Research on Underwater Wireless Power Transmission Technology Based on Ansys Maxwell Simulation

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Abstract. Ocean energy exploration is one of the hottest spots in the world today. For ocean exploration, most of them need the help of autonomous underwater vehicles, which make underwater wireless charging technology become extremely important research. Based on Ansys Maxwell simulation and assisted by Matlab, this study will explore and select the extension structure of wireless transmission technology, and study the influence of coil offset on mutual inductance value according to the simulation results. It is found that the S-S compensation circuit has advantages in short distance, low power, fixed position, cost and structure, while the LCC-S compensation circuit has advantages in long distance, high power, dynamic position and anti-drift ability. It is also found that the coil offset is closely related to the mutual inductance value. By doing this research, people can know the theoretical basis of Underwater radio transmission technology. In addition, these studies have great value in the practical application of underwater radio, which can help people better detect Marine resources.

Keywords: Underwater, Transmission, Simulation, Wireless

1 Introduction

China has a continental coastline of 18,000 kilometers and an island coastline of 14,000 kilometers. The waters under its jurisdiction span tropical, temperate and subtropical zones, with a total area of 3 million square kilometers. There are rich Marine resources, such as Marine organisms, Marine space, Marine minerals, Marine chemistry, Marine energy resources and so on. The development of these resources has greatly eased the resource tension of the country [1].With the continuous exploration of Marine resources, underwater equipment has also been developed, and the importance of underwater radio technology has been increasingly recognized. Underwater radio technology has important applications in the fields of underwater communication, detection and navigation, and has wide application prospects in military, scientific research, engineering and civil fields. Among them, wireless charging technology has attracted wide international attention because it can safely supply power in a specific environment. By completely isolating the charging power supply and the load circuit, the circuit can avoid the safety risks of friction and leakage, and because there is no direct coupling between the circuits, many existing problems such as maintenance

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difficulties, poor flexibility, and poor safety can be perfectly solved [2]. However, the application of underwater radio transmission also has its drawbacks, such as the need to solve the problem of Marine environment adaptation and so on. Among them, the most important is how to solve the problem of low transmission efficiency [3]. Although this technology faces the challenges of various Underwater environments, it has a broad prospect and its application scope will continue to expand in the future. It is expected to be applied to the Autonomous Underwater Vehicle (AUV) and can improve its charging safety, reliability, flexibility and concealment [4]. Therefore, this study will simulate the process of underwater radio transmission and its key influencing factors through Ansys Maxwell modeling coil.

2 Methodology

As shown in Figure 1, in this study, a simulation transmitting coil with a radius of 110mm and a height of 200mm was created through Ansys Maxwell. Inside it, there is a movable receiving coil with a radius of 75mm and a height of 50mm. Both coils are made of copper and they can simulate 100 turns of transmitting copper coil with diameter of 2mm and 25 turns of receiving copper coil with diameter of 2mm, respectively. The two coils are enclosed in a 400mm*400mm*400mm box which simulating a seawater environment.

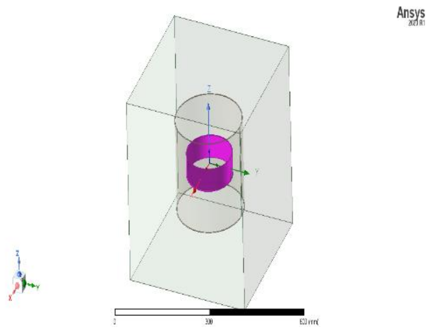

Fig. 1. Ansys maxwell coin model(Picture credit : Original)

As Magnetic field changes (i.e., Magnetic Induction Communication, MIC) transmit signals through alternating magnetic fields, its frequency, intensity, modulation mode and other parameters directly affect the performance of underwater radio transmission [5]. Therefore, it is necessary to ensure that the coil in this study is in an approximately ideal magnetic field environment, so as to ensure that the experimental data is more accurate and representative. In this study, the magnetic field simulation of different cross sections of the transmitting coil is carried out by Ansys Maxwell, and the magnetic field distribution maps of three representative cross sections are obtained.

Figures 2, figure 3, and figure 4 show the magnetic field distribution of the middle cross section of the transmitting coil 50mm up, the middle cross section, and the middle cross section 50mm down, respectively. It can be seen that the magnetic field distribution is relatively stable and concentrated. The magnetic field inside the transmitting coil gradually increases to about 50μT from inside to outside, while the magnetic field outside the coil is mostly below 20μT. It is obvious that the magnetic field inside and outside the coil is quite different. It can be shown that the magnetic field distribution of the model is stable, the magnetic leakage phenomenon is small, and the underwater transmission ability is strong. This stands for the coil can accurately simulate the underwater transmission of electric energy.

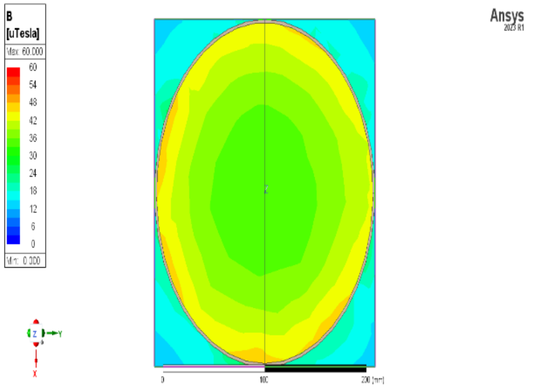

Fig. 2. Magnetic field distribution in upper cross section(Picture credit : Original)

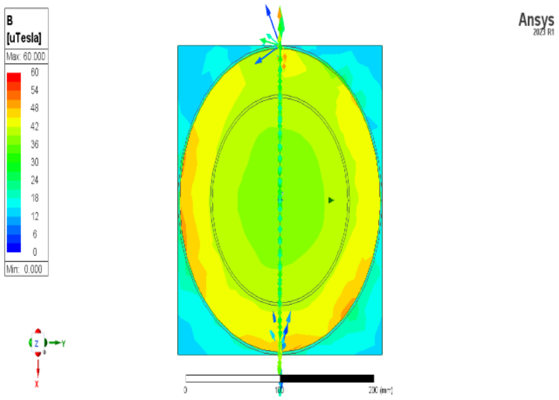

Fig. 3. Magnetic field distribution in middle cross section(Picture credit : Original)

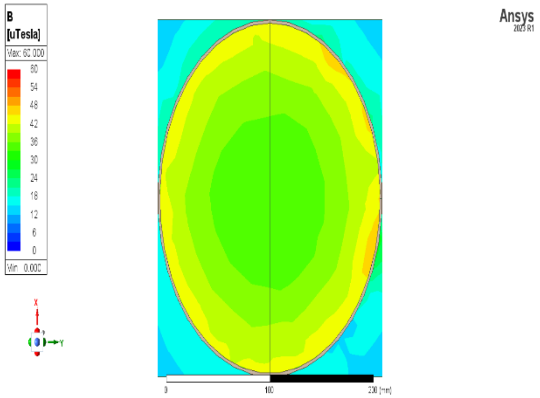

Fig. 4. Magnetic field distribution in lower cross section(Picture credit : Original)

Since the radio energy transmission technology transmits through high frequency alternating current, and there is a large air gap between the transmitter and the receiver, it is easy to produce leakage sensing phenomenon. At the same time, coil inductance in the circuit can also generate power and affect transmission efficiency during operation, so it is necessary to introduce a compensation circuit that can reduce circuit impedance and improve output power and efficiency by adjusting capacitance and inductance to achieve resonance [6].Moreover, in the underwater environment, due to the particularity of the medium, such as the high conductivity of water, the electromagnetic wave attenuation is serious. The pressure change in the underwater environment will also affect the coil parameters. However, the compensation circuit can be dynamically adjusted to maintain efficient transmission, so the design of compensation circuit is particularly important. This research mainly focuses on S-S compensation circuit and LCC-S compensation circuit to simulate and compare their application in the actual situation.

Figure 5 shows the S-S compensation circuit diagram. The primary coil and secondary coil of S-S compensation circuit are compensated by series capacitance, which is suitable for fixed load and medium power transmission. The circuit reduces reactive power loss and improves energy transmission efficiency by compensating circuit in underwater radio energy transmission. The S-S compensation circuit is sensitive to load changes and performs well under fixed load conditions.

However, the disadvantages of this circuit are also obvious: the primary and secondary sides of the S-S are tuned only by series capacitors, and the resonant frequencies are strictly dependent on fixed Lp/Cp and Ls/Cs. When the coil is misaligned (the coupling coefficient k value decreases), the equivalent mutual inductance of the system decreases, resulting in impedance mismatch and a sharp decline in efficiency. Therefore, the circuit is sensitive to the change of coupling coefficient and is not suitable for the underwater environment where the coupling coefficient changes greatly. Moreover, in the case of strong coupling, the output power is very low, which is not suitable for conditions that require high power output. Another point is that the primary side current of the circuit will be large in the case of weak coupling. So it may lead to the destruction of the inverter and thus affect the output power, which is not too friendly for the protection of the circuit.

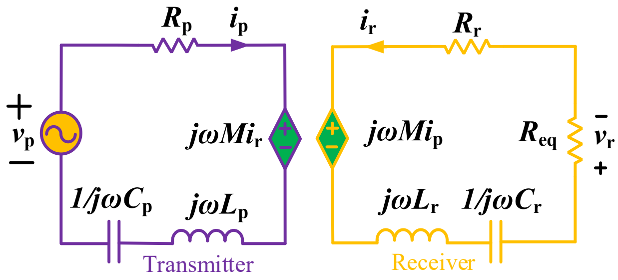

Fig. 5. Topology diagram of S-S compensation circuit(Picture credit : Original)

The LCC-S compensation circuit, as shown in figure 6, adopts LCC compensation (inductor-capacitor-capacitor) in the primary side and series capacitor compensation in the secondary side, adopts multi-resonant point design (usually including a series resonant point and a parallel resonant point), which can better match the impedance of input and output and reduce energy reflection and loss. This makes the circuit have better load adaptability. The LCC-S compensation circuit can achieve higher transmission efficiency, especially in the case of low coupling coefficient. Moreover, the circuit is insensitive to load changes and is suitable for dynamic load conditions. Different from the S-S compensation circuit, it is suitable for underwater radio energy transmission at medium and long distances, and the circuit has strong anti-offset ability. The reason is that when the coil is misaligned (coupling coefficient k decreases), the LCC-S circuit compensates the impedance mismatch caused by the change of mutual inductance by adjusting the equivalent reactance to maintain the resonance of the system. In addition, when the offset degree is large, the input power is weak, which can effectively avoid the influence of coil offset on the circuit components. Therefore, the LCC-S circuit can be used to solve many problems after development. As mentioned by CAI Tianhao and Lv Feng, this circuit model can be applied to the constant voltage charging problem of the underwater robot battery and to improve the anti-offset ability during charging [6].

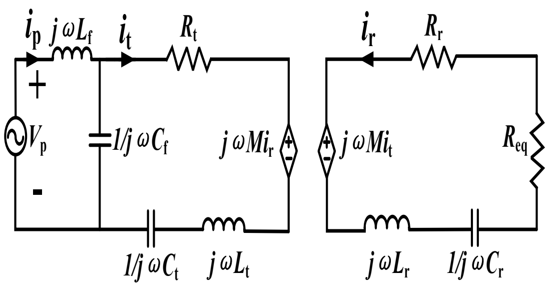

Fig. 6. Topology diagram of LCC-S compensation circuit(Picture credit : Original)

In order to study the transmission efficiency of the S-S compensation circuit and the LCC-S compensation circuit in different environments, this study builds S-S compensation circuit and LCC-S compensation circuit models respectively in Matlab, and import simulation data from Ansys Maxwell into Matlab. The output power of the two circuit models under different conditions is compared, so as to explore how to set up the circuit more reasonably according to the actual situation.

3 Results and Discussion

First of all, according to Table 1 which shown the results of the Ansys Maxwell simulation, the self-inductance Lp of the transmitting coil is set to 1.35mH, and the self-inductance Ls of the receiving coil is set to 113μH. Then set other parameters: input voltage Vp is 100V, mutual inductance factor k is 0.2, operating frequency ω is 100kHz, transmitting coil ESR is 5 times of receiving coil ESR, LCC-S compensation circuit Lf=0.1*Lp.

Table 1. Ansys Maxwell simulation table of two coil self-inductance change with offset

	d1[mm]	Matrix1.L(Rx,Rx)[uH] Setup1:LastAdaptive Freq='100kHz'	Matrix1.L(Tx,Tx)[mH] Setup1:LastAdaptive Freq='100kHz'
1	0.000000	113.079933	1.348503
2	10.000000	113.038246	1.347790
3	20.000000	112.478763	1.345656
4	30.000000	112.58408	1.349838
5	40.000000	113.204880	1.352899
6	50.000000	113.158684	1.347018
7	60.000000	112.583663	1.349135
8	70.000000	113.195918	1.349610
9	80.000000	114.559964	1.350994
10	90.000000	112.437257	1.351492
11	100.000000	113.046206	1.353031

Then the S-S compensation circuit is simulated by matlab, and the curve of the output power with the load resistance Req under the ESR of different receiving coils is obtained. The simulation results of M=0.2*sqrt(Ls*Lp) and M=0.4*sqrt(Ls*Lp) are shown in Figure 7 and 8 respectively. It can be seen that the output power of the S-S compensation circuit increases with the increase of the load resistance, and the smaller the ESR, the higher its output power. However, when the mutual inductance is doubled, the output power decreases more than twice.

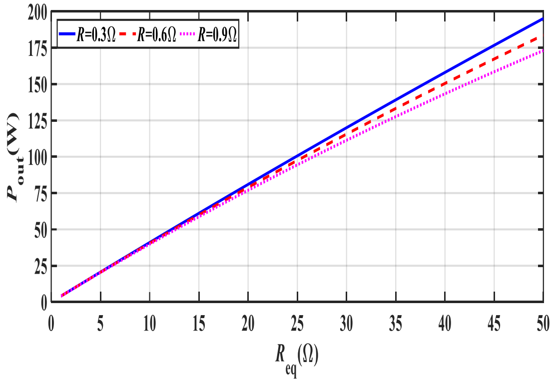

Fig. 7. Curve of load resistance and output power under different ESR (k=0.2)(Picture credit : Original)

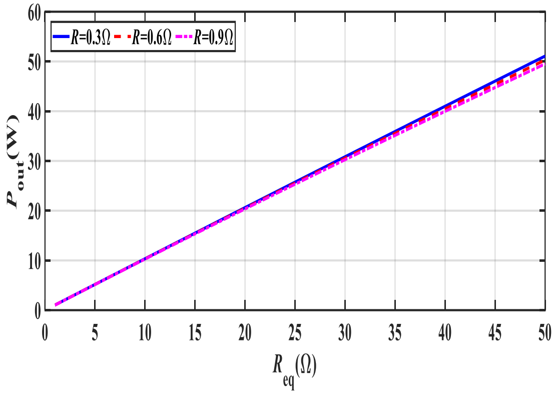

Fig. 8. Curve of load resistance and output power under different ESR (k=0.4)(Picture credit : Original)

Next, the LCC-S compensation circuit is simulated by matlab, and the curve of output power changing with load resistance Req under different ESR is obtained. Figure 9 and 10 show the simulation results of M=0.2*sqrt(Ls*Lp) and M=0.4*sqrt(Ls*Lp) respectively. It can be seen that when the load resistance value is low, the output power is obviously higher than that of S-S compensation circuit. With the increase of load resistance, its output power decreases rapidly, and when the load resistance is large, it tends to be relatively stable. The same as the S-S compensation circuit, when the ESR is smaller, its output power is larger. However, unlike the S-S compensation circuit, when the mutual inductance value increases, the output power increases greatly when the load resistance Req is small.

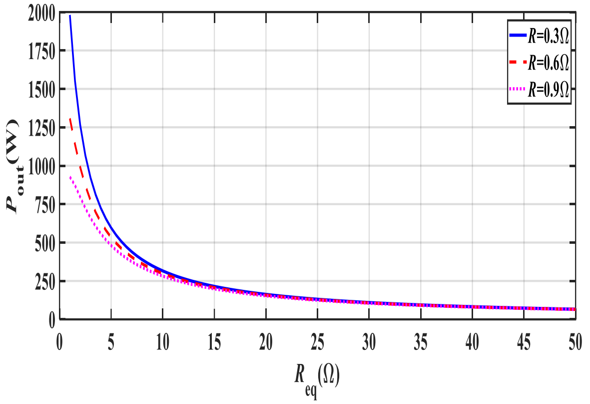

Fig. 9. Curve of load resistance and output power under different ESR (k=0.2)(Picture credit : Original)

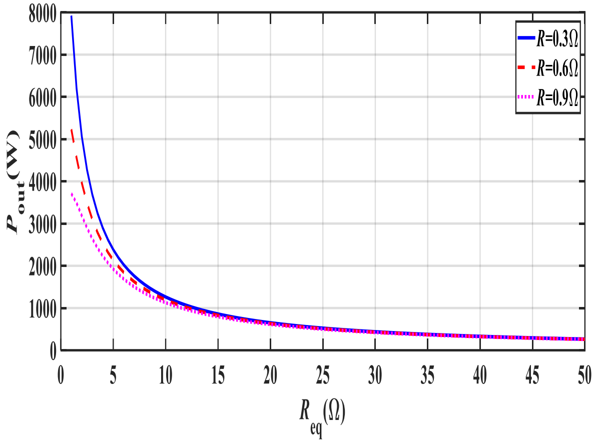

Fig. 10. Curve of load resistance and output power under different ESR (k=0.4)(Picture credit : Original)

Therefore, this study summarizes the S-S compensation circuit has the following advantages: First, the structure is simple: only series capacitors and inductors are required, which is easy to design and implement. Second, it has high efficiency: it can achieve efficient energy transmission at a specific frequency and is suitable for short-distance transmission. Third, low cost: the number of components is small, which is suitable for cost-sensitive application conditions. The disadvantages of this compensation circuit are also obvious: the first is that the anti-offset ability is weak: the coupling coefficient decreases significantly when the coil is mislocated, and the efficiency decreases sharply. The second is sensitive to load: the parameters need to be re-tuned when the load changes, and the adaptability is poor. The third is that the leakage inductance has a large impact: coil leakage inductance may lead to increased reactive power loss.

The LCC-S compensation circuit has the following advantages: The first is high efficiency: By optimizing the parameters, it can maintain efficient transmission in a wide frequency range, and is suitable for long-distance transmission. In the case of strong coupling, the output power is much higher than that of the S-S compensation circuit. Second, strong anti-interference ability: through the LCC network dynamic adjustment of impedance, the efficiency drops slowly when the coupling coefficient changes, and the complex structure makes it better adaptability to frequency offset and load change. Third, it has leakage compensation ability: the primary LCC network can suppress leakage and reduce reactive power loss. However, the circuit also has its disadvantages and limitations: First, the structure is complex: the primary side needs additional inductors and capacitors, and the number of components is large, which will lead to high design cost and complexity. Second, it is difficult to debug: parameter matching needs fine adjustment, which has high requirements on manufacturing process.

To sum up, the S-S compensation circuit is suitable for short-distance, low-power, fixed-position, and cost-sensitive conditions, and has a simple and efficient structure. The LCC-S compensation circuit is suitable for long distance transmission with high power, dynamic position adjustment and high anti-deviation requirement, but it is complicated to design and implement. Therefore, the model can be flexibly selected according to the specific application requirements and environmental conditions to adapt to the complex and changeable underwater environment.

Another point to be considered for underwater radio transmission is that due to the special underwater environment, it is extremely difficult to align the transmitter and receiver devices accurately when they work. When the transmitter and receiver are misaligned, their mutual inductance will have a great impact, which will greatly reduce the transmission efficiency [7].

Gong Zhaowei, Li Jingang et al. made many attempts to the anti-drift ability of the coil[8], such as the coupling structure of asymmetric structure [9], the DDQ (Double-D Quadrature) coil structure [10], and the DD coil structure of four-quadrant mesh [11], etc. Although the existing methods have been relatively perfect, they do not take into account the influence of anti-offset ability on mutual inductance.

Therefore, in order to explore the anti-offset ability of the coil and its influencing factors, this study carried out a simulation on Ansys Maxwell to simulate the position change of the receiving coil. The simulation translated the receiving coil into the transmitting coil along the z-axis direction and recorded the change of the mutual inductance value of the two coils along with the offset d1. The results are shown in Figure 11 and Table 2.

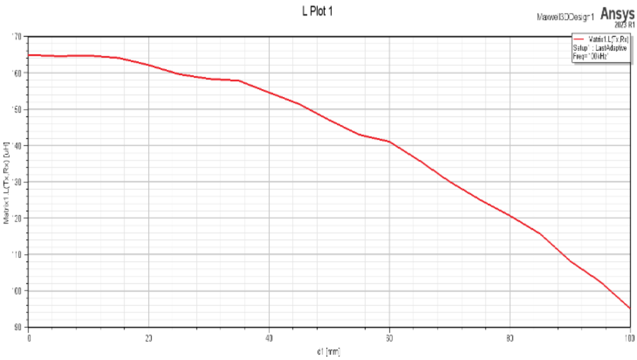

Fig. 11. The curve of coil mutual inductance with offset(Picture credit : Original)

Table 2. Table of coil mutual inductance with offset

	d1[mm]	Matrix1.L(Rx,Rx)[uH] Setup1:LastAdaptive Freq='100kHz'
1	0.000000	164.851510
2	5.000000	164.471760
3	10.000000	164.645142
4	15.000000	163.995818
5	20.000000	162.046120
6	25.000000	159.545541
7	30.000000	158.248428
8	35.000000	157.742817
9	40.000000	154.499554
10	45.000000	151.324476
11	50.000000	146.941049
12	55.000000	142.880384
13	60.000000	140.987463
14	65.000000	135.757718
15	70.000000	130.005505
16	75.000000	125.071197
17	80.000000	120.666831
18	85.000000	115.709097
19	90.000000	108.217143
20	95.000000	102.535182
21	100.000000	95.129860

Figure 11 and Table 2 can clearly show that when the offset is less than 40mm, the reduction of mutual inductance value is less than 10%, and when the offset is greater than 40mm, the reduction range of mutual inductance value is significantly increased. It is concluded that the model has good anti-offset ability in a certain range, but when the offset exceeds a certain range, the mutual inductance value of the model will drop very badly.

Therefore, even if the coil itself has a certain anti-offset ability, in order to achieve high efficiency transmission of underwater radio, a transmission system with strong anti-offset ability should be designed to prevent the mutual inductance decrease caused by the shift, thereby reducing the transmission efficiency of electric energy.

4 Conclusion

In this study, through the modeling and simulation of Ansys Maxwell coil, the advantages and disadvantages of S-S compensation circuit and LCC-S compensation circuit in underwater radio energy transmission application are verified by Matlab assistance, and how to flexibly choose two circuits according to different specific environments is pointed out. At the same time, this study considers the influence of the underwater environment on the coil, which leads to its offset and affects its output power. Through simulation, it is concluded that the self-inductance of the coil changes little when the offset is low, and the mutual inductance value drops seriously when the offset is large. These contents verify the feasibility of underwater radio energy transmission technology and show the importance of compensation circuit design and anti-offset ability optimization. These research results provide theoretical support and technical reference for the practical application of underwater radio energy transmission technology, and are expected to achieve more extensive application in the field of Marine development and scientific research in the future. The current research only involves the research of the S-S compensation circuit and LCC-S compensation circuit, and there are many kinds of circuit structure extension that have not been involved, among which there may be more professional and suitable circuit topologies for underwater radio energy transmission. In addition, for the transmission of underwater radio energy, it is also necessary to consider how to improve the efficiency of its transmission of electric energy and how to reduce the loss of energy. Future research should focus on this direction.

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