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Underwater wireless power transfer: Status of development and future directions

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ABSTRACT
In recent years, mankind's continuous in-depth study of the ocean, the development of underwater robots with the ability to work underwater for long periods of time has become an important direction for underwater exploration and development. Due to the long time underwater work, the traditional wired charging is limited by the working depth, as well as a series of problems such as daily maintenance costs. At present, underwater wireless power transmission(WPT) technology still faces many challenges, such as the limitations of low transmission power, low transmission efficiency and short transmission distance. In this paper, a systematic review of magnetically coupled resonant WPT is conducted, and solutions are proposed from three dimensions, namely, switching device selection, improvement of coil resonant coupling effect, and line protection. This research is to break the shackles of underwater wireless power transmission technology, improve the energy efficiency of underwater equipment in underwater survey, in order to better promote the wide application of underwater equipment in the future.

KEYWORDS
Underwater; Wireless power transmission technology; Resonant; Coupling; WPT

1 Introduction

With the improvement of science and technology, electric power equipment occupies an important market position in the current era. At the same time, the demand for electricity is also increasing exponentially, how to quickly and efficiently charge the equipment is also becoming a stage of the challenge. Compared with the traditional wired charging, wireless charging technology has the advantages of flexibility, safety, durability, and aesthetics, and is beginning to dominate the future development direction. 2024, Tongji University, Wang Li-Kai et al.[1] introduced the Anti-PT symmetry principle of non-Ermion physics into WPT system through the “energy level pinhole” effect, in order to improve the wireless energy. WPT system through the “energy level peg hole” effect, to improve the efficiency of radio energy transfer provides a theoretical breakthrough. The U.S. Navy developed the “Killer Whale” super-large underwater unmanned submersible, and the limitations of the traditional wired charging itself make it unfavorable for charging equipment in the underwater environment. Numerous new energy trams have been introduced to the market one after another, and queuing up for charging on the highway has long been a common occurrence, which triggered the discussion of wireless charging and traditional wired charging piles. The traditional wired charging method has been unable to meet the needs of human daily electricity, the application of wireless power transmission technology, although still a lot of obstacles, but is the key to the future development of technology.

2 Development of wireless power transmission technology

The emergence of wireless power transmission can be traced back to 1890, when Nikola Tesla proposed the idea of global wireless power transmission. The idea of treating the earth as an inner conductor and establishing a low-frequency resonance of about 8Hz between the earth and the ionosphere to realize long-distance electric energy transmission laid an important theoretical foundation for the development of radio energy transmission technology.

Modern wireless power transmission technology is mainly divided into three categories: electromagnetic radiation WPT, electric field coupling WPT and magnetic field coupling WPT[2]. And the magnetic field coupling type can be subdivided into: electromagnetic induction WPT and electromagnetic resonance WPT, the paper is mainly based on the electromagnetic coupling resonance WPT in the electromagnetic resonance WPT for underwater equipment charging research.

3 Magnetic coupling resonant wireless transmission technology

Current wireless power transmission technologies are designed based on the principles of electromagnetic induction, magnetic resonance, radio waves, and magnetic coupling resonance. Traditional electromagnetic induction design of wireless charging devices, because of its design based on Faraday's law of electromagnetic induction, the transmission conditions are very dependent on the strong coupling connection between the two coils, so the distance must be close (usually <5cm) and the two coils axis alignment, in order to maximize the value of the change in magnetic flux.

Formula for Faraday's Law of Electromagnetic Induction:

$$\varepsilon = -N\frac{d\phi}{dt}$$

(ε is the induced Electromotive Force, N is the Number of turns in the coil, Φ is the Magnetic Flux)

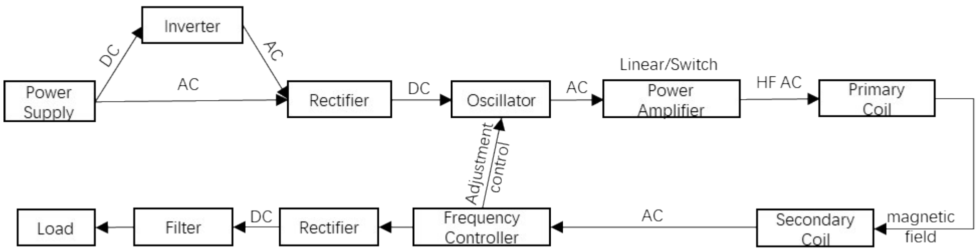

Figure 1 Magnetic coupling resonance schematic

As shown in Figure 1 magnetic coupling resonance is designed with the help of coils on both sides of the transmitter and receiver through the principle of LC oscillator circuit (inductance L and capacitance C in series and parallel), the frequency controller adjusted to control the frequency of the output AC signal of the oscillator on the transmitter side, and the coils on both sides are tuned to the same frequency as required, which can be used to realize efficient energy transfer.

Resonant Frequency Equation:

$$f = \frac{1}{2\pi\sqrt{LC}}$$

In describing the resonant capability of a circuit, the physical quantity Q (quality factor) is introduced to judge the capability. In a single coil, the quality factor Q is expressed as the ratio of the circuit's stored energy to the upper circuit's energy loss, and is given by the formula:

$$Q = \frac{\omega L}{R}$$

However, a magnetically coupled resonant system consists of two coils at the transmitting and receiving ends, and the mutual inductance of the coils, and the coupling coefficient k are taken into account when expressing the quality factor Q. Therefore in the coupled system quality factor Q is defined as:

$$Q=2\pi\times\frac{\text{Maximum energy storage}}{\text{Energy consumption in a cycle}}$$

Which has a maximum stored energy:

$$W = L\int_0^I IdI = \frac{1}{2}LI_{max}^2 = \frac{1}{2}L\left(\sqrt{2}\,I\right)^2 = LI^2$$

So the quality factor:

$$Q = 2\pi\frac{LI^2}{I^2RT} = \frac{\omega_0 L}{R} = \frac{1}{\omega_0 CR}$$

From the derivation of this formula, it can be concluded that the larger the quality factor Q is, the stronger the ability of the coil to store energy when the reaction resonates, and therefore the transmission distance and transmission efficiency of the coil can be effectively improved.

4 Overview of national and international research

Aiming at the problem of how to improve the efficiency of wireless transmission, a large number of scholars at home and abroad have carried out relevant research on this issue. In the existing research, as long as based on the selection of battery materials, improve the quality factor of the coil, frequency tracking and the application of wireless power transmission technology, through the monitoring, data statistics and other methods, the theoretical derivation and simulation combined with experimental proof of a series of studies on the future to carry out the concept of the theoretical and experimental guidance. It contains the following aspects:

4.1 Research on power optimization aspects

Literature[3] designed a resonant WPT power supply based on the combination of control core of STM32 microcontroller and Butterworth filter. It has the advantages of low power, high expandability and low cost. It is suitable for applications in low power WPT systems, but no research has been carried out on the feasibility of low power WPT underwater and the application scenarios of high power. Literature[4] proposes the research direction of hydrogen fuel cell as an ideal energy source, and analyzes the effects of temperature, gas pressure, and membrane water content on the performance of the hydrogen fuel cell by means of MATLAB/Simulink simulation, and the power source has the advantages of long time, high efficiency, and environmental protection. The feasibility of aluminum air (oxygen) and aluminum water batteries was analyzed in the literature[5], and the problems of air electrode polarization and aluminum hydroxide sedimentation affect its performance and it cannot be used in conjunction with hydrogen fuel cells, but the aluminum water battery produces more hydrogen, and it can still be applied to underwater applications with low power and low energy storage.

4.2 Research on improving coil quality factor and frequency tracking control

The transmission efficiency of the system can be improved by increasing the frequency of the AC current, and the literature[6] summarizes the optimal power supply selection for wireless power transmission systems in different power situations. Coil quality factor is the key to affect the transmission efficiency, obtained through theoretical derivation to optimize the quality factor by maximizing the ratio of mutual inductance to internal resistance[7]. Eddy current loss and detuning are the key to underwater wireless transmission, [8] designed a frequency tracking-constant voltage/constant current combination control method[8] based on the output instability of underwater wireless power transmission system, through the control of the front stage inverter, to realize the control of the system output voltage circuit as well as the system operating frequency, but there is no research in battery load and high power.

4.3 On the application of wireless power transmission technology

The combination of electric vehicles using wireless power transmission technology and traditional charging piles[9] has far improved the short range of electric vehicles, reduced fuel costs as well as improved environmental benefits compared to traditional internal combustion engines. With the development of electric vehicles, battery charging and replacement is a major challenge[10]. Battery swapping technology in electric vehicle charging has the advantages of high efficiency, grid peaking, reduced charging costs, and extended battery life [11], so South Korea still uses battery swapping technology applied to electric vehicles[12].

Summarizing the above domestic and international reviews, it can be seen that a large number of domestic and international studies have been conducted in the field of wireless power transmission, but there is little content in the application to the field of underwater environment, and there is still a lot of research value in the future.

5 Analysis of key issues of underwater magnetically coupled resonant WPT system

The nature of air medium and seawater medium is different, so the analysis of seawater medium is the key to apply the magnetic coupling resonance WPT technology underwater. In pure water, the conductivity σ is about 5.5 μS/cm, while in seawater medium the conductivity σ is about 5 S/cm due to the influence of seawater salinity, temperature, and pressure, etc. Conductivity and eddy current loss show a positive correlation, and the high conductivity characteristic of seawater means that the eddy current loss will be larger in the process of wireless power transmission. In order to reduce the negative impact of eddy current loss on transmission efficiency, three aspects are summarized to realize the reduction of energy loss indirectly and directly.

5.1 Switching Device Selection

Switching devices (e.g., BJTs, MOSFETs, IGBTs, SiC/GaN devices, etc.) can change frequency by controlling the ratio of on and off times (also known as the duty cycle), as well as the internal switching speed. Most switching devices today operate in the range of 10kHz to 100kHz, and commercially available MOSFETs, IGBTs, and SiC devices are superior to traditional IGBTs in terms of high-temperature performance, high switching frequency, high-voltage withstand, high power density, low conduction loss, radiation resistance, and reliability, etc. However, SiC operates in hard-switching conditions, and with the increasing frequency, switching loss is also higher than in traditional IGBTs. increasing, the switching loss will also increase as a result.

He Ning's team[13] introduced the zero-voltage switching (ZVS) space vector modulation (SVM) technique to realize the improvement of the efficiency of SiC devices at high frequency states, which provides a technical path for the selection of high-power switches.

5.2 Improvement of coil resonance coupling effect

How to improve the coil resonant coupling effect is an important part of improving transmission efficiency. In wireless power transmission technology, the resonant coupling effect between the coil at the transmitting end and the coil at the receiving end is improved by four basic topologies (PS, PP, SS, and SP). These topologies can improve the transmission efficiency, stability and robustness of the system by optimizing the connection of capacitors and inductors in the resonant circuit. The four topologies are shown in Table 1:

Table 1 Four types of topologies

Topology	Transmitting End (C/L)	Receiving End (C/L)	Application
PS	Parallel	Series	High Power Transfer
PP	Parallel	Parallel	High Robustness & Dynamic Adjustment
SS	Series	Series	Constant Voltage/Current Output
SP	Series	Parallel	Voltage Step-up

Not only need in the selection of topology, but also need to consider the seawater medium, due to the salt, will produce and highly conductive materials (Cu, Al, etc.) in the high frequency under the phenomenon of eddy current. Eddy currents can produce thermal effects (eddy current losses), resulting in a reduction in transmission efficiency. In the case of unusual magnetically conductive media, the insertion of capacitors[14] is usually used to increase the impedance in the eddy current path to reduce eddy current losses, but there are still some limitations in the non-contact environment. Zhang Weimin's team[15] analyzed the information entropy by using a planar eddy current probe to investigate the distribution of eddy currents in different directions, and designed a fractal curve coil with the distribution of eddy currents to reduce the influence of eddy current losses. Fractal curve coils not only have multi-scale distributions but also possess self-similar properties due to their complex geometrical structure. It is not only limited to improving the strength of local magnetic field, but also realizes the uniform distribution of magnetic field in the whole, so it can improve the coupling effect and reduce the length of eddy current path length, reduce the eddy current loss.

5.3 Line protection

Seawater is highly conductive, and the pressure at a certain depth is also a non-negligible problem in line protection. Due to the epoxy resin material has excellent insulation and corrosion resistance, so it is commonly used in line encapsulation protection, underwater coil encapsulation can also be used in the choice of material epoxy resin potting method, isolated from direct contact with seawater. In which then filled with inert gas (column such as nitrogen) to balance the external water pressure. The outermost layer, taking into account the cost, corrosion resistance and pressure resistance, can use high-strength steel, to prevent long-term underwater operation by marine organisms attached, thus affecting the heat dissipation and magnetic coupling efficiency.

6 Conclusion and outlook

The application of underwater magnetically coupled resonant wireless power transmission (WPT) technology is the future direction of breaking through the limitations of traditional wired charging, and will be the key to promote the inconvenience of charging for long-term operation of marine exploration and underwater equipment. In this paper, through a systematic review, for the challenges of high conductivity, eddy current loss, high voltage and complex environmental factors in the seawater environment, the distribution of switching device selection, coil resonance coupling optimization and line protection are summarized in three aspects of the optimization solution, which provides a theoretical basis for improving the efficiency of underwater wireless power transmission and feasible direction for future technical research. Although the current research has made progress in power optimization, frequency tracking control and topology design, underwater wireless power transmission technology still faces many challenges. In the future, it is necessary to combine with new energy technologies, such as hydrogen-oxygen fuel cells, to explore how to further optimize the selection of materials and structural design under the influence of multiple factors, which is suitable for more efficient and safer supply of equipment in the extreme underwater environment. At the same time, the promotion of underwater WPT and battery replacement technology will further promote the commercialization of underwater unmanned underwater vehicles (UUVs), seabed observation networks and new energy extraction, providing the latest technical support for the development of marine resources and sustainable green development.

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