# Modeling and Analysis of Underwater Magnetically Coupled Wireless Power Transmission System Based on S-S System

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**Abstract.** As human demands increase, marine resources have attracted much attention to achieve the rational exploitation and take advantage of the resources. Simultaneously, the changing seabed environment restricts the power supply of seabed facilities. The existing contact wet plug-in technology has problems such as limited years of work, difficult operation, aging, and leakage. Therefore, the magnetic coupling wireless power transmission technology that generates an alternating magnetic field through a coil to realize energy transmission between the transmitter and the receiver has important research significance. This paper is based on the constant current output characteristics of the S-S system. Through Maxwell modeling and simulation, the coil model was built. The simulation results show the curve of the change of coil mutual inductance with offset distance, the distribution law of coil magnetic field, and the phase distribution of magnetic flux lines. The experimental results indicate that as the offset distance increases, the mutual inductance decreases. Eventually, the influencing factors of technical implementation and the deficiencies of the experiments are summarized, and the development direction of magnetically coupled underwater wireless power transmission (MCUWPT) technology in theory and application is prospected.

**Keywords:** Magnetic Field Coupling Wireless Power Transmission System; S-S System; Eddy-Current Losses; Parasitic Parameters

## 1 Introduction

In fields such as marine resource exploration and maintaining national maritime security, underwater robots have become indispensable and important equipment [1, 2]. However, due to problems such as low energy transmission efficiency, blocked signal transmission, and coil offset in the underwater environment, underwater wireless power transmission technology has always faced many challenges [3, 4]. Domestic and foreign researchers have successfully designed and developed high-power underwater wireless charging base stations.

In 2001, a research team from North Carolina State University in the United States successfully developed a 200W AUV underwater wireless charging system. This


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system can provide 200W of electric energy to the AUV at a depth of 2000m [5]. Underwater wireless charging technology has made a breakthrough and laid the foundation for underwater wireless power transmission. In 2012, under the leadership of American researchers Pyle and others, an underwater charging base station was designed and developed for wireless charging of AUVs carried by UUV. The principle is that the small AUV attached to the UUV side boat can enter the underwater WPT base station for charging and data transmission under the guidance of the navigation system, with a maximum power of 450W. After charging, the AUV will return to the side of the UUV to continue working [6]. Professor Zhang Kehan's team from Northwestern Polytechnical University designed a ring-shaped ferrite core structure based on a ring-shaped magnetic coupling device, combined with the principle of magnetic coupling resonance, and through in-depth research on the energy transmission mechanism and eddy current loss in seawater [7]. The primary side is installed in the base station, and the secondary side is installed inside the AUV. It successfully provides 500W of electric energy to the AUV and has a stable output voltage gain. Although existing base stations can already provide high power, issues such as coil offset and eddy current losses caused by the marine environment during the charging process still require in-depth research [8]. Exploring such issues is of great significance to underwater wireless power transmission technology.

This study uses Maxwell modeling and Simulink simulation analysis to attempt to subject the relationship between coil mutual inductance and offset distance, coil magnetic field distribution, and magnetic flux line phase distribution to the test of simulation data.

## 2 Theories

MCUWPT technology is a non-contact energy transmission technology [9]. It uses the electromagnetic field between electromagnetic couplers and fully utilizes Faraday's law of electromagnetic induction and Ampere's law to solve the wireless charging of underwater robots, making it possible for the robot to work underwater for a long time. The principle of the MCUWPT system is shown in Figure 1. The system is composed of an undersea wireless charging station as the transmitter and an underwater robot as the receiver. The power supply at the transmitter is DC power. The DC power is converted into AC power through the DC-DC Cuk chopper circuit and the full-bridge inverter circuit, and then passes through the S-S topology compensation network to excite the transmitting coil to generate an alternating magnetic field [10, 11]. This alternating magnetic field is coupled with the receiving coil and generates an alternating current. After that, it is converted into direct current through S-S topology compensation network, full-wave rectification, and filtering to achieve the battery charging function. The DC-DC Cuk chopper circuit in the system stabilizes the output DC voltage, input power current, and ensures the continuity of the output load current, and has very small pulsation, which is beneficial for filtering the input and output and ensuring the normal operation of the equipment.

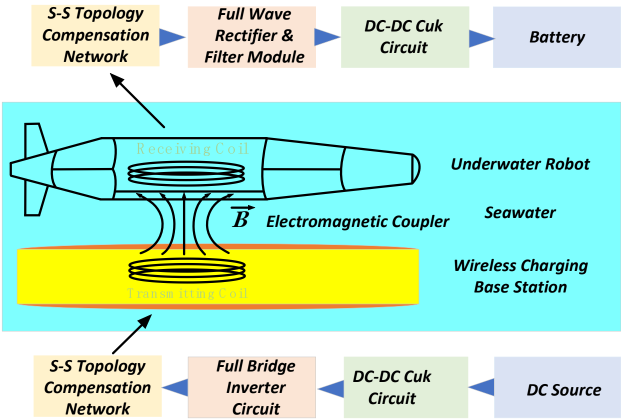


**Fig. 1.** Principle diagram of magnetic field coupling underwater wireless power transmission system [10]

## 3 Method

This article uses Maxwell to simulate the basic model of this coil system and the offset model of two coils, as shown in Figures 2 and 3. The variation of the mutual inductance value of the two coils with the offset distance between the coils is plotted, as shown in Figure 4. Experimental data show that the mutual inductance of the two coils decreases as the offset distance increases.

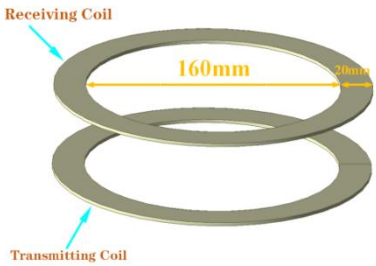


**Fig. 2.** Basic coil model (Photo credit: Original)

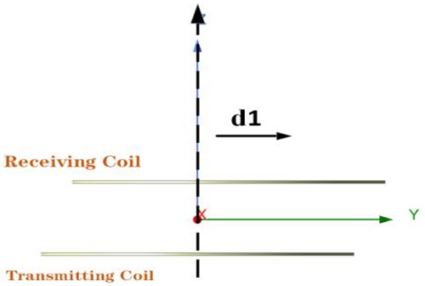

**Fig. 3.** Coil offset model (Photo credit: Original)

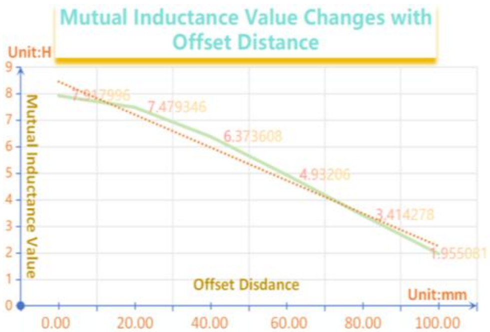


**Fig. 4.** Changes in coil mutual inductance with offset distance diagram (Photo credit: Original)

## 4 Research findings and analysis

The circuit diagram of the S-S system is shown in Figure 5. The system mainly consists of a full-bridge inverter module, a resonant network, and a bridge rectifier module. To facilitate analysis, it is simplified into a simple circuit diagram as shown in Figure 6. The full-bridge inverter module can be equivalent to an AC voltage source; the bridge rectifier module and load can be replaced by an equivalent resistor, and the coil can be equivalently replaced by a controlled voltage source and inductive reactance, which is helpful for formula derivation. It is particularly pointed out that this paper uses Litz coils. The coils wound by Litz wire have high space utilization and low leakage inductance, which can greatly improve the efficiency and remain stable. Moreover, under high-frequency working conditions, Litz coils can reduce the loss caused by the skin effect.

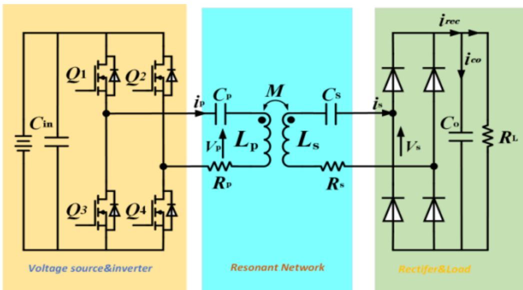


**Fig. 5.** S-S system circuit diagram (Photo credit: Original)

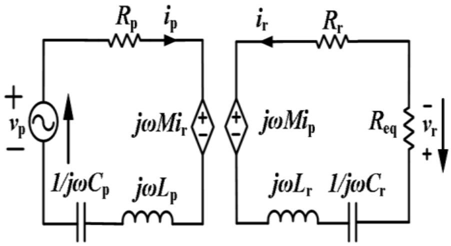


**Fig. 6.** S-S system simple circuit diagram (Photo credit: Original)

On the basis of the simple circuit diagram of the S-S system, the formula is derived as follows:

Compensated capacitors:

$$C_{\mathrm{p}} = \frac{1}{\omega_0^2 L_{\mathrm{p}}} \qquad C_{\mathrm{r}} = \frac{1}{\omega_0^2 L_{\mathrm{r}}} \tag{1}$$

Kirchhoff's Laws on Tx side

$$v_{\mathrm{p}} = (j\omega_o L_{\mathrm{p}} + \frac{1}{j\omega_o C_{\mathrm{p}}}) + j\omega_o M i_{\mathrm{s}} \tag{2}$$

Kirchhoff's Laws on Rx side

$$j\omega_o M i_{\mathrm{p}} = -i_{\mathrm{s}}(j\omega_o L_{\mathrm{p}} + \frac{1}{j\omega_o C_{\mathrm{p}}} + R_{\mathrm{L}}) \tag{3}$$

Based on the designed Cp and Cs, (1) can be rewritten as

$$i_{\mathrm{s}} = \frac{v_{\mathrm{p}}}{j\omega_o M} \tag{4}$$

(2) can be rewritten as

$$i_{\mathrm{p}} = \frac{-i_{\mathrm{S}} R_{\mathrm{L}}}{j\omega_o M} \tag{5}$$

Based on (4), the input impedance can be rewritten as:

$$Z_{\mathrm{in}} = \frac{v_{\mathrm{p}}}{i_{\mathrm{p}}} = \frac{\omega_0^2 M^2}{R_L} \tag{6}$$

The S-S system has a constant current output characteristic when the parasitic resistance is zero. When the parasitic resistance is not zero, the output current decreases as equivalent resistance increases, and the larger the parasitic resistance, the more the output current decreases, as shown in Figure 7. However, it will be affected by the changes in operating frequency and mutual inductance. For example, it can be seen from formula (3) that if two coils are very close to each other, the mutual inductance will increase, which will lead to an increase in the mutual inductance coefficient. The output current value will decrease with the increase in the magnitude of mutual inductance. This means that the output power is very low, and due to the increase in the magnitude of mutual inductance, the magnitude of mutual inductance coefficient increases, multiple resonance points appear, and frequency bifurcation may occur, as shown in Figure 8. Therefore, when transmitting high power under strong coupling conditions, the S-S system is unsuitable. It can be known from formula (4) that the primary side current value will increase with the increase of the secondary side equivalent resistance and decrease with the increase of the magnitude of mutual inductance. It can be seen from this that if the coil is offset, the magnitude of mutual inductance is reduced, which will cause the primary side current to tend to infinity, causing the inverter and power supply to burn out.

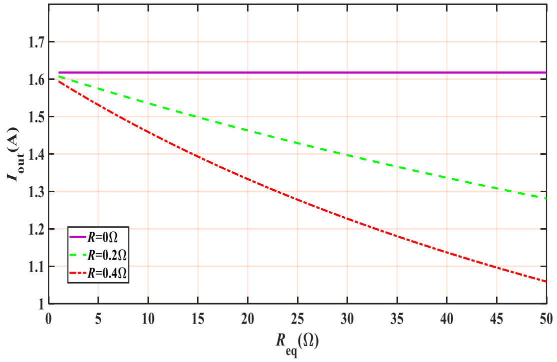


**Fig. 7.** Output current changes with equivalent load under different parasitic resistances diagram (Photo credit: Original)

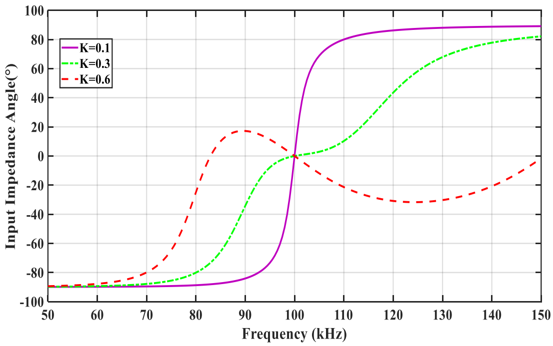


**Fig. 8.** Output impedance angle changes with frequency under different parasitic resistances diagram (Photo credit: Original)

## 5 Method innovation

This article innovates the coil coupling method and uses cylindrical nested coupling as shown in Figures 9 and 10. This method effectively reduces the influence of coil offset on mutual inductance. At the same time, it avoids the trouble of precise docking during charging and has greater adaptability and stability. The cylindrical nested design allows the charging system to have better space utilization, and the increase in coil area gives the system better heat dissipation performance. The Maxwell simulation results are shown in Figure 11. There is almost no change in the magnitude of mutual inductance of the receiving coil within the offset range of -20mm to 10mm. From the coil magnetic field distribution diagram, shown in Figure 12, the closer the primary side coil is to the secondary side coil, the greater the intensity of the induced magnetic field. The magnetic field lines in the receiving coil are distributed more uniformly, as shown in the magnetic field line phase distribution diagram, shown in Figure 13.

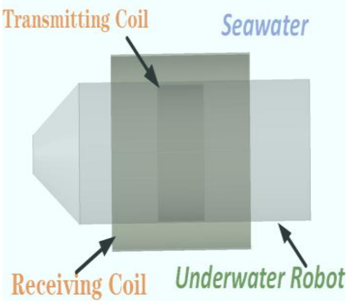


**Fig. 9.** Cylindrical nested coil model (Photo credit: Original)

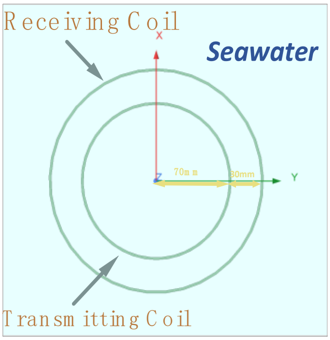


**Fig. 10.** Cylindrical nested coil model top view (Photo credit: Original)

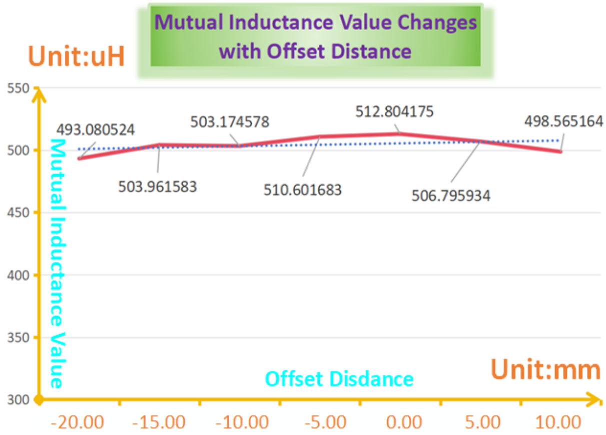


**Fig. 11.** Changes in mutual inductance of cylindrical nested coils with offset distance (Photo credit: Original)

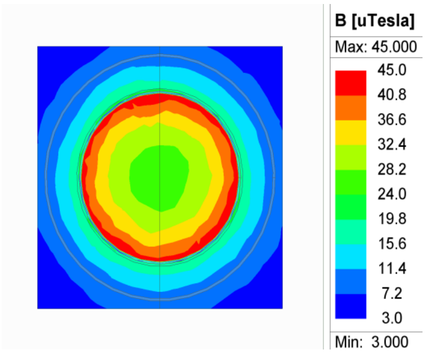


**Fig. 12.** Coil magnetic field distribution diagram (Photo credit: Original)

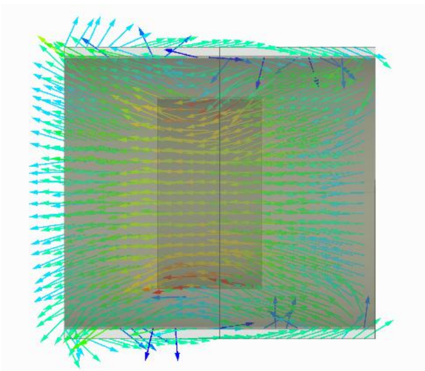

**Fig. 13.** Magnetic flux line phase distribution diagram (Photo credit: Original)

## 6 Limitations and deficiencies

The optimal coil spacing has not been found. Excessive spacing will weaken the mutual inductance and reduce charging efficiency. If the spacing is to be reduced, considering that the primary side coil is inside the secondary side coil, it will be affected by the thickness and material of the robot shell. There is a lack of strong scientific evidence to support the question of whether the magnetic radiation generated by magnetic coupling systems will have adverse effects on the marine environment and marine life, and no definite conclusion has been reached yet [12]. At present, underwater unmanned devices have various calibers, equipment parameters, etc., and the lack of unified industry standards has increased the workload of building charging base stations.

## 7 Conclusion

Through research, this article found that the magnitude of mutual inductance of the coils is inversely proportional to the coil offset distance and coil spacing. This article proposes a nested coil coupling method, but the optimal distance between the two coils still requires in-depth research in theory and application. In terms of theoretical analysis, it is urgent to study the distribution law of underwater electromagnetic fields and coil spacing. In terms of practical application, the coupling coil system is designed by combining a theoretical basis and a simulation model, and the optimal coil spacing is gradually obtained. In practical applications, the load of underwater wireless power transmission systems is generally batteries, so further research on batteries is needed in future experiments. At the same time, optimizing the coupling mechanism can further improve the transmission efficiency of underwater wireless power transmission systems. In addition, there is a lack of a strong scientific basis for whether the magnetic radiation generated by the magnetic coupling system will have adverse effects on the marine environment and marine life. A firm conclusion has not yet been reached. Researchers should detect changes in water quality and changes in the number of marine life while conducting experiments.

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