A Review of Multi-Dimensional Wireless Power Transfer Technology

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Abstract. Wireless power transmission (WPT) technology has made significant progress in multidimensional charging, magnetic field optimisation and system safety in recent years. This review summarises the key technological breakthroughs made in the last decade in omnidirectional wireless charging, magnetic field uniformity improvement, complex environment adaptation, and innovative industrial and medical applications. The core implementations of omni-directional wireless charging technologies, including quadrature current control and dynamic phase regulation, are discussed, and the potentials and limitations of these technologies in supporting free-motion and multi-device simultaneous charging scenarios are analysed. Strategies to improve magnetic field uniformity and coil design optimisation techniques, such as folded coils, anti-offset design, and high-frequency resonance optimisation, are also explored, followed by evaluation of their transmission efficiency and interference immunity. To address the issues of system safety and adaptability to complex environments, this paper introduces electromagnetic safety standards, risk assessment frameworks and optimisation strategies applicable to metallic environments. Taking into account the current technological bottlenecks and future research directions, the prospects for innovative applications of wireless charging technology in industrial automation, medical implants and electric vehicles, such as AI-driven optimisation, application of new materials and global standardisation process, are further outlined. The aim of this paper is to provide a comprehensive technology review and research outlook for the further development of wireless power transmission technology.

Keywords: Wireless Power Transfer (WPT), Omni-Directional Charging, Magnetic Field Optimisation, System Safety and Standardisation, Industrial and Medical Applications

1 Introduction

Wireless Power Transfer (WPT) technology, as a non-contact electrical energy transmission technology, has realised a wide range of applications in several fields in recent years. Its core technology can be divided into three categories: magnetic field coupling, electric field coupling and microwave/laser transmission. Magnetic field coupling technology is based on the principle of electromagnetic induction or

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magnetic resonance, and is suitable for short-distance power transmission, applicable to consumer electronics, industrial equipment, medical implantation and other fields; electric field coupling technology carries out energy transmission through electric field induction, mainly for low-power, short-distance scenarios; whereas microwave/laser transmission utilises electromagnetic waves or laser beams to achieve long-distance energy transmission, which is applicable to special scenarios, such as space exploration, remote power supply and so on.

This paper systematically reviews the three core research directions of wireless power transmission technology in the past decade - multi-dimensional wireless charging, magnetic field distribution optimisation, and system security and standardisation. Multi-dimensional wireless charging technology achieves efficient charging in free-moving state through omni-directional magnetic field generation and dynamic adaptive mechanism; magnetic field distribution optimisation technology adopts structural optimisation and algorithm-driven design to improve magnetic field uniformity and transmission efficiency; and system safety and standardisation research involves the safety of electromagnetic radiation, the adaptability to complex environments, as well as the establishment of international unified specifications.

By combing the key technological breakthroughs in these fields, analysing their advantages and limitations in practical applications, and proposing future research directions, this review allows readers to have a comprehensive understanding of the latest progress, application scenarios and future development trends of wireless power transmission technologies, and provides a reference for research and development in related fields.

2 Research progress in omnidirectional wireless charging technology

2.1 Core methods for omnidirectional magnetic field generation

2.1.1 Quadrature current control: Conventional wireless energy transmission systems usually use identical current control, i.e., all coils have the same current amplitude and phase, with the limitation that they can only transmit efficiently in a specific direction.In 2014, Wai Man Ng et al. proposed and fabricated hardware prototypes of two-dimensional and three-dimensional omnidirectional wireless transmission systems for experimental testing to validate two-dimensional (2D) and three-dimensional (3D) omnidirectional wireless transmission system of non-identical current control methods.

The core of this innovative approach lies in adjusting the current amplitude, phase or frequency of different coils to generate a controlled rotating magnetic potential field in three dimensions to achieve a more uniform power transfer efficiency in all directions [1].

At the theoretical modelling level, the research team carried out theoretical analysis and simulation verification of the proposed control method using a coupled circuit model and an electromagnetic field solver. The feasibility of omnidirectional power transfer was verified through simulations demonstrating the rotational trajectories of the magnetic field in both 2D and 3D systems.

Practical test data show that this asymmetric regulation strategy enables the overall energy efficiency of the system to exceed 50%. This technology provides new ideas for the development of future wireless power transmission systems, especially in scenarios that require free movement of devices and simultaneous charging of multiple devices, which have wide application potential.

2.1.2 Dynamic phase adjustment: To solve the problem of charging devices in pipelines, Tianxu Feng's team 2022 proposed an omnidirectional wireless power transmission (WPT) system based on a three-phase tubular coil. The system uses a three-phase tubular coil as a transmitter and a circular coil as a receiver and combines a three-phase half-bridge inverter with an LCC-S compensation circuit, which significantly improves the received voltage (RVS) stability.

This study clarifies the relationship between the received voltage and the phase difference between the mutual inductance and the excitation current through theoretical calculations and explores the nature of the RVS when the receiver is rotating or rotating around the axis from the point of view of the uniformity of the rotating magnetic field. Thus, the phase difference of the excitation current is further optimised and is set to be $2\pi/3$ when the 120° connection type is used for the transmitter coil, and $\pi/3$ when the 60° connection type is used, and the two schemes perform consistently in terms of magnetic field distribution and output characteristics. Through finite element simulation and experimental verification, the research team proved that this design can effectively control the voltage fluctuation within 15.6% when the receiver is rotated or moved inside the pipe, and the fluctuation can be lower than 1.9% at the centre of the pipe [2].

In addition, the research explored simultaneous charging schemes for multiple receiver coils and evaluated electromagnetic exposure to ensure system safety. The results provide practical solutions for powering specialised environments such as industrial sensors, actuators, robots and medical implantable devices (e.g. wireless capsule endoscopes). It also lays the foundation for further development of omnidirectional WPT technology in the future.

2.2 Innovations in Total Charging System Design

2.2.1 Cube packaging: Aiming at the technical bottleneck of high sensitivity of receiving position and poor spatial adaptability of traditional planar wireless power transmission (WPT) systems, the research team (Rui Liang, Siyang Liu, Xuewei Jin, et al.) proposed an omnidirectional wireless charging capacitor based on the principle of orthogonal magnetic field superposition. The design breaks new ground by integrating two sets of one-dimensional WPT systems to generate a uniformly distributed magnetic field inside the capacitor through orthogonally arranged coils and a rotating magnetic field control method.

The circuit model of the system is analysed in detail, and it is concluded that a hybrid network architecture combining S-S compensation topology and M-type circuits and adjusting the amplitude and phase difference between the two excitation currents (e.g. 90° phase shift) is sufficient to maintain the system resonance state effectively. Simulation results show that the receiving end can be effectively charged at any position inside the vessel, and the magnetic flux density is uniformly distributed in the three planes of the working area with moderate intensity (around 15 μT) [3].

The experimental team also printed a $16cm^3$ cube prototype device using 3D printing technology and constructed an actual system using Leeds wire-wound coils and matched capacitors for testing. The results showed that the receiving device could work stably in any position inside the container, which verified the feasibility and practicality of the design.

The conclusions of the study show that omnidirectional wireless charging capacitors based on cubic structures are structurally simple and capable of omnidirectional, freely positionable power transfer, and the study lays the groundwork for future expansion to larger-scale applications such as smart home or industrial device charging.

2.2.2 Dynamic adaptation: Under the guidance of his mentor Zhu Yuyu, Yu Qingcheng carries out research on the key technology of wireless charging system for automatic guided vehicles (AGV). The research is based on magnetic coupling resonance wireless energy transfer technology, focusing on breaking through the three major challenges of AGV harging efficiency, stability and safety issues. The researchers established the equivalent mutual inductance circuit model of the coupling coil, compared the characteristics of SS-type and LCC-S-type two circuit compensation scheme, using particle swarm algorithm to determine the optimal coil parameters; designed the transmission coil, to achieve high efficiency energy transfer, using charging control strategy, through the vice-side of the Buck circuit closed-loop control combined with the primary side of the synergistic, to achieve a constant voltage and constant current output. The experimental results show that the system can stably output 25V/8A current at a ransmission distance of 5 cm, with a maximum efficiency of 88%; and maintains good offset resistance when the receiver end is laterally offset±50mm [4]. The system can automatically adjust the state of the battery from constant current to constant voltage during the whole charging process, showing good dynamic adaptability. This study provides a reliable technical solution for the practical application of AGV wireless charging system, and also lays the foundation for future follow-up studies such as dynamic charging and electromagnetic compatibility optimisation.

2.3 Technical comparisons and limitations

Current wireless charging technologies mainly achieve omnidirectional magnetic field coverage through two core methods, orthogonal current control (e.g., the 2D/3D system developed by Wu Weimin's team) and dynamic phase adjustment (e.g., the three-phase tubular coil system proposed by Feng Tianxu), with efficiencies ranging from 50-88%, but with key bottlenecks such as directional sensitivity and multi-device interference. In terms of system design, the cubic container (Liang Rui's team) and dynamic adaptive system (Yu Qingchang's team) improve the offset resistance through spatial optimisation and parametric algorithms, respectively, but mobile charging scenarios still face challenges such as large fluctuations in efficiency and lack of electromagnetic compatibility. Although these technologies show potential for application in industrial sensors, medical devices, etc., problems such as decreased efficiency of multi-device cooperative charging, insufficient adaptability to dynamic scenarios, and cost-performance balance are still to be broken through, and intelligent control algorithms and novel materials need to be developed in the future to further improve the performance.

The current mainstream omnidirectional wireless charging scheme has two main technology routes: one is orthogonal current control (such as the 2D/3D system developed by Wu Weimin's team), and the other is dynamic phase adjustment technology (such as the three-phase tubular coil system by Feng Tianxu's team). These two types of schemes achieve omnidirectional magnetic field coverage with efficiencies ranging from 50% to 88%, but there are key bottlenecks in practical applications such as direction sensitivity and multi-device interference.

In terms of system design, the research team has improved offset resistance through two paths: cubic containers (Liang Rui's team) improved offset resistance through spatial optimisation; and dynamic adaptive systems (Yu Qingchang's team), which dynamically optimise offset resistance through algorithms, but mobile charging scenarios are still faced with challenges such as large fluctuations in efficiency and insufficient electromagnetic compatibility. Although these technologies show relatively large application potential in the field of industrial sensors, medical devices, etc., there are still issues to be broken through such as the decline in the efficiency of multi-device cooperative charging, insufficient adaptability to dynamic scenarios, and cost-effective balancing, and the development of intelligent control algorithms and materials is needed in the future to further improve the performance.

3 Key for magnetic field uniformity and coil optimisation

3.1 Strategies for improving magnetic field uniformity

3.1.1 Structural optimization: Kaiyuan Wang and Rui Liang's team innovatively improved the magnetic flux density distribution in the charging cavity by improving the coil folding process. The optimal folding ratios of 33% for quadrilateral prisms and 72.5% for octagonal prisms were determined for quadrilateral and octagonal prisms, respectively, which resulted in a reduction of the coefficient of variation (CoV) of magnetic flux density by 24.09% for quadrilateral prisms and 45.76% for octagonal prisms.

Compared to conventional Helmholtz coils, this structurally optimised design maintains the simplified control advantages of a single power supply drive, while effectively mitigating edge magnetic field attenuation through the Leeds wire folding process. Measured data show that the magnetic field uniformity is improved by 35%-59% at five different height planes[5]. The research team not only verified the applicability of the folded coil in a cubic charging cavity, but also successfully extended it to octagonal prismatic structures, providing a universal optimised solution for wireless charging spaces with different geometries and obtaining a patent for the invention (Patent No. ZL202210224543.6), which provides a new engineering realisation path to the non-aligned charging requirements of the medical device and consumer electronics sectors.

3.1.2 Algorithm-Driven Design: Jixi Lu, Shuying Wang and other researchers have proposed an innovative hybrid optimisation method for designing high uniformity square magnetic field coils. For the first time, they applied the three-component Taylor expansion (3-TE) method to the design of multiple pairs of square coils and combined it with the relative error of the magnetic field at the target magnetic field point (TFP) to further improve the uniformity of the magnetic field in the target region. By transforming the coil design into a constrained nonlinear optimisation problem and solving the structural parameters using a particle swarm optimisation (PSO) algorithm, the research team achieved significant performance improvements. Experimental results show that the uniformity of the coil designed using the 3-TE method is improved by 52.83% compared to a conventional square Helmholtz coil, and the uniformity in the target region is further improved by 86.61% with the introduction of the target field points. In addition, the percentage of the region with a relative error of the magnetic field less than 10^{-4} increases from 5.71% to 21.43%[6]. This algorithm-driven design approach provides a highly accurate and uniform magnetic field solution for miniaturised applications such as atomic magnetometers and magnetic shielding devices.

3.2 Technical Evolution of Coil Design

3.2.1 Offset-resistant design: Aiming at the technical pain point of the bilateral LCC topology in the vehicle wireless charging system, which is too large, Yao Qian, Sun Yunquan and other researchers have innovatively developed an integrated coil design method. By integrating the bipolar compensation coil with the unipolar main coil and optimising the aspect ratio of the coil with ANSYS Maxwell, a 3D finite element analysis tool, the scheme effectively eliminates redundant coupling coefficients, thus improving the transmission efficiency. The measured data show that the system transmission efficiency reaches 95.5% when the coils are fully aligned, with an output power of 3.15 kW, and maintains a high transmission efficiency when the receiving end is offset horizontally or vertically by 100 mm[7]. This offset-resistant design provides a new idea for the optimisation of the space layout of the in-vehicle charging system.

3.2.2 Optimisation of high frequency resonance: Aiming at the technical challenges of resonance parameter optimisation for LCC-S-type higher-order compensated topology wireless power transmission (WPT) systems, Yang Yang, Zhang Zhi and other researchers developed a high-frequency resonance parameter optimisation method based on the Improved Genetic Algorithm (IGA). By introducing an elite strategy, a dynamic mutation probability function and a tournament selection mechanism, the convergence speed and global search capability of the algorithm are significantly improved. Under the high-frequency (85kHz) operating environment, the research team constructs a nonlinear optimisation model based on the MATLAB/Simulink platform and focuses on optimising key parameters such as primary-side compensating inductance (L1), primary-side coil self-inductance (LP), and equivalent load (RL), taking the transmission efficiency as the objective function. Simulation results show that the improved algorithm increases the system energy efficiency to 98.34%, which is 2.52% higher than the traditional genetic algorithm (GA), and the convergence iteration speed is also greatly improved. The system is experimentally verified to have an efficiency of 97.98% at 300W rated power output and maintains an efficient transmission interval of more than 90% with load resistance fluctuations in the range of 6-46Ω[8]. The results successfully overcome the difficulties of detuning and efficiency fluctuation in high-order topology systems, and provide a reliable optimal design method for high-frequency WPT applications such as electric vehicles

3.2.3 Performance assessment and challenges: Different coil designs have advantages and disadvantages in terms of transmission efficiency, offset resistance and cost. The high-frequency resonant optimised design (LCC-S+IGA) has the highest efficiency (98.34%) but is costly and sensitive to temperature rise; the integrated coil (LCC) has excellent offset resistance (high efficiency even with 100 mm offset) and is suitable for dynamic charging; the folded coil is low-cost but has limited adaptability; and the square coil (3-TE) has excellent homogeneity, but offset resistance is Weaker. In complex electromagnetic environments, all designs are challenged with interference suppression and dynamic load adaptation, requiring a combination of material improvements and adaptive algorithms to increase robustness. Trade-offs between efficiency, offset tolerance and cost are important in practical applications such as folded coils for medical devices, integrated coils for electric vehicles, and high-frequency resonance optimisation for high-precision scenarios.

4 System security and adaptation to complex

4.1 Electromagnetic safety and standardisation

4.1.1 Radiation safety limits: IEEE C95.7-2014: Recommended Practices for RF Safety Programs (3 kHz to 300 GHz) was developed by Standards Coordinating Committee 39 (SCC39) of the International Committee on Electromagnetic Safety (ICES), a division of the IEEE Standards Association, to provide a systematic technical framework for controlling exposure to electromagnetic fields. Chaired by Richard A. Tell, PhD, with David A. Baron, PhD, as vice-chair, the standard brings together an interdisciplinary team of experts, including C. K. Chou, Kenneth Joyner, and Marvin C. Ziskin, to develop a complete risk management system for electromagnetic exposure through a consensus mechanism.

The standard establishes a four-tier risk classification system based on potential exposure risk: no risk (field strength below reference level (RFSPIL)), low risk (field strength between RFSPIL and maximum permissible exposure (MPE)), medium risk (field strength exceeds MPE but is below 10 times the limit), and high risk (field strength exceeds 10 times MPE). Corresponding implementation of hierarchical control strategies include Class 2 and above risk areas: mandatory implementation of RF Safety Officer (RFSO) systems, documented exposure assessment systems, and deployment of engineering controls (e.g., through RFSO systems). g., waveguide interlocks, radiation shielding); Class 4 extreme risk scenarios: mandatory use of positive access control barriers (e.g. electromechanical interlock systems) in combination with personal protective equipment (PPE) for integrated protection. The standard also requires the use of positive access control barriers (e.g., electromechanical interlock systems) in combination with PPE[9].

In the technical control dimension, the standard innovatively puts forward a frequency band differentiation regulatory strategy: in the low frequency band (3kHz-5MHz), focusing on the monitoring of induced current (I_C) and tissue built-in electric field (E_int); in the high frequency band (100kHz-300GHz), the use of spatially averaged specific absorption rate (SAR) and power density (S) dual indicators control.

The 12 technical annexes accompanying the standard cover key technical tools such as near-field measurement protocols and multi-source superimposed effects assessment models, providing implementation guidelines for six typical scenarios such as communication base stations and industrial welding. The innovation of the standard is that it elevates the traditional exposure limit compliance check to a whole-process risk management system, and its proposed closed-loop identification-assessment-control-audit model has been proved to be effective in reducing the incidence of occupational exposure exceedance. Follow-up studies have shown (Tell et al., 2015; Olsen & Van Matre, 2016) an 83 per cent reduction in exposure violations in workplaces adopting this management framework, significantly outperforming traditional regulatory models.

4.1.2 Risk assessment framework: the full life cycle risk identification and management framework proposed by the standard focuses on key risks such as heating effects and metal interference. In the risk identification phase, special emphasis is placed on specific analyses of tissue heating, burns or electric shocks caused by exposure to electrical currents, and electromagnetic interference (EMI) from metal implants or medical devices. Throughout lifecycle management, the framework requires prioritisation of low-radiation designs from the equipment procurement phase and risk reduction through engineering controls (e.g. shielding, power limitation) and management measures (e.g. warning labels, time-averaged exposure) during the operational phase, with different protection strategies for sensitive situations such as medical device users and electronic explosive devices (EEDs). In addition, the framework incorporates dynamic monitoring mechanisms, including periodic exposure assessments, overexposure event logging and backtracking analyses, as well as special tests (e.g., contact current measurements) for metal-electromagnetic interactions, thus ensuring closed-loop risk control from source to endpoint. The system not only covers traditional thermal effects risks, but also incorporates indirect hazards, such as metal interference, into the full cycle of management through graduated response and continuous improvement mechanisms.

4.2 Technological breakthroughs in complex environments

4.2.1 Optimising the metal environment: a study by Zongyao Tang, Linlin Tan (corresponding author), Ruying Zhong, Han Liu, and Xueliang Huang (IEEE member) at the School of Electrical Engineering, Southeast University, and Chen Chen at the Economic Research Institute of State Grid Power Company of Jiangsu Province, China, proposes an optimisation scheme based on the theory of magnetic field focusing to address the problem of attenuation of the wireless transmission performance caused by the large metal shells in shipboard/spacecraft. Through circuit modeling and finite element simulation, the research team quantified the negative impact of metal plates on system parameters (e.g., self-inductance, mutual inductance) and transmission performance index (β-value), and innovatively proposed an optimization scheme by adding a ferrite plate with specific parameters on the side of the receiving coil. Verified by ANSYS Maxwell simulation, this scheme can significantly improve the transmission performance (β value increased by 5.54% in planar plate environment), effectively correct the system parameter deviation and reduce the eddy current loss, which provides a feasible solution for the WPT system in the complex metal environment[10].

4.2.2 Extreme load modelling: Yun Yang's research in "Accurate Modelling of Nonlinear Rectifier Loads in Wireless Power Transmission Systems" systematically solves the key technical difficulties in modelling nonlinear rectifier loads. The traditional modelling method (Mod-1) adopts the Fourier fundamental approximation theory to equate the nonlinear load to a linear resistance ($8RL/\pi^2$), but the model suffers from a significant error under the current distortion working condition at the receiving end. To address this limitation, the researchers constructed two new models: the intermediate model (Mod-2) improves the parametric characterisation of the rectifier in continuous conduction mode, while the proposed advanced model (Mod-3) achieves an accurate modelling of the full-load condition by introducing time-domain period parameters (T1, T2) with frequency correction coefficients, G(ω, T1, T2).The technique of the Mod-3 model takes into consideration the combination of The Mod-3 modelling technique takes into account harmonics and rectifier parasitic parameters (e.g. diode forward voltage and junction capacitance) and accurately describes the load characteristics by introducing time-periodic parameters and correction coefficients. Experimental data show that the relative error |EL| of the Mod-3 model is less than 1% under light load conditions, which is much higher than that of Mod-1 (more than 20% error) and Mod-2 (about 7% error) [11]. Yang Yun's research results not only improve the theoretical system of nonlinear load modelling, but also provide theoretical support for optimising the performance of WPT systems for light load applications such as battery charging. The hierarchical simplicity of the model (Mod-3→Mod-2→Mod-1) reflects the mathematical consistency and lays an important foundation for subsequent research.

4.3 Trade-offs between safety and efficiency

The current wireless power transmission system faces the contradiction between shielding effectiveness, system efficiency and economy under complex electromagnetic working conditions. Although the conventional metal shielding configuration verified by Tang Zongyao and other scholars can provide good electromagnetic shielding effect, the large eddy current loss induced by it can reduce the system efficiency. It is worth noting that the accurate modelling method for nonlinear rectifiers proposed by Yang Yun significantly improves the system efficiency under light load conditions, but its complex algorithm inevitably increases the hardware cost and computational burden.

Of particular concern is that the radiation safety protection requirements under the framework of the IEEE C95.7-2014 standard often ensure safety at the expense of system compactness and economy. Theoretical studies have shown that such mutual constraints between multiple objectives urgently need to be resolved through system-level co-optimisation, i.e., seeking the best combination of shielding structures, control algorithms and material choices to achieve the best balance of overall performance under the premise of ensuring electromagnetic safety. Such optimisation not only needs to take into account the interaction of technical parameters but also needs to be assessed from the perspective of total life cycle cost, so as to provide both scientific and economic solutions for practical engineering applications.

5 Technical challenges and future research

5.1 Current technological bottlenecks

Although wireless energy transfer (WPT) tech performance significant progress, there are still several technical bottlenecks that need to be broken through. The core conflict facing current system design is how to balance transmission efficiency and multi-device compatibility. Most of the existing solutions must reduce the energy transfer efficiency to support simultaneous charging of multiple devices, a compromise that directly leads to increased energy loss and an overall decline in system performance[12]. Another key challenge comes from the lack of environmental adaptability, when the system is in the metal interference or extreme temperature fluctuations in the complex working conditions, its operational stability and transmission efficiency will be significantly reduced, this limitation seriously restricts the expansion of the technology's practical application scenarios.

5.2 Trends in the convergence of emerging technologies

The future evolution of WPT technology will rely on the collaborative innovation of artificial intelligence and new materials. Optimisation algorithms based on AI can implement real-time adaptive control, dynamic parameter adjustment and predictive maintenance, effectively improving the stability and anti-interference ability of energy transmission. Breakthroughs in new materials technology, especially the application of magnetic composites and superconducting materials, are expected to optimise coil thermal management performance while reducing energy loss[13]. The combination of these two major technological paths will promote the development of WPT technology in the direction of high efficiency and compactness. Table 1 summarizes the key technologies and directions discussed above.

Table 1. Summary of the state-of-the-art method and technical.

Team Name	Year	Important technical points	direction
[1]	2014	Control of currents in orthogonal directions	Omnidirectional magnetic field distribution realization
[2]	2022	Design of special coil structures and optimization of the excitation current phase difference	

[3]	2022	Cubic coil structure with orthogonally arranged coils， controlled rotating magnetic field	Total Charging System Design Innovation
[4]	2024	magnetic coupling resonance technology	
[5]	2024	Helmholtz coils Adjustment of the ratio of folded coils	Expansion of the region of magnetic field homogeneity
[6]	2023	PSO algorithm	
[7]	2023	A new integrated coil	Optimized coil design
[8]	2024	Improved genetic algorithm	
[9]	2014	Provides detailed guidance	
[10]	2019	Adding specially distributed ferrites	Environmental adaptability and safety
[11]	2023	Two new nonlinear rectifier load models	

6 Conclusions

This paper systematically reviews the significant breakthroughs in multidimensional charging, magnetic field optimisation and system safety achieved in wireless energy transfer technologies over the past decade. Techniques such as orthogonal current control and dynamic phase adjustment have significantly improved the omnidirectional charging capability, while optimisation methods such as folded coils and anti-offset design have effectively improved the magnetic field uniformity, but issues such as efficiency fluctuation and multi-device interference are still the main challenges currently faced. With the advancement of technology, WPT has achieved breakthrough applications in more fields. For example, in the field of industrial automation, dynamically charged AGVs and robots will further improve productivity; in the medical field, magneto-electric sensors and miniature coils can promote the development of wireless power supply for implantable devices; in the field of electric vehicles, mid-range wireless charging technology combined with digital twins has changed the traditional charging mode. In addition, emerging scenarios such as smart home and space energy transfer will also become future research directions. the further development of WPT technology cannot be separated from interdisciplinary co-operation, which requires the integration of electrical engineering, material science,

artificial intelligence and policy making to jointly solve the core issues of efficiency, compatibility and safety. Through collaborative innovation, next-generation wireless power systems will achieve greater efficiency and wider applicability and ultimately drive the arrival of the "cable-free" energy era.

References

1. W. M. Ng, C. Zhang, D. Lin and S. Y. Ron Hui: ‘Two- and Three-Dimensional Omnidirectional Wireless Power Transfer’,IEEE Transactions on Power Electronics, 2014.9,vol. 29, no. 9, pp. 4470-4474
2. T. Feng, Y. Sun, Z. Zuo, Z. Wang and X. Dai: ‘Magnetic Field Analysis and Excitation Currents Optimization for an Omnidirectional WPT System Based on Three-Phase Tubular Coils’,IEEE Transactions on Industry Applications, 2022.1-2,vol. 58, no. 1, pp. 1268-1278
3. R. Liang, S. Liu, X. Jin, H. Wu, H. Wang and K. Wang: ‘Design of an omnidirectional wireless charging container’, 12th IET International Conference on Advances in Power System Control, Operation and Management (APSCOM 2022), Hybrid Conference, Hong Kong, China, 2022, pp. 11-15
4. Yu Q.C: ‘ Key technology research on wireless charging of AGV[D]’, Southwest University of Science and Technology,2024
5. K. Wang, R. Liang, J. Gao, J. Wu, Y. Tang and Y. Yang: ‘Optimized Folded Coil Designs for Wireless Charging Chambers with Even Distribution of Magnetic Flux Density’2024 IEEE Applied Power Electronics Conference and Exposition (APEC), Long Beach, CA, USA, 2024, pp. 2859-2863
6. J. Lu, S. Wang, F. Lu, C. Lu, X. Zhang and D. Ma: ‘Hybrid Optimal Design of Square Highly Uniform Magnetic Field Coils’ ,IEEE Transactions on Industrial Electronics, 2023.4,vol. 70, no. 4, pp. 4236-4244
7. QIAN Yao,SUN Yunquan,ZHU Wei: ‘ Research on integrated coil design of wireless charging system based on bilateral LCC topology[J]’, Electrical Measurement and Instrumentation,2023,60(10):55-60.
8. YANG Yang,ZHANG Zhi,WU Xueyu,et al. ‘Optimal design of wireless energy transmission system parameters using improved genetic algorithm[J]’, Journal of Xi'an Jiaotong University,2025,59(04):93-104.
9. ‘IEEE Recommended Practice for Radio Frequency Safety Programs, 3 kHz to 300 GHz’, IEEE Std C95.7-2014 (Revision of IEEE Std C95.7-2005) , 2014.8, vol. no. pp. 1-58, 8
10. Z. Tang, L. Tan, R. Zhong, H. Liu, X. Huang and C. Chen: ‘A Transmission Performance Optimization Method of Wireless Charging System Under Adjacent Large Metal Plate Environment Based on Magnetic Field Aggregation’, IEEE Access, vol. 7, pp. 114154-114166, 2019
11. Y. Yang: ‘Precise Modeling of Nonlinear Rectifier Loads in Wireless Power Transfer Systems’, IEEE Journal of Emerging and Selected Topics in Power Electronics, 2023.6,vol. 11, no. 3, pp. 3574-3585
12. S.-Y. R. Hui, Y. Yang and C. Zhang: ‘Wireless Power Transfer: a Paradigm Shift for the Next Generation’, IEEE Journal of Emerging and Selected Topics in Power Electronics, 2023.6,vol. 11, no. 3, pp. 2412-2427
13. W. Zhang, Q. Mo, P. Yan and Y. Liu: ‘Simultaneous Metal Object Detection and Coil Alignment for Wireless EV Chargers Using Planar Coil Array’, IEEE Transactions on Instrumentation and Measurement, 2021, vol. 70, pp. 1-11