A Comprehensive Review of Wireless Charging Systems for Electric Vehicles

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Abstract. As non-renewable energy sources such as oil become increasingly scarce, the demand for countries to achieve carbon neutrality goals is also accelerating, and electric vehicles are gradually entering people's sights. How to achieve convenient, efficient, and safe wireless charging for electric vehicles has become a hot research topic. Therefore, this paper reviews the current research status of wireless charging for electric vehicles, organizes and summarizes the problems encountered in current research, including technical overviews and specific optimization directions of research hotspots such as magnetic coupling resonant wireless power transmission systems and millimeter-wave radar dynamic monitoring technology. It also summarizes relevant technical standards for wireless charging, such as GB/T. Through these studies, convenience can be effectively improved, the limitations of physical connections can be overcome, and energy structure transformation and grid optimization can be promoted, enhancing the safety and reliability of charging. At the same time, this paper also summarizes future research directions and proposes some new directions for researchers to explore, providing a theoretical basis and reference for subsequent research and application of wireless charging technology.

Keywords: Wireless charging for electric vehicles; Magnetic coupling resonance; Technical standard; Research Direction.

1. Introduction

Non-renewable petroleum resources are being consumed and are increasingly scarce, and countries around the world need to significantly reduce fossil energy consumption and carbon emissions in the transportation sector to achieve carbon neutrality goals. Therefore, electric vehicles have gradually attracted the attention of the international community with their advantages of low pollution and low carbon emissions.

Compared with fuel vehicles, EVs emit less pollution and contribute to carbon reduction, so they are more favored by the market. With the support of multiple factors, the market share of EVs is also increasing. Compared with wired charging, EV wireless charging technology is more convenient, safe, and intelligent, suitable for more scenarios, and more conducive to the integrated development of automation [1].

Wireless charging of EVs is not only an upgrade of charging methods, but also a reconstruction of the relationship between humans and vehicles. With the continuous maturity of technology, it is expected to make a non-negligible contribution to eliminating people's range anxiety about EVs and promoting the realization of carbon neutrality goals [2,3].

The core objective of researching wireless charging technology for EVs is to achieve more efficient, safe, and convenient energy transmission. Currently, EV charging technologies mainly include slow charging, fast charging, wireless charging, and battery swapping modes [4]. The main research directions focus on improving transmission efficiency and power density, detecting alignment errors and foreign objects, building a stronger safety system, and integrating dynamic wireless charging systems. Significant progress has been made in related technology research in recent years, but multiple challenges still remain. High-power static wireless charging currently faces numerous technical barriers. Compared to wired fast charging technology, wireless charging has a slower charging speed, and the cost of wireless charging equipment in research and development, production, and installation is also higher, limiting its popularity. At the same time, electromagnetic radiation issues generated during wireless charging also concern users [5].

The goal of this paper is to advance knowledge in wireless charging. To do this, this paper first reviews the basic principles and the current state of application. Within the major current research focuses the discussion of different types of contemporary wireless power transmission, specific optimization directions and recent progress are investigated. Following the discussion, the relevant standards of nowadays wireless charging like GB/T are thoroughly studied. This paper also elaborates on the future development trends of charge efficiency, charging methods, and heat dissipation.

2. Overview and application of wireless charging technology for EVs

2.1. The basic way to charge EVs wirelessly

The concept of radio power transmission first appeared in the 19th century. The operational principles of wireless power transfer (WPT) determine its implementation methods. Industry practice groups transmission technologies into two core types: near-field systems leveraging inductive, resonant, or electric field coupling, and far-field approaches employing microwave/laser propagation. Operational range provides another key distinction—short-distance near-field versus extended-range far-field applications. Ultrasound-based energy transfer functions through fundamentally different physical mechanisms [6]. In the field of wireless charging of EVs, near-field wireless transmission is generally used as the main method of wireless charging. A typical wireless power transfer (WPT) setup can be seen in Figure 1.

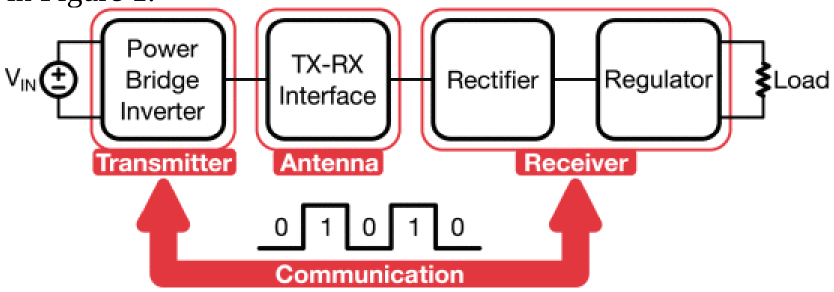

Fig. 1 Block diagram of a typical WPT system [7]

The system is powered by an input voltage source V_{IN}. A transmitter (TX), generally incorporating an inverter circuit, converts and delivers power to the receiver (RX) via an antenna interface. This antenna segment not only couples the TX and RX but also provides compensation and impedance matching functions. On the receiver side, a rectifier and voltage regulator are used to supply a stable output to the load. Optionally, a bidirectional communication link enables dynamic power adjustment based on both the receiver's requirements and the transmitter's available capacity [7].

Wireless charging employs two core electromagnetic principles. Electromagnetic induction-based charging operates by incorporating coils in both the transmitting and receiving units. An alternating current (AC) at a designated frequency is applied to the transmitter coil, which subsequently induces a corresponding current in the receiver coil. This process facilitates the wireless transmission of energy between the two components without physical contact [8]. While achieving high efficiency, for example, 85%, this method demands centimeter-scale even millimeter-scale positional precision.

Magnetic resonance wireless charging achieves extended operational range through synchronized resonant frequencies. Power from the grid is first rectified into direct current (DC), which is then fed into a high-frequency inverter to generate a high-frequency AC square wave. Once the resonant frequencies of both the primary and secondary coils are aligned, the system achieves resonance, enabling highly efficient energy transfer even over an air gap [9]. Transmitter and receiver coils resonating synchronously enable power transmission across 50 cm distances. Efficient charging can be maintained without perfect alignment.

It can be said that wireless charging technology provides a convenient and safe way to charge EVs, but it also faces challenges such as low efficiency, high cost and standardization.

2.2. Current Status Of Wireless Charging Applications for EVs

At present, there are two mainstream wireless charging methods for EVs, one is MCI-WPT and the other is MCR-WPT. MCI-WPT can achieve high power transfer efficiency, but has strict space requirements. It requires very close distances (centimeter-level) and precise alignment, making it difficult to use in real life. On the other hand, MCR-WPT can handle position changes better than MCI-WPT due to its resonant coupling method [6].

Wireless charging technology has been implemented commercially by leading automakers. Genesis offering it as an option on the GV60 and eG80 BEV models, Hyundai having provided it optionally for the Ioniq, and BMW featuring it in a limited-time offering for the 530e [10]. It can be seen that EV wireless charging technology is gradually being implemented.

Many countries around the world have also included wireless charging in their new EV infrastructure planning. For example, China's "New Energy Vehicle Industry Development Plan (2021-2035)"; Regulatory bodies in Europe and North America are catalyzing wireless charging commercialization through fiscal incentives and mandated SAE J2954 compliance, accelerating market-ready deployment.

In February 2025, BYD Company Limited secured a patent addressing critical limitations in wireless charging systems. This patent improves energy transmission efficiency and it will also reduce the requirement for position error during use. It makes commercial value higher [11].

On the basis of MCI-WPT and MCR-WPT, in addition to static wireless charging, there are some research directions that are dynamic wireless charging.

The Korea Advanced Institute of Science and Technology (KAIST) implemented inductive charging technology for EVs. In March 2010, the EVs they studied utilized dynamic wireless charging technology for charging. By 2013, South Korea had put into operation a 24-kilometer-long road equipped with dynamic wireless charging infrastructure. It is characterized by the fact that the put electric buses can be continuously charged while moving. It can reach 85% efficiency at 100 kW of power delivery [12].

A high-power dynamic wireless charging road system integrating “5G + autonomous driving” has made its debut in Changchun, Jilin in 2023. At the innovation base of FAW R&D Institute, an unmanned new energy vehicle glides smoothly along an internal road marked with special signs, while the dashboard inside shows that the vehicle is being charged. Stretching 120 meters, this high-power dynamic wireless charging road can provide enough electricity for new energy EVs to travel an additional 1.3 kilometers after driving over it [13]. The introduction of such a dynamic wireless charging road system signals that new energy vehicles can now achieve real-time wireless charging while on the move. Dynamic wireless charging technology can effectively reduce people's battery life anxiety.

Researchers continually optimize dynamic wireless charging systems to overcome real-world implementation challenges. They embed transmitter coils directly into roadways, enabling continuous power delivery to moving EVs. It can dynamically regulate power flow through real-time impedance matching networks to maintain stable charging during acceleration or lane changes [14].

3. Current Major Research Hotspots

3.1. Magnetic Coupling Resonant Wireless Power Transmission System

The magnetic coupling resonant wireless power transmission system primarily enhances the charging efficiency and distance during wireless charging of electric vehicles. Based on the magnetic resonance principle, magnetic coupling resonant wireless charging technology achieves wireless energy transmission through a resonator. It primarily consists of a high-frequency power module, an impedance matching circuit, a transmitting coil, a receiving coil, and a receiving-end power management module. When the transmitting coil and the receiving coil operate at the same frequency, resonance occurs between them. The energy obtained by the receiving coil is rectified by the power management module, and the output current energy is then available for the load, thus achieving wireless charging. Additionally, to maintain the circuit in a resonant state, resonant compensation networks are incorporated between the transmitting coil and the inverter circuit, as well as between the receiving coil and the rectifier circuit. Therefore, with the addition of resonant compensation networks, magnetic coupling resonant technology exhibits higher transmission capacity and efficiency compared to electromagnetic induction technology. Its basic structure is shown in Figure 2 [15].

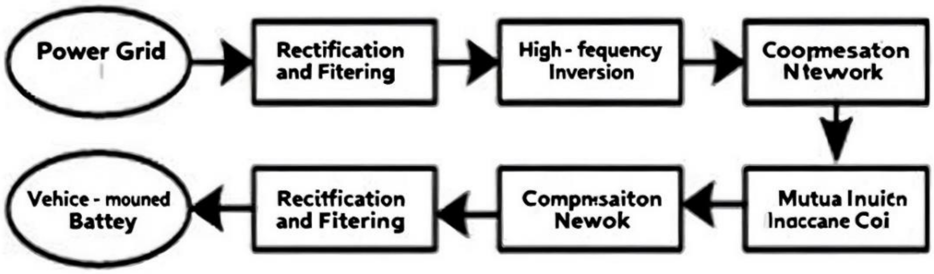

Fig. 2 Magnetic coupling resonant wireless charging system for EVs [15]

There have been new research breakthroughs in addressing the main issues currently facing this technology. Through optimizing the coil and shielding mechanism, the coupling coefficient of the coil has been improved within a certain range, thereby enhancing the transmission efficiency of the system. At the same time, a maximum efficiency tracking control strategy based on active impedance matching has been designed, achieving decoupling between load and transmission efficiency. This strategy enables real-time identification of the coupling coefficient and impedance matching for tracking control to achieve the maximum efficiency point. The maximum efficiency point has been found and achieved, as shown in Figure 2, while maintaining a constant output voltage [16].

In terms of metal foreign object detection in wireless power transmission (WPT), there are currently three main methods. The first is a sensor-based foreign object detection method. In 2019, Timothy Sonnenberg and colleagues from North Carolina State University in the United States proposed a method based on a real-time thermal imaging-based foreign object detection and living body protection combined system, which is used to detect foreign metal objects and living organisms during WPT. It uses a single sensor, namely the FLIR Lepton thermal imager, which has both foreign object detection and living body protection capabilities, and can ignore objects that pose no threat to the WPT system [17].

The second method is a system parameter-based foreign object detection method. However, this method has some obvious disadvantages. It can only detect when the system is in operation, and it is not sensitive to small metal foreign objects during high-power WPT. Therefore, its use is still limited. The third method is an auxiliary coil-based foreign object detection method. The basic principle is that when there are some metal foreign objects near the system, the magnetic field generated by the auxiliary coil installed on the surface of the transmitting coil or receiving coil will couple with the eddy currents inside the metal. By detecting changes in parameters such as the equivalent impedance and quality factor of the coil, the voltage and current of the detection circuit are altered. Once the change exceeds a set threshold, it can be determined that a foreign object is present, and the charging device can be stopped or not started. Compared to the second method, it has higher sensitivity and more accurate detection of foreign objects. The schematic diagram is shown in Figure 3 [17].

3.2. Research on an Automotive Wireless Charging System Based on ESP32

EPS32 is a low-cost, low-power WIFI and Bluetooth dual embedded system-on-chip (SoC) with strong data processing and computing capabilities. Zhang Chi and others have improved and optimized the coils and circuits of the transmitting and receiving ends based on the wireless charging system of STM32 and ESP32. They designed a new full-bridge inverter circuit (see Figure 3), wrote a program, constructed the corresponding circuit, and designed a new wireless charging system. This system can achieve high-frequency power transmission, elegant rectification, remote control, and other functions. It operates stably in various environments and possesses good safety and intelligence [18].

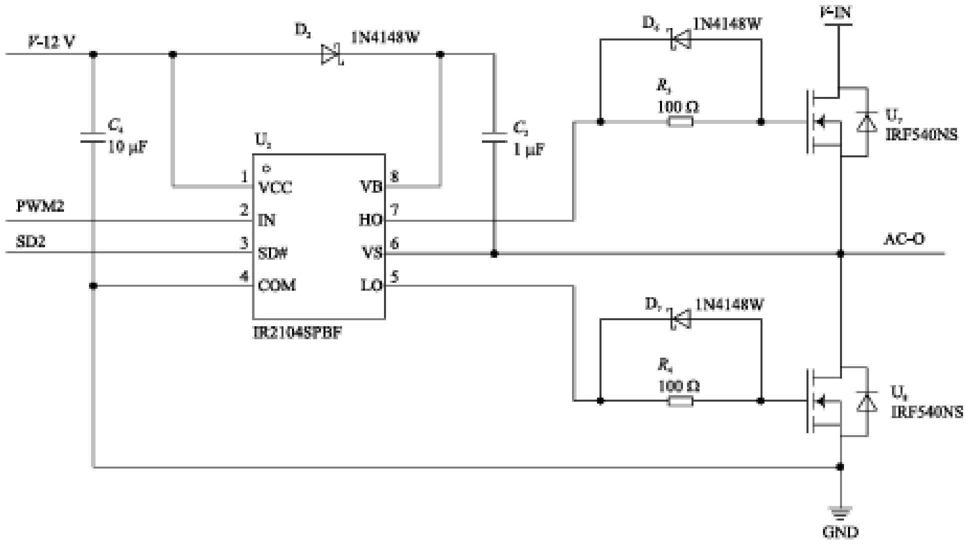

Fig. 3 Full Bridge Inverter Circuit [17]

3.3. Application of Millimeter-wave Radar Dynamic Monitoring Technology in the Field of Wireless Charging for EVs

Millimeter-wave radar dynamic monitoring technology utilizes millimeter waves as the detection medium, transmitting and receiving reflected signals to achieve real-time perception and dynamic tracking of target information such as distance, speed, and azimuth. The wireless charging highway developed by Tsinghua University in collaboration with the State Grid Corporation of China adopts this technology. The millimeter-wave radar can monitor the relative position of vehicles and the built-in charging coils on the road in real time, guiding vehicles to maintain their position in the optimal charging area, ensuring efficient coupling for wireless charging and reducing energy loss. It can also automatically adjust the charging power when severe weather conditions such as rain and snow occur, ensuring the continuity and safety of charging.

In terms of motion detection and foreign object detection for this radar, Tian Yong and his team have studied a multi-target moving foreign object detection and trajectory tracking method based on 77GHz millimeter-wave radar. They analyzed the principles of distance, speed, and angle measurement using frequency-modulated continuous-wave radar, elaborated on the multi-target moving object detection and trajectory tracking algorithm, verified its effectiveness through simulation experiments, and obtained the actual trajectories and results of five experimental targets through experiments. It was found that the maximum tracking error for each target occurred in the initial stage, and the tracking error generally showed a downward trend over time, stabilizing after decreasing to a certain extent. When a new tracking target appeared, the radar could still track it, and after a period of time, the tracking error could be reduced to a lower level, solving this difficult problem [19].

4. The Introduction of Wireless Charging Standards

The formulation of wireless charging standards is of great importance in various aspects, which can enhance safety and reliability, ensure device interoperability and promote the efficiency of charging. Under the modern setting, the major international standards include: the International Electrotechnical Commission (IEC), the Society of Automotive Engineers (SAE) and the International Standardization Organization (ISO), and SAE J2594 is the most acceptable standard internationally [20]. The table 1 shows the development of the wireless charging standard for EVs. For these standards, they establish the norms of wireless charging and define the standard of serious angles: safety, compatibility, minimum requirement and power [21].

Table 1. The timetable of the development of wireless charging [20]

Organization	Standard number	Date	Description
SAE	J2954	2022	Wireless Power Transfer for Light-Duty Plug-In/ Alignment
	J2847/6	2019	Communication between Wireless Charged Vehicles and Plug-In electric vehicle
IEC	IEC 61980−1:	2020	Electric vehicles wireless power transfer systems-Part 1: General requirements
	IEC TS 61980−2	2023	Electric vehicles wireless power transfer systems-Part 2: Specific WEV communication requirements
	IEC TS 61980−3	2022	Electric vehicles wireless power transfer systems-Part 3: Special requirements for magnetic field wireless charging system
ISO	ISO/IEC JTC 1	2022	Road vehicles — Vehicle-to-grid communication interface — Part 20: 2nd generation network and application protocol requirements
	ISO 19363: 2020	2020	Electrically propelled road vehicles - Magnetic field wireless power transfer - Safety and interoperability requirements

In China, the most popular standard is GB/T 38875, which was published in 2020. It contains sort, communication, environment test, and structure modules, which are similar to other standards. And especially the safety module, which is extremely strict in electromagnetic radiation, and other safety hazards like overheating, circuit overload and other mechanical accidents [22][23].

5. Future development

5.1. High-power and Efficiency Electric Transfer

Nowadays, the common charging power of traditional wired charging for EV can be 30kw, 60kw, 100kw, 150kw and even 200kw, which is high enough for charging and with high efficiency [22]. However, for wireless charging, the transfer ability is limited to a very low range and only about 30kw. To overcome this, main researchers are attempting to enhance the magnetic coupling between transmitting coils and receiving coils to improve transfer efficiency. It seems that when using the resonance of the near-field coil, which can realize high transfer efficiency between a huge air gap [24]. However, this method still needs to be perfected. In ensuring high transfer efficiency, more research should be conducted in this field in the future.

In other aspects, the material of the coil and the iron core are also of great importance. The demand for higher permeability material is still very huge nowadays. The Ni-Zn ferrite is the most common material these years. And in my opinion, the attempt to add Si, B, Nb and Cu with Fe to make nanoscale crystals is necessary. Nanoscale allays always have better performance than ferrite, which means higher magnetic induction intensity and lower loss of core. In addition, the choice of the number of coil turns and winding method is also very important, which needs to be analyzed based on specific situations.

5.2. Charging Method

The wireless charging methods of EV can be classified into near-field charging, medium-field charging and far-field charging by distance, which are all static charging methods, and the major method is near-field charging. Because the far and medium field charging can not reach the highest efficiency. For example, the efficiency of radio wave charging is extremely low, between only 1% to 5%. The transmitting coil needs to be well designed to realize the rational utilization of electricity to expand the distance of wireless charging in the future.

Besides the static wireless charging, the dynamic wireless charging means while the vehicles run on the road, the transmitting coil and high voltage and frequency alternating current supply under the road will cause magnetic coupling with the receiving coil on vehicles then charge, which causes the needs of electromagnetic field will greatly reduced and solves the problems of restrictions on static charging locations effectively [25-27]. And in terms of economy, in my opinion, because the charging and discharging occur simultaneously, there is no need to use large capacity and volume batteries. The dynamic wireless charging can reduce the size of the battery instead of the expensive traditional EV to lower the cost.

There is also a Quasi-dynamic charging, which can deliver power when the car drives slowly or in a stop-and-go state, which will influence the normal driving of EVs and only special vehicles like buses are suitable. Thus, in the future, the QWC will have significant practical value and market potential, and should be further developed.

6. Conclusion

As a significant part of the smart transport system in the future, the wireless charging of vehicles is at a critical juncture, which is gradually moving from theory to practical and commercial application. This essay has systematically sorted out the current development, core challenges and future trends. The current major technology involves MCI-WPT and MCR-WPT. In commercial applications, BMW is the first to launch static wireless charging. Furthermore, the KAIST in Korea and the dynamic wireless charging in Changchun verify the possibility of dynamic wireless charging. The research hotspots focus on efficiency optimization, foreign objects detection and the integration of dynamic wireless charging. However, the limitation of transform efficiency, the efficiency reduction in remote transmission and the high cost of infrastructure construction remain problems. In the future, the primary directions for technological breakthroughs will include improving the power level of resonant coupling technology and expanding the coverage of dynamic wireless charging traffic networks, after which wireless charging technology is expected to revolutionize EV energy replenishment paradigms, serving as a pivotal technological enabler for intelligent transportation systems and carbon neutrality objectives.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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