Design of Capacitive Wireless Power Transmission System in Seawater
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Abstract. As an emerging power supply method, wireless power transmission has attracted extensive attention from researchers at home and abroad. Since there is no direct contact of the wires, it is expected to solve the problem of power supply life of the underwater robot. First of all, this paper combines the working principle of capacitive wireless power transmission, analyzes the working state of the circuit by using the generalized state space average, and obtains the working frequency of realizing the soft switching state. Secondly, two different coupling mechanisms are designed and Maxwell finite element simulation is carried out to calculate the capacitance value and field strength distribution. Finally, the underwater wireless power transmission system is built. The influence of transmission distance $d$ and different coupling mechanisms on output power is discussed. The following conclusions are obtained: (1) As the transmission distance $d$ increases, the output power decreases and the electromagnetic interference increases. (2) Cylindrical capacitors have higher power density and smaller electromagnetic interference than parallel plate capacitors. The research results provide an important reference for future underwater wireless power transmission systems.

Introduction

In recent years, as marine exploration techniques have gradually moved from shallow seas to deep seas, the marine environment has become increasingly harsh. Underwater robotics such as Autonomous Under-water Vehicle (AUV) have become the focus of many ocean field research. Because these robots carry high-performance sensors and cameras, they consume a lot of power and require frequent battery replacement or charging, which makes operation less efficient. However, Underwater Wireless Power Transfer (UWPT) will become a solution to this problem. The key technology is to recharge the AUV by setting up a charging station under seawater, and the distance of wireless charging will become a few millimeters. The Japanese research team has applied the wireless power transmission technology to the underwater AUV power supply mode[1]. The navigation positioning algorithm guides the AUV to dock at the underwater charging station through inductive wireless power technology [7]. However, applying it to the contactless power supply in seawater environment brings two problems that cannot be ignored. First, there is an eddy current effect when a conductor is present around the magnetic field. Since seawater is a good conductor, the eddy current loss phenomenon is obvious, resulting in a sharp drop in transmission efficiency. Second, the magnetic field around the coupled coil creates electromagnetic interference (EMI)[2]. Therefore, inductive coupled power transfer technology is not suitable for contactless charging in seawater environments. Relatively speaking, capacitive power transmission transmits energy through a high-frequency electric field, can pass through metal obstacles, and has low electromagnetic interference, so it is suitable for use in a seawater environment[3].

Anwar studied the relationship between coupling coefficient and frequency of capacitive coupling mechanism by vector analysis tool, analyzed and evaluated the wireless power transmission efficiency under different types of underwater, and performed the performance of parallel plate capacitors immersed in seawater[4]. The experimental results show that in the case of deionized water and tap water, the tendency of coupling is more dependent on the dielectric properties, while in seawater, the coupling tendency is more dependent on the conductivity characteristics due to the
conductivity of the ions. Therefore, the wireless power transmission mechanism and specific implementation methods in the seawater environment have yet to be further studied.

**Underwater CPT System**

Capacitive Power Transfer (CPT) technology was first verified by Tesla's lighting experiment in 1891. It transmits energy from the transmitter to the receiver through the electric field between the coupling capacitors. Figure 1 shows the basic components of a capacitive power transmission system, including DC power, inverter circuits, capacitive couplers, rectifier circuits, and loads. The DC power supply is an input unit for electrical energy and is responsible for the power input of the entire system. The components of the wireless energy transmission system mainly include a primary transmitting circuit, a coupling unit and a secondary receiving circuit. The transmission circuit includes a DC power supply, a high frequency inverter circuit, and a tuning network, and includes a rectifier circuit, a filter circuit, and a load in the receiving circuit. The coupling unit is composed of an emitter plate and a receiving plate, and the intermediate filling medium is seawater[5].

![Figure 1. The composition of a CPT system.](image)

**CPT System Modeling**

In this paper, the generalized state space average method is used to establish a mathematical model to analyze the CPT system, as shown in Figure 2, which is used to calculate the ZVS soft switching operating point of the full-bridge inverter circuit and reduce the switching loss of the system[6]. When the MOSFET transistors S1 and S4 are turned on and S2 and S3 are turned off, according to the Kirchhoff voltage-current law, the differential equation of the equivalent circuit of the ECPT system shown in Figure 2 has the Eq.1 description:

![Figure 2. Circuit equivalent model of CPT system.](image)
\[
\begin{align*}
\frac{di_{ld}}{dt} &= -\frac{R_{ld}}{L_d} i_{ld} - \frac{1}{L_d} v_{cp} + \frac{1}{L_d} v_{dc} \\
\frac{dv_{cp}}{dt} &= \frac{1}{C_p} i_{ld} - \frac{1}{C_p} i_{lp} - \frac{1}{C_p} i_{LS} \\
\frac{di_{lp}}{dt} &= \frac{1}{L_p} v_{cp} - \frac{R_{lp}}{L_p} i_{lp} \\
\frac{di_{ls}}{dt} &= \frac{1}{L_s} v_{cp} - \frac{1}{L_s} v_{cs} - \frac{(R_{ls} + R_{cs} + R_w + R_d)}{L_s} i_{ls} \\
\frac{dv_{cs}}{dt} &= \frac{1}{C_s} i_{ls}
\end{align*}
\]

(1)

Let the state variable \( X = [i_{ld}, v_{cp}, i_{lp}, i_{ls}, v_{cs}] \), and the system input vector \( U = [v_{dc}] \), the state space model of the system can be transformed into the following matrix form:

\[
\dot{X} = A_{1}X + B_{1}U
\]

(2)

where \( A_{1} = \)

\[
\begin{bmatrix}
-\frac{R_{ld}}{L_d} & -\frac{1}{L_d} & 0 & 0 & 0 \\
\frac{1}{C_p} & 0 & -\frac{1}{C_p} & -\frac{1}{C_p} & 0 \\
0 & \frac{1}{L_p} & -\frac{R_{lp}}{L_p} & 0 & 0 \\
0 & \frac{1}{L_s} & 0 & -\frac{(R_{ls} + R_{cs} + R_w + R_d)}{L_s} & -\frac{1}{L_s} \\
0 & 0 & 0 & \frac{1}{C_s} & 0
\end{bmatrix}
\]

\[
B_{1} = \begin{bmatrix}
\frac{1}{L_d} \\
0 \\
0 \\
0 \\
0
\end{bmatrix}
\]

Since the CPT system can be divided into two modes according to the switching state of the full-bridge inverter circuit, namely:

\[
\begin{align*}
\text{State I} & : S1, S4 is on, S2, S3 is off, v_{cp} > 0 \\
\text{State II} & : S2, S3 is on, S1, S4 is off, v_{cp} < 0
\end{align*}
\]

(3)

Therefore, when the switches S2 and S3 are turned on and S1 and S4 are turned off, we can also get the state space coefficient matrix of State II. Since the circuit has an excitation input, the matrix is reversible. This gives the solution of Eq.1:

\[
X = e^{A_{1}t}X_{0} + A_{1}^{-1}(e^{A_{1}t} - I)BU \quad (i = 1, 2)
\]

(4)

In the steady state, State I and State II each work for half a cycle. Here, a cycle is taken as an example for analysis, and the period is \( T \). When \( t = T/2 \), the value of the state variable \( X \) is \( X_{1} \), when \( t = T \), the value of the state variable \( X \) is \( X_{2} \). Due to the continuity of the signal, the final state of State II is the initial state of State I. Satisfy \( X_{2} = X_{0} \), substitute the formula, and get \( X_{0} \):

\[
X_{1} = X(t) |_{t=T/2} = \varphi_{1}X_{0} + A_{1}^{-1}(\varphi_{1} - I)BU
\]

(5)

\[
X_{2} = X(t) |_{t=T} = \varphi_{2}X_{1} + A_{2}^{-1}(\varphi_{2} - I)BU
\]

(6)

\[
X_{0} = (1 - \varphi_{2}\varphi_{1})[\varphi_{2}A_{1}^{-1}(\varphi_{1} - I) + A_{2}^{-1}(\varphi_{2} - I)]BU
\]

(7)

To achieve ZVS soft switching conditions, the following boundary conditions are met in Eq.8:

\[
v_{cp}|_{t=0} = YX_{0} = 0
\]

(8)

In the Eq.8, \( Y = [0 \quad 1 \quad 0 \quad 0 \quad 0] \) is a parameter selection vector, and the \( v_{cp} \) component is taken out from the state space \( X \). With all circuit parameters known, the switching frequency of the VS can be determined by a combination of equations. If the period is known, the steady state of State
I and State II can be found by the formula. At this point, we have obtained the transient response of each state component at each moment in the steady state one cycle:

\[
\begin{align*}
  v_{cp} &= \begin{cases} 
    Y[e^{A_1t}x_0 + A_1^{-1}(e^{A_1t} - I)BU] & t \in (2k\pi, 2k\pi + T/2) \\
    Y[e^{A_2t}x_1 + A_2^{-1}(e^{A_2t} - I)BU] & t \in (2k\pi + T/2, 2k\pi + T)
  \end{cases}
\end{align*}
\]

(9)

Underwater Coupling Mechanism

Coupling Capacitor

For underwater power transmission systems, the design of the coupling mechanism is the key to improving output power and efficiency. Common coupling mechanisms come in two forms: parallel plate capacitors and cylindrical capacitors[8], as shown in Figure 3 and Figure 4. The parallel plate capacitor has a simple structure, it consists of two plates, the distance between them is \(d\). Assuming that the area of the plate is \(S\), the capacitance value of the parallel plate capacitor of distance \(d\) can be expressed as Eq.10:

\[
C = \frac{\varepsilon_r\varepsilon_0 S}{d}
\]

(10)

where \(\varepsilon_r\) is the relative dielectric constant of the medium; \(\varepsilon_0\) is the dielectric constant of the vacuum; \(S\) is the area of the coupled plate.

The cylindrical capacitor consists of two cylinders inside and outside, which have a common center, and the distance between the inner and outer cylinders is \(d\). Assuming that the height of the cylinder is \(h\), when \(h\) meets the condition \(h>>d\), the capacitance of the cylindrical capacitor can be calculated by the Eq.11:

\[
C = \frac{\pi \varepsilon_r\varepsilon_0 h}{\ln \frac{R_2}{R_1}}
\]

(11)

where \(h\) is the height of cylinder, \(R_1\) is the radius of the inner cylinder, and \(R_2\) is the radius of the outer cylinder.

For the application background of AUV wireless charging, the coupling capacitor is established as shown in Figure 5 and Figure 6. The upper and lower plates of the parallel plate capacitor are round copper plates with a radius of 51 mm. In order to isolate seawater, the copper plates are embedded in a PVC mold. On the side of the contact between the copper plate and the seawater, a layer of PVC medium having a thickness of 1 mm is coated, and on the other side, the connecting wire is taken out by pouring the epoxy to isolate the seawater. The contact side of the cylindrical capacitor with seawater also needs to isolate seawater. The inner surface of the outer cylinder and the outer surface of the inner cylinder are covered with a layer of 1 mm PVC medium. The thickness of the electrode plate is not considered here. \(R_1 = 23mm\) is the radius of the inner cylinder, \(R_2 = 27mm\) is the radius of the outer cylinder, \(h = 150mm\) is the height of the cylinder, \(d_1 = 1mm\) is the thickness of the PVC medium, and \(d\) is the thickness of the seawater. The dielectric loss of the PVC material is tan \(\delta = 0.03\), and the loss resistance can be expressed as \(R_{cs} = \tan \delta / \omega C_s\).
Field Strength Distribution

In order to calculate the capacitance value of the coupling mechanism under seawater conditions, the field strength distribution of the capacitor is analyzed, and the finite element model is solved by Maxwell software. The Figure 7 shows the electric field intensity distribution of a parallel plate capacitor with a sea gap of 1 mm. It can be found that in the region where seawater is distributed, the electric field strength is almost zero, which means that the coupling mechanism can be regarded as a series of capacitors in which two dielectrics are PVC. Adding an excitation voltage to the plate can be used to find a capacitance of 109 pF. At the edge of the parallel plate capacitor, there is a significant diffusion phenomenon, which affects the transmission efficiency of the coupling mechanism when the transmission distance increases.

Experimental Platform Construction and Results Analysis

Experimental Platform Construction

In order to study the influence of transmission distance on the underwater capacitive power transmission system, a CPT system as shown in Figure 8 was constructed. Considering that the influence of other factors on the transmission efficiency of the system is excluded as much as possible, the resonant circuit adopts a tuning network structure of parallel-series resonance, and the inductance and the coupling mechanism are connected in series to compensate the capacitive reactance of the coupling capacitor. At the same time, in order to improve the output power of the underwater wireless power transmission system, the inverter circuit uses a full bridge circuit.
Combined with the modeling method of Section 3, the soft switching operating frequency of the switching tube can be obtained. In this system, the input DC voltage $V_{dc}$ is 12V, and other circuit parameters are listed in Table 1 below. By substituting these values into Eq.7 and Eq.8 and treating the switching period as a variable, the steady-state resonant voltage for different switching cycles can be found. By considering the boundary conditions, all zero crossings of the resonant voltage represent possible ZVS switching periods. In general, we choose the frequency corresponding to the first zero crossing as the resonant frequency.

Table 1. Values of circuit parameters.

| parameters | parallel type | Cylinder type |
|------------|---------------|--------------|
| $L_1$      | 1.2mH         | 1.2mH        |
| $V_{dc}$   | 12V           | 12V          |
| $f_0$      | 420kHz        | 420kHz       |
| $L_p$      | 31uH          | 31uH         |
| $L_s$      | 2.7mH         | 2.4mH        |
| $C_p$      | 4.7nF         | 4.7nF        |
| $R_{cs}$   | 5.8Ω          | 7.8Ω         |
| $R_{L1}$   | 1.8Ω          | 1.8Ω         |
| $R_w$      | 100Ω          | 32Ω          |
| $R_{LP}$   | 0.3Ω          | 0.3Ω         |
| $R_{LS}$   | 3Ω            | 2.4Ω         |
| $C_s$      | 109pF         | 120pF        |
| $R_L$      | 200Ω          | 200Ω         |

**Influence of Transmission Distance d on Output Power**

Figure 9 and Figure 10 show the waveforms of the underwater experiment. When the transmission distance is 2mm, the peak-to-peak value of the output voltage obtained on the load is 9.4V, and the output power of the system is 55mW. When the transmission distance is 10 mm, the output voltage obtained on the load is reduced to 5.8 V, and the output power is 21 mW. The experimental results show that the output power of the underwater wireless power transmission system decreases significantly with the increase of the transmission distance d. However, the frequency of the resonance operation of the system does not change significantly, and the system is still in the resonant working state. The output voltage of the system is low, which is due to the large inductance of the series resonance, which causes the resistance to be large, resulting in power loss. Second, the coupling mechanism will also have a certain degree of attenuation under water. It can be found that as the transmission distance increases, the output signal quality of the coupling mechanism deteriorates.
This is due to the increase of interference signal sources in the environment and the electromagnetic interference phenomenon. Therefore, when designing the coupling mechanism of the underwater wireless power transmission system, it is also necessary to consider the influence of the transmission distance on the output power and transmission performance of the system. Since the seawater is electrically conductive, the capacitance of the coupling mechanism depends on the dielectric material.

The plate gap changes within a certain distance range, and has little effect on the capacitance value of the coupling mechanism. Compared with the air, the capacitance value is not sensitive to the position change of the plate.

**Influence of Coupling Mechanism on Output Power**

Replace the parallel plate capacitor with a cylindrical capacitor, the capacitance of the underwater coupling mechanism is 120pF, which is slightly larger than the parallel plate capacitor. The main parameters of the circuit are shown in Table 1. Figure 11 and Figure 12 show the output voltage waveform. When the transmission distance is 2mm, the peak-to-peak value of the output voltage on the load is 17.4V, and the output power of the system is 189.3mW. The output power of the system is significantly improved. When the transmission distance is increased to 10 mm, the output power of the system is 66 mW. This is because the electric field strength of the cylindrical coupling mechanism is relatively concentrated, and the field strength is limited between the emitter plate and the receiving plate. Compared with the parallel plate capacitor, the electric field diffusion phenomenon is not obvious. Secondly, the seawater of the cylindrical coupling mechanism is in the PVC groove of the emitter plate and the receiving plate, the volume of the seawater is small and relatively constant, and the attenuation caused by the seawater resistance is small, and the transmission performance is also improved. However, when the transmission distance is increased to 10 mm, the output power is also significantly reduced, and the output waveform glitch is increased. Experiments show that the cylindrical coupling capacitor is more suitable for the coupling mechanism in seawater than the parallel plate capacitor. In the case of similar capacitance values, the output power is higher and the electromagnetic interference is relatively small.
Conclusion
This paper combines the working principle of capacitive wireless power transmission technology to design a wireless power supply system for use in the ocean environment. Through experiments on two coupling mechanisms at different transmission distances, the results show that with the increase of transmission distance, the output power decreases and the electromagnetic interference phenomenon is serious. Due to the conductive properties of seawater, the power loss of underwater transmission is large, the volume of seawater in the cylindrical capacitor is fixed, the loss is low, and the interference is small, which is more suitable as a coupling mechanism for underwater wireless power transmission.

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