Research on the Design of Coils for Underwater Wireless Power Transmission

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Abstract. Wireless Power Transfer (WPT) technology has attracted widespread attention in recent years and has shown great potential in the fields of smart homes, electric vehicle charging, medical implant devices, and underwater equipment energy supply. Compared with traditional wired transmission methods, wireless power transmission has the advantages of high flexibility, no physical contact, and strong environmental adaptability. It is especially suitable for underwater environments and can avoid complex cable layouts and maintenance problems. However, the coil design, as one of the key links in the wireless power transmission system, directly determines the energy transmission efficiency and stability of the system. To address this issue, this report proposes an optimized coil design suitable for underwater environments through in-depth research on wireless power transfer theory, and simulates and analyzes it using Maxwell simulation software. The data collection and analysis methods are described in detail in the simulation process, and the influence of key parameters on the performance of the coil is demonstrated. The research results show that the optimized coil design can effectively improve the performance of underwater wireless power transfer systems, providing an important reference for subsequent practical engineering applications and further research.

Keywords: Wireless Power Transfer, Coil Design, Maxwell Simulation

1 Introduction

Wireless Power Transfer (WPT) technology has been a research hotspot in recent years, with broad application prospects in fields such as smart homes, electric vehicle charging, and medical implantable devices. Compared with traditional wired power supply methods, wireless power transfer has significant flexibility and convenience, and can achieve long-distance, physically-unconnected energy transmission. It is therefore regarded as an important future trend in energy transmission.

In a wireless power transfer system, the transmission efficiency and effective distance are affected by many factors, among which the coil design is one of the key factors affecting system performance. The shape, size, winding method, and material selection of the coil will directly affect the distribution of the electromagnetic field and the transmission efficiency. As a key component, the design of the coil directly affects

J. Iqbal (ed.), *Proceedings of the 2025 2nd International Conference on Mechanics, Electronics Engineering and Automation (ICMEEA 2025)*, Advances in Engineering Research 272,
https://doi.org/10.2991/978-94-6463-821-9_123

the performance indicators such as the efficiency, distance, and stability of power transmission. An optimized coil design can effectively improve the overall performance of the wireless power transfer system and reduce energy loss. Therefore, in-depth research and analysis of the coil design of wireless power transmission is of great theoretical and practical significance.

A large number of domestic and foreign literature have been studied, and it is found that many scholars have conducted in-depth research on the design of wireless power transmission coils. Some studies focus on optimizing the transmission efficiency by changing parameters such as the number of turns, wire diameter, and shape of the coil. For example, literature 1 proposes the design of a multi-turn flat spiral coil, which significantly improves the transmission efficiency at a given distance by adjusting the number of turns and coil spacing [1]. Literature 2 investigated the performance differences of coils with different shapes (e.g., circular-circular, rectangular-rectangular, D-D, etc.) in wireless power transmission and found that orthogonal D-D coils have better magnetic field uniformity and transmission efficiency in some application scenarios [2]. However, current research still faces some challenges, such as the optimal design of coils in complex environments and how to reduce system cost while improving transmission efficiency.

Against this background, this study proposes an optimized coil design scheme for the specific needs of the underwater submarine environment [3], and uses Maxwell simulation software to perform in-depth analysis and verification of the coil performance, with the aim of providing an important reference for improving the transmission efficiency and reliability of underwater wireless power transmission systems.

This project aims to explore a coil design for underwater submarine wireless power transmission and comprehensively evaluate its performance by combining theoretical analysis with Maxwell simulation.

2 Related Work

The law of electromagnetic induction is one of the fundamental theories of wireless power transmission technology. This theory states that a changing magnetic field will induce an electric current in a conductor. In a wireless power transmission system, alternating current is passed through the transmitting coil, thereby creating a time-varying magnetic field in the space around it. When the receiving coil is placed in this changing magnetic field, the change in magnetic flux will induce an electromotive force in the receiving coil, thereby achieving wireless transmission of electrical energy.

The principle of magnetic resonance coupling is an important theoretical basis for realizing wireless power transmission over medium and long distances. This principle emphasizes that when the transmitting coil and the receiving coil are designed to have the same resonant frequency, efficient electromagnetic energy transmission can be achieved through the magnetic field resonance effect. This resonant method not only improves transmission efficiency, but also reduces the requirement for precise alignment of the coil position, so it is widely used in fields such as smart consumer electronics and medical equipment.

The theory of electric field coupling wireless power transmission is another way to achieve wireless transmission. This theory uses the high-frequency voltage applied by the transmitting electrode to form an alternating electric field in the surrounding space. The receiving electrode is placed in this alternating electric field environment, and the current is induced and obtained by capacitive coupling. This method is simple in structure and low in cost, and is especially suitable for wireless power supply scenarios for short distances and low-power devices.

The theory of microwave wireless power transmission focuses on long-distance wireless transmission applications. The specific implementation method is that the transmitter converts electrical energy into a high-frequency microwave signal through a specific device, and then transmits the electrical energy to the remote receiver in the form of microwave radiation with the help of a directional antenna. The receiver completes the wireless energy transmission process by rectifying the received microwave signal and converting it back into direct current electrical energy through a rectifying antenna. Although microwave technology can achieve long-distance energy transmission, its application must take into account the potential impact of electromagnetic waves on the environment and human health, and provide safety protection.

Impedance matching theory is the key to improving the efficiency of wireless power transmission. According to this theory, in a wireless transmission system, when a good impedance match is achieved between the transmitting coil and the receiving coil, the system can achieve a higher transmission efficiency and reduce energy loss. Therefore, the design of the system usually uses an impedance matching network to optimize the transmission circuit and ensure that the transmission power is used to its maximum potential, thereby improving overall performance.

Electromagnetic induction wireless power transfer technology uses the electromagnetic induction effect between the primary and secondary coils to achieve wireless power transfer. This technology has a relatively simple structure and low manufacturing costs, but is limited by the fast attenuation of magnetic fields. Its effective transmission distance is usually only a few centimeters, making it suitable for close-range charging scenarios.

Magnetic resonance coupling wireless power transfer technology uses the resonance principle to achieve efficient power transmission by setting the same resonant frequency for the transmitter and receiver coils. This technology can achieve high-efficiency energy transmission over a range of tens of centimeters or even further. However, compared with electromagnetic induction technology, magnetic resonance technology has higher requirements for the structural design of the coils and the matching of the resonant frequency, and the system is relatively more complex [4].

Microwave wireless power transfer technology uses microwave signals to transmit power wirelessly over long distances. In this technology, electrical energy is first converted to high-frequency microwaves at the transmitter, which are then transmitted over long distances using directional transmission, and finally converted back into usable electrical energy at the receiver. Microwave wireless transmission technology can transmit over distances of several kilometers or more, and is widely used in special applications such as space solar power stations. However, the transmission efficiency of this technology is generally low, and the propagation process of microwave signals needs to be handled with care to avoid negative impacts on human health and the ecological environment.

3 Methodology

3.1 Coil design scheme

In this study, a helical coil was selected as the main design type of the wireless power transfer coil. Helical coils have the characteristics of high magnetic field concentration and excellent transmission efficiency, which can effectively improve the overall performance of the wireless power transfer system and meet the strict requirements for electromagnetic coupling in practical application scenarios [5].

During the parameter design stage of the coil, key parameters such as the height, radius, current excitation method, and material selection were determined based on the expected transmission distance, power requirements, and operating frequency of the project. Specifically, the operating frequency was set to 85 kHz. The transmitting coil (Tx) was designed to be 200 mm high and 100 mm in radius, while the receiving coil (Rx) was designed to be 50 mm high and 70 mm in radius. In addition, in order to simulate the real underwater working environment, the air domain material is set to seawater, and the geometric dimensions of the air domain are 400mm long, wide and high respectively, to ensure the authenticity of the simulation environment. At the same time, both coils are made of pure copper with excellent electrical conductivity. In terms of current excitation, 100 conductors are arranged in the transmitting coil as the current excitation source, and 25 conductors are arranged in the receiving coil as the current excitation source. The specific design of the coil further clarifies the spatial position and relative relationship of the coil by establishing a reference plane along the central axis of the two coils.

After the initial parameter design was completed, the coil design was optimized during the research process to further improve the transmission efficiency of the system. Mainly considering the mutual inductance effect between the coils and the efficiency of magnetic field coupling, this study adopts an optimized design method of nesting the transmitting and receiving coils [6]. After multiple rounds of parameter adjustment and simulation verification, the optimal coil structure scheme was finally determined, and the specific coil design schematic is shown in Figure 1.

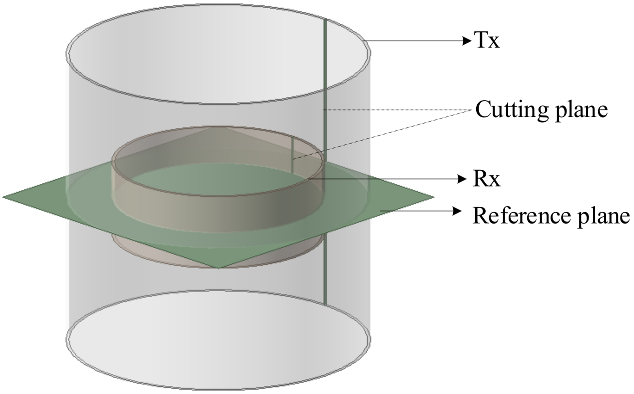

Fig. 1. Coil design diagram

3.2 Experimental design

In order to systematically evaluate the performance of the designed coil and ensure the validity and accuracy of the experimental results, the following three specific experiments were designed in this study:

The first experiment is to analyze the distribution law of the magnetic induction intensity between the coils. The specific method of the experiment is to generate a magnetic induction intensity distribution map on the transverse reference surface in the Field Overlays function module of the Maxwell simulation software and adjust the software view to the top view mode (Top, -Z direction) to visually observe the distribution characteristics and change law of the magnetic field intensity between the coils.

The second experiment focuses on the spatial distribution of the magnetic induction vector on the longitudinal reference plane. This experiment also uses the Field Overlays module of the Maxwell software to generate a magnetic induction vector distribution map on the longitudinal reference plane, and adjusts the viewing angle to isometric to clearly show the spatial shape and directional characteristics of the coil magnetic field distribution.

The third experiment aims to explore the influence of the coil spacing on the mutual inductance of the two coils. Specifically, the distance correlation matrix between the transmitting coil (Tx) and the receiving coil (Rx) is established using the Parameters module of the simulation software, and the curve of the mutual inductance L (Tx, Rx) varying with the spacing d2 between the coil centers is generated using the Results module, so as to obtain the intuitive law of the influence of the coil spacing on the mutual inductance and provide data support and optimization guidance for subsequent designs.

3.3 Project implementation

3.3.1 Maxwell Simulation Environment Setup.

To successfully carry out the coil simulation of the wireless power transfer system, it is first necessary to reasonably configure the Maxwell simulation environment. At the initial stage of project implementation, first open the Maxwell simulation software on the computer and create a new Maxwell 3D Design simulation project. Since this study involves the analysis of high-frequency alternating currents and dynamic magnetic fields, the Eddy Current solver mode is selected in the software to effectively simulate the dynamic changes of the magnetic field around the coil.

Next, the material properties of the coil need to be determined and accurately defined in the software. The material of the coil selected in this study is pure copper, so the relevant electromagnetic property parameters such as the electrical conductivity and magnetic permeability of copper must be set in the material library of the Maxwell software to ensure that the simulation results accurately reflect the real physical properties of the material.

Finally, the simulation model space and its boundary conditions were set reasonably according to the actual design dimensions of the coil in this study and the characteristics of the underwater working environment. The selection of the size of the space should take into account the influence of boundary effects. It is necessary to ensure that the simulation boundary is far enough away from the research object, so that the simulation environment can accurately reflect the real physical environment and improve the validity and reliability of the simulation results.

3.3.2 Simulation Experiment Steps

The simulation experiment process mainly includes three stages: model establishment, excitation and boundary condition setting, and simulation calculation and operation.

First, in the model building stage, the 3D geometric model of the coil needs to be accurately drawn in strict accordance with the determined coil design scheme using the geometric drawing tools in Maxwell software. The geometric parameters of the coil, including the number of turns, coil radius, and height, should be set one by one according to the design scheme, and the relative spatial position relationship between the transmitting coil and receiving coil should also be clarified to ensure the accuracy of the model.

Next, excitation and boundary conditions are set after the model is built. In this study, an excitation current is applied to the transmitting coil, and the frequency and magnitude of the excitation current need to be clearly set to simulate the actual working state of wireless power transmission. At the same time, the boundary conditions of the simulation model are set according to the actual working environment of the coil, so as to reasonably simulate the propagation characteristics of the electromagnetic field in an open space (underwater environment) and minimize the interference and errors of the boundary on the simulation results.

Finally, after the above two steps are confirmed, the simulation calculation of the model is performed. After confirming that the model parameters and boundary conditions are set correctly, the simulation calculation task is submitted through the simulation software, and key parameters such as the total simulation time and calculation step size are clearly set. The Maxwell simulation calculation task is then started, and the software automatically completes the calculation and analysis process of the electromagnetic field, ultimately providing detailed simulation data and result analysis charts for subsequent in-depth analysis and evaluation.

4 Results

Figure 2 shows the magnetic flux density distribution of the coil obtained using Maxwell software. The colour gradually transitions from red to blue from the centre outward, intuitively reflecting the spatial distribution characteristics of the magnetic field strength. The figure shows that the magnetic induction intensity in the centre of the coil is significantly higher. This concentration of magnetic fields is crucial for improving the efficiency of wireless power transmission. In practical applications, this magnetic field distribution pattern can help to optimise the layout of the coil in an underwater wireless charging system and determine the optimal position and operating distance of the receiving coil, thereby effectively improving the efficiency of energy transmission and reducing losses. It has important engineering reference value.

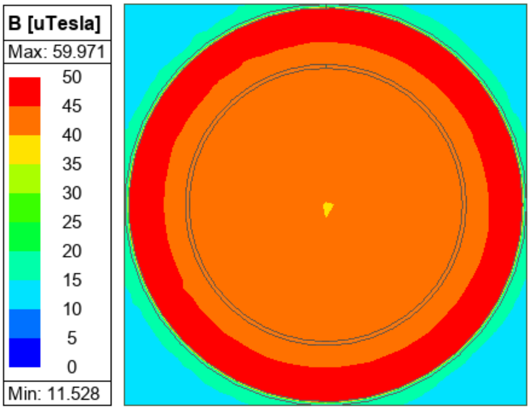

Fig. 2. Magnetic induction distribution of the coil

Figure 3 shows the distribution of the magnetic flux density on the reference surface. The direction and colour of the arrows provide a visual representation of the strength and direction of the magnetic field. As can be seen from the figure, the magnetic induction inside the coil is high and the vector direction is regular, forming a closed magnetic field loop, which reflects a good magnetic field concentration effect. This distribution feature is of great significance for the efficiency and stability of wireless power transmission, and helps to achieve efficient coupling of the magnetic field and effective transfer of energy. In practical applications, this vector distribution law can guide the layout and optimisation design of the coil of underwater wireless charging equipment [6][7] to ensure efficient and stable energy transmission performance.

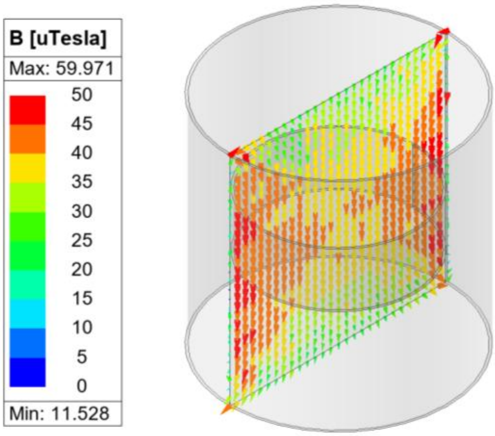

Fig. 3. Distribution of the magnetic field strength on the reference surface

Figure 4 shows the curve of the change in the mutual inductance between coils with distance. It can be clearly observed that as the coil spacing increases, the mutual inductance between the two coils shows a gradual downward trend, indicating that the coil distance has a significant effect on the mutual inductance. This trend reflects the fact that the transmission efficiency of wireless power transmission systems is highly dependent on the coil spacing, revealing the importance of optimising the coil spacing to improve system performance [8]. In practical applications, the coil spacing should be determined reasonably according to this law to ensure a high transmission efficiency [9][10] and reduce energy loss. This is especially suitable for the design optimisation of high-efficiency energy transmission scenarios such as underwater submarine wireless charging.

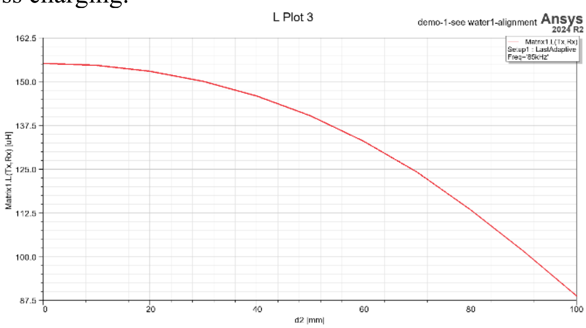

Fig. 4. Graph of the variation of mutual inductance with coil spacing

5 Conclusion

This study verifies the key role of the coil structure in energy transmission in an underwater environment through simulation, providing an important reference for the engineering design of wireless energy supply systems for deep-sea equipment. The research results not only reveal the laws of change in magnetic field distribution and mutual inductance characteristics, but also provide a feasible solution for improving underwater charging efficiency through parameter optimization. In the future, intelligent control algorithms and new magnetic materials can be further combined to explore dynamic adjustment of coil spacing and adaptive matching technology to adapt to complex underwater working conditions. At the same time, this research approach can be extended to multiple scenarios such as ocean monitoring buoys and underwater robots to help build an efficient and reliable marine energy network and lay the technical foundation for the intelligent development of the marine development sector.

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