Design and research of wireless charging system of autonomous underwater vehicle based on magnetic coupling resonance

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Abstract. In order to apply wireless charging technology to autonomous underwater submersibles, exploring the application of magnetic coupling resonance wireless charging in the field of underwater wireless charging. To expand the application range of autonomous underwater submersibles and improve their endurance. Based on Matlab and multisim 14.0 co-simulation, the wireless charging system flow was designed, and the design of wireless charging device was optimized. Based on the design and modeling analysis of the implementation scheme, the underwater wireless charging system was studied and simulated, and the circuit load resistance was applied. The average power, the average power of the power supply output, the overall efficiency of the circuit, the coupling resonant radio energy transmission efficiency and the coupling coefficient between the coils are compared with theoretical calculations. The simulation results of the wireless charging system of the autonomous underwater submersible with magnetic coupling resonance are highly consistent with the trend of the calculation results, with verification method being effective. The circuit modeling method of underwater wireless charging system is proposed, which provides reference for underwater wireless charging system design. The wireless coupled system with magnetic coupling resonance is a feasible solution for autonomous underwater submersibles, and it is one of the important measures to improve the application performance of autonomous underwater submersibles.

1. Introduction

The rapid development of artificial intelligence and wireless charging technology in the new era. Autonomous underwater vehicles are one of the high-end marine equipment, and they are widely used in military and civilian applications. They are heavy equipment for marine observation, detection systems, and marine development and utilization. In 2017, China issued a guide for pre-research and innovation projects of equipment, in which underwater artificial intelligence technology has become the focus. Autonomous underwater vehicles are a kind of intelligent and autonomous navigation. The development goals are "faster, longer range, deeper submergence, and better concealment." Autonomous underwater submersible power units are currently mainly powered by electric power. When the built-in power storage equipment runs out of power, the charging methods mainly include recovery charging, wired charging, and wireless charging. The underwater radio energy transmission of the autonomous underwater vehicle mainly uses the "mother ship", a wireless charging station on
the sea floor, and the power supply of the underwater part of the buoy. In 2017, Tianjin University designed and implemented a buoy system with underwater wireless power transmission function. The 710th Research Institute of China Shipbuilding Industry Corporation invented a "hybrid hydroelectric device for underwater unmanned aerial vehicles. It enables autonomous underwater diving to achieve underwater wireless charging and complete long-duration missions. The U.S. Pentagon plans to build a charging station for autonomous underwater diving. The plan is called "Eisenhower Highway Network and will become autonomous underwater. Latent charging facility. Russian scientific research institutions have made nuclear power charging stations that are deployed on the seabed and are expected to form a charging network. The Russian Federation's Arctic Development Plan project planned to be completed by 2020. The main purpose of the charging stations is to explore submarine deposits and monitor underwater oil and gas pipelines. For underwater diving.

At present, the charging of autonomous underwater vehicles needs to float to nearby ships and land bases. Underwater wireless charging technology can improve the effectiveness of autonomous underwater vehicles and also increase the safety of autonomous underwater vehicles in performing tasks. Underwater wireless energy charging technology mainly faces the particularity of the seawater environment, leading to the problem of unstable power transmission, charging distance problems, and safety assessment of surrounding marine life during charging. There will be better conditions and brighter development prospects, and it is expected to become a key technology for the future development level of marine underwater unmanned engineering.

This paper researches and designs a wireless charging system based on magnetic coupling resonance. First, the Matlab software theoretical simulation of the wireless charging system is performed. Then the wireless charging system process is designed and the wireless charging device design is optimized. Finally, based on the multisim 14.0 simulation, the design, modeling and analysis of the implementation scheme, the research and simulation of the underwater wireless charging system, the average power of the circuit load resistance, the average power output power, the overall efficiency of the circuit, the coupled resonant wireless power transmission efficiency and The relationship between the coupling coefficient between the coils and the theoretical calculation is compared to verify the reliability and effectiveness of the simulation. It is a reference for the design of an underwater autonomous underwater vehicle wireless charging system.

2. Theoretical simulation of magnetic coupling resonance wireless charging system

The magnetic coupling wireless charging technology is based on the amplification technology. The direct current is converted into radio waves through the coil transmission. The radio waves transfer energy through resonance. [1-2] is an underwater autonomous underwater with a receiver of the same frequency. Submersible charging, magnetic coupling wireless charging performance indicators include charging power, charging efficiency, charging distance, charging stability, safety, service life and other indicators. Magnetic coupling resonance research is in its infancy, and inductive coupling underwater application research There are many researches on magnetic resonance coupling. Marin Soljacic, a professor of physics at the Massachusetts Institute of Technology, published a paper on "Resonant Wireless Energy Transmission Technology" in Science in 2007 [3]. Technical advantages such as large rate and long transmission distance [4-5], this system scheme has broad application prospects in underwater scenarios such as marine buoys, autonomous underwater vehicles, and underwater sensors.

The coupled resonant wireless charging system circuit model is based on two resonant coils, and a magnetic energy wireless charging model is shown in Figure 1.
Figure 1. Circuit model of coupled resonant wireless charging system.

In Figure 1, U1 on the left is an AC voltage source, C1 is the resonant capacitance of the transmitting coil, L1 is the self-inductance of the transmitting coil, and R1 is the transmitting coil resistance. In the circuit on the right, L2 is the self-inductance of the receiving coil, and R2 is the resistance of the receiving coil. The loop impedance Z1 of the transmitting coil is shown in equation (1), where $\omega = 2 \pi f$.

$$Z_1 = j \omega L_1 + \frac{1}{j \omega C_1} + R_1$$

The loop impedance of the receiving coil is shown in equations (2) and (3).

$$Z_2 = j \omega L_2 + \frac{1}{j \omega C_2} + R_2$$
$$Z_3 = Z_4 + (\omega M)^2 \frac{1}{Z_2 + R_L}$$

The transmitting coil current is shown by equation (4).

$$I_1 = \frac{U_1(Z_2 + R_L)}{(\omega M)^2 + Z_1(Z_2 + R_L)}$$

The coil current at the receiving end is shown in equation (5).

$$I_2 = \frac{-j \omega M U_1}{(\omega M)^2 + Z_2(Z_2 + R_L)}$$

The load power is shown in equation (6).

$$P_{RL} = \frac{U_1^2 |j \omega M|^2 R_L}{Z_1(Z_2 + R_L) + (\omega M)^2}$$

The system transmission efficiency is shown in equation (7).

$$\eta = \frac{|j \omega M|^2 R_L}{Z_2 + R_L^2 R_L(Z_1 + (\omega M)^2)}$$

In formula (1-7), Cs is the resonance capacitance of the receiving coil. When the system frequency f1 resonator is close to or the same as the natural frequency f2, the coupled resonant wireless charging system is in a resonance state, and the coupled resonant wireless charging system mainly passes the coil. Determination of parameters, topology design of wireless charging system, size design, impedance matching design for power transmission optimization], by adjusting the frequency f at the receiving end and the frequency at the transmitting end, coupled resonant wireless charging generates resonance The receiver gathers enough energy to complete the conversion of magnetic energy to electrical energy, thereby achieving efficient power transmission efficiency. The determination of the
inductance \( L \) and the capacitance \( C \) of the coupled resonant wireless charging system is the research focus in the resonant wireless transmission model.

Based on Matlab simulation, the analysis is to determine the inductance \( L \) and capacitance \( C \) of the coupled resonant wireless charging system, and study the high frequency characteristics the input voltage of the wireless charging system is 220V, and the characteristics at the resonant frequency of 200kHz are simulated. Results . The load power and the load power of the transmitting coil and the receiving coil are changed. When the load power is 312W, the three-dimensional characteristics of the efficiency and the inductance of the transmitting and receiving coils are obtained.

When coupled resonant wireless charging has high efficiency and the power supply current is as small as possible, the power supply current is selected to be less than 3A in the simulation, and the value of the coupled resonant inductor \( L \) is selected. By controlling the transmitting and receiving coils, debugging with the power supply 220v Match and determine the parameters of the inductive coil in the high-efficiency transmission.

the coupled resonant wireless charging system, the X-axis is the coupling coefficient \( k \), and its value range is 0.1 to 0.9. The Y-axis is the figure of merit \( Q \), and its value ranges from 20 to 200. The Z axis is the maximum transmission efficiency, and its value depends on the coupling coefficient \( k \) and the quality factor \( Q \). The change law between the coupling coefficient \( k \) and the maximum transmission efficiency of the coils is positively related to the maximum transmission efficiency of the system with the coil quality factor \( Q \). Assuming the figure of merit \( Q \) is infinite and the coupling coefficient \( k \) is low, the coupled resonant wireless charging efficiency will be very high. Assume that the coupling coefficient \( k \) is large and the coil quality factor \( Q \) is small. The coupling resonant wireless charging efficiency changes greatly. Generally, the larger the natural frequency of the coupled resonant wireless charging system, And the larger the quality factor \( Q \) of the coil, the higher the operating frequency \( f \) of the magnetic coupling resonance wireless charging system is also an effective method to improve the charging efficiency...

As shown in Figure 1, the optimized design of the coupled resonant wireless charging system mainly includes the optimization design of the coil, the effect of seawater on the coil parameters, and the system impedance matching to control the charging current. Unless other conditions remain the same, the resonant wireless charging system can be coupled the value of the quality factor \( Q \) of the charging coil improves the efficiency of the coupled resonant wireless charging system. To avoid and reduce electromagnetic wave damage in seawater media, the coupling resonance wireless charging system is used to adjust the position and charge detection of additional devices to reduce the transmission loss of electromagnetic waves in water.

![Figure 1](image1)

**Figure 1.** Optimized design of coupled resonant wireless charging system.

3. Optimized design of coupled resonant wireless charging system

3.1. Design steps

The wireless charging technology does not need to be connected to the charging cable. The autonomous underwater vehicle is on the charging board or the charging device, and the operation is
simple. The operation is simpler than inserting the power cable. The wireless charging technology is combined with the autonomous underwater vehicle to greatly improve the life and work efficiency of the submersible. The wireless charging is used to completely close the electronic system of the autonomous underwater vehicle, avoid the corrosion of oxygen and seawater, and improve efficiency, safety and reliability, the underwater coupled resonant wireless charging system mainly includes coupling design, top macro design, communication and control design. The coupling design and macro top design interact with each other to promote constraints, improve the performance of the device through control and communication, and wireless charging. The shape and structure of the device are designed through the guarantee of design and choice of rechargeable batteries, as well as coupling design, Hongtuo design, communication and control design.

The output pulse square wave signal of the control circuit design control module cannot be directly connected to the gate of the switching tube, and it needs to be electrically isolated from weak current and strong current. The linear optocoupler is used for electrical isolation. The disadvantage is that the linear optocoupler has a slower transmission speed and a higher delay. When the input signal frequency is high, the output signal will be distorted, affecting the accuracy of the system. High-frequency driving needs to select high-speed driving optocoupler. After the control module outputs a pulse square wave signal, it is input to the driving optocoupler chip through a resistor. The circuit converts DC power into high-frequency AC power and excites the electromagnetic field. After electromagnetic conversion through a coupling device consisting of an enameled wire coil and a resonant capacitor, it provides power to the load and realizes high-power underwater wireless power supply. The coupling device is composed of a receiving coil, a transmitting coil, and a resonant capacitor. The high-frequency AC current emitted by the transmitting circuit passes through the transmitting end of the coupling device to excite the magnetic field. The magnetic field energy is received by the receiving end of the coupling device and converted into electrical energy to power the load. When the load is a DC load, a fast rectification filter circuit composed of a fast recovery diode needs to be considered.

3.2. Wireless charging device design optimization

The design of an autonomous underwater submersible wireless charging device mainly uses a wireless power charging system, which is to transmit electrical energy from the transmitter to the receiver by wireless connection. The transmitting coil and the receiving coil resonate, transfer energy through magnetic coupling, and the closed design of the receiving coil prevents interference by isolating and non-magnetic materials. The structure of the wireless charging device is shown in Figure 2. The power supply uses a rectifier circuit and a filter circuit to convert the electrical energy into DC power. The inverter is set up for high-frequency inversion. Using the compensation effect of high-frequency alternating current, the high-frequency alternating electromagnetic field was obtained and matched with the changing frequency of the inverter. The electric coil was received in the high-frequency alternating electromagnetic field, and the same frequency was generated under electromagnetic induction. Alternating current, under the action of the wireless power receiving device, the alternating current will produce an alternating electromagnetic field with the same frequency. The transmitter and receiver oscillate at the same frequency or are close to each other, which improves the energy transfer efficiency through resonance. Based on the electromagnetic coupling technology, the power transmission from the wireless power transmitting coil to the receiving coil is completed, and the purpose of wirelessly charging the autonomous underwater vehicle is achieved. By improving the efficiency of rectification a high-frequency synchronous rectification is set in the system Circuit to improve the overall charging efficiency.
3.3. Application of coupled resonant wireless charging system

At present, China uses a large number of autonomous underwater vehicles for reconnaissance, search and rescue tasks, but it is not possible to dock and recharge drones on the sea. In order to make it convenient and safe to dock and realistic wireless charging, autonomous systems are designed. The wireless charging device first detects the position of the autonomous underwater vehicle that needs to be charged. The wireless charging device communicates with the autonomous underwater vehicle, adjusts the position of the autonomous underwater vehicle, detects whether it is adjusted in place, and performs the wireless charging device after it is in place. Turning on the transfer of electric energy and conducting a charging check. When the charging is completed, the charging is stopped, and the autonomous underwater vehicle continues to perform the task to complete the power supply, which is of great significance to the improvement of the endurance of the autonomous underwater vehicle.

4. Coupled resonant wireless charging system verification simulation

The design of the multisim 14.0 simulation implementation scheme is adopted. The circuit of the coupled resonant wireless charging system includes a power supply part, a high frequency oscillation part, a high frequency power amplification part, a transmitting coil part, a receiving coil part, a high frequency rectification part, and a filtering part. The oscillator circuit is simulated.

The circuit shown in Figure 3 is established in Multisim 14.0, where the coupling resonance type transmitting coil and receiving coil inductance are 1.1 μH. Based on the parameter scanning analysis function of Multisim 14.0, the coupling coefficient k of the coupled resonance type is studied for scanning analysis. The parameter variation range of the coupling coefficient k is 0.1 to 0.99. The relationship between the average power of the load resistance of the circuit, the average power output from the power supply, the overall efficiency of the circuit, the efficiency of the coupled resonant wireless power transmission, and the coupling coefficient between the coils is studied and simulated.

The parameter scanning analysis is performed, and the load resistance varies from 0 to 100Ω. The transmit and receive coil inductance of this circuit is 1.1 μH. Study the change law of the average power consumed by the load resistance when the coupling coefficient k between the coupled resonance equations changes, the change law of the average power output of the power supply when the coupling coefficient changes, the change law of the overall efficiency of the circuit when the coupling coefficient changes, and when the coupling coefficient changes. As shown in Figure 4, the left ordinate is efficiency, the right ordinate is power watts, and the maximum value of the average power of the load resistance appears near 2Ω, which is consistent with the calculation result of the maximum output power and optimal resistance value of the coupled resonant wireless charging system. The average output power of the power supply becomes larger as the load resistance becomes larger. When the load resistance becomes large, it is inversely related to the equivalent input impedance of the coupled resonant
transmitting end, and has a positive correlation with the average output power of the power supply. When the load resistance is zero, the load does not consume power, and the overall efficiency of the circuit is zero. When the load resistance value continues to increase, the equivalent input impedance at the transmitting end of the system continues to decrease, and when the load resistance value is less than the receiving coil resistance, the load The power received by the resistor is affected, so the overall efficiency of the system circuit first increases from zero to a maximum, and then gradually decreases. The coupling resonance type wireless energy transmission efficiency reaches a maximum value at a load resistance of about 2Ω, and the calculation results of the optimal resistance value of the coupling resonance type wireless charging system are consistent. The simulation results are highly consistent with the theoretical calculation results. Based on Multisim 14.0 software simulation, it is an effective tool for analyzing coupled resonant wireless charging systems, and it has a verification function for the underwater wireless charging system design.

Figure 4. Effect of coil coupling coefficient on wireless charging power and efficiency.

5. Conclusions
Based on the research of the coupled resonant wireless charging system and its application to autonomous underwater vehicles,
First, the research shows that magnetically coupled resonance wireless charging is a feasible solution for autonomous underwater vehicles. The underwater wireless charging scheme can be designed and modeled.

Secondly, the magnetic coupling resonance wireless charging system is modeled and simulated by Multisim 14.0 to verify the effectiveness of the simulation platform. The simulation software is suitable for the development, design and verification of underwater wireless charging systems. To reduce the radiated electromagnetic waves, reduce electromagnetic interference as much as possible, reduce the intensity of radiated electromagnetic waves to the environmental system, and learn from advanced materials technology, advanced materials are introduced into the design of underwater wireless energy transmission systems.

Finally, the magnetic coupling resonance wireless charging system is a systematic project. This article focuses on the magnetic coupling resonance wireless charging system from the perspective of the coupling of the coil. The next step is to study the impact of the underwater wireless charging process on the surrounding biological environment. To assess the impact of wireless charging on marine life and the environment, and to formulate relevant standards and regulate the application and promotion of magnetically coupled resonance wireless charging systems in autonomous underwater vehicles.

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