Proceedings of the 4th International Conference on Mathematical Physics and Computational Simulation
DOI: 10.54254/2753-8818/2026.33622

# *Research and Development of Magnetic Coupling Resonant Wireless Charging for Electric Vehicles*

**Shaotong Zhou**

*Department of Physics, Guizhou University, Guiyang, China*
*mm.stzhou23@gzu.edu.cn*

***Abstract.*** At present, the world is vigorously promoting the development of the electric vehicle industry. As a key technology in the field of electric vehicle energy replenishment, wireless charging technology has received extensive attention from the academic and industrial circles. The research on improving the charging efficiency of wireless charging technology has become a hot spot in the field. In this paper, the development history of the magnetic coupling resonant structure is reviewed. The traditional DD coil, DDQ coil, D4 coil, D4 Q magnetic coupling structure, cooperative coil wireless charging system, integrated Boost active bridge power converter, and other typical structures are systematically introduced and compared. The advantages and disadvantages of various technical schemes are summarized, and the future development trend of wireless charging technology is prospected. The research results can provide reference and guidance for the development and application of subsequent wireless charging technology. This research not only provides theoretical support for optimizing existing wireless charging systems but also offers direction for the innovative design of future high-efficiency magnetic coupling mechanisms.

***Keywords:*** Electric vehicle, wireless charging electromagnetic, coupling resonance

## 1. Introduction

At present, the electric vehicle industry is developing rapidly, and charging technology has become the core link restricting the development of the industry. Traditional conductive charging has problems such as interface wear, inconvenient plug-in, and poor safety of harsh night scenes. Wireless charging technology is increasingly widely used, and electric vehicle wireless charging is also gradually promoted. How to improve its charging efficiency has become a major challenge. The coupling mechanism determines the magnetic field transmission capacity and is the core carrier of efficiency improvement. DD coil structure has been proposed by predecessors, and based on this structure, DDQ coil, D4 coil structure and so on have been extended, but there is still room for improvement in charging efficiency. On this basis, this paper designs a new structure to further improve charging efficiency and anti-offset ability. How to design a new coupling structure to improve efficiency and anti-offset ability has become the focus of the moment. This paper focuses on the development history of the magnetic coupling structure of the wireless charging system for electric vehicles, introduces the development process of various magnetic coupling structures such

DOI: 10.54254/2753-8818/2026.33622

as DD, D4 coils, and analyzes their advantages and limitations. This paper summarizes the experience and discusses the design direction of the new structure, which plays a guiding role in the future development of wireless charging technology. This paper aims to summarize and analyze how to further improve the charging efficiency and anti-offset ability, so as to help promote the application and popularization of wireless charging technology for electric vehicles.

## 2. Wireless power transmission and magnetic coupling structures

Wireless power transmission is to convert electric energy into other forms of relay energy through the transmitter, such as electromagnetic field energy, laser, microwave and mechanical wave. After a certain distance of transmission, the relay energy is converted into electric energy through the receiver to realize the wireless transmission of electric energy. The magnetic coupling structure is the core component of the wireless power transfer (WPT) system. The essence is to use the magnetic field as a medium to achieve contactless energy transfer between the transmitter (primary) and the receiver (secondary). The magnetically coupled resonant system can be equivalent to a mutual inductance circuit model. Common compensation circuit topologies include low-order and high-order compensation circuit topologies. Among them, the low-order basic compensation circuit topology: series-series (SS) type, series-parallel (SP) type, parallel-series (PS) type, and parallel (PP) type; high-order compensation circuit topology : double LCC type, LCC-S type, double LCL type.

## 3. Current status of research on wireless charging technology for electric vehicles

In 1964, William Brown successfully used wireless technology to charge model aircraft to verify the feasibility of wireless charging technology, which opened the prelude to the development of wireless charging technology [1].

The Boys team of the University of Auckland proposed the DD coil structure for the first time [2], which adopts the classical SS compensation topology. The DD coil is composed of two D-type coils side by side, with a common edge in the middle. It produces a strong magnetic field in the horizontal direction, rather than the vertical magnetic field of the traditional circular coil, and the lateral anti-offset ability is much higher than that of the traditional circular coil. This scheme creatively proposes a new coil structure, which solves the problem of poor anti-offset ability of the traditional circular coil, solves the anti-offset problem of the wireless charging system, and lays a theoretical foundation for the wireless charging system. It is a milestone in the development of static and dynamic wireless charging technology for electric vehicles. All high-performance coils such as DDQ, BP, and D4 are improved on the basis of DD coils. This lays the foundation for the wireless charging coupling structure.

Later, the Covic team proposed the DDQ coil structure [3]. The structure adds a Q coil to the DD coil, which is perpendicular to the DD coil to generate a vertical magnetic field, which is responsible for lateral anti-offset. The two coils are decoupled from each other and do not interfere with each other. Compared with the DD coil, this structure solves the pain point of its poor lateral anti-offset ability, and designs an omnidirectional anti-offset coupling mechanism, which realizes the omnidirectional high anti-offset of wireless charging for electric vehicles for the first time. It is a key turning point for static wireless charging from laboratory to commercialization, which directly lays the industrial standard for wireless charging of modern electric vehicles, and has a profound impact on the subsequent development of wireless charging of electric vehicles.

DOI: 10.54254/2753-8818/2026.33622

Based on the above two structures, Sun proposed a D4 coil structure to improve the coupling efficiency [4]. Double-to-Double (D4) coil is a high-performance magnetic coupling structure for wireless charging of high-power electric vehicles. Its core design is double-layer orthogonal DD coil stacking. The structure is composed of two mutually perpendicular DD coils, which are stacked up and down. The mutual inductance decoupling between coils is realized by orthogonal layout, which effectively avoids magnetic field interference and energy loss. Compared with the traditional single-layer DD coil, the D4 structure significantly improves the coupling coefficient through the superposition of double-layer magnetic fields, and can still maintain efficient transmission under the condition of large air gap of 200-230 mm. Its unique quadrupole magnetic field distribution endows it with strong anti-offset ability, which can maintain stable output in a wide offset range of ± 300 mm laterally and ± 400 mm longitudinally. It has both high power density and excellent dynamic adaptability. It is one of the mainstream solutions to solve the problem of wireless charging efficiency attenuation under high power, large spacing and complex parking scene. It further improves the efficiency of wireless charging and promotes the commercialization of wireless charging technology.

At present, Xu Xianfeng 's team is based on the D4 structure. In order to further improve the wireless charging efficiency and anti-offset ability, an asymmetric D4 Q coil structure is proposed [5]. The asymmetric D4 Q magnetic coupling structure adopts the asymmetric layout of the double-layer orthogonal DD (D4) at the transmitting end and the DDQ coil at the receiving end. Compared with the traditional symmetrical D4 structure [6], the orthogonal Q coil is introduced at the receiving end to realize the magnetic field complementarity, which effectively makes up for the problem of insufficient lateral anti-offset ability of the D4 structure. The structure can maintain efficient and stable transmission in a large air gap of 230 mm and a wide offset range, and has higher space utilization. It is more suitable for high-power, space-constrained electric vehicle wireless charging scenarios. Compared with the traditional D4 structure, this structure significantly improves the charging efficiency and anti-offset ability. The maximum output power of the asymmetric D4Q magnetic coupling structure increases by 60.34 %, and the maximum transmission efficiency increases by 11 %. Significantly improve the transmission efficiency and space utilization under large air gap. The structure reduces the parking accuracy requirements, adapts to high-power, space-constrained vehicle scenarios, promotes the practicality and commercialization of wireless charging, and provides an important technical direction for the next generation of high-performance magnetic coupling mechanisms.

The above structure solves the problem of charging efficiency, but how to further enhance the anti-offset ability has become an urgent problem to be solved. Chongqing University of Technology proposed a cooperative coil wireless charging system [6]. Based on the traditional transmitting-receiving dual coils, the system adds additional auxiliary / relay / cooperative coils to form a multi-coil coupling structure. The purpose is to broaden the effective charging area, suppress the efficiency drop under offset, and improve the power stability of the dynamic scene. The core is to break through the physical limitations of the traditional single coil or fixed coil structure, and realize the intelligent and adaptive energy transmission through the dynamic coordination, time-sharing excitation and magnetic field reconstruction of the multi-coil array. The collaborative coil system reconstructs the design logic of the magnetic coupling mechanism. Traditional DDQ, D4 and other structures rely on fixed topology to achieve anti-offset. Although the performance is excellent, the flexibility is limited, and it is difficult to cope with complex scenarios such as random parking, chassis height difference and dynamic driving. Through the independent control of the array coil at the transmitting end, the magnetic field distribution can be adjusted in real time according to the

DOI: 10.54254/2753-8818/2026.33622

position of the receiving end, so that the coupling coefficient can be kept stable in the full offset range, and the problem of efficiency drop caused by parking deviation can be effectively eliminated. At the same time, the modular design of multi-coil reduces the dependence on high-precision alignment mechanism, improves the robustness of the system, and provides technical feasibility for scenarios such as dynamic wireless charging and multi-vehicle parallel charging. In addition, the coordinated control strategy can realize the on-demand distribution of power, avoid energy waste, and further improve the overall efficiency of the system. In line with the development trend of high power and high efficiency, the coordinated coil system significantly expands the applicable boundary of wireless charging. For static charging scenarios, its wide range and high fault tolerance characteristics reduce the difficulty of parking lot renovation and user operation threshold, and promote the popularization of household and commercial charging piles ; for dynamic wireless charging, the cooperative coil array laid along the lane can realize continuous power supply during vehicle driving, break through the mileage limit, and provide the underlying support for autonomous driving and intelligent transportation. At the same time, the modular coil structure facilitates mass production and maintenance, reduces deployment costs, and accelerates the technology from the laboratory to large-scale commercialization.

The Integrated Boost Active Bridge (IBAB) power converter proposed by the University of Auckland is a major innovation in the power electronics topology in the field of wireless charging of electric vehicles. This technology was proposed by the Covic / Boys team [7]. The core is to deeply integrate the Boost boost function with the active bridge inverter function, and innovatively integrate the current shunt function into the DD magnetic coupling mechanism, completely reconstructing the back-end topology of the traditional WPT system. The traditional WPT system needs to adopt a three-stage cascade structure of ' rectifier + Boost + DC / DC ', which has many devices, large loss and large volume. IBAB integrates rectification, boost and inverter functions, reduces the first-order power conversion, significantly reduces the conduction loss and switching loss, and increases the peak efficiency of the system to more than 94 %. Traditional BAB (Boost Active Bridge) requires two independent DC inductors. IBAB integrates the current shunt function into the central tap of the DD coil, and replaces the independent inductance with the magnetic coupling mechanism itself, so that the volume of the magnetic element is reduced by about 70 %, which greatly improves the power density of the vehicle end and solves the engineering problem of limited chassis space. IBAB has a wide voltage gain adjustment capability, and can achieve constant power and high efficiency output in the full offset range of coupling coefficient 10 % -30 % ( SAE J2954 standard ) without additional matching network. The introduction of integrated Boost active bridge ( IBAB ) not only solves the three major pain points of low efficiency, large volume and poor adaptability of traditional wireless charging system, but also reshapes the design boundary of power electronic topology with the innovative concept of magnetoelectric integration. It is a key milestone to promote the wireless charging technology of electric vehicles to be efficient, miniaturized and practical.

Guo Pifeng of Yangtze River University has studied the anti-offset characteristics of the coupling mechanism of the MC-WPT system of electric vehicles [8], and directly hit the parking offset of electric vehicles to affect the pain point of wireless charging. The LCC-S / bilateral LCC compensation MC-WPT system is taken as the research object, and a high anti-offset coupling mechanism is designed. The anti-offset research of Guo Pifeng 's team is based on engineering practice, taking into account performance and cost, effectively solving the core pain points of wireless charging, providing important support for the practical and popularization of technology,

DOI: 10.54254/2753-8818/2026.33622

and playing a positive role in promoting the upgrading of electric vehicle energy supply system in the future.

The concave-convex magnetic core + packet winding magnetic coupling mechanism proposed by Sun Yue, Dai Xin and Wang Zhizhi of Chongqing University [9], aiming at the problems of coupling coefficient attenuation and power fluctuation caused by longitudinal offset in wireless charging of electric vehicles, the magnetic core structure and coil winding method are optimized. The structure guides the magnetic flux path through the concave-convex core, enhances the uniformity of the longitudinal magnetic field, and cooperates with the grouped string winding coil to suppress the mutual inductance mutation during the offset, which significantly improves the longitudinal anti-offset ability of the system, while reducing the core volume and magnetic loss, to achieve high coupling, high efficiency, lightweight comprehensive performance. This research is based on engineering pain points, taking into account performance, cost and practicality, and plays an important role in promoting the practical and large-scale development of wireless charging technology for electric vehicles. It provides an important reference for the design of the next generation of high-performance magnetic coupling mechanism, and provides a low-cost and easy-to-implement engineering solution for static and dynamic wireless charging. Traditional coils (circular, DD ) are extremely sensitive to rotation offset. Once the vehicle is misaligned ( rotation angle > 15 ° ), the coupling coefficient will drop sharply, resulting in interruption of charging or a sharp drop in efficiency. Although DDQ can solve rotation, it has complex structure and high cost.

Aydin E 's team proposed a new scheme to design an orthogonal coil [10]. The transmitting end is composed of two fully decoupled rectangular coils that cross vertically and share the center. Using magnetic field orthogonality. No matter how the receiving end rotates, there is always one transmitting coil that maintains parallel coupling with the receiving end, and the other is decoupled due to the vertical magnetic field . The power supply of the two transmitting coils is switched in real time by the detection circuit to realize 360 ° dead angle energy transmission. The orthogonal coil is the most concise and efficient solution to solve the rotation offset after DD and DDQ, which provides a low-cost technical path for future non-inductive charging and random parking.

## 4. Analysis and outlook of wireless charging technology

At present, improving charging efficiency is the core issue that needs to be broken through in the development of wireless charging technology. The existing relevant literature provides a solid theoretical and technical reference for optimizing wireless charging efficiency and anti-offset performance. The traditional circular coil has the technical defects of large magnetic flux leakage and weak anti-offset ability. The research and application of DD coil effectively solves this pain point, which is an important technical innovation in the field of electromagnetic coupling mechanism of electric vehicle wireless charging. It lays a foundation for the development of modern electric vehicle wireless charging technology, and also derives a variety of new coil structures.

Through the combing and analysis of the existing research results, it can be seen that the adjustment of the relative size of the coil and the improvement of the quality factor Q value of the single coil have a significant impact on the wireless charging efficiency. Based on this, the peak range of output power can be further explored by optimizing the coil size; at the same time, the optimization design of the pole direction and the winding direction of the coil is carried out. Aiming at the problem of insufficient complementarity of the pole direction distribution of the bipolar magnetic field of the D4Q structure, the staggered reverse pole direction design is adopted, and the gradient magnetic field is constructed by means of the weak magnetic winding direction of the edge coil and the strong magnetic winding direction of the central coil, so as to improve the anti-offset

DOI: 10.54254/2753-8818/2026.33622

ability of the system and achieve a more stable magnetic coupling effect. Aiming at the problems of uneven magnetic field distribution and defects in structural design of wireless charging system with cooperative coils, multiple small cooperative coils can be used to replace a single large coil to construct a uniform magnetic field area, so as to greatly improve the anti-offset performance of the system. At the same time, combined with asymmetric design, the stability of mutual inductance is further improved. Aiming at the problem of low charging efficiency caused by magnetic flux leakage, the integrated design of collaborative coil and magnetic core can be realized to reduce magnetic flux leakage loss and improve coil coupling coefficient.

For the IBAB converter, there is still room for optimization of its magnetic flux leakage control performance. The magnetic flux leakage can be reduced by structural optimization. At the same time, based on the deep magnetic integration technology, the resonant inductance, leakage inductance and Boost energy storage inductance are integrated into the DD coil. In addition, the selection of soft magnetic materials with high permeability and low loss can effectively reduce the magnetic flux leakage and eddy current loss. The installation of electromagnetic shielding device can improve the concentration of energy transmission. Reasonable optimization of the vehicle chassis off-ground gap, within the scope of safety specifications to shorten the transmission distance of the transmitting and receiving coils ; with the adaptive compensation network, the system inductance is eliminated, the resonant working state is realized, the reactive power loss is reduced, and the multi-technical path synergy is used to further improve the overall performance of the wireless charging system.

At present, the research core in the field of wireless charging focuses on the optimal design of magnetic coupling structure to achieve the dual improvement of charging efficiency and anti-offset ability. The research and development of efficient coupling structure has also become the main development direction in the future. Wireless charging technology will continue to be iteratively upgraded in the direction of high efficiency and high anti-offset. Based on the existing technical research foundation, the design and research of high-performance magnetic coupling structure can be further carried out in the future, and the coupling mechanism with stronger anti-offset ability and higher charging efficiency can be developed to promote the industrialization and commercialization of wireless charging technology for electric vehicles. From the perspective of long-term development, wireless charging technology is expected to reconstruct the energy supplement system of new energy vehicles, reduce the excessive dependence of vehicles on battery capacity, effectively alleviate the user 's mileage anxiety, promote the upgrading of electric vehicles to the direction of intelligence and networking, and become the core support technology for the development of electrification and low-carbon in the future transportation field.

## 5. Conclusion

In this paper, the technical principles and performance characteristics of various magnetic coupling structures in the field of wireless charging of electric vehicles are systematically introduced and deeply analyzed. The technical path to improve the wireless charging efficiency and anti-offset ability is clarified, which provides a reference for the research and development of new coupling structures. It is of great theoretical and practical significance to promote the future development and commercial application of wireless charging technology.

Under the policy background of vigorously promoting the development of new energy automobile industry, the optimization and upgrading of magnetic coupling structure is very important to the popularization of wireless charging technology for electric vehicles. The magnetic coupling mechanism is the core component that determines the efficiency of wireless charging. The

DOI: 10.54254/2753-8818/2026.33622

development of a coupling mechanism with high efficiency and high offset resistance is the key research direction in the current field. In the future, it is necessary to further deepen the design and research of the coupling structure, continuously improve the wireless charging efficiency of electric vehicles through technological innovation, expand the application scenarios and scope of wireless charging technology, and help the sustainable and high-quality development of the new energy automobile industry.

## References

[1] Brown, W. C. (1965). Experimental airborne microwave supported platform (RADC-TR-65-188). Rome Air Development Center.
[2] Boys, J. T., Covic, G. A., & Green, A. W. (2007). Development and validation of a model for an inductive power transfer system. IEEE Transactions on Power Electronics, 22(3), 1000–1010.
[3] Covic, G. A., Boys, J. T., Kissin, M. L. G., et al. (2013). A bipolar primary pad topology for EV inductive charging. In 2013 IEEE Energy Conversion Congress and Exposition (ECCE) (pp. 3114–3121). IEEE.
[4] Sun, Y., Dai, X., & Wang, Z. H. (2015). A two-layer DD-type wireless power transfer coupling mechanism and its core design. Journal of Electrical Engineering, 30(19), 68–75.
[5] Xu, X. F., Wu, H. L., Yang, X. Z., et al. (2024). Optimization of magnetic coupling structures for wireless charging systems of electric vehicles under spatial constraints. Journal of Electrical Engineering, 39(12), 3581–3588.
[6] Liu, J. X., Li, Q. Y., & Liu, Z. F. (2020). Analysis of the influence of coaxial coils on dynamic wireless charging systems for electric vehicles. Journal of Chongqing University of Technology (Natural Sciences), 34(2), 57–63.
[7] Thrimawithana, D., Riar, B., & Kalra, G. (2020). Integrated boost active bridge based secondary inductive power transfer converter. IEEE Transactions on Power Electronics, 35(9), 9241–9251.
[8] Guo, P. F. (2020). A study on offset compensation in wireless charging for electric vehicles. Yangtze University.
[9] Sun, Y., Dai, X., Wang, Z. H., et al. (2026). Optimized design of the offset characteristics of the magnetic coupling mechanism in EV-WPT. Journal of Electrical Engineering, 41(2), 456–465.
[10] Aydin, E., et al. (2021). A novel orthogonal coil structure for 360° misalignment tolerance in WPT. IEEE Access.