Comprehensive Performance Improvement Method for Wireless Power Transfer Compensation Network

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***Abstract*—An effective way to solve the problem of insufficient transmission efficiency and stability of wireless power transfer systems is to introduce a compensation topology into the system. However, the traditional compensation topology makes it difficult to balance the system transmission efficiency and stability. To enhance the comprehensive performance of wireless power transfer systems with compensation topology, this paper provides a thorough review of the topology performance enhancement methods that have been proposed for wireless power transfer systems. These methods are classified into basic compensation topology, higher-order compensation topology, hybrid compensation topology, and integrated compensation topology. Based on the published research results, it can be found that the above methods can bring new problems and challenges while achieving comprehensive performance improvement. Typical problems and challenges include four main aspects: insufficient system misalignment tolerance, difficult parameter design, insufficient topological performance of dynamic wireless power transfer systems, and difficult suppression of electromagnetic radiation from wireless power transfer systems. Finally, four key issues that still need to be addressed in the above types of compensation topologies are discussed, and reasonable development suggestions are given in light of the future development of wireless power transfer technology, to solve the problem of insufficiently integrated performance of the topologies of wireless power transfer systems.**

***Keywords*—wireless power transfer, compensation topology, transmission efficiency**

I. Introduction

Magnetic Coupling Resonant Wireless Power Transfer (MCRWPT) refers to the technology of converting electrical energy into a high-frequency time-varying magnetic field through the transmitter and then converting the time-varying magnetic field into electrical energy through the receiver for a distance. MCRWPT has attracted much attention due to its novel contactless energy transfer method and has been fully developed and applied in typical application scenarios including implantable medical devices, consumer electronics, electric vehicles, deep water and high power supply, robotics, etc. As one of the most popular charging methods, wireless power transfer technology has the advantages of safe operation and flexible power supply compared with contact power transmission. MCRWPT system is generally composed of an inverter circuit, compensation network, transceiver coil, rectifier circuit, filter, and load. When the system works, the DC power supply generates high-frequency AC power through the inverter circuit, and its frequency can be adjusted automatically. The transceiver coil is adjusted to match the same resonant frequency through the compensation network. When the input current frequency reaches the resonant point, the transceiver coil produces magnetic coupling resonance, generates induced current in the receiving coil, and supplies power to the load through the rectifier circuit and filter. Please note that the mutual inductance between transceiver coils determines the transmission efficiency, and how to stabilize and improve the mutual inductance between transceiver coils is a key design goal of high-performance wireless power transfer technology.

At present, for the stability and enhancement of mutual inductance between transceiver coils, a general method is to design a better compensation topology network. As a key part of the MCRWPT system, compensation topology plays a role in compensating reactive power and improving system transmission performance. Existing basic topologies include Series-Series (SS), Series-Parallel (SP), Parallel-Series (PS), and Parallel-parallel (Parallel-Parallel, PP) four kinds, by the transmitting end and the receiving end of the circuit elements through the series or parallel. The MCRWPT system with SS compensation topology, has good current transmission stability, but the transmission efficiency is insufficient. The MCRWPT system using SP compensation topology, has good voltage transmission stability but also has the disadvantage of insufficient transmission efficiency. The MCRWPT system using PS compensation topology, has relatively stable transmission efficiency, but the current transmission stability is insufficient. The MCRWPT system using PP compensation topology, also has high transmission efficiency, but the problem of voltage transmission stability still needs to be solved. It can be seen that the traditional four compensation topologies are difficult to take into account the stability and efficiency of the system transmission, and it is necessary to design a topology with better comprehensive performance. However, at present, the compensation topology design of the MCRWPT system mainly focuses on the improvement of single performance, and there is no mature design method for the improvement of comprehensive performance of topology. Therefore, it is necessary to comprehensively review the existing topological compensation techniques and circuit design methods in wireless power transfer systems, synthesize the advantages and disadvantages and applicability of various methods, and put forward suggestions for future development.

This article reviews the existing compensation topologies and integration methods of wireless power transfer systems. Firstly, the existing compensation topologies are classified into traditional topologies and hybrid topologies, and the advantages disadvantages, and applicability of each topology method are discussed. Then, the existing topology integration methods of wireless power transfer systems are summarized, and the principle and implementation of topology integration methods are discussed. Finally, based on the existing compensation topology and integration methods, several development suggestions are put forward in order to further improve the comprehensive performance of the wireless power transfer technology compensation network.

II. The Summary of the Existing Compensation Topologies of MCRWPT Systems

A. Topology Compensation of Wireless Power Transfer

1) Basic compensation topology

The transceiver coils can be compensated using parallel compensation capacitors, or a combination of series and parallel compensation capacitors can be used. Considering all possible combinations of series and parallel capacitor compensation strategies, four basic compensation topologies can be formed. Generally, these four combinations are called Series-Series (SS), Parallel-Parallel (PP), Series-Parallel (SP), and Parallel-Series (PS) tuned MCRWPT systems.

The earliest SS topology method applied to WPT systems dates back to 1999. A Contactless Energy Transfer System (CETS) based on SS compensation topology is proposed to replace plug-in power connections in humid or hazardous environmental conditions. Although this technology can transmit electrical energy through non-magnetic media with low conductivity, achieving up to 5 kW of power over a 10 mm gap without the need for electrical connections or physical contact, under light load conditions the equivalent impedance at the primary resonant frequency is zero. This results in a very high voltage at the receiving side, creating a safety hazard [1].

SP is also a compensation topology widely used in magnetic coupling resonant wireless power transfer systems. In 2014, a segmented track WPT system for moving vehicles based on SP compensation topology was proposed to allow smooth flux conversion and power transmission when the vehicle moves from one track to the next. Although the WPT system under SP compensation has stable transmission characteristics and high transmission efficiency, its optimal system parameters are affected by the load, which makes the system tuning extremely complicated [2].

PS topology, one of the four basic compensation topologies, is often compared to the SS topology due to its identical transfer impedance. Therefore, PS topology is also widely used in the compensation network of wireless power transfer systems. In 2014, a resonant reactive power shielding method based on PS compensation topology was proposed to reduce magnetic field leakage in wireless power transfer systems. Utilizing LC resonance, reactive shielding can generate a counteracting magnetic field, reduce the incident magnetic field of the WPT coil, and effectively reduce the total magnetic field without consuming additional power. The PS-based compensation method determines the high-efficiency output of the system under a large load and mutual inductance variation range. Although this method has been successfully applied to a wireless charging electric vehicle, a major drawback is that it requires a current source input to avoid any transient changes in voltage [3].

Due to similar impedance transmission methods, PP and SP are the most similar compensation topologies, so they are often used in wireless power transfer systems. In 2009, a parameter optimization design method for PP topology was proposed to improve the overall transmission performance of the wireless power transfer system. Although the optimal PP compensation topology is achieved based on the proposed method, the disadvantages of this configuration are the low PF (The PF is defined as the ratio of the real power delivered by the voltage source to the apparent power) of the parallel secondary lines, the high load voltage, and the large current source requirements of the parallel primary lines. Due to these shortcomings, this configuration has not been extensively studied [4].

2) High-order compensation topology

In order to improve the comprehensive performance, more components are added to the basic compensation topology to form a high-order compensation topology. From an energy perspective, the introduction of more components such as capacitor, C, and inductor, L, will inevitably increase system impedance, thereby reducing system efficiency. However, additional circuit components greatly improve the flexibility of resonant parameter design. The component supplement based on the basic compensation network can achieve various characteristics required by the system, including high transmission efficiency, constant current, and voltage output. The well-known high-order compensation topologies include S/SP, S-LCC, S-CLC, CLC-S, LCL-S, LCC-S, LCC-P, LCL-LCL, and LCC-LCC. Different from the basic topology, various high-order compensation topologies can achieve high transmission efficiency and stable transmission performance. Although high-order topology effectively improves comprehensive performance, it also creates new problems that need to be solved [5].

3) Hybrid compensation topology

In order to overcome the shortcomings of a single compensation topology, a hybrid compensation topology is proposed. Hybrid compensation topology refers to a compensation network that combines two or more topologies, which can complement each other's weaknesses. Usually, hybrid topology can stabilize mutual inductance and load changes. Hybrid compensation topologies can be roughly summarized as Input-Parallel-Output-Parallel (IPOP), Input-Series-Output-Parallel (ISOP), Input-Parallel-Output-Series (IPOS) and Input-Series-Output-Series (ISOS) topology. For high-power and highly flexible output wireless power transfer systems, a multi-inverter/rectifier WPT system based on hybrid compensation topology is proposed. The additional mutual inductance between the primary and secondary coils provides more induced voltage in the secondary coil. However, due to the large number of interference signals, especially cross-coupling between primary and secondary sides, the design of compensation topology parameters becomes complicated. At the same time, it will bring higher power loss and current stress [6].

B. Topology Integration of Wireless Power Transfer

Since the coupling coil replaces the compensation inductor in power transmission, some special magnetic couplers are used to design topological integration to solve the above problems. This section provides the basic coil structures used in integrated designs. An overview of different integration methods is given below.

1) Unilateral integration

In order to improve the transmission performance of the wireless power transfer system, a third coil is used in reverse series connection with the primary coil of the coupling mechanism. The advantage of this method is that the parasitic coil integrated into the single-sided coupling mechanism can retain the inherent output characteristics of the original compensation topology to the greatest extent. The integrated system improves the shortcomings of insufficient transmission efficiency of traditional topology while retaining its stable transmission characteristics. In addition, this article also built a 3.4kW prototype, and the experimental results show that the proposed single-sided coil integration method is feasible. Although this method solves the single performance deficiency problem of traditional topology to a certain extent, it is obvious that additional parasitic coils will lead to a complex system structure, and circuit parameter design will also become very difficult [7].

In 2021, in order to improve the overall performance of traditional topology, a magnetically integrated design for Wireless Power Transfer (WPT) systems is proposed, in which the compensation coil and the transmitting coil overlap each other to share the ferrite layer without considering decoupling issues. In order to enhance the magnetic field without reactive power flow between the compensation coil and the transmitting coil, a compensation method is proposed. This new integrated system achieves high efficiency and high transmission stability of the system. Additionally, a scaled-down WPT prototype was built and tested to verify the performance and effectiveness of the design. The results of this work provide insights into the magnetically integrated design of higher-order compensation topologies with greater compactness and less ferrite usage. However, how to realize the design of its circuit parameters more concisely is a problem that still needs to be solved in the future of this method [8].

2) Bilateral integration

Wireless Power Transfer (WPT) offers significant advantages over traditional charging systems. Improving the transmission efficiency of WPT systems with constant current and constant voltage output is of great significance to battery charging. In order to make the system more compact and thus improve the comprehensive performance, it is necessary to propose a double-sided integrated design. Due to the multi-transmitter/receiver structure, hybrid compensation topologies often adopt double-sided integrated designs. However, there are still some issues that need to be paid attention to in the double-sided integrated design. Although both transmitters and two receivers use unpolarized and polarized coils, the effects of cross-coupling can only be avoided in one misalignment direction [5].

In 2018, a hybrid and reconfigurable WPT system consisting of LCC-S topology and S-LCC topology for CC and CV outputs was proposed by Yang Chen. In addition, a new parametric design method is proposed, which can suppress the fluctuation of output voltage/current within a certain error range. In order to verify the performance of the proposed topology, a 1 kW prototype was built and corresponding experiments were performed. However, the current in S-compensated topology increases exponentially and can even destroy the system when there is high misalignment [9].

In order to avoid overcurrent in the S compensation topology, a hybrid WPT topology based on four-dimensional orthogonal pads (QDQPs) connecting the main LCC and S topology in series is proposed by Yang Chen in 2019. A hybrid IPT system using four-D quadrature pads (QDQPs) is proposed, which can tolerate x, y, z, and diagonal misalignments at load-independent output voltages, simplifying or even eliminating the control scheme. This method can limit the output voltage fluctuation within a certain range given a predetermined deviation distance. To verify the feasibility of the proposed system, a 3.5 kW prototype was built to validate the proposed hybrid IPT system. The primary and secondary coil dimensions are both 400mm×400mm, with an air gap of 150mm. Experimental results show that the overcurrent problem in the S-compensated topology is solved [10].

Currently, the problem of insufficient performance of a single traditional compensation topology in Wireless Power Transfer (WPT) systems is mainly addressed by three types of approaches: introduction of higher-order compensation topologies, introduction of hybrid topologies, and integrated topologies. Based on the above literature review, it can be seen that the above three types of methods will bring new problems and challenges while achieving comprehensive performance improvement. Typical problems and challenges include both the lack of misalignment tolerance and the complexity of system parameter design. This paper will follow up with an analysis and discussion of the above two issues and put forward corresponding solution ideas and development proposals.

III. Issues in Topology Integration and Its Solution Strategies and Recommendations

Based on the review in this paper, the stability, reliability, and efficiency of Wireless Power Transfer (WPT) WPT systems are greatly affected due to the lack of single performance of conventional topologies. Integrated higher-order compensation topologies and control methods have been proposed to address these issues. Although topology integration can reduce system volume and increase design freedom, the following points need to be focused on in future research: 1, the misalignment tolerance of the hybrid WPT system is improved; 2, Parametric design methodology for integrated WPT systems; 3, Topology design methods applicable to dynamic wireless power transfer techniques; 4, Electromagnetic safety shielding design for the space environment. In this section, I will analyze and discuss the above issues one by one, and put forward reasonable solution strategies and future development proposals in conjunction with existing mature approaches for reference.

A. Improved Misalignment Tolerance of Hybrid WPT System

To address the existing problem of insufficient misalignment tolerance in hybrid topologies, this paper gives the following development proposals. Consideration may be given to proposing a novel integrated topology of semi-hybrid-semi-independent type to enhance the lateral, vertical, and rotational misalignment tolerance of the system as much as possible while keeping the circuit parameters unaffected. Existing hybrid topologies achieve increased efficiency by constraining the magnetic field, which inevitably leads to a concentration of the field in a smaller energy transfer range, thus reducing the system misalignment tolerance. However, the proposed semi-hybrid-semi-independent new integrated topology solves the problem by reducing the topological constraints on the magnetic field, thereby releasing the range of the magnetic field energy transfer. In addition, thermal and heat dissipation issues in the topology integration design need to be considered to ensure the stability of the system's semi-standalone performance.

B. Parameter Design Method of Integrated WPT System

To address the problem of difficult parameter design in integrated topologies, this paper gives development suggestions as follows. A parameter tracking control method can be considered to be proposed to stabilize the parameter variations induced by the integrated topology. Moreover, the parameter tracking method can be normalized to a frequency tracking method, which is realized on the principle that the transmission performance of a WPT system is constrained by the design of various types of parameters and that the parameter-induced efficiency degradation and the lack of transmission stability can be attributed to the detuning of the system's resonance matching. Therefore, the problem of parameter design in the integrated topology is solved by monitoring the changes in system transmission efficiency and transmission stability, which are subsequently fed back into the control of the integrated topology frequency, thus resonating the system again.

C. Topology Design Method for Dynamic WPT System

To adapt to the development of future autonomous driving, a topological integration method suitable for dynamic wireless power transfer needs to be developed. For dynamic wireless power transfer conditions, this paper gives the following suggestions for the future development of its topology. Consideration can be given to the design of a multi-D coil based on a double-D coil, i.e., the transmitting coils on the rail are all integrated using a forward or reverse connection. The advantage of this method is that all the transmitting coils involved in the dynamic energy transfer can share a set of compensation topology networks, which greatly reduces the system size as well as the switching loss of the compensation network. Although the method is effective in reducing the impact of topological networks on dynamic WPT systems, the main challenge will be to ensure electromagnetic safety in the space of multi-D coils.

D. Electromagnetic Safety Shielding Design for Space Environment

In order to ensure the electromagnetic safety of the hybrid/integrated topology cyberspace, it is necessary to carry out the relevant electromagnetic shielding design. In view of the existing electromagnetic safety problems, this paper gives the following suggestions for the development of electromagnetic shielding. The optimization of both core material and core structure can be considered as a solution. In terms of core materials, conventional ferrites are not suitable for complex topological network structures in the future due to their lower saturation densities and lower permeability. Nanocrystalline materials, which currently have the best performance, can be considered to replace traditional ferrite materials. Also in recent years, the proposal of electromagnetic metamaterials has provided new ideas for the development of complex topological networks. Core structure, the traditional rectangular core can better guide the magnetic field, but the shielding performance of the magnetic field is insufficient, the core can be considered to be designed as a multi-layer composite structure, to ensure the introduction of a certain air gap between the layers and layers. The principle behind this method of enhancing shielding performance is that the introduction of an interlayer air gap will lead to an abrupt change in the magnetoresistance in the lamination direction, which in turn will lead to a more difficult transfer of magnetic flux between the layers, thus reducing the level of magnetic leakage in the non-operating region on the backside of the core.

IV. Conclusion

Based on an extensive literature review, it is known that traditional topology methods have always suffered from a lack of comprehensive performance, while the existing design methods while solving the performance problems of traditional topologies, have led to problems such as a lack of misalignment tolerance and difficulty in parameter design. To this end, this paper provides a comprehensive overview of topology-compensated network design methods in wireless power transfer (WPT) systems and summarizes and analyses four types of existing problems therein, as well as giving clear development suggestions for reference in light of the future development needs of wireless power transfer technology.

Conflict of Interest

The author declares no conflict of interest.

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