Current situation and breakthrough of wireless charging technology

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Abstract. With the rapid development of smart devices and the Internet of Things (IoT), wireless charging technology has gained increasing attention. However, its practical applications still face challenges such as significant efficiency loss due to transmission distance, interference from multiple coupled devices, and energy loss caused by thermal effects. This paper explores two core wireless charging technologies-electromagnetic induction and magnetic resonance-through literature review, experimental analysis, and case studies. It systematically examines their theoretical foundations, application scenarios, key performance indicators, and commonly used data sources. By analyzing typical applications in smartphones, electric vehicles, and smart home devices, this study identifies the limitations of current technologies in terms of efficiency, transmission distance, and safety. Furthermore, future directions for innovation and expanded application scenarios are discussed. The findings provide theoretical support and practical insights for advancing wireless charging technology, highlighting the need for further research to enhance its efficiency, stability, and scalability.

Keywords: Wireless charging technology, electromagnetic induction, magnetic resonance, technology limitations, future prospects.

1. Introduction

1.1. Research background and significance

With the popularity of smart devices and the booming development of the Internet of Things, wireless charging technology, as a new energy transmission mode, is gradually changing people's life and production mode. With the wide application of smart phones, smart home appliances, electric vehicles and other devices, people's demand for convenient and efficient charging methods is increasing. Wireless charging technology, through electromagnetic induction, magnetic resonance and other contactless energy transmission mechanism, gets rid of the shackles of traditional wired charging, and brings great convenience to users.

However, at present, wireless charging technology still faces many technical bottlenecks in its practical application. For example, the charging efficiency decreases significantly with the increase of transmission distance, the energy loss caused by the coupling interference of multiple devices, and the energy dissipation caused by the thermal effect, which seriously restrict its large-scale application. Solving these technical bottlenecks is not only of great significance to promote the development of related industries, but also will promote the reform of energy transmission mode, and provide a more efficient and convenient energy supply mode for the future intelligent life and industrial production.

1.2. Study Objectives and Methods

The purpose of this study is to deeply analyze the principle, application status and existing limitations of wireless charging technology, and propose feasible optimization strategies and future development direction. During the study, the following methods are mainly applied:

1. Literature research method: By consulting the relevant literature at home and abroad, the theoretical basis, research status and development trend of wireless charging technology are sorted out to provide theoretical support for the research.

2. Experimental analysis method: build an experimental platform, conduct experimental tests on electromagnetic induction and magnetic resonance wireless charging technology, obtain the charging

efficiency, transmission distance, energy loss and other data under different conditions, and explore its performance characteristics.

3. Case study method: Analyze the practical application cases of wireless charging technology in smart phones, electric vehicles, smart home and other fields, summarize experience, find problems, and provide practical basis for technological improvement.

2. Theoretical basis of wireless charging technology

2.1. Specific model and method of electromagnetic induction wireless charging

In the field of wireless charging technology, electromagnetic induction wireless charging technology is widely used. The basic principle is based on Faraday's law of electromagnetic induction and Lenz's law. Faraday's law of electromagnetic induction shows that when the magnetic flux in the closed-circuit changes, the induced electromotive force is generated in the circuit, and the magnitude of the induced electromotive force is proportional to the rate of change of the magnetic flux [1]. Lenji's law further states that the direction of the induced current always hinders the change of the magnetic flux that causes it, that is, the magnetic field generated by the induced current changes in the opposite direction of the original magnetic field.

In the electromagnetic induction wireless charging system, the transmission end coil uses an alternating current to generate an alternating magnetic field. The coil of the receiving end is in the alternating magnetic field, and the magnetic flux changes, thus generating the induced electromotive force, which drives the electric current flowing in the receiving end circuit to realize the transmission of electric energy. This technology has high charging efficiency in close range (<5 cm) energy transmission. However, its performance is extremely sensitive to the coil alignment.

The experimental data show that when the coil offset reaches 30% of the coil radius, the system leakage sense can increase to 2.5 times of the initial value, and the energy loss accounts for more than 50%. However, by introducing adaptive impedance matching circuits (such as L-type or $\prod$ -type networks), the efficiency loss can be controlled within 15% of the 10% offset range.

In addition, the power also has a significant effect on the electromagnetic induction wireless charging efficiency. With the power increase from 5 W to 15 W, the total system loss increased from 15% to 28%, with the coil eddy current loss and core hysteresis loss contributing about 60% and 35% of the loss increment, respectively. According to the Qi standard commercial equipment by optimizing the coil layer structure and ferrite shielding layer design, in 15 W high power scenario can control loss within 22%, proved the feasibility of the technology in low power scenario, but also highlights it’s in practical application, need to solve the efficiency fluctuations caused by equipment placement deviation or mobile, as shown in figure 1.

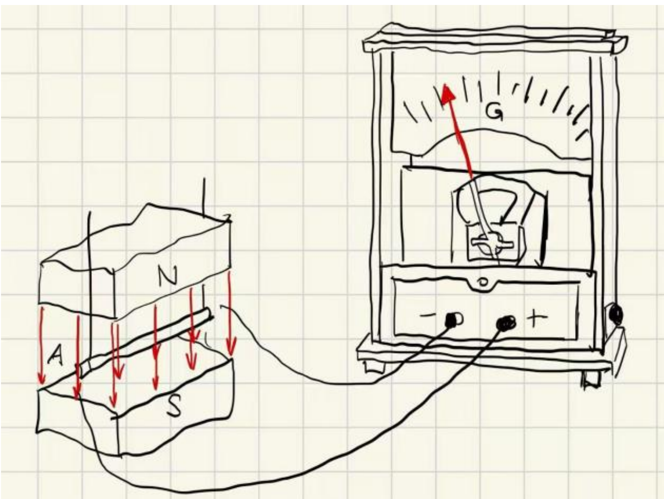

Figure 1. A specific model of wireless electromagnetic

2.2. Method of the MR model as well as the model

The magnetic resonance wireless charging technology is based on the nuclear magnetic resonance principle. The nucleus progresses at the Ramall frequency in a strong magnetic field, and when the frequency of the applied radio frequency field is consistent with the Ramall frequency, and the nucleus moves from low level to high level [2]. After stopping the RF pulse, the nucleus returns to equilibrium through the relaxation process, releasing energy.

In an MR wireless charging system, the coils at the transmitter and receiver are tuned to the same resonance frequency. When the transmitting end coil passes into the alternating current, the generated alternating magnetic field produces magnetic resonance with the receiving end coil to realize efficient energy transmission. Figure 2 shows the magnetic resonance model; the technology shows a high charging efficiency within a medium transmission distance (20-50 cm).

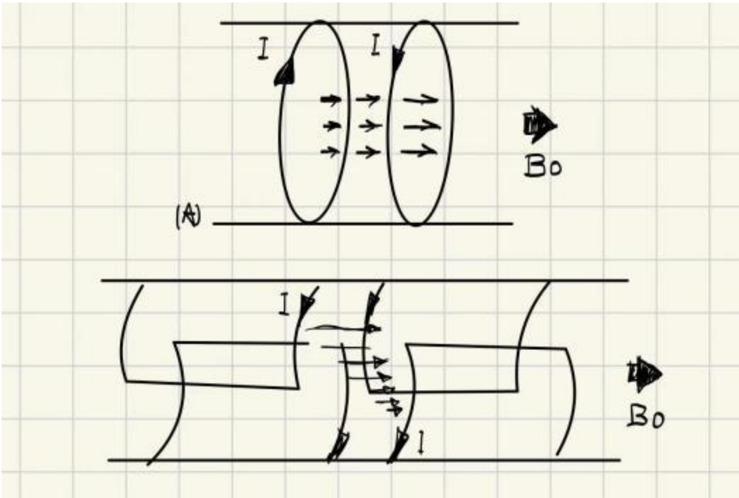

Figure 2. The magnetic resonance model

In an MR wireless charging system, the coils at the transmitter and receiver are tuned to the same resonance frequency. When the transmitting end coil passes into the alternating current, the generated alternating magnetic field produces magnetic resonance with the receiving end coil to realize efficient energy transmission. The technology shows a high charging efficiency within a medium transmission distance (20-50 cm). Figure 3 presents the relationship between transmission efficiency and distance from both theoretical calculations and experimental measurements. As shown in the figure, the transmission efficiency in wireless charging gradually decreases with increasing distance, and the experimental values exhibit an overall trend consistent with the theoretical predictions.

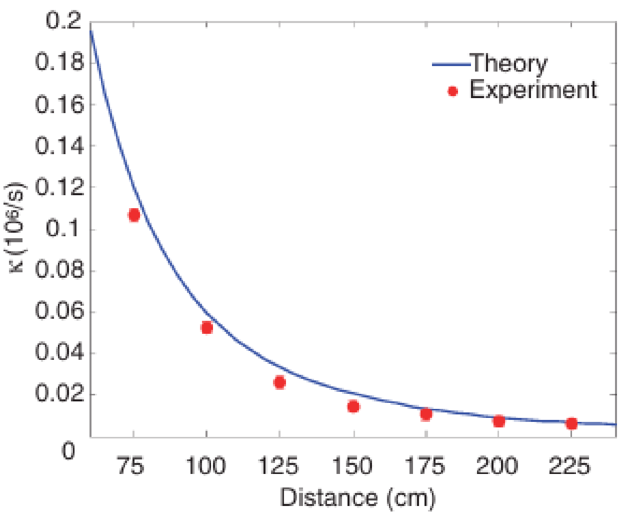

Figure 3. Transmission efficiency and distance relationship diagram

The study data show that the charging efficiency decreases significantly with increasing transmission distance. The energy loss also varies at different resonance frequencies, and the resonance frequency has an important influence on the energy transmission efficiency. In practical application, MR technology has advantages in the medium distance range, but in the long distance transmission, it still needs to optimize the resonance frequency and reduce environmental interference to reduce the energy loss and improve the overall efficiency.

2.3. Analysis of the key performance indicators

Charging efficiency, transmission distance and energy loss are the key indicators to measure the performance of wireless charging technology. In the two technical models of electromagnetic induction and magnetic resonance, the influencing factors and interrelationships of these indicators have their own characteristics.

Charging efficiency refers to the effective utilization rate of energy transmission from the transmitter to the receiver, Is presented as a percentage, In the electromagnetic induction model, Charging efficiency is first affected by coil design, magnetic field coupling strength, coil alignment and other factors, Improved coil layered structure, using ferrite shielding layer can improve the full effect, And coil offset reduces efficacy [3], In the MR model, Resonance frequency matching degree and coil quality factor play a fundamental role in charging efficiency, When the resonant frequencies of the transmitter and the receiver are matched well, And when the coil quality factor is high, Can implement high charging efficiency, Transmission distance determines the application scenario of wireless charging technology, The electromagnetic induction model has a short transmission distance, Generally limited to within a few centimeters, This is due to the rapid decay of its magnetic field with distance, While the MR model uses the resonance principle, Ability to implement transmission distances of tens of centimeters or more, Supply of greater flexibility for the equipment layout, But, along with the increased transmission distance, Magnetic resonance technology will also reduce [4], Energy loss refers to the loss of energy with heat energy or other patterns in the process of energy transmission, In terms of watt (W) units, The energy loss of the electromagnetic induction model first comes from the coil resistance, the magnetic core loss, Such as coil eddy current loss, magnetic core hysteresis loss, The MR model energy loss is closely related to the resonance frequency shift and environmental interference, Environmental factors such as metal object interference or humidity changes can cause resonant frequency drift, Increase in the energy loss.

The experimental and simulation data can quantify the performance of each indicator in different scenarios. The experimental data can directly reflect the performance of the technology in the real environment, but is limited by the experimental conditions and equipment accuracy. Simulation data can be simulated with a variety of design parameters and scenarios through electromagnetic field simulation software to quickly obtain the results, but the accuracy depends on the accuracy and assumptions of the model, which needs to be verified with the experimental data.

2.4. Common data source resolution

In the research of wireless charging technology, common data sources include experimental data and simulation data, which are different in terms of acquisition methods, advantages and limitations. Measurement and acquisition are made by building an actual wireless charging test platform. For example, build an electromagnetic induction or magnetic resonance charging system, and use professional test equipment to measure charging efficiency, energy loss and other parameters at different transmission distances. The advantage of the experimental data is that it is reliable and can directly reflect the performance of the technology in the real environment [5]. However, the experimental process is affected by the experimental conditions and the equipment accuracy, and there may be some measurement error. For example, during the measurement process, factors such as ambient temperature, humidity, and electromagnetic interference may affect the measurement results. Based on the simulation of the electromagnetic field simulation software (such as COMSOL, ANSYS, etc.), Lay the precise mathematical model, the boundary conditions, Simulated parameters such as electromagnetic field distribution and energy loss during energy transmission, The advantage of simulation data is that it can test a variety of design parameters and scenarios at high speed, Save the experimental cost and time, Researchers can conduct simulation analysis of different coil structures, resonance frequency and other parameters in a short time, Select out the better design scheme, but, The accuracy of the simulation results depends on the model accuracy, the assumption conditions, The experimental data must be approved for verification, calibration, If the model foundation is inaccurate or the assumptions are inconsistent with the actual situation, The simulation results probably have a large deviation from the actual situation [6].

In practical studies, experimental data and simulation data are often used together. Conduct preliminary analysis and scheme screening through simulation data, and then verify and optimize the simulation results through experimental data, so as to improve the research efficiency and accuracy. Table 1 gives the relevant experimental data; Table 2 shows the configuration parameters of the laboratory wireless charging test platform.

Table 1. Example experimental data

Technology type	Transmission distance (cm)	charge efficiency (%)	energy loss (W)	ambient temperature (℃)	Measure the equipment error of (±%)
Electromagnetic Induction	5	85.2	2.1	25±0.5	1.5
Electromagnetic Induction	10	62.7	4.8	25±0.5	1.5
Electromagnetic Induction	15	15.4	8.9	25±0.5	1.5
Magnetic Resonance	5	78.3	3.2	25±0.5	2.0
Magnetic Resonance	10	73.5	4.1	25±0.5	2.0
Magnetic Resonance	15	45.6	6.7	25±0.5	2.0

Table 2. Configuration parameters of the laboratory wireless charging test platform

Electromagnetic induction system	Transmitter / receiver coil with 20cm diameter, operating frequency 110 kHz, power class 30 watts
Magnetic resonance system	Four-coil structure, Q factor> 200, operating frequency 6.78M Hz, and power class 50 watts
Instrumentation	Keysight N6705C DC power supply analyzer, Rohde & Schwarz ZNB20 vector network analyzer
Environmental control	Temperature 25℃, relative humidity 50%, electromagnetic shielding room (IEC 61000-4-3)

3. Application cases of wireless charging technology

3.1. Smart phone field applications

In the smartphone field, the electromagnetic induction technology based on the Qi standard has become the mainstream wireless charging solution. The technology uses the magnetic field coupling between the transmitter and the receiver coil to realize energy transmission, which has the advantages of simple structure and low cost. The Qi standard also strictly stipulates safety mechanisms such as foreign body detection and temperature control to ensure the safety of users. In addition, when the mobile phone case is too thick or contains metal components, it will also affect the charging efficiency, and even cannot charge normally [7].

3.2. Applications in the field of electric vehicles

Magnetic resonance technology has promising applications in wireless charging of electric vehicles. The wireless charging system of electric vehicles is generally composed of the ground transmitting end and the on-board receiving end. By adjusting the resonance frequency matching between the transmitting end and the receiving end, the energy transmission efficiency is enhanced by using the electromagnetic field resonance. This technology can meet the changing needs of high power (11-22 kW), medium distance (10-30 cm) and strong anti-offset ability of electric vehicles. It can still maintain high charging efficiency (60-85%) even in the case of non-precise alignment or obstacles.

3.3. Smart home field applications

Wireless charging technology also has a wide range of application scenarios in the field of smart home. Smart home devices such as intelligent lamps and sweeping robots use wireless charging technology to get rid of the shackles of power lines, make the home environment cleaner and more beautiful, and also improve the convenience of the use of equipment. For intelligent lamps and lanterns, wireless charging technology can implement wireless installation of lamps and lanterns, charging, users need not worry for wiring, and can adjust the position of lamps and lanterns, sweeping the robot can automatically return wireless charging, automatic operation, in the field of smart home, wireless charging technology must meet the demand of different equipment power, at the same time to ensure charging tripod, security, with the intelligent household market expansion, wireless charging technology in the field, but still facing the charging efficiency to improve, equipment compatibility.

4. Limitations of wireless charging technology

4.1. Efficiency and distance constraints

Electromagnetic induction technology and magnetic resonance technology have significant constraints in charging efficiency and transmission distance. When the electromagnetic induction technology is used at more than 5 cm distance, the efficiency may decrease by more than 50%, and its magnetic field will decay rapidly with the distance, resulting in a sharp reduction in the energy transmission efficiency. Although the efficiency of magnetic resonance technology is high in medium distance (20-50 cm), the efficiency will also decrease significantly during long-distance transmission, and it is easily affected by environmental factors. For example, the presence of metal objects can cause eddy current loss, and humidity fluctuations can lead to the resonant frequency drift, thus reducing the charging efficiency. There are many difficulties in improving charging efficiency and extending transmission distance, such as optimizing coil design, adjusting resonance frequency and other technical means are limited by cost, space and other factors in practical application.

4.2. Potential safety hazard

In the high-power application scenario, wireless charging technology has many safety risks. First, the risk of electromagnetic radiation exceeding the standard. High-power wireless charging equipment will produce strong electromagnetic radiation in employment, and permanent exposure to this radiation environment may cause potential harm to human health [8]. Moreover, equipment overheating cause fire hazards also nots allow to be ignored, in the process of charging energy loss into heat, if improper cooling measures, probably lead to equipment temperature, cause fire, strong magnetic field also probably interference of implantable medical equipment, affect its normal employment, pose a threat to the wearer life safety, the safety guidelines, protective measures at a certain level to reduce risk, but there are still insufficient, not one hundred percent to eliminate security hidden trouble.

5. The future outlook of wireless charging technology

5.1. The direction of technological innovation

In order to break through the limitations of the existing technology, the future wireless charging technology will develop in the direction of long-distance efficient transmission and multi-device collaborative charging. Wireless charging technology based on RF energy collection has made some progress. In addition, the multi-device collaborative charging system is optimized by space magnetic field shaping technology (such as phased array coil) or time division / frequency division multiple access protocol to realize dynamic energy distribution and improve charging efficiency and device compatibility [9].

5.2. Application scenario expansion

Electric car and smart home field fusion will bring new development opportunities for wireless charging technology, dynamic wireless charging road construction, can make the electric car in the process of wireless charging, effectively fix life problem, promote the development of electric car industry, wireless power supply furniture such as IKEA launched wireless charging table, will further enhance the intelligent household convenience, intelligent level, wireless charging technology also has broad application prospects in the field of public facilities, such as wireless charging facilities in public places, can meet people charging demand at any time, enhance the level of public service [10].

6. Conclusion

This study deeply discusses wireless charging technology, covering its theoretical cornerstone, application cases, limitations and future prospects, electromagnetic induction and magnetic resonance as the first technical path, each has its own characteristics and applicable scenarios, electromagnetic induction technology performs well in zero distance and low medium power applications, but requires high coil alignment; magnetic resonance technology has advantages in medium distance and high power scenarios, but the long distance transmission efficiency needs to be improved.

In terms of the application, Wireless charging technology has been widely used in smartphones, electric vehicles, smart homes and other fields, Bring convenience to people's lives, But also facing efficiency and distance constraints, safety risks, cost and standards and other problems, Against these limitations, Future research will focus on technical originality, Such as long-distance full-effect transmission scheme, multi-device collaborative charging technology; Expand the application scenarios, Promoting the integration of electric vehicles and smart homes; Strengthen the standard construction, capital control, To promote the large-scale application of wireless charging technology and industrial development, Wireless charging technology development is expected to reshape the energy transmission paradigm, For the future intelligent life, industrial production supply more efficient, convenient energy supply methods.

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