sensors. However, these methods are not easily compatible with magnetic couplers and are sensitive to the environment, thus giving false alarms. There has been a suggestion for a less complex and cheaper technique of using comb capacitors to detect living organisms. In high-power wireless power transmission systems, comb capacitor-based detection devices have been introduced and analyzed, especially for structural parameters and capacitance spacing. Parallel resonant circuits and integral circuits are intended for the detection of living organisms due to their impact on comb capacitors.

For metal foreign object detection, detector coil arrays are used due to their low cost and high integration. Studies have been made on the coil array configuration, the absence of blind area in detection, and the reliability of detection. Some of the active detection schemes that have been suggested to overcome the problems associated with passive detection schemes include impedance changes. These active schemes include the use of an excitation source on the detection coil, proper coil design to reduce blind areas, and the use of high-sensitivity frequencies that are slightly off the resonance point. It is impossible to avoid misalignment between the location of electric vehicles and ground-mounted power transmitters. To reduce this effect, techniques involving passive sensing coils and voltage vector decomposition have been suggested. In addition, non-cooperative MOD mechanisms for the safe operation of WEVC systems are used in the case of wireless electric vehicle charging. Optimal positioning of the sensing coils, size variation of the patch coils, and correct polarity arrangements reduce the blind zones and adjust to the magnetic field of the DD coils.

Moreover, the research will include case studies and examples from recent patent filings to illustrate how these detection methods have been implemented in real-world applications. These examples will provide valuable insights into the practical challenges and benefits associated with different detection technologies, highlighting their impact on improving wireless charging systems. This research aims to provide a thorough overview of metal foreign object detection methods from the perspective of patent applications, focusing on their role in enhancing wireless charging efficiency. By understanding the strengths and limitations of various detection technologies, industry professionals and researchers can make informed decisions about the most suitable approaches for their specific needs, ultimately contributing to the advancement and reliability of wireless charging solutions.

Metal foreign object detection methods

Q-value detection method

The Q-factor is an indicator representing the relationship between energy maintenance and energy loss in a circuit, which includes the coil on the power transmitting side and the coil on the power receiving side[6]. The Q-factor indicates the strength of resonance in a resonant circuit. The advantage of the magnetic resonance method is that the axis of the power-receiving side coil does not need to be adjusted to the axis of the power-transmitting side coil. There is a high degree of freedom in selecting the positions of the power transmitting side and power receiving side, and in setting the distance between the power transmitting side and the power receiving side[7]. Technology that determines the presence of metal foreign objects by measuring the Q-value of a circuit that includes coils electromagnetically coupled to the outside is applied in situations where a primary side charges multiple secondary sides. However, the Q-value detection method requires a dedicated Q-value detection circuit, which increases costs accordingly.

Temperature detection method

Since the presence of metal foreign objects causes an increase in the temperature of the transmitting and receiving coils, a temperature-based detection method has been proposed to perform foreign object detection. The principle mainly involves setting a temperature sensor on the transmitting coil side to detect the temperature of the coil. When the temperature detected by the temperature sensor exceeds a certain threshold, it is determined that a metal foreign object is present[8]. Detection methods based on this principle also include improving the arrangement of multiple temperature sensors, the selection of temperature sensor precision, the detection position of temperature sensors, and temperature detection methods.

Voltage, current, and power loss detection

Detection methods for determining the presence of metal foreign objects between the transmitting end and receiving end of a wireless charging device also include voltage, current, and power loss methods. For voltage and current methods, a voltage sensor or current sensor is set on the transmitting side[9]. When a foreign object is present, the voltage on the transmitting coil side or the current flowing through the transmitting coil will change. Comparing the sensed signal with the corresponding threshold allows the determination of whether a foreign object is present[10].

The principle of detecting foreign objects by measuring power loss at the transmitting end is: if the detected power loss exceeds a preset threshold, it is determined that a metal foreign object is present, and the transmitting end of the wireless charging device will terminate power transmission[11,12]. However, power loss in the circuit at the transmitting end is difficult to calculate due to the influence of voltage, switching frequency, and temperature on semiconductor device loss. In addition, during power loss measurement, synchronous measurement of power loss at the transmitting and receiving ends is required, but the system response usually has a time delay of several hundred milliseconds[13]. To prevent sudden changes in power during the measurement process, synchronous calibration of the power compensation system measurement error is needed, resulting in high operational difficulty and complexity.

Infrared, image, or ultrasound detection

Detection using infrared, image or ultrasound methods is relatively intuitive, and in recent years, patent applications in this area have been successively proposed. The principle is to acquire infrared thermal images between the wireless power transmitting end and the wireless power receiving end during the wireless charging process to determine whether an abnormal object is present. When an abnormal object is present, it is judged whether the temperature value or power loss of the abnormal object meets preset rules[14]. If the temperature value or power loss of the abnormal object meets the preset rules, a wireless charging termination command is sent to the wireless power transmitting end, terminating the wireless charging process. Infrared thermal images can accurately determine abnormal objects and their temperature values, improving the accuracy of foreign object detection during the wireless charging process, and thereby enhancing safety[15].

Feedback authentication

Feedback authentication involves mutual authentication between the transmitting end and the receiving end through communication. If authentication fails, it is determined that a foreign object is present the receiving end is incompatible, and the power supply is stopped[16]. One authentication principle is: that in response to the reception of predetermined data from the power supply side, the communication device on the receiving side sends a specific data sequence to the power supply side, which then determines whether the receiving end is a legitimate receiving end. Feedback authentication can effectively detect the presence of foreign objects, but the detection device structure is relatively complex[17].

Other methods

Other methods include pressure or gravity detection, such as determining the presence of foreign objects by detecting the pressure parameter values on the upper surface of the charging housing[18]; frequency detection, such as judging the presence of foreign objects affecting non-contact power transmission by detecting deviations in the resonant frequency[19]; and capacitance detection, such as determining the presence of foreign objects in the effective transmission area of the transmitting coil array based on the capacitance value detected by the capacitance detection circuit[20] as shown in Fig. 1.

Wireless power transfer technology

Wireless Power Transfer Technology (WPTT) was first proposed by the famous electrical engineer Nikola Tesla in the mid-to-late 19th century. It is a transmission mode that uses invisible soft media (such as electric fields, magnetic fields, sound waves, etc.) to transfer electrical energy from the power source to the electrical equipment. Compared with the traditional method of transmitting electrical energy using cables, this transmission method is safer, more convenient, and more reliable, and is considered a revolutionary advancement in energy transmission and access[21−24].

Classification of wireless power transmission technology

With the deepening and development of theoretical research on wireless power transmission technology, researchers have continuously proposed new terms and concepts related to wireless power transmission technology in response to different application scenarios and practical problems[25−28]. This paper classifies wireless

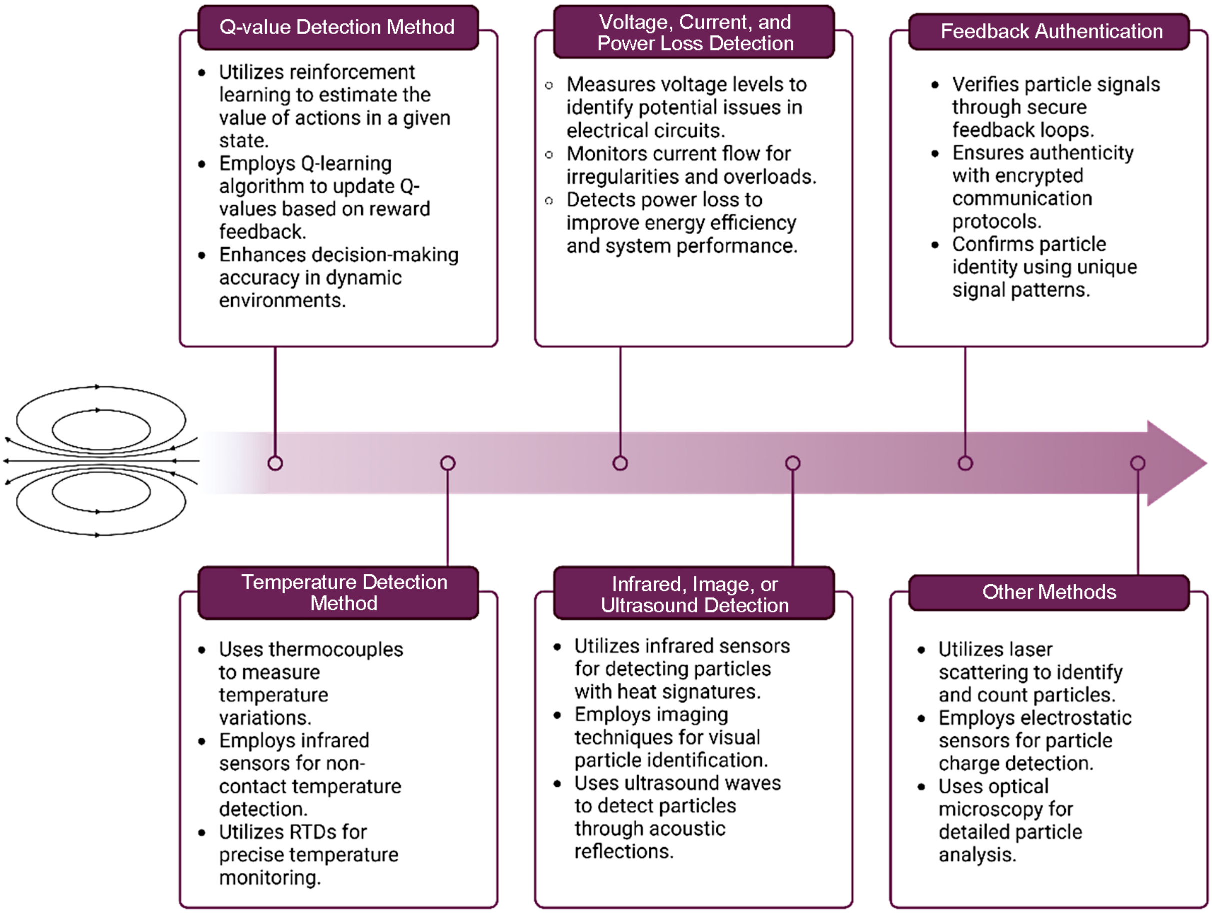

Fig. 1 Different metal detection methods used in wireless power transfer.

power transmission technology by energy transmission mechanism and energy transceiver coupling spatial position change by consulting existing literature. Figure 2 is a basic diagram of wireless power transmission technology.

Magnetic coupling wireless power transfer system

Among the current wireless power transmission methods, the magnetic coupling wireless power transmission method has been the most theoretically studied and has the fastest application progress[29,30]. Existing literature has made a detailed introduction to the composition of the magnetic coupling wireless power transmission system from the perspective of energy transmission principle classification. This article explains it from the perspective of whether the relative position of the coupling space between the energy transmitting and receiving ends changes[31,32].

Static wireless charging system

The static wireless charging system is based on the principle of electromagnetic fields. The high-frequency power supply, electromagnetic coupler, energy conversion module, and static load are the main paths for power flow[33]. It integrates detection, communication, control, and protection circuits. The transceiver relies on a high-frequency electromagnetic field to charge the static load. Its applications mainly include electronic devices, smart homes, and medical devices with low power requirements, as well as high-power energy transmission scenarios such as electric vehicles and industrial robots[34–38]. Figure 2 shows the structure of the static wireless charging system for electric vehicles.

Dynamic wireless power supply system

The dynamic wireless power supply system is based on the principle of electromagnetic fields. High-frequency power supply, electromagnetic coupler, energy conversion module, and mobile load are the main paths for power flow. It integrates detection, sensing, communication, control, and protection circuits. The transceiver relies on a high-frequency dynamic electromagnetic field to realize a real-time power supply for mobile loads[39,40].

Compared with the static wireless power transmission system, its principle adopts the collaborative working mode of inductive coupling and electromagnetic resonance. The biggest difference lies in the structural design, compensation topology, and control strategy of the electromagnetic coupling system. In addition, the dynamic power supply system needs to be further improved in terms of system complexity, technical maturity, and construction economy[41].

The system is mainly used in high-speed trains, trams, and electric vehicles. This power supply method can ensure that the mobile power receiver obtains power in real time, effectively avoiding the disadvantages of weak battery life and long charging time, and also greatly reducing the mass of the power receiver.

Quasi-dynamic wireless power transmission system

The structure of the quasi-dynamic wireless power transmission system is similar to that of the static wireless charging system. Its technical maturity lies between that of the static system and the dynamic system. It is mainly used to charge the onboard energy storage device when the mobile power receiver (tram or electric car, etc.) moves slowly or stops briefly (such as at a traffic light intersection)[42,43]. Compared with the traditional dynamic wireless transmission system, it simplifies the system control complexity, reduces the infrastructure cost, and enables a high degree of magnetic field coupling between the transmitter and the receiver, thereby achieving efficient energy transmission.

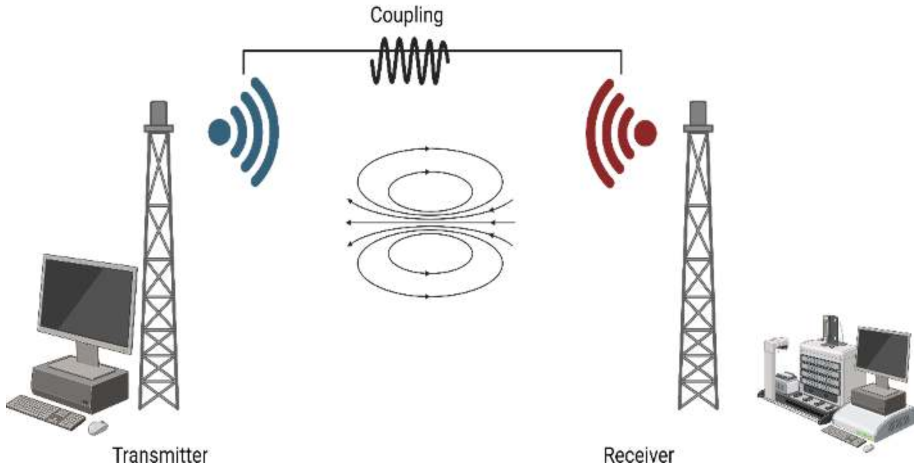

Fig. 2 Block diagram of wireless power transmission technology.

Application level and key issues of wireless power transmission technology

With the rapid application of wireless power transmission technology in many fields, this article reviews the research results at home and abroad over the past 10 years and explains the current application level of this technology in eight major fields: home electronic devices, smart homes, medical equipment, transportation, industrial robots, the Internet of Things, underwater detection equipment, and aerospace[44]. It also summarizes the difficult problems to be solved in each field. Table 1 is a comparative analysis of this technology in different application fields.

Consumer electronics

The use of wireless charging has proven to be very convenient and portable in the sense that consumers are not restricted to the use of cables and sockets[45−48]. This technology is mostly used in charging pads for charging smartphones and tablets. However, major disadvantages encompass lower power delivery, as well as the restricted area of coverage and charging capabilities as compared to a wired connection. It is mildly efficient, so it is relatively practical to use it regularly without a huge loss of power[49,50]. The expenses required in this field for wireless charging solutions are relatively low to moderate for the broad consumer market[51−54].

Electric vehicles

In the context of EVs' use, wireless charging decreases the dependency on plug-in technologies, which makes the process more accessible[55]. It can be installed in static and dynamic charging stations as per electric vehicle requirements, charging process may occur while the electric vehicle is parked or even when it is in motion. However, it is not devoid of challenges; the main ones being the high infrastructure cost as well as the efficiency incompatibility whereby the structure undergoes dramatic efficiency loss during the power transfer[56−58]. On efficiency, it ranges from moderate to high based on the level of implementation, however on cost, it is high because it involves the use of advanced technology and infrastructure[59].

Medical devices

In medical devices, wireless charging removes wires and thus cuts the spread of infection through invasive charging solutions. This is apparent, especially in connection with implants and any other wearable healthcare devices[60−62]. However, in turn, it is a challenge regarding power transfer and is subject to strict legislation that sets back its use. The level of accuracy is comparatively low to moderate; however, the improvement of the patient safety conditions and device usability fully justifies the mentioned high costs[63].

Industrial automation

Wireless charging in industrial automation is advantageous as it enhances mobility, cuts down the connections' susceptibility to fatigue, and plays a critical role in the durability of industrial automation systems. Some of the real-life applications among them are the use in AGVs and robotics[64−66]. The main drawbacks are the disturbance by other electrical pertinent systems and high initial

Table 1. Comparative analysis of wireless power transmission technology in different application fields.

Application field	Key benefits	Key challenges	Efficiency	Cost	Examples of use
Consumer electronics	Convenience and mobility	Limited range, slower charging	Moderate	Low to moderate	Wireless charging pads for phones, tablets
Electric eehicles	Reduces the need for plug-in charging	High infrastructure cost, efficiency loss	Moderate to high	High	Static and dynamic wireless charging stations
Medical eevices	No wires, reducing infection risk	Power transfer limitations, regulatory hurdles	Low to moderate	High	Implants, wearable medical devices
Industrial eutomation	Flexibility, reduced wear on connectors	Interference, high initial setup cost	High	High	Automated guided vehicles (AGVs), robotics
Military	Reduced need for fuel transport	Security risks, high-tech implementation	Moderate	Very high	Remote charging of UAVs, field equipment
Space exploration	Enables long-distance energy transfer	Extreme environmental conditions, tech reliability	Low to moderate	Very high	Powering satellites, rovers
Smart homes	Enhanced user experience, convenience	Interference with other devices, efficiency	Low to moderate	Low to moderate	Wireless charging for smart home devices
Wearable technology	Improved user experience, flexibility	Battery life limitations, power transfer efficiency	Low to moderate	Low to moderate	Fitness trackers, smartwatches

investments. On the other hand, the efficiency of wireless charging in these applications is quite high hence the technology is worth the investment irrespective of the costs incurred[67–70].

Military

This method of charging is advantageous in military operations that entail charging a large number of batteries; it eliminates the need for a source of fuel hence improving the movement of operations logistics and overall readiness. It is for charging UAVs and other field appliances from a distance using electrical energy[71–73]. Nonetheless, its application is mainly security-sensitive and requires a high level of technical requirements. The degree of efficiency is rather low but the costs are rather significant because the production of army equipment is highly specialized and rather expensive[74].

Space exploration

Wireless charging in space exploration is crucial in charging satellites and rovers, and energy transfer through long distances is vital. Severe environmental factors as well as the requirements that must be met in terms of technology are the main challenges[75–78]. The operating efficiency is often low to average, primarily because of the severe environment and distance over which operations are managed, though the overall cost is very high because of the technology incorporating sophisticated equipment and materials[79,80].

Smart homes

For smart homes, wireless charging helps to improve their usability by removing the need for untidy wires and enabling power to many devices. Nevertheless, one must note the issue of the interference with other electrical appliances and the efficiency which may not be present at an optimum level at all times[81–83]. The cost is considered low to moderate, which will enable owners to increase the intelligibility of their house without massive expenses[84–87].

Wearable technology

Wireless wearable technology enhances user experience by making it flexible and less required to be recharged through normal methods[88–90]. Some of the applicable devices are body monitoring devices such as fitness trackers and smartwatches. Some of them are; the use of batteries and the efficiency at which power is transferred between the batteries[91–95]. Nonetheless, the cost is relatively low to moderate while the gains in ease of use for clients and capability of the devices are high[96].

Related issues in the development of wireless power transmission technology

Wireless power transmission technology has a wide range of applications and has achieved relevant industrialized results from low power to high power, from low frequency to high frequency, and from static to dynamic[97–99]. To further promote the rapid development of wireless power supply-related industries, we should focus on practical application fields, speed up the solution of key common problems in wireless charging technology, and focus on the wireless charging industry chain to speed up the breakthrough of bottleneck problems that restrict industrial development[100–102].

Key common issues in the application of wireless power transmission technology in various fields

Multi-objective parameter combination optimization

The key parameters of wireless power transmission systems include time-varying parameters such as quality factors, coupling coefficient, transmission impedance, and power frequency[103–105]. Some scholars have studied the influence relationship between transmission parameter combinations, but all are qualitative analyses[106]. In the overall design of wireless power transmission systems, to maximize energy efficiency, the analytical relationship between each parameter and energy efficiency and the quantitative relationship between parameters are important aspects of theoretical research on wireless power technology[107].

Robustness of electromagnetic energy transfer

In static wireless charging systems, foreign metal objects (including magnetic metals) are ingested into the gap of the coupling mechanism or living things such as cats and dogs invade. In dynamic wireless power supply systems, the vibration of the electromagnetic coupling structure and lateral displacement of the receiving coil are inevitable in practical applications and the severity of the impact on the system varies under different environmental conditions[108]. A slight impact will cause the quality of the receiving body to decline, and in severe cases, the power device of the receiving body will be damaged and stop working[109].

Therefore, studying the topological structure of the magnetic coupling system that is resistant to external disturbances and the highly robust control method to ensure stable and reliable power reception of the power-receiving object is a basic requirement for the industrialization of dynamic wireless power transmission.

Multi-source and multi-load technology

To meet the power supply requirements of loads in different application scenarios, the electromagnetic coupling system structure has three forms: one-to-one, one-to-many, and many-to-many. Therefore, in complex environments, the coordinated management of multiple loads and multiple transmitters, the automatic charging and discharging of loads, and the mutual influence between loads are issues that need to be solved in the application of wireless power transmission technology[110].

Electromagnetic environmental biosafety

The biological safety of the electromagnetic environment has always been an important issue in the industrial application of wireless power transmission technology.

In 2000, the Jet Propulsion Laboratory of the United States first raised the safety issue of wireless power transmission from solar power satellites. If people and other living things are in an electromagnetic environment that exceeds the safety limit for a long time, their biological functions will be damaged. The research team of Nagoya Institute of Technology in Japan conducted a three-level study on electromagnetic safety based on the MIT wireless power transmission system model[111].

Some scholars have analyzed the S parameters of the system based on the 2/3 muscle tissue equivalent cylindrical model and concluded that the system with an open coil is more affected by the human body than the system with a closed coil. Some scholars have used the quasi-static method to approximate the electric field distribution of the system and analyzed the safety of the system by calculating the specific absorption ratio (SAR) value of the human tissue equivalent model at a fixed point in the approximate electric field. Some scholars have used the quasi-static method to approximate the distribution of the system's electric field and magnetic field, respectively, and studied the electromagnetic safety of the system by calculating the SAR values based on several different human equivalent models[112,113].

The Electromagnetic and Acoustic Experimental Center of the Swiss Federal Institute of Technology and the University of Washington in the United States conducted a comprehensive study on the electromagnetic environment of wireless power transmission systems with a coil diameter of 580 mm, and a frequency range of 1 to 20 MHz, and a small wireless power transmission system with a coil diameter range of 20 to 150 mm, a system power of 5 W, and a frequency of 100 kHz[114,115].

There is little research in China on electromagnetic safety. Further research is needed on the impact of high-intensity magnetic fields on surrounding organisms in different application scenarios, especially the degree of harm to the human body.

Analysis on the current status of industrial development of wireless power transmission technology

With the rapid penetration of wireless power transmission technology in various fields, various component manufacturers in the wireless power transmission industry chain and related technical companies are developing rapidly. According to the '2017-2022 China Wireless Charging Industry Market In-depth Analysis and Investment Prospect Forecast Research Report' released by China Industry Information Research Network, the wireless charging market will reach USD$ 14 billion in 2022, with a penetration rate of more than 60%[116].

From the perspective of electric vehicle applications, according to the forecast of foreign research institution Research and Markets, the electric vehicle charging market size will grow overall due to the growing demand for electric vehicles and plug-in hybrid vehicles and the increased research and development efforts of wireless charging system manufacturers. It is estimated that by 2025, the electric vehicle wireless charging market size is expected to reach USD$ 407 million, and the annual compound growth rate from 2020 to 2025 will reach 117.56%[117].

Regarding important components of the entire wireless charging industry chain, such as system solution design, chip and magnetic material components, and manufacturing processes, the technical barriers formed by the United States, Japan, and other countries against China are still very strong. Figure 3 shows the structure of the entire wireless charging industry chain.

Based on this, China urgently needs to strengthen the research and development of related results with independent intellectual property rights with high technical parameters, higher reliability, and higher safety operation and maintenance for the entire industrial chain of wireless power transmission technology, and promote the transformation of its wireless charging industry from 'following, running side by side to leading' at home and abroad, to ensure the sustainable and healthy development of Chinas wireless charging industry.

Conclusions

This research has provided an in-depth analysis of the diverse technologies and methodologies for metal foreign object detection in the context of wireless power transmission (WPT). By evaluating approaches based on Q-factor, voltage, current, power loss, and temperature, the strengths and weaknesses of each method have been presented. The present investigation underscores the importance of combining multiple detection methods to mitigate the limitations inherent in individual approaches, thus enhancing the overall safety and efficiency of wireless charging systems. The analysis reveals that the integration of various detection techniques can substantially improve the reliability and performance of WPT systems. Methods such as Q-factor detection offer high precision but at a higher cost, while temperature-based methods are

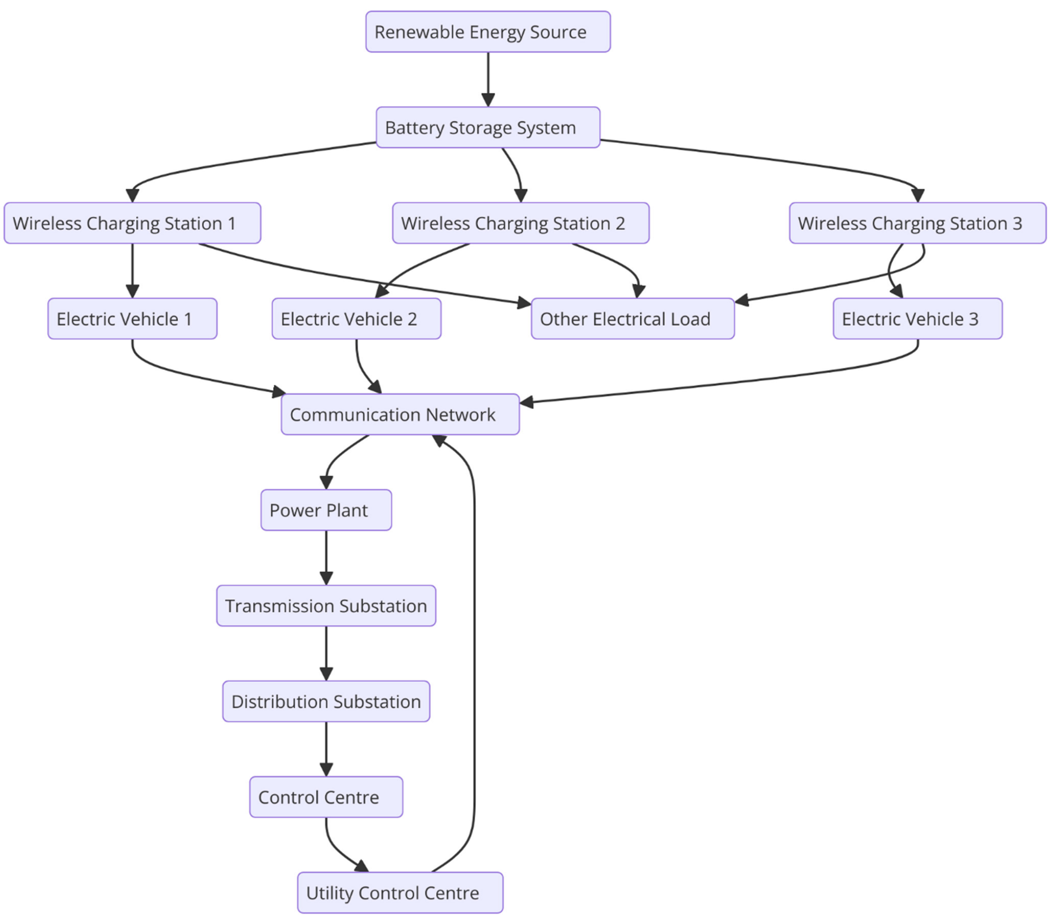

Fig. 3 Structure of the entire wireless charging industry chain.

cost-effective but sensitive to environmental variations. Advanced techniques like infrared, image, and ultrasound detection provide high accuracy but require sophisticated processing algorithms. The significant increase in research activity, particularly from 2015 onwards, with notable contributions from China, highlights the growing academic and practical interest in optimizing WPT technologies. This is further corroborated by the surge in patent applications, indicating robust innovation and commercial potential in this field.

Future research directions

Multi-objective parameter optimization

Future research should focus on developing algorithms for optimizing multiple parameters simultaneously to enhance the efficiency and effectiveness of WPT systems. This includes balancing factors like power transfer efficiency, detection accuracy, and cost.

Robust electromagnetic energy transmission

Investigating methods to improve the robustness of electromagnetic energy transfer, especially in dynamic environments with varying distances and orientations between the transmitter and receiver, is crucial.

Multi-source and multi-load technology

Developing WPT systems capable of efficiently handling multiple power sources and loads will be essential for applications in smart homes, industrial automation, and electric vehicles.

Biological safety of electromagnetic environments

Comprehensive studies on the long-term biological effects of electromagnetic fields generated by WPT systems are necessary to ensure safety standards are met and to alleviate public concerns.

Standardization of WPT products

Establishing global standards for WPT products will facilitate interoperability, improve consumer confidence and accelerate the adoption of wireless charging technologies across various industries.

Technology implementations for improvements

Advanced sensor integration

Incorporating advanced sensors and machine learning algorithms to enhance the accuracy and reliability of metal foreign object detection systems. This could involve real-time data analysis and adaptive control mechanisms.

Hybrid detection systems

Developing hybrid detection systems that combine multiple detection methods (e.g., Q-factor, infrared, and ultrasound) to leverage the advantages of each approach while mitigating their individual limitations.

Improved calibration techniques

Enhancing calibration techniques for voltage, current, and impedance detection methods to reduce false positives and improve the precision of anomaly detection.

Miniaturization and cost reduction

Focusing on the miniaturization of detection circuits and sensors to reduce costs and integrate them seamlessly into compact and portable WPT devices.

Integration with IoT

Leveraging the Internet of Things (IoT) to create intelligent WPT systems that can communicate with other devices, providing real-time status updates, diagnostics, and automated responses to detected anomalies.

By addressing these future research directions and implementing advanced technologies, the field of wireless power transmission can achieve significant advancements, ensuring efficient, safe, and ubiquitous power solutions that meet the growing demands of modern applications.

Author contributions

The authors confirm contribution to the paper as follows: investigation; resources; data curation; writing - original draft; supervision; project administration: Han H; conceptualization; methodology; software; validation; formal analysis; funding acquisition; formal analysis: Bhatti MA; writing - review & editing; visualization: Han H, Bhatti MA. Both authors reviewed the results and approved the final version of the manuscript.

Data availability

The corresponding author can provide the datasets used and/or analyzed for this study upon reasonable request.

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Conflict of interest

The creators of this research state unequivocally that no known conflicting financial interest or personal relationship may have influenced any of the work disclosed in this study.

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