

# Review of High-Misalignment Tolerance Techniques in Wireless Power Transfer Systems

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## Abstract

Wireless power transfer (WPT) technology, leveraging the unique advantage of contactless power supply, has been recognized as a core power supply solution for mobile devices such as automated guided vehicles (AGVs) and electric vehicles (EVs). However, its transmission performance is highly susceptible to lateral offset, longitudinal misalignment, and angular deflection of the coils, resulting in a sharp decline in efficiency and unstable output. This has become a key bottleneck restricting the engineering application of the technology. This paper presents a comprehensive review focusing on the misalignment tolerance technologies for WPT systems. First, taking the LCC-S/LCC topology as an example, the influence of coil misalignment on the system output performance is analyzed, and various misalignment tolerance methods are enumerated. Subsequently, the basic principles and main research achievements of four categories of misalignment tolerance technologies, namely coupling structure optimization, compensation topology optimization, control strategies, and alignment guidance technology, are systematically summarized, with their limitations identified. Finally, the future research directions of misalignment tolerance technologies are discussed.

**Keywords:** wireless power transmission; misalignment tolerance; stable output

## 1. Introduction

With the rapid development of intelligent terminals, new energy transportation, and industrial automation, the problems faced by traditional wired power transmission methods, such as cable constraints, contact losses, and potential safety hazards, have become increasingly prominent. Wireless power transfer (WPT) technology, leveraging the unique advantage of contactless power supply, has emerged as one of the core directions to address the aforementioned dilemmas. Based on core principles including electromagnetic induction, magnetic resonance coupling, and microwave radiation, this technology enables the transmission of electrical energy from the transmitter to the receiver without physical contact, completely breaking the spatial layout limitations of traditional power supply modes. From the wireless charging of consumer electronics [1–3] to the mobile power supply of new energy vehicles [4–6] and automated guided vehicles (AGVs) [7–9], and further to the safe power supply of medical implantable devices [10–12] and special energy supplementation in the aerospace field [13], WPT technology has penetrated into diverse scenarios. It not only significantly improves the convenience and safety of power supply but also promotes the transformation of energy supply modes towards flexibility and intelligence. As a key link connecting energy sources and terminals, the



Academic Editor: Oh-Soon Shin

Received: 23 December 2025

Revised: 14 January 2026

Accepted: 26 January 2026

Published: 29 January 2026

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innovative development of WPT technology holds significant strategic significance for promoting efficient energy utilization and constructing an intelligent energy system and has become a global research hotspot and industrial upgrading direction in the fields of energy and electronics.

In practical engineering scenarios such as consumer electronics and electric vehicles, planar coils are widely applied in wireless power transfer systems due to their installation space adaptability. Such systems generally face the bottleneck of alignment deviation of the coupling mechanism: the primary coil is fixed on the ground or at the end of charging piles, while the secondary coil is integrated inside the equipment. Insufficient positioning accuracy of the secondary equipment is prone to causing lateral misalignment, longitudinal misalignment, and changes in transmission distance, leading to dynamic fluctuations of key electromagnetic parameters such as coil self-inductance and mutual inductance. Consequently, a series of severe issues arise, including decreased system stability, attenuation of transmission capacity, resonant characteristic mismatch, and a sharp surge in energy losses. Therefore, numerous scholars have conducted research from aspects such as coupling structures, resonant topologies, and control methods, proposing various constant-output methods for WPT systems. Reference [14] focuses on the misalignment issue of inductive charging systems for electric vehicles; reviews three categories of misalignment-tolerant technologies (coupling structure design, compensation topologies, and control methods); analyzes the advantages, disadvantages, and application scenarios of various methods; points out challenges such as cost, complexity, and communication delay; and proposes future research directions including sensor-assisted alignment and application of metamaterials, providing comprehensive references for technological research and development in this field. Reference [15] focuses on the key technology optimization of WPT systems, presumably centering on specific compensation topologies (e.g., hybrid resonant topologies) or misalignment adaptation mechanisms. Through simulations and experiments, it analyzes the impacts of coil structures and compensation parameters on transmission efficiency and stability and proposes topology improvement or control strategy optimization schemes for application scenarios such as electric vehicles or mobile robots, offering academic references for enhancing the misalignment tolerance and engineering practicality of WPT systems. Reference [16] targets low-voltage and high-current electric mobile equipment (LEVs and AGVs) and reviews the magnetic coupling structures (DD coils, BP coils, etc.), compensation topologies (SS, LCC-LCC, etc.), and power electronic architectures and control methods of inductive WPT systems. It proposes an asymmetric LCC-LCC compensation topology and passive current-sharing technology, designs a 2.5 kW/48 V experimental system, and verifies its current balance and transmission stability under component mismatch and misalignment scenarios, providing technical solutions for the engineering application of low-voltage and high-current WPT.

Although the aforementioned scholars have conducted detailed reviews on the misalignment tolerance technologies of wireless power transfer systems, the research outcomes they covered are limited to the relevant progress up to 2023. By 2025, through the continuous efforts of numerous scholars, significant breakthroughs have been achieved in the three core misalignment tolerance technologies, namely magnetic coupling structure design, compensation topology optimization, and control strategy improvement, with a wealth of innovative research results emerging, which urgently require systematic sorting and induction. In addition, some scholars have innovatively proposed a misalignment tolerance technology based on alignment guidance. This technology first achieves precise alignment of the coupling structure of unmanned equipment through alignment guidance means and then conducts wireless energy transmission, thereby ensuring the stability of the system's transmission power and transmission efficiency.

This paper systematically reviews the main research achievements in the field of misalignment tolerance for current WPT systems from four dimensions, control strategy optimization, coupling mechanism topology improvement, compensation topology design, and alignment guidance technology; deeply analyzes the advantages and limitations of different misalignment tolerance technical schemes; and proposes future development directions of this field.

## 2. The Impact of Coil Misalignment on Systems

Coil misalignment is one of the main causes of transmission power variations in wireless power transfer systems. Clarifying the influence law of misalignment on systems constitutes the foundation for enhancing misalignment tolerance capability. Commonly used topologies in WPT systems are categorized into basic topologies and hybrid topologies. Specifically, the basic topologies mainly include SS, SP, PP, and PS, as shown in Figure 1, while the hybrid topologies primarily consist of LCC-S and LCC-LCC, as shown in Figure 2.

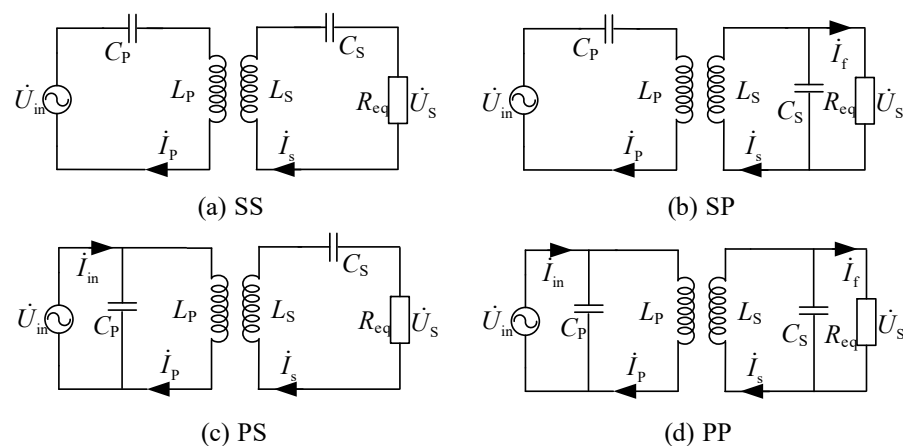


**Figure 1.** Different compensation topologies: (a) SS, (b) SP, (c) PS, and (d) PP.

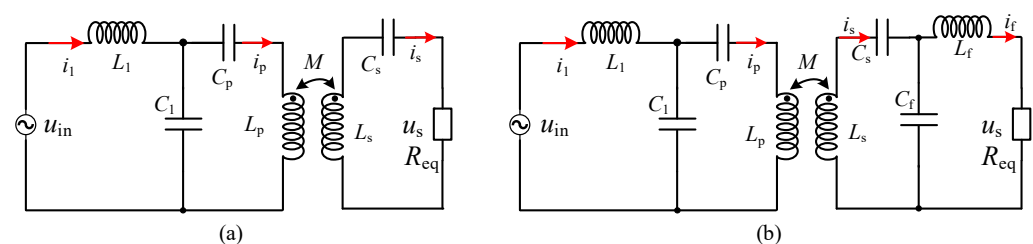


**Figure 2.** Equivalent circuit diagrams of WPT systems, (a) LCC-S; (b) LCC-LCC.

The capacitance values and output characteristics of the four basic topologies are presented in the table below.

This paper takes the LCC-S and LCC-LCC topologies as examples, as shown in Figure 2, and investigates the relationship between output voltage and mutual inductance. A typical WPT system is mainly composed of an equivalent AC voltage source inverter ( $u_{in}$ ), a transmitting compensation inductor ( $L_1$ ), a parallel resonant capacitor ( $C_1$ ), a series resonant capacitor ( $C_p$ ), a transmitting coil ( $L_p$ ), a receiving coil ( $L_s$ ), a receiving series resonant capacitor ( $C_s$ ), a receiving compensation inductor ( $L_f$ ), a parallel resonant capacitor ( $C_f$ ), and an equivalent resistance ( $R_{eq}$ ).  $M$  denotes the mutual inductance of the coupling structure.  $i_p$ ,  $i_s$ , and  $i_f$  represent the inverter output current, receiving coil current, and rectifier bridge input current, respectively. The red arrows in Figure 2 indicate the direction of the current.

According to Kirchhoff's Voltage Law (KVL) and neglecting the internal resistance of the coils, the two topologies in Figure 1 can be formulated into the following equations, respectively.

$$\begin{cases} u_{in} = i_1 j\omega L_1 + i_1 \frac{1}{j\omega C_1} - i_p \frac{1}{j\omega C_1} \\ 0 = i_p j\omega L_p + i_p \frac{1}{j\omega C_p} + i_p \frac{1}{j\omega C_1} - i_1 \frac{1}{j\omega C_1} - i_s j\omega M \\ 0 = -i_p j\omega M + i_s j\omega L_s + i_s \frac{1}{j\omega C_s} + i_s R_{eq} \end{cases} \quad (1)$$

$$\begin{cases} u_{in} = i_1 j\omega L_1 + i_1 \frac{1}{j\omega C_1} - i_p \frac{1}{j\omega C_1} \\ 0 = i_p j\omega L_p + i_p \frac{1}{j\omega C_p} + i_p \frac{1}{j\omega C_1} - i_1 \frac{1}{j\omega C_1} - i_s j\omega M \\ 0 = -i_p j\omega M + i_s j\omega L_s + i_s \frac{1}{j\omega C_s} - i_f \frac{1}{j\omega C_s} - i_p j\omega M \\ 0 = -i_s \frac{1}{j\omega C_s} + i_f j\omega L_s + i_f \frac{1}{j\omega C_s} + i_f R_{eq} \end{cases} \quad (2)$$

Under resonant conditions, the relationships between the output voltage, output current, and mutual inductance can be derived as follows:

$$\begin{cases} u_s = \frac{Mu_{in}}{L_1} & \text{LCC-S} \\ i_f = \frac{Mu_{in}}{j\omega L_1 L_f} & \text{LCC-LCC} \end{cases} \quad (3)$$

The voltage gain  $G_{cv}$  and current gain  $G_{cc}$  of the LCC-S and LCC-LCC topologies can be expressed as

$$\begin{cases} G_{cv} = \frac{u_s}{u_{in}} = \frac{M}{L_1} & \text{LCC-S} \\ G_{cc} = \frac{i_f}{u_{in}} = \frac{M}{j\omega L_1 L_f} & \text{LCC-LCC} \end{cases} \quad (4)$$

It can be seen from Table 1 and Equation (3) that the output characteristics of a WPT system are closely correlated with  $M$ . Furthermore, it can be derived from Equation (4) that the LCC-S and LCC-LCC topologies can achieve a constant voltage or current gain; yet, under operating conditions where the mutual inductance fluctuates, the constant gain characteristic of the system will be compromised. To intuitively reveal the influence of coil misalignment on the operating characteristics of a WPT system, this paper plots the correlation characteristic curves of coil misalignment with the system's mutual inductance, output voltage, and output current, as shown in Figure 3. It can be observed from Figure 3 that as the coil misalignment displacement increases, the mutual inductance of the WPT system exhibits a gradual attenuation trend, which in turn leads to a synchronous decrease in the system's output voltage and output current. To ensure the constancy of the system gain, improving its misalignment tolerance capability is of great engineering significance, and relevant design and optimization work can be carried out for the following aspects.

- (1) Optimization design of coupling structures: By designing a specific coupling structure according to the system application scenario, the mutual inductance fluctuation is minimized or even kept unchanged when the coils are misaligned.
- (2) Optimization design of compensation topologies: Optimizing the topology parameters or adopting a hybrid use of multiple topologies based on the variation in the coupling structure to ensure the system maintains stable gain under mutual inductance changes.
- (3) Control strategies: Real-time collection of output voltage or current is compared with the reference value, and control algorithms are used to adjust the input voltage, conduction angle of the inverter, resonant parameters, or conduction angle of the rectifier bridge, thereby ensuring the stability of the system gain.

- (4) Alignment guidance: Utilizing auxiliary coils or circuit reconstruction to achieve precise alignment of the coupling structure first, followed by normal charging. This avoids the problem of coil misalignment and ensures the stability of the system gain.

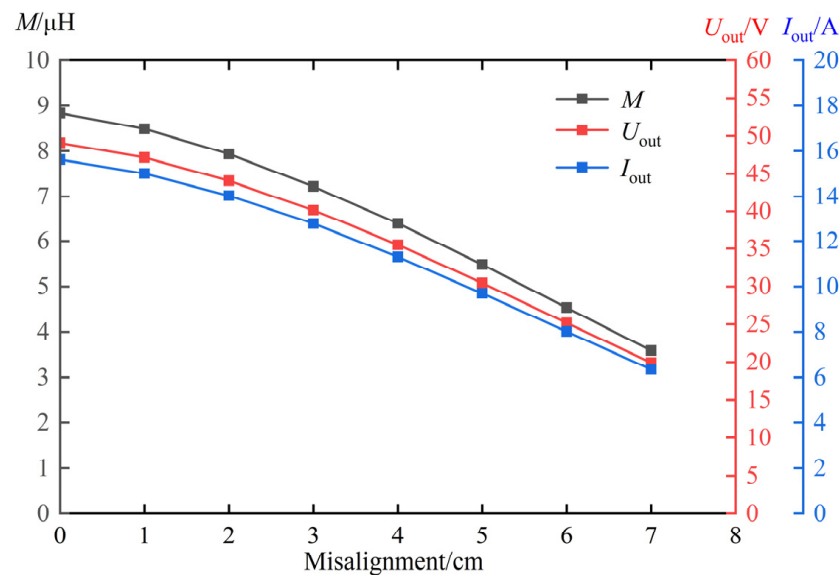


**Figure 3.** Mutual inductance, output voltage, and output current versus misalignment in WPT systems.

**Table 1.** Compensation capacitors and output of different compensation topologies.

| Compensation Topology | $C_p$                                        | $C_s$                    | Output                                   |
|-----------------------|----------------------------------------------|--------------------------|------------------------------------------|
| SS                    | $\frac{1}{\omega^2 L_p}$                     | $\frac{1}{\omega^2 L_s}$ | $I_f = -\frac{U_{in}}{j\omega M}$        |
| SP                    | $\frac{L_s}{\omega^2 (L_p L_s - M^2)}$       | $\frac{1}{\omega^2 L_s}$ | $U_s = \frac{L_s U_{in}}{M}$             |
| PS                    | $\frac{1}{\omega^2 (L_p - \frac{M^2}{L_s})}$ | $\frac{1}{\omega^2 L_s}$ | $I_s = \frac{I_{in}}{\omega^2 C_p M}$    |
| PP                    | $\frac{1}{\omega^2 L_p}$                     | $\frac{1}{\omega^2 L_s}$ | $U_s = \frac{L_s I_{in}}{j\omega M C_p}$ |

### 3. Key Technologies for Misalignment Tolerance

In wireless power transfer systems, misalignment between the transmitting and receiving coils (including lateral, angular, and axial misalignment) is one of the key factors affecting system performance. Such misalignment is prone to causing problems such as a significant decrease in transmission efficiency and unstable output power. To address these issues, numerous scholars have conducted extensive research on misalignment tolerance technologies, which can be mainly categorized into four types: (1) optimization design of coupling structures; (2) optimization design of compensation topologies; (3) real-time parameter control; (4) alignment guidance. This paper reviews the research progress of these four types of high-misalignment tolerance technologies, as shown in Figure 4, providing guidance for other scholars engaged in research on high-misalignment-tolerance technologies.

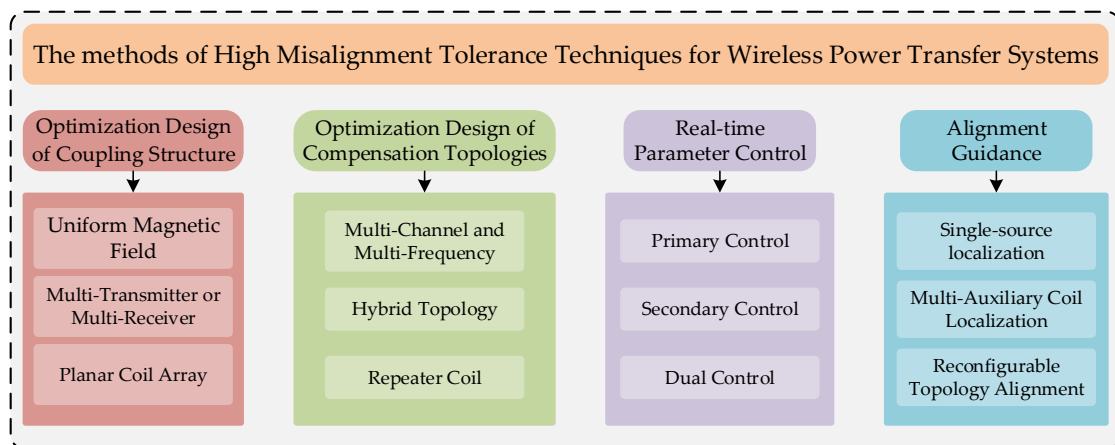


**Figure 4.** Classification of High-Misalignment Tolerance technologies for wireless power transfer systems.

### 3.1. Misalignment Tolerance Technology Based on Optimization Design of Coupling Structures

The coupling structure is a crucial component in WPT systems, and the fundamental cause of output fluctuations stems from the variation in coupling conditions induced by misalignment. To enhance offset tolerance through the design of coupling mechanisms, the core lies in constructing a uniform magnetic field to maintain the relative constancy of coupling strength. Such methods primarily involve the segmented winding and uniform distribution of either the transmitting or receiving coil, ensuring that the total mutual inductance of the coils remains essentially unchanged [17–21].

Reference [17] proposes a novel magnetic coupling structure composed of a four-quadrant primary coil and a single-quadrant secondary coil, as illustrated in Figure 5. The authors divide the transmitting coil into four Q-shaped coils with identical turn numbers and consistent dimensions, which are uniformly arranged across the four quadrants and connected in series. As depicted in the figure, the four coils carry currents in the same direction, thereby generating magnetic flux with negative polarity in the central region. By elaborately optimizing the dimensions of the coil in each quadrant, the variation in the overall mutual inductance with lateral displacement is minimized, leading to reduced mutual inductance fluctuations and improved misalignment tolerance. Experimental validation indicates that when the external dimension of the coupling structure is misaligned by 30% of its length, the output voltage of the system decreases by only 5.42%.

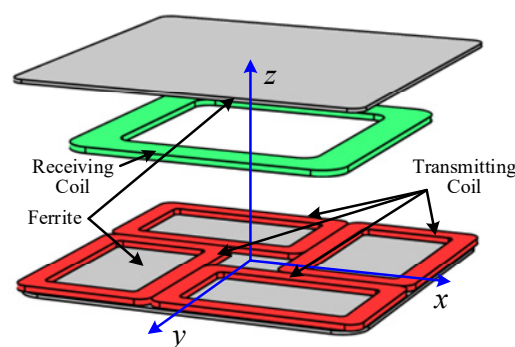


**Figure 5.** The overview of the magnetic coupler in Reference [17].

Reference [21] proposes and analyzes a multi-winding solenoid transmitting coil designed for autonomous underwater vehicles (AUVs), as shown in Figure 6. In contrast to the conventional solenoid coil, the transmitting coil is divided into three segments (Coils 11, 12, and 13), where Coils 11 and 13 are wound in the same direction while Coil 12 is wound in the opposite direction. Consequently, regardless of whether the misalignment direction

is  $+z$  or  $-z$ , Coil 12 weakens the coupling under aligned conditions, whereas Coils 11 and 13 enhance the coupling under misaligned scenarios. Furthermore, the widths of Coils 11 and 12 are adjusted to achieve stable coupling between the segmented transmitting coil and the receiving coil when misalignment occurs. Experimental validation demonstrates that when the axial misalignment increases to 100 mm (80% of the coil width), the output power fluctuation rate of the system remains below 6%.

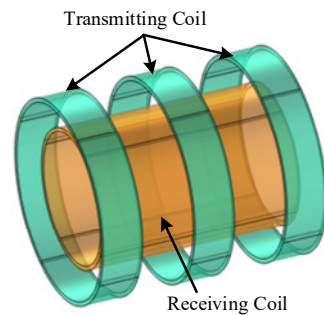


**Figure 6.** The proposed magnetic couplers in Reference [21].

To reduce the complexity of the transmitting coil, some researchers have abandoned its segmented design and instead divided the receiving end into two groups. Reference [22] proposes a static wireless charging system for AGVs with dual receiving coils, as shown in Figure 7. The transmitting end adopts a Q-type coil, while the receiving end consists of two asymmetric DD coils to ensure the stability of mutual inductance in the  $y$  direction for the coupling structure. The two DD coils are connected to two diode rectifiers, which are paralleled on the DC side. Thanks to the reverse-blocking characteristic of the diodes, the system can automatically select the maximum voltage (i.e., maximum coupling) for power transmission. Experimental results demonstrate that the system can maintain stable output under a maximum coupling misalignment of 50%.

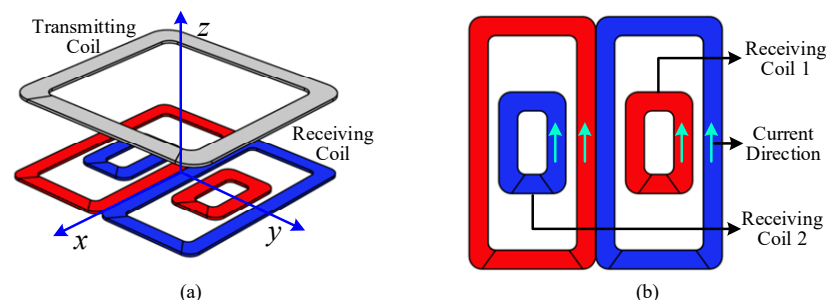


**Figure 7.** Proposed coil structure of dual receiving coils in Reference [22]. (a) Overall diagram. (b) Top view of receiving coil.

In addition to designing either the transmitting coil or the receiving coil as a segmented structure, some researchers have designed both coupling coils as segmented structures. Reference [23] proposes a split-type solenoid coupler for AUVs, as shown in Figure 8, where both the transmitting and receiving ends are divided into two solenoids with the same number of turns and consistent dimensions. Finite element comparative analysis with the traditional solenoid structure demonstrates that the split-type solenoid design exhibits significant advantages in suppressing inductance fluctuations: under an axial misalignment of 80 mm, the fluctuation of the coupling coefficient is reduced by 22%, and the fluctuations of self-inductance and mutual inductance are decreased by 24.8% and 25.6%, respectively. Experimental verification demonstrates that the system can still maintain the maximum output power under an axial misalignment of 80 mm.

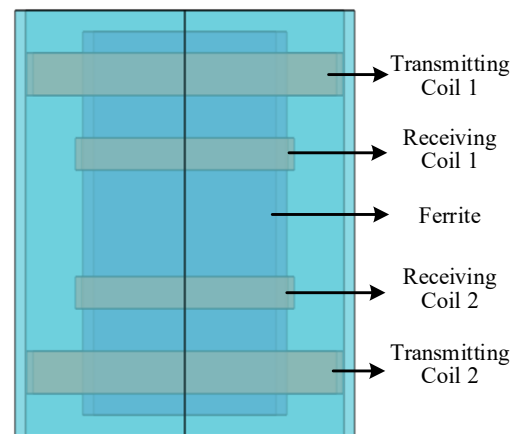


**Figure 8.** Proposed split solenoid magnetic coupler structure in Reference [23].

In addition to the segmented design of coupling mechanisms, numerous researchers have adopted multiple inverters or receiving terminals for energy transmission. For the WPT system of AUVs, Reference [24] proposed a free-rotating WPT system equipped with a novel magnetic coupler, as shown in Figure 9. In this system, six solenoid coils are arranged to form a regular hexagon as the receiving coil, while four solenoid coils are orthogonally distributed around the receiving coil to serve as transmitting coils. The receiving coils are reverse-wound, enabling mutual inductances between the receiving coils and the two transmitting coils to compensate for each other. Furthermore, by integrating phase control between the two transmitting coils, the system can achieve more stable output power under conditions of rotation and axial misalignment. Experimental verification has demonstrated that the output power fluctuation of the system is less than 5% at different rotation angles.

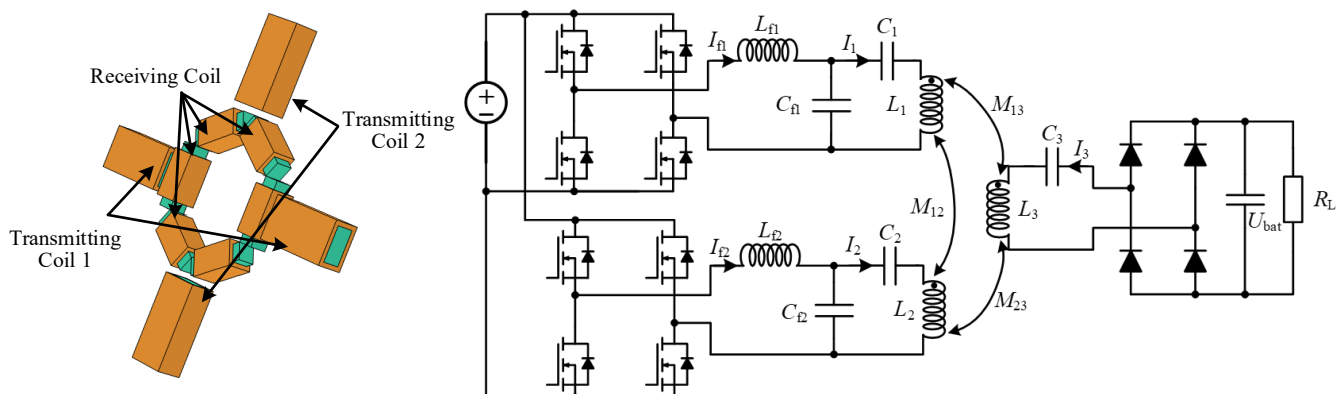


**Figure 9.** The proposed coupling structure and LCC-S circuit topology in Reference [24].

Similarly, Reference [25] proposed a novel coupler design, where the transmitting coils are configured as six solenoid coils arranged in a regular hexagon, while only one coil is required at the receiving end. This configuration enhances the stability of the output voltage against diagonal misalignment. Furthermore, three inverters operate with the same amplitude but are phase-shifted by  $120^\circ$ , as shown in Figure 10, and appropriate series capacitors are designed to mitigate the impact of cross-coupling on the system. Experimental verification has confirmed that the output voltage fluctuation of the system is less than 5% under different rotation angles.

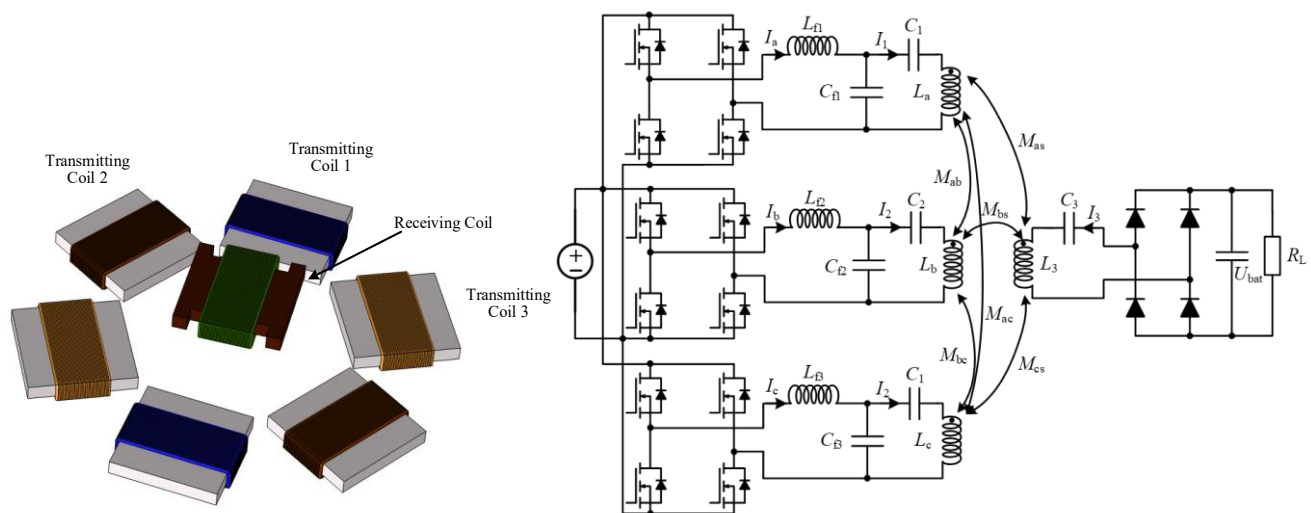


**Figure 10.** The proposed coupling structure and three-phase circuit topology in Reference [25].

In addition to designing multiple inverters as the transmitting end, some researchers have also designed the receiving end with multiple receiving sides in series or parallel to achieve stable output [26–28]. To address the problem of coil misalignment in unmanned aerial vehicle (UAV) wireless charging systems, Reference [26] proposes a novel magnetic coupler with high misalignment tolerance, as shown in Figure 11. A bipolar magnetized solenoid transmitter generates a rotating horizontal magnetic field, which is simultaneously captured in both axial and radial directions by a multi-channel conformal receiver seamlessly integrated into the UAV landing gear. Experimental verification demonstrates that under various misalignment conditions, the maximum fluctuations of the system output voltage and efficiency are only 2.7 V and 3.5%, respectively.

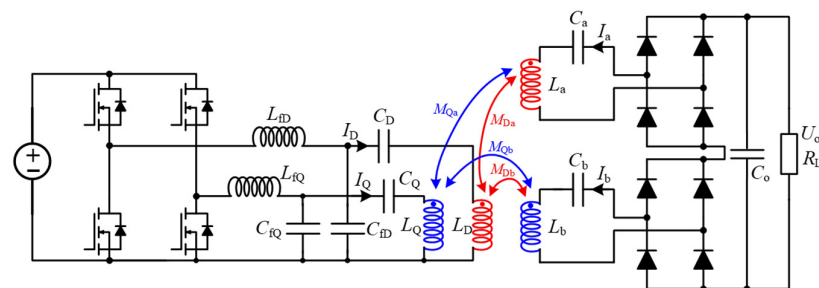


**Figure 11.** Circuit topology of the UAV WPT system in Reference [26].

Reference [29] addresses the challenges of insufficient misalignment tolerance and simultaneous charging for multiple UAVs in WPT systems, as shown in Figure 12, proposing an array-based wireless charging platform. This platform employs a two-step search strategy for position detection and coil matching to ensure operational efficiency. A logarithmic search algorithm is adopted for position detection, while a fuzzy control-based greedy algorithm is utilized for further coil matching. Equipped with a reconfigurable array, the platform can generate an omnidirectional rotating magnetic field and suppress output fluctuations, which is tailored specifically to the structure and charging requirements of UAVs. Experimental results demonstrate that the proposed strategy can accurately achieve UAV position detection and coil matching on a large-scale array platform. The charging efficiency reaches 83.13% when two UAVs are charged simultaneously, indicating its potential in multi-UAV WPT applications.

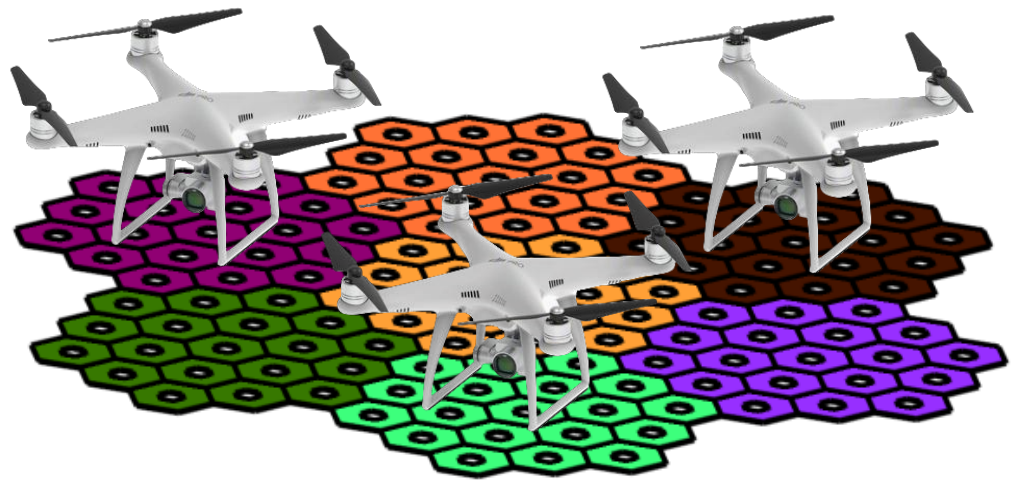


**Figure 12.** Overview of array transmitting platform in Reference [29].

Reference [30] presents a reinforcement learning-augmented wireless charging system for UAVs, which addresses the key challenges of misalignment tolerance and energy-efficient coil matching in autonomous landing scenarios. A reconfigurable magnetic array generates a 2D rotating magnetic field to adapt to position/angle deviations, as shown in Figure 13, while a Q-learning framework maps random UAV positions to grid states via voltage feedback acquisition, optimizing the activation of energy transfer units through a multi-objective reward function (efficiency, switching cost, boundary constraints). Experimental verification demonstrates that the system achieves an average activation of 5 steps and a coarse positioning error of less than 4.2 cm.

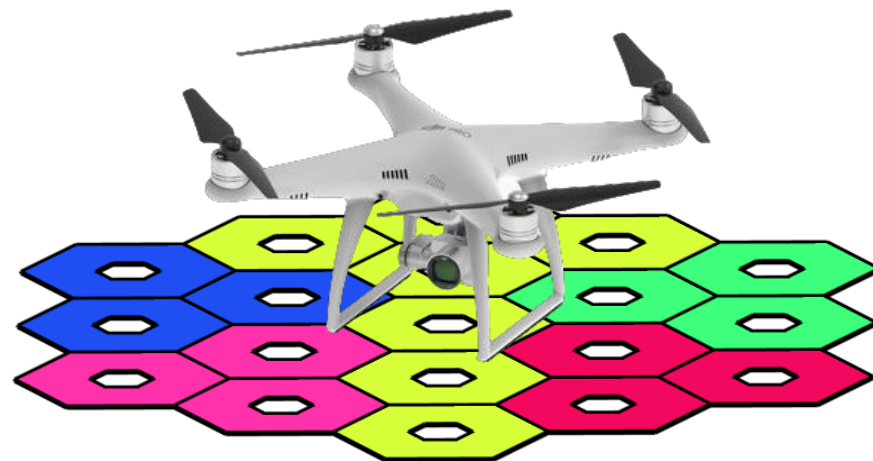


**Figure 13.** Overview of the proposed magnetic structure in Reference [30].

From Table 2 and corresponding analysis, the research on misalignment tolerance of WPT coupling mechanisms exhibits distinct advantages and drawbacks. Single/dual-coil schemes (e.g., [17,22]) feature a simple structure. Specifically, Ref. [17] can accommodate 30% coil misalignment along the  $x$  and  $y$  directions, but its tolerance is restricted to specific directions. Dual-solenoid configurations (e.g., [21,24]) are suitable for AUV applications: [21] achieves a fluctuation below 6% under 80% coil-width misalignment along the  $z$  direction, and [24] enables free rotation with a fluctuation of less than 5%, though both lack sufficient multi-directional tolerance. In UAV scenarios, the multi-transmitter/receiver coil design in [26] supports multi-directional misalignment with a fluctuation below 3.9%, thus demonstrating strong tolerance. Array-based schemes (e.g., [29,30]) can support simultaneous charging of multiple UAVs, yet they suffer from complex transmitting coil

configurations and intricate topology algorithms. Additionally, enhancing tolerance by increasing the number of coils leads to higher costs and greater system complexity. Therefore, synergistic integration with other methods (such as compensation topologies) is required to achieve improved misalignment tolerance.

**Table 2.** Comparison of system characteristics for misalignment tolerance achieved via coil optimization methods.

| Reference | Background    | Method                                  | Type and Quantity of Coils                     | Direction               | Misalignment                                    | Output Type | Fluctuation  |
|-----------|---------------|-----------------------------------------|------------------------------------------------|-------------------------|-------------------------------------------------|-------------|--------------|
| [17]      | Not mentioned | Uniform Magnetic Field                  | Primary: Q, 4<br>Secondary: Q, 1               | $x$ and $y$             | 30% of primary coil                             | CV          | 6.13%        |
| [21]      | AUV           | Uniform Magnetic Field                  | Primary: solenoid, 3<br>Secondary: solenoid, 1 | $z$                     | 100 mm (80% of the coil width)                  | CP          | below 6%     |
| [22]      | AGV           | Uniform Magnetic Field                  | Primary: Q, 1<br>Secondary: DD, 2              | $y$                     | 50% of primary coil                             | CV          | /            |
| [23]      | AUV           | Uniform Magnetic Field                  | Primary: solenoid, 2<br>Secondary: solenoid, 2 | $z$                     | 80 mm                                           | /           | /            |
| [24]      | AUV           | Multi-transmitting and single-receiving | Primary: solenoid, 2<br>Secondary: solenoid, 1 | Rotational Misalignment | Free rotation                                   | CP          | less than 5% |
| [25]      | Not mentioned | Multi-transmitting and single-receiving | Primary: solenoid, 3<br>Secondary: solenoid, 1 | Rotational Misalignment | Free rotation                                   | CV          | below 5%     |
| [26]      | UAV           | Multi-transmitting and multi-receiving  | Primary: solenoid, 2<br>Secondary: solenoid, 2 | Diverse Misalignment    | Axial and radial within 7 cm, and free rotation | CV          | below 3.9%   |
| [29]      | UAV           | Planar Coil Array                       | Primary: Planar Coil<br>Secondary: Planar Coil | Rotational Misalignment | Free rotation                                   | CV          | /            |
| [30]      | UAV           | Planar Coil Array                       | Primary: Planar Coil<br>Secondary: Planar Coil | Rotational Misalignment | Free rotation                                   | CV          | /            |

### 3.2. Misalignment Tolerance Technology Based on Optimization Design of Compensation Topologies

The parameter design method of traditional compensation topologies enables WPT systems to maintain a constant output characteristic against load variations, while their misalignment tolerance is unsatisfactory when facing changes in the coupling coefficient. Therefore, researchers have enhanced the system's misalignment tolerance from two aspects: topology parameter optimization and hybrid compensation topologies [31–42].

References [31,32] conducted research on different topological structures and output characteristics in wireless power transfer systems, as shown in Figure 14, revealing that dual-channel topologies can be formed by series or parallel connections on the transmitter/receiver side or AC/DC side to achieve misalignment tolerance. The authors investigated the characteristics of full series-parallel constant current (CC) and constant voltage (CV) topologies, including their combination principles and operating modes. Based on the S-S and LCC-LCC topologies with parallel connection on the DC side, a dual-frequency dual-channel misalignment-resistant WPT system was proposed. Experimental verification has demonstrated that the output voltage fluctuation of the system does not exceed 4.6% under 53.3% misalignment.

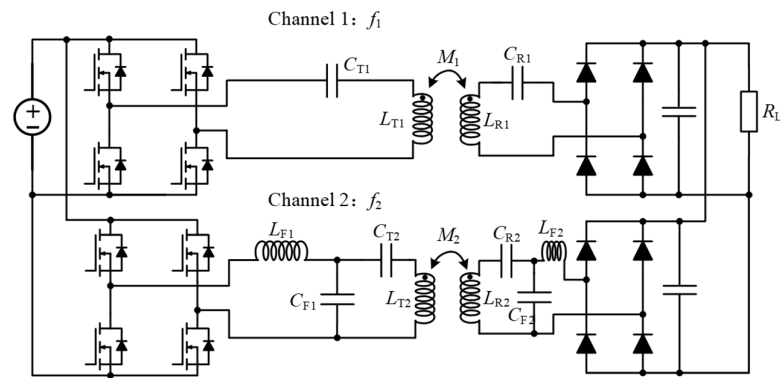


**Figure 14.** Proposed dual-frequency dual-channel misalignment tolerance WPT topology in Reference [31].

References [33,34] considered the coupling between the transmitting compensation inductor and the receiving coil, derived the relationship between the output current and mutual inductance, and took this as the basis for the design of the coupling mechanism to establish a WPT system with misalignment tolerance capability. Reference [34], based on a system architecture with one flux compensation winding, as shown in Figure 15, which generates a compensation magnetic flux relative to that produced by the primary transmitting winding on the receiving winding, conducted a general theoretical analysis on the adaptive characteristics for lateral misalignment and summarized various adaptive compensation topologies for lateral misalignment. Experimental verification demonstrates that within the coupling coefficient range of 0.12–0.40, the output current fluctuation of the system is less than 6%.

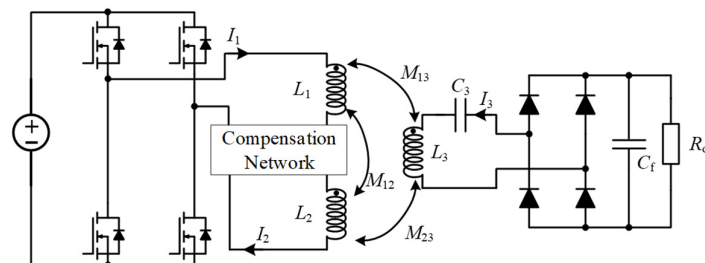


**Figure 15.** Two-to-one WPT system with a general compensation network in Reference [34].

Existing single topologies struggle to balance misalignment tolerance with CC/CV output characteristics, which limits the application of WPT systems in complex scenarios. References [35–37] adopt hybrid topology approaches, which are crucial for improving the reliability of wireless charging by integrating the advantages of multiple topological structures to optimize coupling characteristics and output regulation performance. Reference [37] proposes a dual-coupling wireless power transfer system with LCCC-LCC compensation to enhance the system's anti-interference capability against variations in the coupling coefficient, as shown in Figure 16. This system only adds a single capacitor to the primary side of the LCC compensation network. Not only does this method retain transmission characteristics similar to those of the LCC-LCC compensation system, but it also flexibly designs an enhanced stable equivalent mutual inductance (MI) by introducing the MI adjustment factor  $\lambda$ , thereby efficiently providing a stable output. Experimental verification demonstrates that the fluctuation of the system's output current is 5% within a misalignment range of 120 mm.

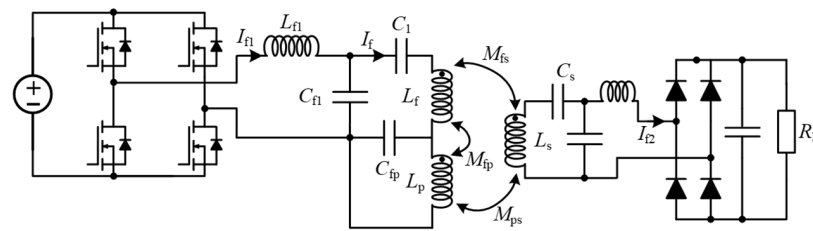


**Figure 16.** Equivalent circuit of the proposed LCCC-LCC compensated dual-coupled WPT system in Reference [37].

It is difficult for a single coupling mechanism to break through the limitation of magnetic field coverage, while relay coils can effectively extend the magnetic field action distance, optimize the energy transfer path, and significantly improve the system's misalignment tolerance capability [38–42]. Reference [42] presents a tuning method to enhance the system's tolerance to planar and vertical misalignment, as shown in Figure 17. In this system, the relay coil is located at the receiving end and wound in the same direction as the receiving coil to improve misalignment tolerance. By adjusting the tuning ratio of the relay coil, constant voltage output and high misalignment tolerance are achieved. Experimental verification demonstrates that within a planar misalignment range of 80 mm (53.3% of the primary coil diameter), the output voltage fluctuation of the system is within 3%. Within a vertical transmission distance range of 30–65 mm (70% of the normal transmission distance), the output voltage fluctuation is within 5%, and the peak dc–dc efficiency is 86.87%

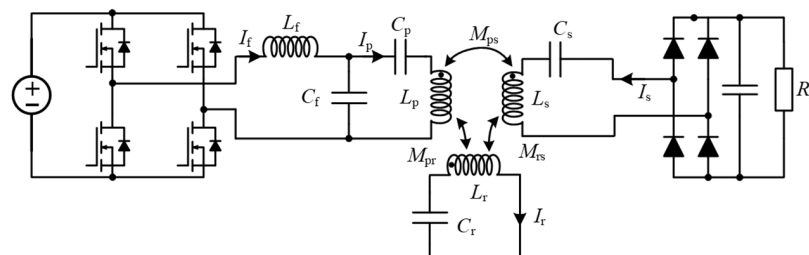


**Figure 17.** Structure of the proposed intermediate aided WPT system in Reference [42].

Based on the analysis from the perspective of Table 3 and compensation topology, these WPT misalignment tolerance schemes each present distinct strengths and limitations: Reference [31] adopts a multi-channel and multi-frequency approach paired with DD/Q-type coils, capable of handling 53.3% coil-size misalignment along the  $x$  direction with a fluctuation of only 4.59%, yet it is restricted to a single misalignment direction. Reference [34] leverages a hybrid topology combined with Q-type coils, supporting 50% coil misalignment along the  $x/y$  directions with a fluctuation below 6%. This demonstrates the misalignment tolerance advantage of hybrid topologies, while its misalignment range is constrained by the coupling mechanism. Reference [37] employs a hybrid topology matched with circular coils, exhibiting a fluctuation of approximately 5% under 120 mm misalignment along the  $y$  direction. It delivers stable output but has a limited applicable direction. Reference [42] utilizes circular repeater coils, accommodating planar/transfer-distance misalignment with fluctuations controlled within 3%. Despite its prominent tolerance performance, it suffers from a complex coupling structure design and relatively low transmission efficiency. These schemes enhance misalignment tolerance through compensation topologies, yet they are constrained either by direction or the coupling mechanism. Thus, enhanced collaborative design is required to overcome these limitations.

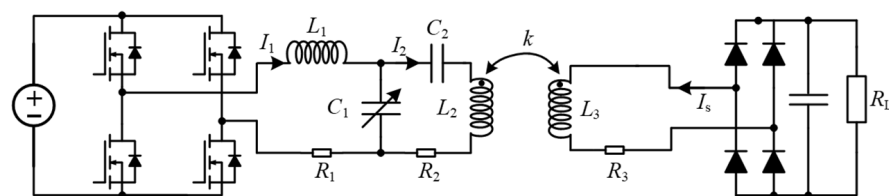
**Table 3.** Comparison of system characteristics for misalignment tolerance achieved via compensation topology methods.

| Reference | Method                            | Type of Coils                                                              | Direction                                | Misalignment                                                                                    | Output Type | Fluctuation |
|-----------|-----------------------------------|----------------------------------------------------------------------------|------------------------------------------|-------------------------------------------------------------------------------------------------|-------------|-------------|
| [31]      | Multi-Channel and Multi-Frequency | Primary: DD and Q<br>Secondary: DD and Q                                   | $x$                                      | 53.3% of primary coil                                                                           | CV          | 4.59%       |
| [34]      | Hybrid Topology                   | Primary: Q<br>Primary compensation: Q<br>Secondary: Q                      | $x$ or $y$                               | 50% of primary coil                                                                             | CC          | below 6%    |
| [37]      | Hybrid Topology                   | Primary: circular<br>Primary compensation: circular<br>Secondary: circular | $y$                                      | 120 mm                                                                                          | CC          | about 5%    |
| [42]      | Repeater Coil                     | Primary: circular<br>Repeater Coil: circular<br>Secondary: circular        | planar misalignment or transfer distance | 80 mm (53.3% of the primary coil diameter) and 30–65 mm (70% of the standard transfer distance) | CV          | within 3%   |

### 3.3. Misalignment Tolerance Technology Based on Real-Time Parameter Control

Numerous researchers have adopted control methods to enhance the system's misalignment tolerance. By integrating real-time position feedback from sensors, combined with dynamic adjustment of resonant parameters using switched control capacitors (SCCs) and optimization of modulation strategies via zero-voltage switching (ZVS), precise compensation for coil misalignment and adaptive regulation of output characteristics can be achieved. Such control schemes effectively suppress efficiency degradation and power fluctuation caused by misalignment, significantly improving the operational stability and robustness of the system under multi-dimensional misalignment conditions [43–45].

Reference [44] proposes an LCC-N WPT system, as shown in Figure 18, which reduces the weight and volume of AUVs. Meanwhile, based on the SCC technology and frequency modulation technology at the transmitting end, the WPT system can maintain a stable output current when the coupling coefficient and load resistance vary over a wide range. The paper details the method for determining system parameters (including operating frequency, SCC capacitance value, and compensation inductance under different alignment deviation conditions) and achieves full-range zero-phase angle (ZPA) characteristics. Experimental verification demonstrates that when the coupling coefficient varies within the range of 0.3 to 0.54, the output current fluctuation of the proposed WPT system is less than 4.47%.

**Figure 18.** Proposed AUV WPT system with LCC-N topology in Reference [44].

References [46,47] both adopt the secondary-side control strategy to achieve stable regulation of the system output. This strategy effectively obviates the need for complex communication link design between the primary and secondary sides, and features prominent technical merits such as fast response speed and strong anti-interference capability, thus being well suited for dynamic charging and multi-load power supply scenarios of WPT systems. Reference [47] proposes a novel control strategy to maintain constant power

(CP) output under variations in load and coupling coefficient, as shown in Figure 19. The CP WPT system employs a dual LCC compensation topology, where the secondary-side compensation inductor is connected in series with a semi-active rectifier and an SCC. Furthermore, a parameter cooperative regulation strategy is specifically proposed: by configuring the equivalent load impedance on the secondary side, the CP-WPT system can operate in a resonant state and deliver CP output. Experimental verification demonstrates that the proposed system can achieve CP output when the load and coupling coefficient vary by more than 50%, with the output power fluctuation less than 5%.

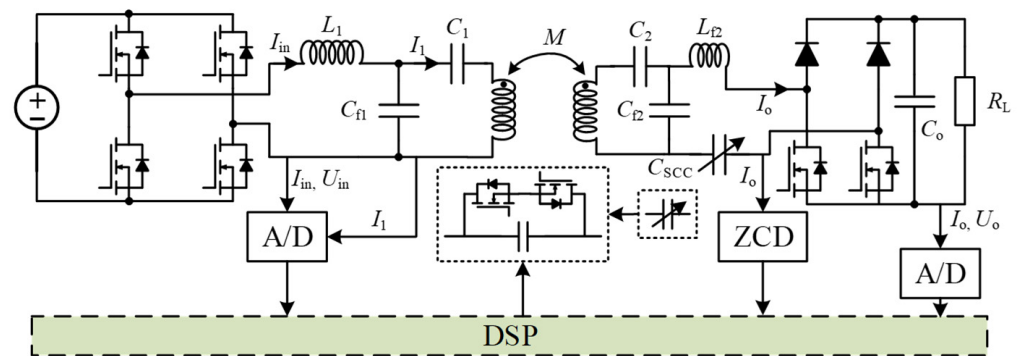


Figure 19. Diagram of parameter collaborative adjustment strategy in Reference [47].

Reference [48] addresses the detuning issue caused by coil misalignment and capacitor parameter drift in dynamic wireless power transfer systems, as shown in Figure 20, proposing an adaptive tuning cooperative control strategy for the LCC-S topology based on dual-side switch-controlled capacitors. First, a unified impedance detuning model is established to reveal the adverse effects of detuning on transmission characteristics. The transmitter adopts a simple phase detection combined with PI control to achieve zero-phase-angle operation, while the receiver implements maximum output voltage tracking via the adaptive-step perturb and observe algorithm for decoupled control. This method requires no additional phase detection circuits or wireless communication, relying only on a zero-crossing detection unit with a concise structure. Experimental verification shows that within the range of output power 200–600 W and coupling coefficient 0.32–0.69, the system can realize maximum output voltage tracking with a maximum efficiency of 92.19%.

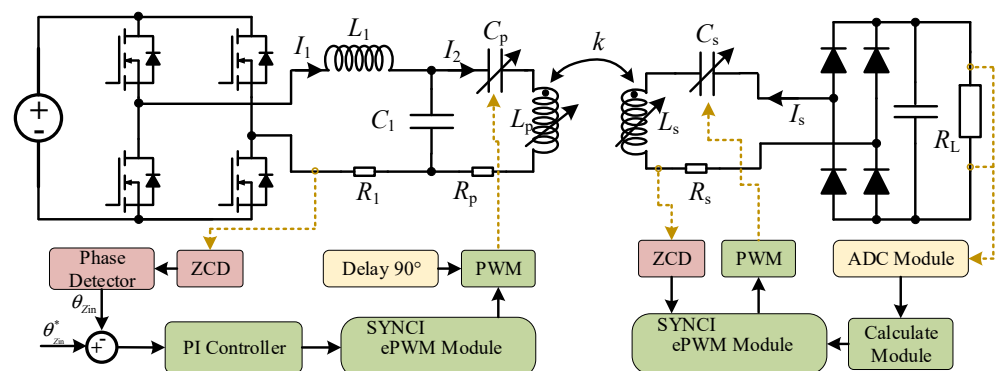


Figure 20. Control block diagram in Reference [48].

Based on the analysis from the perspective of Table 4 and control methods, these WPT misalignment tolerance schemes each exhibit distinct characteristics: Reference [44] adopts a transmitter-side control strategy, accommodating scenarios with z-direction misalignment and a coupling coefficient ranging from 0.3 to 0.54. It achieves constant current output with a fluctuation below 4.47%, yet suffers from a limited control direction. Reference [47] relies

on receiver-side control, supporting over 50% coupling variation and realizing constant voltage output with a fluctuation of less than 5%. It is adaptable to a wider range of misalignment directions but may face a trade-off between efficiency and complexity when addressing large-range variations. Reference [48] implements hybrid topology control, covering scenarios with y/z-direction misalignment and a coupling coefficient of 0.32 to 0.69. It enables maximum output voltage tracking with outstanding control precision, though the fluctuation performance is not clearly specified. While these control-oriented schemes can accurately maintain output, as analyzed, they are prone to the dilemma of reduced efficiency and increased control complexity when coping with large-range coupling/load variations. Thus, it is necessary to achieve a balance between the control range and system performance.

**Table 4.** Comparison of system characteristics for misalignment tolerance achieved via control methods.

| Reference | Method            | Direction | Coupling Coefficient    | Output Type                     | Fluctuation     |
|-----------|-------------------|-----------|-------------------------|---------------------------------|-----------------|
| [44]      | Primary Control   | z         | 0.3 to 0.54             | CC                              | less than 4.47% |
| [47]      | Secondary Control | -         | varies by more than 50% | CP                              | less than 5%    |
| [48]      | Hybrid Topology   | y or z    | 0.32 to 0.69            | Maximum Output Voltage Tracking | -               |

### 3.4. Precise Coil Alignment Technology Based on Alignment Guidance

Alignment guidance technology is a key solution to enhance the misalignment tolerance of WPT systems. Its core principle lies in the real-time acquisition of coil position information via sensors such as visual and electromagnetic induction sensors, combined with closed-loop control algorithms and the motion control unit of unmanned equipment, to achieve precise alignment between the transmitting and receiving coils [49–52]. This technology does not require complex hardware reconstruction and can quickly correct lateral, angular, and axial misalignments, effectively suppress efficiency degradation and output fluctuations caused by misalignment, and significantly enhance the coupling stability and robustness of the system under dynamic operating conditions.

To achieve precise coil alignment, Reference [49] proposes a single-source coil magnetic vector partial discharge (PD) method for vehicle position detection. This method uses a power coil and an inverter as the magnetic field source for positioning, integrates the WPT power transfer system with the PD system to assist in completing position correction, and establishes an experimental platform to achieve coil alignment with an accuracy of 2 cm.

Reference [50] proposes a method to locate the charging position using multiple auxiliary secondary coils to assist in position correction, as shown in Figure 21. Furthermore, an additional resonant topology with three U-shaped auxiliary coils is connected in parallel at the transmitting coil, and when combined with secondary coil positioning and directional guidance methods, the goal of high-precision alignment is achieved. However, these methods all require adding one or more auxiliary coils to determine and guide the position of the receiving coil, which may result in bulky system volume and structural redundancy.

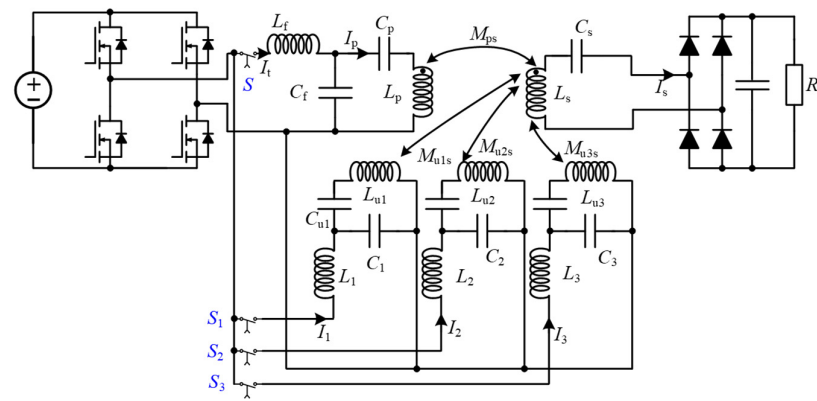


Figure 21. Configuration of the WPT system with the triple-U auxiliary coil in Reference [50].

References [51,52] propose a precise coil alignment method based on output voltage detection, as shown in Figure 22. By adding one or two AC MOSFETs to switch the system's operating modes, the method leverages the decoupling characteristics of DD coils and Q coils to achieve precise alignment in the traveling direction of the AGV. Meanwhile, the lateral misalignment tolerance of DD coils is utilized to enhance the system's misalignment tolerance in the  $y$  direction. Experimental verification demonstrates that the proposed method achieves an alignment accuracy of 5 mm in the  $x$  direction, a misalignment tolerance of 40% in the  $y$  direction, and an output current fluctuation of only  $\pm 3.2\%$ .

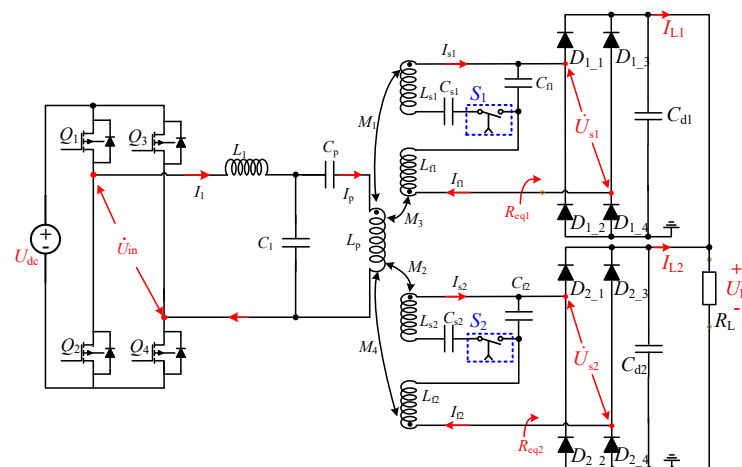


Figure 22. Circuit diagram of the proposed WPT system in Reference [52].

Based on the analysis of alignment-guided misalignment tolerance technologies in Table 5, these schemes each have their respective strengths and limitations: Reference [49] adopts single-source localization paired with Q-type coils, achieving an alignment accuracy of 2 cm in the  $x/y$  directions. However, single-source localization requires additional components, which increases the system cost. Reference [50] leverages multi-auxiliary coil localization combined with DDQ coils, attaining an alignment accuracy of 10 mm in the  $x/y$  directions. Nevertheless, the integration of multi-auxiliary coils not only raises hardware costs but also necessitates real-time communication to adjust path strategies, thereby increasing the system's control complexity. Reference [52] employs reconfigurable topology alignment with DDQ coils, accommodating misalignments of 5 mm in the  $x$  direction and 40% of the primary coil size in the  $y$  direction; its constant current output fluctuation is only  $\pm 3.2\%$ , demonstrating strong alignment adaptability. However, components such as AC switches required for the reconfigurable topology increase costs, and the receiver being divided into two groups enlarges the receiver's volume. While these schemes achieve

precise alignment, they all face issues of increased cost and control complexity. Optimized component integration is thus required to balance performance and cost.

**Table 5.** Comparison of system characteristics for misalignment tolerance achieved via alignment guidance methods.

| Reference | Method                                   | Type of Coils                     | Direction   | Accuracy/<br>Misalignment                        | Output<br>Type | Fluctuation       |
|-----------|------------------------------------------|-----------------------------------|-------------|--------------------------------------------------|----------------|-------------------|
| [49]      | Single-Source<br>Localization            | Primary: Q<br>Secondary: Q        | $x$ and $y$ | 2 cm                                             | -              | -                 |
| [50]      | Multi-<br>Auxiliary Coil<br>Localization | Primary: DDQ<br>Secondary:<br>DDQ | $x$ and $y$ | 10 mm                                            | -              | -                 |
| [52]      | Reconfigurable<br>Topology<br>Alignment  | Primary: DD<br>Secondary: DD      | $x$ and $y$ | 5 mm in $x$ and<br>40% of primary<br>coil in $y$ | CC             | about $\pm 3.2\%$ |

### 3.5. Comparative Analysis of Misalignment Tolerance Technologies in WPT Systems

Sections 3.1–3.4 of this paper focus on four major misalignment tolerance technology paths, namely the optimization design of coupling structures, the optimization design of compensation topologies, real-time parameter control, and alignment guidance. Relevant research achievements in this field are systematically sorted out and summarized, and the advantages and limitations of each technology path are as follows:

**Optimization Design of Coupling Structures:** The magnetic coupling structure design, through the segmented winding of coils, array arrangement, or topology reconstruction (e.g., four-quadrant Q-type coils or segmented solenoid coils), can directly construct a uniform magnetic field and achieve high misalignment tolerance in specific directions. Some schemes can still control the output fluctuation within 6% under a coil size offset of 30%~80%. This technology does not require complex external regulation and exhibits strong reliability after structural solidification, high magnetic field utilization efficiency, and excellent stray magnetic field control performance, thus demonstrating prominent practical feasibility. It is suitable for static/dynamic charging needs for scenarios such as AGVs, AUVs, and UAVs. Among them, single/dual-coil schemes (e.g., Q-type and DD-type coils) feature a simple structure, and some multi-coil designs (e.g., BP-type coils) can achieve a balance between lightweight design and high misalignment tolerance by optimizing copper usage. However, there is an inherent contradiction between offset resistance and structural complexity: multi-coil or special-shaped structures will increase copper consumption and parasitic losses, leading to a rise in system cost. Most schemes are only suitable for misalignment in a single direction (e.g.,  $x/y$  direction or  $z$  direction), lacking sufficient full-dimensional misalignment tolerance. Under extreme offsets, magnetic field nulls are prone to occur, causing a sharp drop in efficiency. Additionally, different coil topologies have poor compatibility, resulting in great difficulty in standardization and limited cross-scenario scalability. Array-based schemes also face issues such as complex transmitting coil configuration and cumbersome topology algorithms.

**Optimization Design of Compensation Topologies:** Compensation topology optimization, through multi-channel and multi-frequency design, hybrid topology integration, or the introduction of relay coils, can dynamically offset mutual inductance fluctuations without modifying the physical structure of the coils, adapting to a wide range of coupling variations (coupling coefficient: 0.12~0.69). Some schemes (e.g., LCC-LCC and LCCC-LCC topologies) can achieve ZVS with a maximum efficiency of 92.19% and can balance multi-directional misalignment tolerance with CV/CC output. The output fluctuation can be controlled within 3~6%, featuring high flexibility in engineering modification. It

is suitable for scenarios such as dynamic wireless charging and multi-load power supply, exhibiting strong practical feasibility. However, this technology has a topology switching delay under wide-range coupling fluctuations, and switching devices face the contradiction between voltage stress and losses under high-frequency operating conditions. The theoretical boundaries of multi-objective optimization (misalignment tolerance, low loss, and constant voltage output) are ambiguous, leading to great design difficulty. Reconfigurable topologies lack unified industry standards and have low modularity, resulting in high cost for large-scale deployment. Although the relay coil scheme improves misalignment tolerance, it involves complex coupling structure design, which is prone to causing a decrease in transmission efficiency.

**Real-Time Parameter Control:** Control strategy optimization relies on technologies such as SCCs, frequency modulation, and adaptive PI control. It can compensate in real time for coil misalignment and parameter drift and improve misalignment adaptability without the need for hardware upgrades. This technology enables non-contact misalignment detection and dynamic regulation, maintaining stable output within a coupling coefficient range of 0.3~0.69, with the output current fluctuation of some schemes being less than 4.47%. Additionally, it boasts strong generalization ability, which can adapt to different power levels and multi-device collaborative systems through algorithm iteration, featuring outstanding scalability and suitability for complex dynamic operating conditions. However, there is an inherent contradiction between algorithm real-time performance and computational power consumption, leading to potential regulation delays under complex operating conditions. Multi-sensor data is susceptible to electromagnetic interference (EMI), which affects detection accuracy and control stability; embedded algorithms also have high requirements for hardware resources, increasing system costs and resulting in poor adaptability to low-power scenarios. Furthermore, engineering verification lacks standardized test platforms, so the algorithm robustness needs long-term validation in practical scenarios. When facing wide-range coupling/load variations, it also tends to encounter a trade-off dilemma between efficiency and complexity.

**Alignment Guidance:** Alignment guidance technology achieves precise alignment of coils from the micrometer level ( $\pm 5$  mm) to centimeter level (2 cm) through visual sensing, auxiliary coil positioning, or reconfigurable topology switching. It avoids coupling attenuation at the source, enabling the system efficiency to approach an ideal state. This technology does not rely on coil or topology optimization and can be directly adapted to existing standardized coils, featuring strong compatibility and the ability to reduce transformation costs. Additionally, it meets the automated collaboration needs of unmanned equipment such as AGVs, UAVs, and autonomous vehicles, realizing the synchronization of autonomous alignment and energy transfer and improving the level of power supply automation. However, it relies on high-precision positioning and sensing systems, its reliability degrades in complex environments such as occlusion and strong EMI, and the positioning process increases system response time, making it incompatible with scenarios involving rapid movement or high-frequency start-stop operations. Extra positioning modules or auxiliary coils raise system costs and energy consumption and impose requirements on installation space and equipment mobility, rendering it difficult to adapt to miniaturized medical implants and equipment in extreme environments (e.g., underwater and high-temperature conditions). Furthermore, some schemes require real-time communication to adjust path strategies, increasing control complexity, and the grouped design of the receiving end may lead to an increase in equipment volume.

#### 4. Future Development Directions of Misalignment Tolerance Technology

With the widespread application of WPT technology in fields such as new energy vehicles, UAVs, medical implants, and industrial AGVs, issues including coupling weakening, efficiency reduction, and output instability caused by relative misalignment of coupling structures have emerged as the core bottleneck restricting its large-scale implementation. In the future, misalignment tolerance technologies for WPT systems will advance towards “multi-dimensional optimization and integration, intelligent dynamic adaptation, and scenario-specific customization.” Through interdisciplinary integration, the synergistic improvement of misalignment tolerance, transmission efficiency, and engineering practicality will be achieved, with specific development directions summarized into four core areas.

First, precision optimization of novel magnetic coupling mechanisms and magnetic circuits will focus on breakthroughs in multi-dimensionality and high integration. Innovative coupling structures (e.g., diagonal-cross solenoids and non-centrosymmetric matrix coils) achieve full-dimensional misalignment tolerance through coil reconstruction, while the integration of special-shaped magnetic cores with negative magnetic metamaterials and high-permeability composite materials can constrain stray magnetic fields and enhance magnetic field focusing capability. Open technical challenges currently include a surge in coil parasitic losses caused by multi-dimensional structural design, the risk of electromagnetic compatibility non-compliance induced by highly integrated magnetic circuits, and the difficulty in suppressing interface magnetic resistance between different materials. Promising yet underexplored research directions cover the integrated molding process of negative magnetic metamaterials and special-shaped magnetic cores, quantitative trade-off methods between lightweight conformal design and high misalignment tolerance, and the stability control mechanism of magnetic circuit parameters under extreme environments. Key engineering bottlenecks for industrial-scale deployment concentrate on micro-scale tolerance control in high-precision magnetic circuit processing, a consistency guarantee for mass production of composite magnetic materials, and the lack of unified design specifications for the engineering balance between magnetic circuit losses and misalignment tolerance.

Second, reconfigurable innovation of compensation topologies will center on adaptive schemes. Detuning compensation technology offsets mutual inductance fluctuations using coil self-inductance to improve reliability in harsh environments, while reconfigurable hybrid topologies adapt to wide-range coupling variations through structural switching or parameter adjustment, balancing multi-directional misalignment tolerance and constant voltage output. Open technical challenges are reflected in the dynamic response delay of topology switching under wide-range coupling fluctuations, the ambiguous theoretical boundary of multi-objective optimization (misalignment tolerance, constant voltage output, and low loss), and the contradiction between voltage stress and loss of reconfigurable switching devices under high-frequency operating conditions. Promising yet underexplored research directions include the hybrid integration of parity–time symmetric topologies with traditional compensation architectures, dynamic self-tuning methods for compensation parameters based on multi-physics field coupling, and the design of reconfigurable topologies for bidirectional WPT systems. Key bottlenecks for industrial deployment lie in the lack of industry standards for modular design of reconfigurable topologies, the difficulty in balancing the cost and reliability of high-frequency switching devices, and the failure of disturbance-free transition technology for topology switching to meet industrial-grade stability requirements.

Third, intelligent control and algorithms will drive misalignment tolerance technology to evolve from passive adaptation to precise regulation. Particle swarm optimization, genetic algorithms, and other methods will be used for global optimization of compensation

parameters to minimize output fluctuations; the combination of multi-sensing coil perception and adaptive control will enable non-contact precise detection and dynamic regulation of misalignment; and the deep integration of AI technologies such as deep learning will realize autonomous iterative optimization of control strategies. Open technical challenges include the suppression of electromagnetic interference in multi-sensing data, the balance between algorithm real-time performance and computational power consumption under complex operating conditions, and the insufficient generalization ability of algorithms in dynamic misalignment scenarios. Promising underexplored directions cover the application of federated learning in multi-device collaborative WPT systems, the coupled optimization of digital twins and control algorithms, and fault self-healing control strategies based on reinforcement learning. Key engineering bottlenecks for industrial-scale deployment are the high hardware resource occupancy of embedded algorithms, the great difficulty in integrating low-power sensing and control modules, and the lack of standardized test platforms for the engineering verification of algorithms.

Fourth, engineering implementation of scenario-specific customized schemes will abandon the one-size-fits-all approach. For mobile scenarios, high-misalignment tolerance and fast-response coupling mechanisms need to be developed to achieve smooth switching of energy transmission; for special environments, underwater equipment will adopt arch-shaped coils and corrosion-resistant magnetic cores, while medical implant devices will focus on biocompatibility and miniaturization, and for rotating equipment, sleeve-type coupling mechanisms will be optimized to adapt to axial and radial misalignments through parameter self-compensation. Meanwhile, low-cost design is promoted through structural simplification and the use of general-purpose materials. Open technical challenges include standardization conflicts between scenario-specific design and cross-scenario compatibility, significant system performance degradation under extreme environments, and the lack of a life-cycle cost assessment system for customized schemes. Promising underexplored directions include modular design methods for cross-scenario universal modules, optimization of customized schemes based on the full-life-cycle theory, and the development of adaptive adjustment modules for multi-scenario adaptation. Key bottlenecks for industrial deployment are the great difficulty in balancing customization and low cost in engineering, the complexity and high cost of multi-scenario adaptive test and verification systems, and the lack of unified safety certification standards across different scenarios.

## 5. Conclusions

This paper provides a comprehensive review of the research achievements and development status of misalignment tolerance technologies for WPT systems, clarifying the impact mechanisms of coil misalignment on WPT systems. From the aspects of control strategies, coupling mechanisms, compensation topologies, and alignment guidance, the basic principles and key achievements of various methods are elaborated. Finally, the potential future development directions of misalignment tolerance technologies are pointed out. It can be observed that misalignment tolerance technologies have achieved certain progress, but there are still issues that require further resolution and improvement. To accelerate the development of misalignment tolerance technologies, further in-depth research can be conducted in multiple directions, such as multi-method collaboration, specific misalignment tolerance requirements of different application scenarios, and WPT technologies with external auxiliary means.

**Author Contributions:** All authors, C.W., W.R., Y.C. and X.L., contributed equally to this work. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Data Availability Statement:** No new data were created or analyzed in this study.

**Conflicts of Interest:** Authors Wei Ren and Yang Chen were employed by the CNPC Chuanqing Drilling Engineering Company Limited. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Nomenclature

|       |                                     |
|-------|-------------------------------------|
| WPT   | Wireless Power Transfer             |
| AGV   | Automated Guided Vehicle            |
| EV    | Electric Vehicle                    |
| AUV   | Autonomous Underwater Vehicle       |
| UAV   | Unmanned Aerial Vehicle             |
| ZVS   | Zero-Voltage Switching              |
| ZPA   | Zero-Phase Angle                    |
| MI    | Mutual Inductance                   |
| SCC   | Switched Control Capacitor          |
| EMI   | Electromagnetic Interference        |
| LCC-S | Inductor–Capacitor–Capacitor Series |
| SS    | Series–Series                       |
| SP    | Series–Parallel                     |
| PP    | Parallel–Parallel                   |
| PS    | Parallel–Series                     |
| DD    | Double Dee                          |
| CC    | Constant Current                    |
| CV    | Constant Voltage                    |
| CP    | Constant Power                      |
| PD    | Partial Discharge                   |

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