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Research on Design and Optimization of Wireless Charging Circuits for Electric Vehicles

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Abstract: Recent years have seen heightened global focus on energy shortages and carbon emissions, driving the shift to low-carbon and environmental protection. Despite efforts, carbon emission growth remains a challenge for a low-carbon economy. Electric vehicles (EVs), due to their low-carbon benefits, have seen rapid adoption worldwide. However, issues like limited driving range, long charging times, and inadequate charging infrastructure hinder EV development. Dynamic wireless charging technology for EVs offers potential solutions. It introduces Wireless Power Transfer (WPT) for EVs, addressing charging issues and enhancing range, albeit with challenges in efficiency and cost. This article reviews the research history and principles of wireless charging, analyzing advancements in both static and dynamic wireless charging for EVs globally. Future research should focus on integrating advanced materials, machine learning algorithms, and multi-objective optimization techniques to further improve the efficiency, cost-effectiveness, and scalability of dynamic wireless charging systems for EVs. Significant achievements have been made in improving electromagnetic efficiency, reducing resistivity, and enhancing anti-misalignment. Optimization schemes like fan-shaped annular guides, bipolar guides, secondary-side resonance, and rectangular coils have been introduced to further enhance performance.

Keywords: System Optimization, Dynamic Wireless Charging, Electric Vehicles

1. Introduction

In recent years, energy shortages and carbon emissions have garnered significant attention from countries worldwide, making "low-carbon and environmental protection" a global consensus. However, the current growth rate of carbon emissions has not shown notable improvement, posing severe challenges for humanity's transition to a low-carbon economy. Traditional vehicles consume a substantial portion of total petroleum consumption, prompting electric vehicles (EVs) to emerge as a key area of focus and active promotion by various countries due to their low-carbon and non-polluting advantages [1].

Consequently, the global EV ownership has seen rapid growth. During this promotion process, problems like short single-charge driving distances, charging times, and inadequate charging infrastructure have emerged as critical bottlenecks hindering EV development. The proposal of dynamic wireless charging technology for EVs offers new solutions to these problems. The application of Wireless Power Transfer (WPT) technology in EVs introduces wireless EV charging, providing a promising direction for addressing EV charging issues. EV wireless charging can be

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divided into static wireless charging and dynamic wireless charging. Compared to static wireless charging, dynamic wireless charging can significantly enhance EVs' range, but its implementation is more challenging due to efficiency and cost considerations.

Therefore, this article introduces the research history and principles of wireless charging. It analyzes the domestic and international advancements in both static and dynamic wireless charging for EVs.

2. Fundamental Analysis of Wireless Charging Systems

2.1. General Structure and Classification of Wireless Charging Systems

2.1.1. Dynamic Wireless Charging

Dynamic Wireless Charging (DWC) is a pioneering wireless charging technology which is designed to function while a car is moving, addressing the prevalent Range anxiety pertaining to electric cars. Leveraging the principle of magnetic field coupling, DWC enables the seamless transfer of electric energy from charging equipment to a moving vehicle without requiring a halt, thereby enhancing charging convenience and potentially bolstering the driving distance of electric cars. This innovation could diminish the dependency on extensive charging station infrastructure [2].

However, a persistent challenge in DWC lies in the continuous variation of the mutual inductance between the receiving coils and transmitting coils as the vehicle is in the motion, causing fluctuations in charging power. Additionally, the technology currently faces obstacles in terms of low charging efficiency, power instability, and overall performance.

Despite these hurdles, DWC holds immense potential for diverse applications. It can be utilized on highways, urban roads, and rail transit systems, providing uninterrupted power supply to electric and smart vehicles. Furthermore, this technology can be extended to mobile devices, drones, and other sectors, ensuring reliable energy support for extended operations. As technological advancements continue and costs decline, DWC is poised to emerge as a significant trend in the future evolution of the field of wireless charging.

2.1.2. Static Wireless Charging

Static wireless charging pertains to the non-contact transfer of electrical energy from a charging device to an electric vehicle or electronic device while it is stationary. This charging method primarily encompasses three categories: electromagnetic radiation, electric field coupling, and magnetic field coupling. Within magnetic field coupling, there are two subclasses: inductive and resonant charging. The inductive method, grounded in the laws of electromagnetic induction, necessitates close proximity between the devices. Conversely, the resonant method, leveraging the principle of magnetic resonance, allows for greater transmission distances and remains unaffected by non-magnetic obstacles in the environment. Research endeavors in static wireless charging are extensive, resulting in relatively high system efficiencies, with notable companies like Qualcomm and ORNL achieving efficiencies exceeding 95% [2].

However, static wireless charging also has its limitations. Primarily, the driving range after a single charge is constrained, posing challenges for extended travel. During long-distance journeys, frequent charging becomes necessary, potentially necessitating the use of rapid charging techniques, which may adversely impact the battery's lifespan. Consequently, the advent of quasi-static and dynamic wireless charging technologies is essential to effectively enhance the vehicle's driving range.

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2.2. Research Status of Dynamic Wireless Charging in China and Abroad

2.2.1. Research Status Abroad

In the field of optimizing electromagnetic coupling mechanisms, the University of Auckland (UOA) in New Zealand, the Korea Advanced Institute of Science and Technology (KAIST) in South Korea, and the Oak Ridge National Laboratory (ORNL) in the United States have conducted in-depth research. UOA proposed E-type and coaxial magnetic core structures for rectangular long-coil power supply rails, but these structures are significantly affected by lateral movement of the receiving end [3, 4].

Building on this, KAIST has continuously optimized its designs [5-7]. In 2009, they developed the Online Electric Vehicle (OLEV), with the first-generation product adopting an E-type magnetic core structure, achieving the efficiency of 80% at a transmission distance of 1 cm. In 2010, KAIST introduced the W-type magnetic core structure for the third-generation OLEV, significantly improving system transmission performance, reaching an efficiency of 83% at a 20 cm transmission distance. In 2013, a 24 km-long OLEV electric bus line equipped with a 100 kW dynamic wireless charging system was opened in Gumi City, South Korea [6]. Although KAIST subsequently proposed I-type and S-type magnetic core structures to further increase transmission gaps and reduce magnetic core width, the system's adaptability to lateral movement remains unsatisfactory under rectangular long-coil power supply rails [8, 9]. In 2016, ORNL designed a 6.6 kW dynamic wireless charging system for Toyota RAV4 electric cars and found that positional offsets between the receiving and transmitting ends significantly affected system output power [10].

In terms of control strategies of the whole process, which can be classified into transmitting-end control, receiving-end control, and bilateral control. KAIST proposed a transmitting-end constant current control strategy, which uses a DC/DC converter at the transmitting end to achieve constant current output from the inverter, thereby controlling output power [11]. The University of Tokyo (U-Tokyo) in Japan proposed a receiving-end control strategy, which estimates the coupling coefficient and controls the Buck converter on the receiving-end rectification side to achieve maximum efficiency control [12-14]. ORNL, on the other hand, proposed a bilateral control strategy that can simultaneously achieve constant power control and maximum efficiency control, but requires additional wireless communication.

In the area of power conversion topologies, KAIST proposed a power conversion scheme for the receiving end, employing series-series compensation, uncontrolled rectification, and interleaved parallel Boost converters to reduce individual power levels to meet the required output power [15].

Research on electromagnetic shielding is divided into active shielding and passive shielding [16-18]. Active shielding utilizes metals to suppress high-frequency electromagnetic interference, while passive shielding constrains the distribution of magnetic flux in space through ferromagnetic materials. KAIST and ORNL use low-permeability metallic materials for active shielding, but the eddy current effect in metals can generate losses. Passive shielding does not produce excess losses but has limited shielding effectiveness. KAIST improved its electromagnetic shielding performance by inserting periodic metals into ferromagnetic oxide plates [18].

Apart from these universities and research institutions, many foreign automobile companies such as BMW and Mercedes-Benz have also conducted related research, but due to commercial confidentiality, relevant technical information has not been disclosed [19].

2.2.2. Domestic Research Status

Research on dynamic wireless charging technology for electric cars in China started relatively late, with the main research efforts concentrated in higher education institutions and scientific research

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organizations. These institutions primarily focus on the optimization of electromagnetic coupling mechanisms, power conversion topologies, system modeling, control strategies, and electromagnetic shielding.

In terms of electromagnetic coupling mechanism optimization, Harbin Institute of Technology proposed a segmented power supply rail scheme with multiple primary windings in parallel, significantly enhancing the performance of the charging system [20]. Southeast University, on the other hand, analyzed the impact of lateral movement of the receiving end on the dynamic wireless charging system and designed a segmented power supply rail for dual lanes, but did not provide a clear method for determining the width of the rail for power supply [21].

Regarding power conversion topologies, Southwest Jiaotong University, aiming to achieve high-power output for the wireless charging system, proposed a cascaded multilevel inverter based on the step wave phase-shifting synthesis method. By adjusting the phase-shifting angle and pulse width, continuous adjustment of output power can be achieved without the need for a DC/DC converter [22].

In system modeling, Chongqing University proposed a parameter identification theory and a load detection method based on energy transmission channels to address the difficulty in adjusting secondary side parameters during primary side control [23, 24]. Tianjin Polytechnic University established a mathematical model using coupled mode theory and derived the prerequisites for maximum efficiency power transmission [25].

In terms of control strategies, Southeast University analyzed the system's equivalent circuit at high frequencies, derived an expression for the resonant capacitor under maximum transmission efficiency, and achieved real-time dynamic tuning control by adjusting the trigger angle of the designed phase-controlled inductor circuit [26]. Tianjin Polytechnic University, on the other hand, analyzed the change in the natural frequency of the transmitting coils and receiving coils during movement and proposed a frequency tracking technique that can adjust the power factor of the transmitting end [11].

Regarding electromagnetic shielding, the Institute of Electrical Engineering of the Chinese Academy of Sciences analyzed the eddy current loss in the vehicle chassis during the operation of the wireless charging system and proposed adding MnZn ferrites with high magnetic permeability and low electrical conductivity between the receiving coil and the car chassis to reduce eddy current loss [27].

Apart from these universities and research institutions, companies such as ZTE and State Grid have also actively participated in related research and development efforts. For example, ZTE New Energy Automobile Co., Ltd., in collaboration with State Grid Chengdu Branch, developed an EV dynamic wireless charging system with a maximum charging current of 50A and a maximum output power of 20kW [28].

3. Application and Optimization Analysis of Dynamic Wireless Charging Systems for Electric Vehicles

3.1. Application Scenarios

Currently, the majority of application scenarios for dynamic wireless charging primarily revolve around public transportation systems. The fundamental operating principle involves transmitting electrical energy, generated by high-frequency alternating magnetic fields, from underground power supply rails to energy-receiving equipment mounted on vehicles traveling along designated tracks on the ground. This process effectively recharges the vehicle's battery, thereby extending its driving range and prolonging battery life.

In May 2017, Qualcomm Halo established a 100-meter-long demonstration system for electric bus dynamic wireless charging in Versailles, France. This system achieved a speed of 100 km/h and the power output of 20 kW, utilizing a DD-type coil on the secondary side. This demonstration route is now close to commercialization. In China, a landmark achievement was made in 2015 when Chongqing University, in collaboration with Guangxi Electric Power Research Institute, constructed the country's first dynamic wireless charging line for electric vehicles in Guangxi. This 100-meter-long line boasts a maximum system output power of 30 kW and an on-the-go power supply efficiency of 75%. In 2018, Chongqing University partnered with State Grid to build another dynamic wireless charging line in Tongli, Jiangsu, specifically for demonstrating the technology in conjunction with autonomous vehicles. This system offers an output power of 11 kW and spans a length of 400 meters. Utah State University (USU) spun off the startup company WAVE to develop and commercialize IPT technology for electric buses. This technology achieves a charging performance of 50 kW power and 25A at 20 kHz by embedding the primary transmitting coil in the road, with a corresponding receiving coil on the bus, enabling significant power transmission over a larger air gap. The German manufacturer AKASOL has produced a water-cooled lithium-ion battery pack tailored for buses, as part of the PRIMOVE IPT electric bus project. This project is scheduled for implementation in Berlin, Germany, and Brussels, Belgium. More recently, in 2023, the Oak Ridge National Laboratory in the United States successfully demonstrated a high-power 200 kW dynamic wireless charging system for electric cars. This system enables vehicles to travel 10 kilometers after charging for just 1 kilometer, even at high speeds, thereby significantly reducing the proportion of electrified roads required to maintain electric vehicle power [29].

3.2. Comprehensive Optimization Methods

3.2.1. Research on Rail Improvement

Zhu Guofu, from Wuhan University of Technology, conducted an exhaustive analysis on the switching strategy for system rails, particularly focusing on the substantial mutual inductance fluctuations within the switching zone. By comparing the mutual inductance-displacement characteristics when 1 to 4 transmitting coils were powered concurrently, he discovered that utilizing a dual-transmitting coil power supply mode could markedly decrease system losses and stabilize mutual inductance fluctuations. On this basis, he introduced two charging modes within the switching zone and a comprehensive rail activation/deactivation strategy, ensuring the system's swift adaptation to changes in the spatial position of the receiving coil during testing. To tackle the steep decline in mutual inductance observed in curved rails, Zhu Guofu delved deeper into the relationship between mutual inductance fluctuations and the radius of curved rails, ultimately proposing a fan-ring curved rail structure. This innovative design can seamlessly adapt to any curve radius without significant alterations to the transmitting coil's structural parameters. A comparative analysis between the new structure and an enhanced curved rail design revealed that within the curved rail's switching zone, the fan-ring structure significantly mitigated mutual inductance fluctuations and power output variations. Notably, at the switching zone's center, mutual inductance fluctuations decreased by approximately 8.25%, and power output fluctuations were reduced by about 10.35%. To validate the efficacy of this improved structure, Zhu Guofu established an experimental setup for a curved dynamic wireless charging system. He evaluated the optimal load of the coupling mechanism, output power to vehicles, and transmission efficiency for both the original and improved curved rails. Experimental results indicated that at the center of the curved rail's switching zone, the fan-ring curved rail structure, compared to the pre-improvement structure, boosted output power by 41.24W, enhanced transmission efficiency by 7.55%, and minimized output power fluctuations and transmission efficiency drops across the entire switching zone. These findings unequivocally underscore the effectiveness and superiority of the refined structure [30].

Shi Yuntong, from China University of Mining and Technology, conducted an extensive investigation into the challenge of output power instability stemming from mutual inductance

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fluctuations during guideway-based dynamic wireless charging. To tackle this issue, he devised a solution that integrates a dual-polarity primary transmitting coil, a combined secondary receiving coil, and a dual-output circuit structure. This innovative design drastically minimizes mutual inductance variations when the secondary coil moves across the junctions of segmented guideways. Furthermore, Shi introduced a novel topology capable of seamlessly switching between constant current (CC) and constant voltage (CV) modes. Notably, in this topology switching circuit, there exists a 180° phase shift in AC voltage across the equivalent resistance before and after the switch. However, in wireless power transfer systems, the secondary receiving circuit typically includes a rectification stage in series, converting the AC voltage across the load's equivalent resistance to DC before powering the load. Consequently, the 180° phase shift in AC voltage does not impact the overall system's operation. Initially, Shi provided an overview of common compensation topologies in wireless charging systems and conducted a thorough analysis of the application of LCCL-LCCL and LCCL-S topologies in dual-output circuits. His findings indicate that the system's output power remains stable when dual receiving coils are employed on the secondary side and the total mutual inductance between them and the primary coil remains constant. Additionally, Shi established a mathematical model for the magnetic coupling mechanism, laying a solid theoretical foundation for subsequent optimizations. Subsequently, Shi conducted a detailed examination of the transmission characteristics of the wireless charging system in both CC and CV modes, exploring the influence of compensation inductance on the output characteristics of the LCCL topology under resonant conditions. He also proposed a new topology switching mechanism for CC and CV. At the junctions of single-polarity long guideways, the opposite current directions in the parallel coil segments cause the generated magnetic fields to cancel each other out. Conversely, in dual-polarity long guideways, the current directions at the same position are identical, preventing magnetic field cancellation. Therefore, dual-polarity long guideways utilize wire resources more efficiently compared to single-polarity designs. Utilizing the mutual inductance coefficient per unit length of wire as the primary optimization metric, Shi meticulously designed the secondary magnetic coupling mechanism, determining the optimal size ratio for the secondary combined coil. He further refined the coil sizes of the primary and secondary magnetic coupling mechanisms using the mutual inductance change rate at the junctions of long guideway coils as another crucial optimization metric. Ultimately, Shi derived the optimal size parameters for the magnetic coupling mechanism [31].

3.2.2. Research on Coil Improvements

Dong Yifan from Jiangnan University conducted an in-depth analysis of dynamic wireless charging systems for electric cars and compared different power supply schemes for segmented EV dynamic wireless charging systems. Starting from the mutual inductance circuit model of a two-coil series-series (S-S) configuration in static wireless charging systems, he theoretically derived the multi-transmitter coil S-S mutual inductance circuit model for segmented dynamic wireless charging systems and obtained an expression for transmission efficiency. By analyzing this expression, he identified the issue of mutual inductance changes due to lateral displacement of the receiving coil and decided to address it through coil design optimization. To optimize the coil design, Dong Yifan conducted in-depth analysis and simulation studies on four optimization factors and horizontal offset characteristics of the coil. Based on this, he optimized the coils for segmented EV dynamic wireless charging systems. To further understand the impact of coil size parameters on mutual inductance, he derived an expression for the mutual inductance between rectangular coils. According to the findings of horizontal offset characteristics, he analyzed the power-on modes of the transmitting coils in segmented dynamic wireless charging systems and determined a power-on scheme with two transmitting coils in series. Subsequently, he analyzed the equivalent circuit representation for wireless power transmission. (WPT) system with two transmitting coils in series and simulated the

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charging process, verifying the effectiveness of the dual-coil series power-on scheme. To tackle the problem of lateral replacement of the receiving coil, Dong Yifan optimized the design of the transmitting coil using mutual inductance analysis to ensure stable mutual inductance and transmission efficiency during lateral displacement. He adopted an S-S topology with only the secondary side resonating to reduce output power fluctuations caused by lateral displacement of the receiving coil. Simulation results validated the optimization effects on mutual inductance, transmission efficiency, and output power [32].

In addition, scholars from Jilin University proposed a segmented EV dynamic wireless charging system that comprehensively considers power pulsation and efficiency optimization. They analyzed three major factors affecting system power pulsation and efficiency: coil structure selection, coil parameter design, and coil power-on strategy selection. These factors can be further divided into coil design and compensation circuit design. Through analysis, they found that simultaneously exciting two coils is the optimal power-on strategy as it keeps both branches of the compensation circuit in resonance. With mutual inductance within the transmitting coils, powering two or more coils simultaneously prevents all powered branches from achieving resonance. Furthermore, the scheme of powering two coils simultaneously reduces thermal losses in the main coils and compensation circuits, improving system efficiency. Therefore, they chose a system design with rectangular coils on both the transmitting and receiving sides, and a scheme to power two coils simultaneously. After completing the design, they simulated the coil and circuit models, including the mutual inductance pulsation curve varying with position between the powered transmitting coil and the moving receiving coil, and the power pulsation curve plotted using a combined field-circuit method. Simulation results showed that the system achieved a power pulsation of about ±3% in the middle section, with a maximum efficiency of about 90.7%. Based on this model, they built an experimental prototype, and the results showed that the experimental waveforms closely matched the simulation waveforms, with a middle section power pulsation of ±3.97%, an average efficiency of 90.77%, and a maximum efficiency of 91.26%. The system achieves high efficiency while maintaining low power pulsation, and features a simple coil structure with identical component parameters in each branch, demonstrating certain advantages. A simulation was conducted to model the transmission characteristics of a magnetically coupled resonant wireless power transfer system that incorporates an advanced LCC-LCC compensation network of higher order. The simulations indicated that it has a constant current characteristic and can prevent short circuits on the transmitting side under significant misalignment or no-load conditions. A comparative simulation study was carried out to assess the misalignment resistance of three distinct topologies: S-S, LCC-S, and LCC-LCC. The findings revealed that the LCC-LCC topology exhibits the least variation in efficiency when subjected to misalignment, rendering it ideal for dynamic wireless charging systems. To identify the optimal coil structure for such systems, typical coil misalignments were categorized and analyzed using COMSOL finite element simulations. The results indicated that both circular and rectangular coils are insensitive to angular misalignment, with horizontal misalignment being the primary factor. Despite having lower mutual inductance values compared to circular coils, rectangular coils demonstrate lesser fluctuations in mutual inductance under horizontal misalignment, suggesting superior misalignment tolerance. Utilizing the electromagnetic transient program algorithm, the switching process of the lumped dynamic wireless charging system was modeled and simulated. The results highlighted that the hard-switching approach could result in hazardous voltage spikes during the switching phase, whereas the soft-switching strategy efficiently minimizes system impacts and ensures overall system safety. The switching strategy during dynamic wireless charging was studied, and simulations showed that the dual-coil power supply strategy can effectively reduce mutual inductance and power fluctuations during switching, improving system stability. For the issue of significant current impact on the secondary side during switching, simulations were conducted to

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study control methods for optimizing switching phases and positions. The results indicated that to ensure maximum transmission performance, the voltage phase on the primary side should always be consistent during coil switching, and a switching region that reduces output voltage fluctuations was identified [1].

4. Conclusion

From the above analysis, this paper can conclude that although research on dynamic wireless charging has developed rapidly, with operational public transportation systems emerging in some cities both domestically and internationally demonstrating its feasibility, various research institutions worldwide have conducted extensive studies on modeling, coils, and guides. Significant achievements have been made in improving electromagnetic efficiency, reducing resistivity, and enhancing anti-misalignment capability. Additionally, this paper introduces several optimization schemes for coils and guides: the use of fan-shaped annular guides can significantly increase transmission efficiency, while bipolar guides can effectively reduce fluctuations. For coils, utilizing secondary-side resonance and rectangular coils can optimize efficiency.

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