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A Robust AUVs Wireless Power Transfer System Based on Seawater Cross-coupling Capacitance Model

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Abstract

Autonomous underwater vehicles (AUVs) serve as crucial equipment for marine exploration and operations. However, the output power and efficiency of the underwater wireless power transfer (WPT) system are affected by underwater unique electrical parameters, and ocean current disturbances can easily trigger coil angular deflection, thereby influencing the system output characteristics. To address this critical challenge, this paper establishes an equivalent circuit model for seawater environments by considering the cross-coupling parasitic capacitance. By incorporating the parity-time (PT) symmetry principle and a DD coupling coil structure, a novel AUVs underwater wireless power transfer system is proposed. Within the strong coupling PT symmetric operating region, the output power and transfer efficiency of the proposed topology become independent of the coupling coefficient k . Consequently, alignment insensitive constant power transfer is achieved without wireless communication modules. The theoretical derivations of the system are detailed through equivalent impedance simplification. Furthermore, the transmission characteristics in air and seawater media are compared, and an experimental prototype is built to conduct multidimensional misalignment tests. Experimental results indicate that the transferred power and efficiency of the system remain remarkably stable under an axial misalignment of ± 80 mm and various angular deflections. The DC-DC power transfer efficiency in seawater environments is stabilized at approximately 90%, demonstrating that the proposed system exhibits exceptional tolerance against both axial and rotational misalignments.

Keywords autonomous underwater vehicles (AUVs), wireless power transfer (WPT), misalignment performance.

1 INTRODUCTION

As essential platforms for marine resource exploration and scientific research, autonomous underwater vehicles (AUVs) play an irreplaceable role in complex or hazardous operational environments [1,2,3].

AUVs typically rely on onboard batteries for power supply, a method that grants them high mobility unrestricted by terrain or distance. However, due to constraints on physical dimensions, the battery capacity that AUVs can carry is strictly limited, resulting in the need for frequent energy replenishment during missions [4,5]. Currently, the primary replenishment method for AUVs involves returning to land or a mother ship for battery swapping [6], which not only consumes a significant amount of energy during transit but also frequently introduces faults due to repetitive battery replacement, thereby severely degrading marine exploration efficiency [7,8]. The energy replenishment mode that relies on coupling and charging via the mother ship after AUVs recovery exhibits a relatively low level of automation. Furthermore, its supporting launch and recovery mechanisms are bulky and time-consuming to operate, which reduces overall operational efficiency while

degrading underwater acoustic stealth performance [9]. Alternatively, the umbilical cable charging scheme is constrained by the deployed length of the cable, directly limiting the operational radius of the AUVs; moreover, the frequent plugging and unplugging of the charging interface is highly susceptible to underwater safety hazards such as sealing failure, electrical leakage, and short circuits [10]. In summary, traditional charging methods impose significant bottlenecks on the practical operational capabilities of AUVs from the perspectives of both mobility range and intelligence level [11]. To address these critical challenges, wireless power transfer (WPT) technology emerges as a promising supply alternative [12]. Currently, multiple countries are advancing the construction of seafloor observation scientific networks, within which the subsea base stations can provide stable wireless charging platforms for AUVs, thereby supporting their efficient operations.

WPT technology possesses the capability to accomplish wireless power transfer across varying media without physical electrical contact. Compared to wired charging schemes, this technology can effectively mitigate latent fault hazards induced by the underwater environment, such as cable corrosion and mechanical coupling failures, thereby supporting the automated energy replenishment of AUVs at predetermined docking stations. Consequently, it serves as a critical technological pathway to break through the AUVs endurance bottleneck, optimize underwater operational efficiency, and advance the intelligent operation and maintenance of underwater equipment, demonstrating prominent value for engineering applications and industrialization research [13,14]. However, regarding the

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underwater environment in which AUVs operate, the constant fluidity of seawater makes it extremely difficult for AUVs to maintain a stable posture during the charging process. Therefore, maintaining system stability faced with potential physical offsets and enhancing misalignment tolerance have emerged as a primary focus of current research. To address this critical challenge, researchers across various domains have conducted extensive investigations from distinct technical perspectives.

The first optimization category focuses on system circuit parameters [15,16,17,18,19,20,21]. By precisely tuning the electrical parameters of the magnetic coupler and compensation network, these schemes flatten the system output curve to enhance stability against coil misalignments. Specifically, references [15] and [16] configured operating points near the output extreme points; leveraging the low sensitivity of output to coupling variations at these points, they effectively suppressed misalignment-induced power fluctuations and expanded the tolerance range. References [17] and [18] constructed a priority-ranking multivariable strategy to optimize operating conditions for spatial misalignments. Reference [19] optimized coil turns and inverter phase shift angles to smooth the output power curve, ensuring stable transfer across all-angle misalignments. To mitigate the impact of coupling coefficient fluctuations on input impedance, reference [20] employed a dual-port impedance matching network to stabilize anti-misalignment performance. However, due to practical constraints like component tolerances and environmental perturbations, system parameters can rarely maintain theoretical optima constantly. Moreover, since these methods mostly predefine an allowable output fluctuation interval, they face an inherent upper limit in improving misalignment tolerance.

The second optimization category focuses on configuring magnetic couplers [22,23,24,25,26], which minimizes mutual inductance fluctuations under misalignments by optimizing coil arrangements to enhance performance. Specifically, reference [22] designed a composite magnetic coupler where the mutual inductances of two coupling branches varied inversely during misalignments, stabilizing the equivalent total mutual inductance through their complementary characteristics. Reference [23] adopted a reversely wound series winding scheme to effectively suppress misalignment-induced mutual inductance degradation, achieving constant-current power transfer and reliable data demodulation within the rated misalignment range. Reference [24] integrated conical and planar spiral coils to form a hybrid transmitter structure, which optimized the magnetic field uniformity in the coupling space to improve the misalignment tolerance of the system. However, relying solely on magnetic coupler optimization presents inherent limitations, as these schemes typically achieve superior tolerance against misalignments in only a single direction.

To mitigate coil misalignments induced by parasitic impedances and ocean current disturbances in seawater environments, and to enhance the misalignment tolerance of the AUVs underwater WPT system, an equivalent coupling model incorporating parasitic parameters is constructed based on the seawater medium, and a novel WPT system adapted to seawater conditions is proposed, as illustrated in

Fig. 1. When operating within the strong-coupling region, the output power and transfer efficiency of the proposed system are minimally affected by coupling coefficient fluctuations. Furthermore, a DD coil structure is selected as the magnetic coupler to accommodate the hull installation requirements of various AUVs specifications. The proposed system demonstrates high tolerance against both axial and angular misalignments, effectively counteracting the dynamic perturbations of ocean currents.

The main contributions of this paper are summarized as follows:

- 1) By integrating the electrical parameters of seawater environments, an underwater circuit model incorporating cross-coupling parasitic capacitances and equivalent impedances is constructed, correcting the modeling errors of conventional air-medium mutual inductance models applied in seawater.
- 2) A DD coil structure is selected as the magnetic coupler, offering enhanced structural flexibility to accommodate the design and installation layout requirements of various AUVs profiles, capsule dimensions, and vehicle scales.
- 3) Without wireless communication modules, stable power transfer under wide range axial misalignments and multi angle deflections is achieved solely relying on the inherent topology characteristics, perfectly fitting practical underwater AUVs power transfer scenarios.

The remainder of this paper is organized as follows. Section II establishes the system equivalent model, theoretically analyzes the transmission characteristics in both strong and weak coupling regions, and compares system performance in air and seawater media. Section III details the realization scheme of the inverter-side negative resistance and presents the step-by-step design procedure for system parameters. Section IV establishes experimental platforms in both air and seawater environments to validate the theoretical analysis through multiple sets of axial misalignment and multi-angle deflection tests. Finally, Section V concludes this paper.

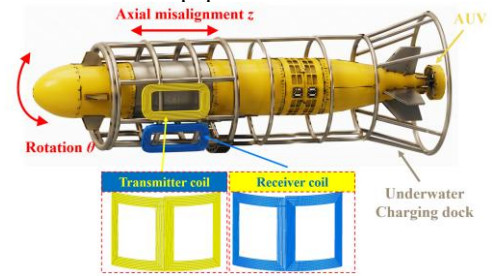


Fig. 1. Overview of underwater docking station and AUVs power transfer system

2 System Analysis

2.1 System Modeling

Under seawater environments, when seawater serves as the transmission medium, its electrical parameters are significantly different from those in air, as listed in Table 1. According to the electromagnetic field theory, when a potential difference exists between two conductors, it will exhibit capacitance. The value of the capacitance depends on the shape of the conductors, the distance between the two conductors, and the dielectric medium [27]. Therefore, a

cross coupling equivalent capacitance inevitably exists between the two coils of the electromagnetic coupler, and parallel capacitance also exists within the coil itself. However, in general application scenarios, the medium is air, which features a small relative permittivity and a very small capacitance value. In contrast, the relative permittivity of seawater is much larger, making the equivalent capacitance between the coils much greater than that in air. Moreover, since the electrical conductivity and relative permittivity in seawater are much larger than those in air, the IPT system will generate a time varying electromagnetic field in the surrounding space during operation, thereby inducing eddy currents in seawater. The magnetic flux linkage excited by the eddy currents will in turn affect the parameters of the coupling mechanism, causing the original system to detune. Meanwhile, the eddy currents will cause additional copper loss, leading to a decrease in transfer efficiency in seawater and increasing the system complexity. Therefore, the circuit model in air is no longer fully applicable, and it is necessary to establish the circuit model of the IPT system in the seawater medium.

TABLE I

CONDUCTIVITY AND PERMITTIVITY OF SEVERAL GAP MEDIA

Medium	Relative permittivity	Electrical conductivity
Air	1.0006	0 S /m
Pure water	81	0.0002 S /m
Tap water	81	0.01 S /m
Seawater	81	4 S /m

The seawater equivalent impedance originates from two coupled effects: (1) The high relative permittivity of seawater introduces parasitic cross-coupling capacitance between coil turns and between the transmitter and receiver coils, which is represented by equivalent capacitances C_{e1} and C_{e2} ; (2) The conductivity of seawater induces eddy currents under the alternating magnetic field, which manifests as equivalent resistance loss R_{e1}/R_{e2} and equivalent inductance variation L_{e1}/L_{e2} . This equivalent modeling framework has been widely adopted in underwater WPT studies and can accurately reflect the influence of seawater medium on circuit parameters.

Due to the difficulty in directly measuring the distributed cross-coupling capacitance between coils in seawater environments, the equivalent capacitance values are not experimentally extracted in this work. Instead, the values of the seawater-induced equivalent capacitance are selected based on previously reported underwater wireless power transfer studies, which have characterized the parasitic capacitive effect caused by the high permittivity of seawater. Accordingly, the equivalent cross-coupling capacitance is set to 36 pF in air and 3.08 nF in seawater for subsequent theoretical analysis.

Based on the IPT system mutual inductance model, the electrical characteristics of the seawater medium are fully considered. The seawater is equivalent to a circuit with certain impedance characteristics connected to the transmitter side and receiver side coils. The underwater cross coupling capacitor wireless power transfer system based on the PT symmetry principle proposed in this paper is illustrated in Fig. 2.

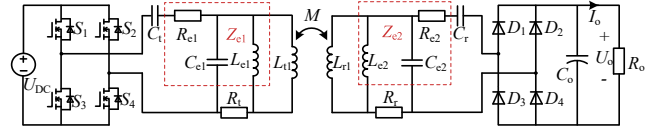


Fig. 2. Equivalent circuit model of wireless power transfer in seawater environment

In the established network, L_{t1} and L_{r1} represent the self-inductances of the transmitting and receiving coils, respectively. C_t and C_r denote the tuning capacitances of the transmitting and receiving compensation networks, while M is the mutual inductance between the two coils, and R_o is the load resistance. Seawater is modeled as external circuits Z_{e1} and Z_{e2} with specific impedance characteristics, which are connected to the transmitting and receiving coils. These seawater equivalent circuits are composed of equivalent capacitances C_{e1} and C_{e2} , equivalent resistances R_{e1} and R_{e2} , and equivalent inductances L_{e1} and L_{e2} .

2.2 Equivalent model of system

When the output voltage of the inverter is in phase with its output current, the inverter can be modeled as a negative resistance $-R_N$ to supply energy to the system. The relationship between the equivalent resistance R_L and the load resistance R_o is given by $R_o = \pi^2 R_L / 8$. Consequently, the simplified equivalent schematic diagram can be obtained as illustrated in Fig. 3.

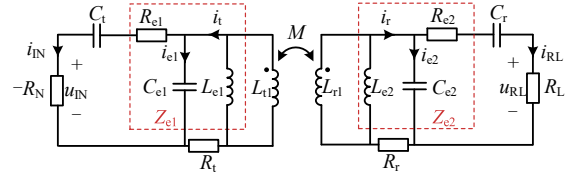


Fig. 3. Underwater cross coupling capacitor wireless power transfer system based on PT symmetry principle

The equivalent impedance of seawater alters the original impedance value of the magnetic coupler, thereby changing the inductance value of the coils to

$$\begin{cases} L_t = L_{t1} \square L_{e1} \\ L_r = L_{r1} \square L_{e2} \end{cases} \quad (1)$$

At this juncture, R_t and R_r represent the modified loss resistances of the transmitting and receiving coils after equivalent transformation, while i_t and i_r denote the currents flowing through the modified transmitting and receiving coils, respectively. i_{e1} and i_{e2} are the currents passing through the parallel capacitances, i_{IN} is the system input current, and i_{RL} is the current circulating through the load. Furthermore, u_{IN} and u_{RL} represent the system input voltage and output voltage, respectively.

To simplify the analysis, the wireless power transfer system only considers the fundamental components of voltage and current. Therefore, i_{IN} , i_{e1} , i_t , i_r , i_{e2} , i_{RL} , u_{IN} , and u_{RL} can be represented as phasors $\dot{I}_{IN}$, $\dot{I}_{e1}$, $\dot{I}_t$, $\dot{I}_r$, $\dot{I}_{e2}$, $\dot{I}_{RL}$, $\dot{U}_{IN}$, $\dot{U}_{RL}$. The circuit equations for the equivalent model of the PT-symmetric wireless power transfer system are formulated as shown in the Eq. (2). Compared to the conventional series-series wireless power transfer system, this topology introduces two additional passive components due to the underwater impedance model, which increases the system order. As observed from the Eq. (2), the model established using circuit theory is highly complex, making it difficult to derive the analytical expressions for the operating

frequency and the critical coupling coefficient. Consequently, characterizing the performance of the proposed system directly through this model remains a challenge.

$$\begin{cases} \left(-R_N - R_{e1} - j\frac{1}{\omega C_t}\right) \dot{I}_{IN} + j\frac{1}{\omega C_{e1}} \dot{I}_{e1} = 0 \\ -j\omega M \dot{I}_t + (R_t + j\omega L_t) \dot{I}_t + j\frac{1}{\omega C_{e1}} \dot{I}_{e1} = 0 \\ -j\omega M \dot{I}_t + (r_t + j\omega L_t) \dot{I}_t + j\frac{1}{\omega C_{e2}} \dot{I}_{e2} = 0 \\ \left(R_L + R_{e2} - j\frac{1}{\omega C_r}\right) \dot{I}_{RL} + j\frac{1}{\omega C_{e2}} \dot{I}_{e2} = 0 \end{cases} \quad (2)$$

To facilitate the analysis of the transmission characteristics of the PT symmetric wireless power transfer system based on the underwater impedance model, the equivalent impedance theory is utilized to transform the high order system into an equivalent low order system.

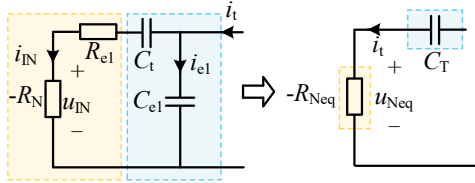


Fig. 4. Equivalent transformation of series-parallel compensation network on transmitter side

The series-parallel (SP) compensation network on the transmitting side can be transformed into an equivalent series compensation network as illustrated in Fig. 4, where the equivalent system parameters are expressed as

$$\begin{cases} C_T = \frac{(C_t + C_{e1})^2 + \omega^2 C_t^2 C_{e1}^2 (-R_N + R_{e1})^2}{(C_t + C_{e1}) + \omega^2 C_t^2 C_{e1}^2 (-R_N + R_{e1})^2} \\ -R_{Neq} = \frac{(-R_N + R_{e1}) C_t^2}{(C_t + C_{e1})^2 + \omega^2 C_t^2 C_{e1}^2 (-R_N + R_{e1})^2} \end{cases} \quad (3)$$

Based on the wireless power transfer system parameters, the following simplification conditions can be obtained as

$$\begin{cases} \omega^2 C_t^2 C_{e1}^2 (-R_N + R_{e1})^2 \ll C_t + C_{e1} \\ \omega^2 C_t^2 C_{e1}^2 (-R_N + R_{e1})^2 \ll (C_t + C_{e1})^2 \end{cases} \quad (4)$$

Neglecting the components $\omega^2 C_t^2 C_{e1}^2 (-R_N + R_{e1})^2$ and $\omega^2 C_t^2 C_{e1}^2 (-R_N + R_{e1})^2$, Eq. (3) can be simplified to

$$\begin{cases} C_T = C_t + C_{e1} \\ -R_{Neq} = \frac{(-R_N - R_{e1}) C_t^2}{(C_t + C_{e1})^2} \end{cases} \quad (5)$$

Define α as the capacitance allocation ratio of the series parallel combination of the seawater parasitic capacitance and the resonant capacitance on the transmitting side as

$$\begin{cases} C_t = \alpha C_T \\ C_{e1} = (1 - \alpha) C_T \end{cases} \quad (6)$$

The equivalent negative resistance can be expressed as

$$-R_{Neq} = (-R_N - R_{e1}) \alpha^2 \quad (7)$$

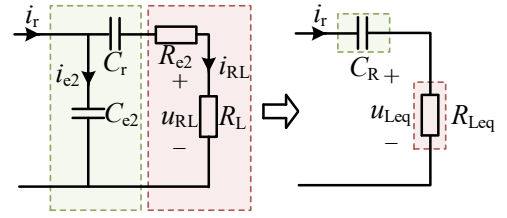


Fig. 5. Equivalent transformation of series-parallel compensation network on receiver side

The parallel-series (PS) compensation network on the receiving side can be transformed into an equivalent series compensation network as illustrated in Fig. 5, where the equivalent system parameters are expressed as

$$\begin{cases} C_R = \frac{(C_r + C_{e2})^2 + \omega^2 C_r^2 C_{e2}^2 R_L^2}{(C_r + C_{e2}) + \omega^2 C_r^2 C_{e2}^2 R_L^2} \\ R_{Leq} = \frac{R_L C_r^2}{(C_r + C_{e2})^2 + \omega^2 C_r^2 C_{e2}^2 R_L^2} \end{cases} \quad (8)$$

Based on the wireless power transfer system parameters, the following simplification conditions can be obtained as

$$\begin{cases} \omega^2 C_r^2 C_{e2}^2 R_L^2 \ll C_r + C_{e2} \\ \omega^2 C_r^2 C_{e2}^2 R_L^2 \ll (C_r + C_{e2})^2 \end{cases} \quad (9)$$

Neglecting the components $\omega^2 C_r^2 C_{e2}^2 R_L^2$ and $\omega^2 C_r^2 C_{e2}^2 R_L^2$, Eq. (8) can be simplified to

$$\begin{cases} C_R = C_r + C_{e2} \\ R_{Leq} = \frac{C_r^2 R_L}{(C_r + C_{e2})^2} \end{cases} \quad (10)$$

Which further leads to

$$\begin{cases} C_r = \beta C_R \\ C_{e2} = (1 - \beta) C_R \end{cases} \quad (11)$$

Where β represents the capacitance allocation ratio of the parallel series combination of the seawater parasitic capacitance and the resonant capacitance on the receiving side.

The equivalent load resistance can be expressed as

$$R_{Leq} = \beta^2 R_L \quad (12)$$

The equivalent circuit of the wireless power transfer system based on the PT symmetry principle is illustrated in Fig. 6.

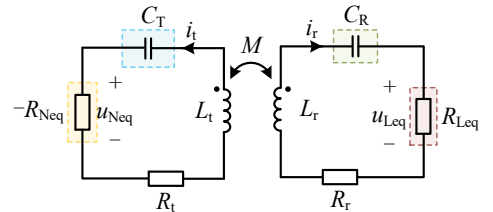


Fig. 6. Equivalent circuit of PT symmetry wireless power transfer system

According to circuit theory, the circuit equations of the equivalent PT system can be formulated as

$$\begin{cases} (-R_{Neq} + R_t) \dot{I}_t + j\left(\omega L_t - \frac{1}{\omega C_T}\right) \dot{I}_t + j\omega M \dot{I}_r = 0 \\ j\omega M \dot{I}_t + (R_{Leq} + R_r) \dot{I}_r + j\left(\omega L_r - \frac{1}{\omega C_R}\right) \dot{I}_r = 0 \end{cases} \quad (13)$$

Where ω represents the operating angular frequency,

$\omega_T = 1/\sqrt{L_T C_T}$ is the resonant angular frequency on the transmitting side, $\omega_R = 1/\sqrt{L_R C_R}$ is the resonant angular frequency on the receiving side, and $k = M/\sqrt{L_T L_R}$ denotes the coupling coefficient between the transmitting and receiving coils. Meanwhile, $\omega_T = \omega_R = \omega_0$ must be satisfied to meet the PT symmetry condition.

The matrix form expression of Eq. (13) can be written as

$$\begin{bmatrix} \frac{-R_{\text{Neq}} + R_t}{L_t} + j\left(\omega - \frac{\omega_0^2}{\omega}\right) & j\omega k \sqrt{\frac{L_t}{L_r}} \\ j\omega k \sqrt{\frac{L_r}{L_t}} & \frac{R_{\text{Leq}} + R_r}{L_r} + j\left(\omega - \frac{\omega_0^2}{\omega}\right) \end{bmatrix} \begin{bmatrix} i_t \\ i_r \end{bmatrix} = 0 \quad (14)$$

To obtain the stable solutions for the system operating angular frequency ω , the characteristic equation of Eq. (14) can be formulated as

$$\left[\frac{-R_{\text{Neq}} + R_t}{L_t} + j\left(\omega - \frac{\omega_0^2}{\omega}\right) \right] \left[\frac{R_{\text{Leq}} + R_r}{L_r} + j\left(\omega - \frac{\omega_0^2}{\omega}\right) \right] - j\omega k \sqrt{\frac{L_t}{L_r}} j\omega k \sqrt{\frac{L_r}{L_t}} = 0 \quad (15)$$

Separating the real and imaginary parts of Eq. (15) yields

$$\left(\omega - \frac{\omega_0^2}{\omega} \right) \left(\frac{R_{\text{Leq}} + R_r}{L_r} + \frac{-R_{\text{Neq}} + R_t}{L_t} \right) = 0 \quad (16)$$

$$\left(\frac{-R_{\text{Neq}} + R_t}{L_t} \right) \left(\frac{R_{\text{Leq}} + R_r}{L_r} \right) - \left(\omega - \frac{\omega_0^2}{\omega} \right)^2 + \omega^2 k^2 = 0 \quad (17)$$

Solving Eq. (16) and (17) simultaneously yields the system operating angular frequency as

$$\omega = \begin{cases} \omega_0, k < k_c \\ \omega_{1,2} = \omega_0 \sqrt{\frac{(Q_{\text{Req}}^{-2} - 2) \pm \sqrt{(Q_{\text{Req}}^{-2} - 2)^2 + 4(k^2 - 1)}}{2(k^2 - 1)}}, k_c \leq k \leq 1 \end{cases} \quad (18)$$

Where $Q_{\text{Req}} = \frac{\omega_0 L_r}{R_{\text{Leq}} + R_r}$ represents the quality factor of the resonant network on the receiving side, and $k_c = Q_{\text{Req}}^{-1} \sqrt{1 - \frac{1}{4} Q_{\text{Req}}^{-2}}$ denotes the critical coupling coefficient. The expression of k_c can be obtained as

$$k_c = \frac{\beta^2 R_L + R_t}{\omega_0 L_r} \sqrt{1 - \frac{1}{4} \left(\frac{\beta^2 R_L + R_t}{\omega_0 L_r} \right)^2} \quad (19)$$

As observed from the system operating angular frequency, the critical coupling coefficient divides the operating region of the system into two distinct parts, namely the PT symmetric state where $k_c \leq k \leq 1$ and the PT broken state where $k < k_c$.

2.3. Characteristic analysis of strong coupling region

When the system operates in the PT symmetric state or the strong coupling region, the coupling coefficient k must satisfy the constraint condition where $k_c \leq k \leq 1$ to ensure that the operating angular frequency ω is a pure real number. Under this condition, the operating frequency of the system

is expressed as

$$f_{1,2} = f_0 \sqrt{\frac{(Q_{\text{Req}}^{-2} - 2) \pm \sqrt{(Q_{\text{Req}}^{-2} - 2)^2 + 4(k^2 - 1)}}{2(k^2 - 1)}} \quad (20)$$

When the system operating angular frequency $\omega \neq \omega_0$, Eq. (16) yields

$$\frac{R_{\text{Leq}} + R_r}{L_r} + \frac{-R_{\text{Neq}} + R_t}{L_t} = 0 \quad (21)$$

The magnitude of the equivalent negative resistance can be derived as

$$R_{\text{Neq}} = \frac{L_t}{L_r} (R_{\text{Leq}} + R_t) + R_r \quad (22)$$

The magnitude of the negative resistance can be expressed as

$$R_N = \frac{1}{\alpha^2} \frac{L_t}{L_r} (\beta^2 R_{\text{Leq}} + R_t) + R_r - R_{e1} \quad (23)$$

Substituting Eq. (17) and (21) into Eq. (23) yields the ratio of the currents flowing through the receiving coil and the transmitting coil as

$$\frac{I_R}{I_T} = \left| \frac{i_r}{i_t} \right| = \sqrt{\frac{L_t}{L_r}} \quad (24)$$

The ratio of the load current to the input current can be obtained as

$$\frac{I_{\text{RL}}}{I_{\text{IN}}} = \frac{\beta}{\alpha} \frac{I_R}{I_T} = \frac{\beta}{\alpha} \sqrt{\frac{L_t}{L_r}} \quad (25)$$

The ratio of the output voltage to the input voltage can be obtained as

$$\frac{U_{\text{RL}}}{U_{\text{IN}}} = \frac{I_{\text{RL}} R_L}{I_{\text{IN}} R_N} = \sqrt{\frac{L_t}{L_r}} \frac{\alpha \beta R_L}{L_t (\beta^2 R_L + R_t) + R_t} \quad (26)$$

Through derivation, the output power and transmission efficiency of the system can be expressed as

$$P_O = \frac{U_{\text{RL}}^2}{R_L} = \frac{\alpha^2 \beta^2 R_L U_{\text{IN}}^2}{\frac{L_t}{L_r} (\beta^2 R_L + R_t)^2 + 2R_t (\beta^2 R_L + R_t) + \frac{L_t}{L_r} R_t^2} \quad (27)$$

$$\eta = \frac{I_{\text{RL}}^2 R_L}{I_T^2 R_t + I_R^2 R_r + I_{\text{RL}}^2 R_L} = \frac{\beta^2 R_L}{\beta^2 R_L + R_t + \frac{L_t}{L_r} R_t} \quad (28)$$

As indicated by Eq. (27) and (28), the expressions of the output power and transmission efficiency are merely related to the inherent parameters of the coupling mechanism, the capacitance allocation ratio, and the load resistance. When the wireless power transfer system parameters are fixed and the system operates in the PT symmetric region, both the output power and transmission efficiency will remain constant, independent of the coupling coefficient.

2.4 Characteristic analysis of weak coupling region

When the coupling coefficient k between the transmitting and receiving coils satisfies the condition where $k < k_c$, the PT symmetry of the system is broken, entering the PT broken state or the weak coupling region. Under this circumstance, the operating frequency will automatically track the resonant frequency f_0 , and the magnitudes of both the equivalent negative resistance and the negative resistance can be

derived from Eq. (17) as

$$R_{\text{Neq}} = \frac{k^2 \omega_0^2 L_t L_r}{\beta^2 R_{L\text{eq}} + R_r} + R_t \quad (29)$$

$$R_N = \frac{k^2 \omega_0^2 L_t L_r}{\alpha^2 \beta^2 R_{L\text{eq}} + \alpha^2 R_r} + \frac{R_t}{\alpha^2} \quad (30)$$

According to Eq. (13), the ratio of the coil currents flowing through the receiving side and the transmitting side can be obtained as

$$\frac{I_R}{I_T} = \left| \frac{\dot{I}_R}{\dot{I}_T} \right| = \frac{\omega_0 k \sqrt{L_t L_r}}{\beta^2 R_L + R_r} \quad (31)$$

The ratio of the load current to the input current can be obtained as

$$\frac{I_{RL}}{I_{IN}} = \frac{\beta I_R}{\alpha I_T} = \frac{\beta \omega_0 k \sqrt{L_t L_r}}{\alpha \beta^2 R_L + \alpha R_r} \quad (32)$$

Utilizing Eq. (30) and (32), the ratio of the output voltage to the input voltage can be expressed as

$$\frac{U_{RL}}{U_{IN}} = \frac{I_{RL} R_L}{I_{IN} R_N} = \frac{\alpha \beta R_L \omega_0 k \sqrt{L_t L_r}}{k^2 \omega_0^2 L_t L_r + R_t (\beta^2 R_L + R_r)} \quad (33)$$

The transmission power and transmission efficiency of the system can be derived as

$$P_O = \frac{U_{RL}^2}{R_L} = \frac{\alpha^2 \beta^2 R_L U_{IN}^2 \omega_0^2 k^2 L_t L_r}{[k^2 \omega_0^2 L_t L_r + R_t (\beta^2 R_L + R_r)]^2} \quad (34)$$

$$\eta = \frac{I_{RL}^2 R_L}{I_T^2 R_t + I_R^2 R_r + I_{RL}^2 R_L} = \frac{\beta^2 R_L \omega_0^2 k^2 L_t L_r}{R_t (\beta^2 R_L + R_r)^2 + (\beta^2 R_L + R_r) \omega_0^2 k^2 L_t L_r} \quad (35)$$

As indicated by Eq. (34) and (35), the expressions of the output power and transmission efficiency simultaneously contain the inherent parameters of the system and the coupling coefficient. When the system operates in the PT broken region, both the output power and transmission efficiency will vary with the change of the coil transmission distance. Therefore, the PT symmetry system should widen the symmetric operating interval as much as possible to avoid the PT broken operating state.

2.5 Analysis of system transmission characteristics

The transmission characteristics of the system are

TABLE II

PERFORMANCE COMPARISON OF PT SYMMETRY WIRELESS POWER TRANSFER SYSTEM BETWEEN AIR AND SEAWATER

Symbol	Air	Seawater
f	$f_0 \sqrt{\frac{(Q_R^2 - 2) \pm \sqrt{(2 - Q_R^2)^2 + 4(k^2 - 1)}}{2(k^2 - 1)}}$	$f_0 \sqrt{\frac{(Q_{\text{Req}}^2 - 2) \pm \sqrt{(2 - Q_{\text{Req}}^2)^2 + 4(k^2 - 1)}}{2(k^2 - 1)}}$
k_c	$\frac{R_L + R_r}{\omega_0 L_r} \sqrt{1 - \frac{1}{4} \left(\frac{R_L + R_r}{\omega_0 L_r} \right)^2}$	$\frac{\beta^2 R_L + R_r}{\omega_0 L_r} \sqrt{1 - \frac{1}{4} \left(\frac{\beta^2 R_L + R_r}{\omega_0 L_r} \right)^2}$
P_O	$\frac{R_L U_{IN}^2}{\frac{L_t}{L_r} (R_L + R_r)^2 + 2R_t (R_L + R_r) + \frac{L_r}{L_t} R_t^2}$	$\frac{\alpha^2 \beta^2 R_L U_{IN}^2}{\frac{L_t}{L_r} (\beta^2 R_L + R_r)^2 + 2R_t (\beta^2 R_L + R_r) + \frac{L_r}{L_t} R_t^2}$
η	$\frac{R_L}{R_L + R_r + \frac{L_r}{L_t} R_t}$	$\frac{\beta^2 R_L}{\beta^2 R_L + R_r + \frac{L_r}{L_t} R_t}$

analyzed below using the parameters listed in Table III.

Fig. 7 presents the frequency bifurcation diagram of the system during operation. Different values of β correspond to different critical coupling coefficients k_c . Specifically, k_c decreases as β decreases, so reducing β can significantly extend the PT symmetric region of the PT symmetry wireless power transfer system. Meanwhile, two stable frequency solutions exist within the PT symmetric regions corresponding to different values of β . When the system operates in the strong coupling region, the system will automatically select either the high frequency or the low frequency to operate stably.

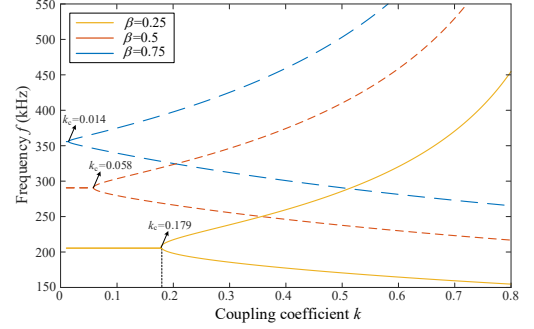


Fig. 7. Operating frequency bifurcation curves of system in PT symmetric region

As observed from Fig. 8, the output power remains constant within the PT symmetric regions corresponding to different capacitance allocation ratios, and the objective of increasing the system output power can be achieved by reducing β .

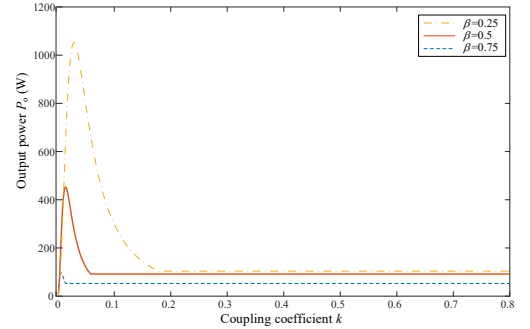


Fig. 8. Wireless power transfer system output power curves under different values of β

As indicated by the Eq. (28), the expression of the system transmission efficiency is related to β , so increasing the output power and extending the PT symmetric region by reducing β will simultaneously exert a certain impact on the transmission efficiency. The transmission efficiency curves under different values of β are illustrated in Fig. 9, which shows that the transmission efficiency gradually decreases as β decreases.

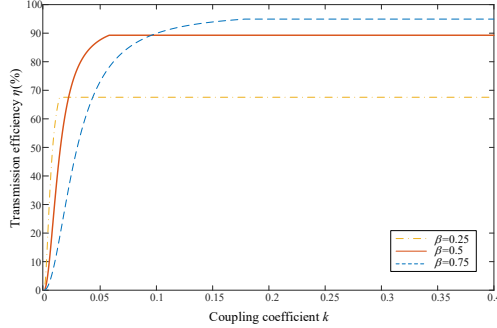


Fig. 9. Wireless power transfer system transmission efficiency curves under different values of β

According to the above analysis, the capacitance allocation ratio affects the transmission characteristics of the system. C_r is related to the output power, the PT symmetric region, and the transmission efficiency. As C_r decreases, the transmission power and the PT symmetric region continuously increase, while the transmission efficiency continuously decreases as shown in Fig. 10.

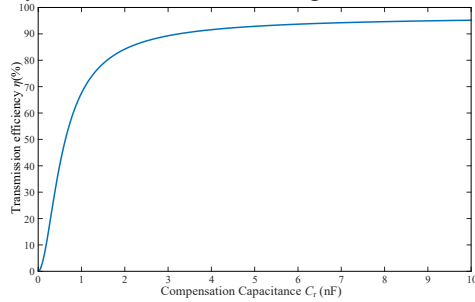


Fig. 10. Transmission efficiency curve as a function of capacitance allocation ratio

2.6 Comparative analysis between air and seawater media

Based on the PT symmetry principle, this paper compares and analyzes the characteristics of the wireless power transfer systems in air and seawater. When both systems operate within the PT symmetric interval, the expressions of the operating frequency f , the critical coupling coefficient k_c , the output power P_o , and the transmission efficiency η are listed in Table II.

As indicated by the table, the expressions of the output power and transmission efficiency in both air and seawater are independent of the coupling coefficient k_c , demonstrating that both types of systems can maintain stable output power and transmission efficiency when the coil distance varies within the strong coupling interval.

As illustrated in Fig. 11, the critical coupling coefficients k_c of the air and seawater systems are 0.2020 and 0.1025 respectively, and both systems exhibit the frequency splitting phenomenon in the strong coupling region where $k > k_c$. Due to the decrease in the equivalent quality factor, the seawater system features a lower critical coupling point and a broader PT symmetric interval.

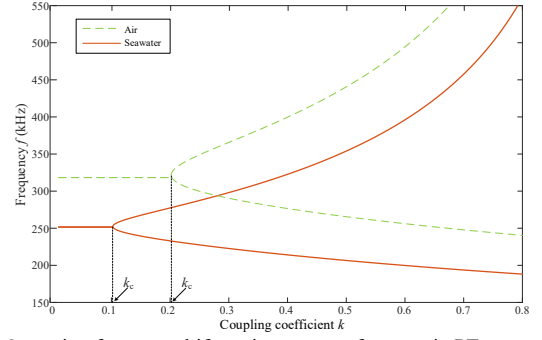


Fig. 11. Operating frequency bifurcation curves of system in PT symmetric region under air and seawater media

Fig. 12 illustrates the variation characteristics of the WPT system output power with the coupling coefficient k under air and seawater media. In the weak coupling region where $k < k_c$, the output power in both media rises rapidly as k increases and reaches the peak value near their respective critical coupling points, where the power peak in air is significantly higher than that in the seawater medium. Upon entering the PT symmetric strong coupling region where $k > k_c$, the output power of both types of systems tends to stabilize, and the values are independent of the coupling coefficient. The eddy current loss of the seawater medium reduces the power peak, and the overall power level is lower than that in the air environment.

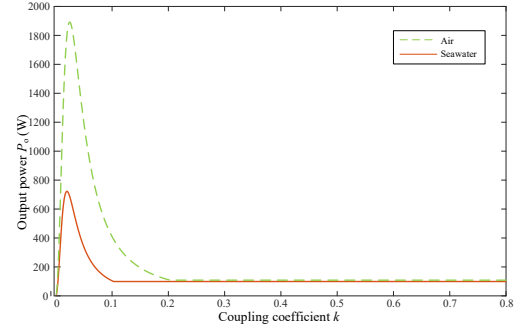


Fig. 12. System output power curves under air and seawater media

Fig. 13 illustrates the variation characteristics of the transmission efficiency with the coupling coefficient k for the wireless power transfer system based on the PT symmetry principle under air and seawater media. When $k < k_c$, the transmission efficiency in both media rises rapidly as the coupling coefficient increases, and the curve trends are similar. When $k > k_c$, the efficiency tends to stabilize, and the values are independent of the coupling coefficient. The transmission efficiency in air is slightly higher than that in the seawater medium.

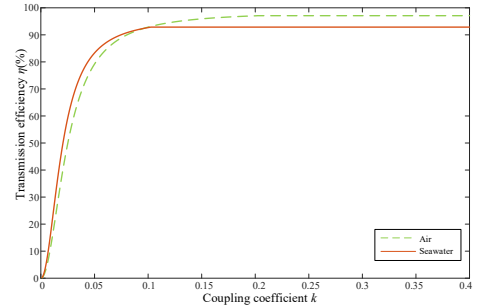


Fig. 13. Transmission efficiency curves under air and seawater media

3 System design

3.1 Negative resistance design

The current is detected at the inverter output terminal to generate driving signals and control the turn off of the switching tubes, thereby keeping the inverter output voltage in phase with the output current. Consequently, the inverter can be equivalent to a negative resistance. As illustrated in Fig. 14, the output current i_{IN} of the full bridge inverter is sampled, and the sampled current signal is compared with the zero level to generate the switching tube driving signals based on the comparison result. When the sampled current $i_{IN} > 0$, the switching tubes $S_{1,4}$ are controlled to conduct, causing the loop to generate a forward voltage. When the sampled current $i_{IN} < 0$, the switching tubes $S_{2,3}$ are controlled to conduct to generate a reverse voltage. By adopting the aforementioned control strategy, the inverter output voltage u_{IN} and output current i_{IN} can always remain in phase under the nonassociated reference direction, achieving the equivalent negative resistance.

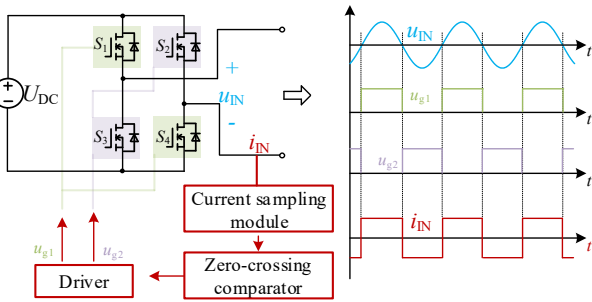


Fig. 14. Negative resistance based on full bridge inverter

3.2 System parameter design

Fig. 15 presents the parameter design flowchart of the symmetrical underwater wireless power transfer system in this paper. During the design, the primary inductance L_{t1} and the secondary inductance L_{r1} are first determined by combining the DD coil structure form and the hull installation dimensions of different types of AUVs. Then, the lower limit of the coupling coefficient k_{min} is determined based on the specific requirements of the system misalignment and transmission characteristics. Subsequently, the critical coupling coefficient k_c is checked. When $k_c \geq k_{min}$, the coefficient β is modified according to Eq. (19), and the critical coupling parameters are iteratively updated until the constraint condition where $k_c < k_{min}$ is satisfied. On this basis, Eq. (6) and Eq. (11) are solved simultaneously to synchronously obtain the primary and secondary symmetrical compensation capacitances C_i , C_r , completing the preliminary finalized design of the system theoretical parameters.

To counteract the impacts brought by the seawater medium parameters, seawater prototype experiments are further conducted to measure the seawater equivalent impedances Z_{e1} , Z_{e2} . Relying on the measured impedance data, the critical coupling condition is checked again. If the check fails to meet the requirement where $k_c < k_{min}$, the parameters are optimized through back substitution by adjusting the coefficient β . Once the critical coupling index meets the standard, the entire parameter design is completed.

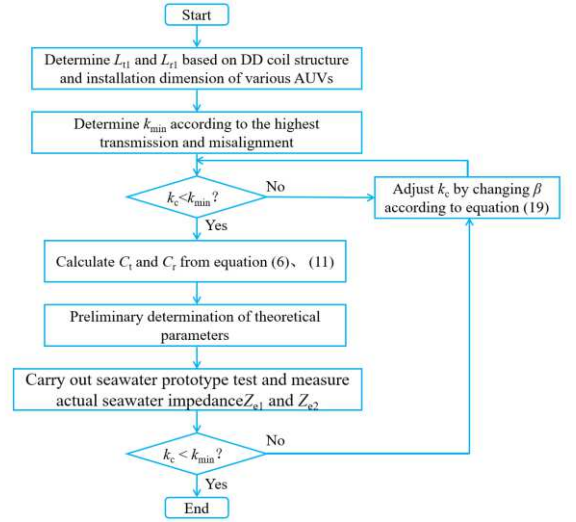


Fig. 15. System parameter design process

4 Experimental verification

To verify the theoretical analysis, an experimental prototype of the AUVs power transfer system based on the SS topology was built as illustrated in Fig. 16. The direct current voltage of the system is provided by the KXN 6030D direct current power supply. The differential sampling circuit is composed of the operational amplifier with the model of LMH6628, and the model of the comparator that compares with the amplified signal is TL3016. The driving chip model that processes the comparator output signal is SI8271, the MOSFET model is IRF3710PBF, and the diode model adopted by the rectifier is SBR40U100CT. Seawater used in the experiment was collected from coastal waters of Qingdao. The seawater boundary conditions used in this model are established based on published in-situ buoy observations at the Xiaomaidao site (120.44°E, 36.05°N). The mean surface salinity of 30.4 (Practical Salinity Scale, PSS-78), measured during July 1–25, 2024, is selected as the representative summer seawater condition for the proposed model.

In this paper, the DC-DC power transfer efficiency is defined as the ratio of the DC output power at the receiver-side load to the DC input power supplied by the input power source. It includes the losses in the inverter, compensation network, wireless power transfer coils, and rectifier, representing the overall efficiency of the complete wireless power transfer system from the DC input terminal to the DC output terminal.

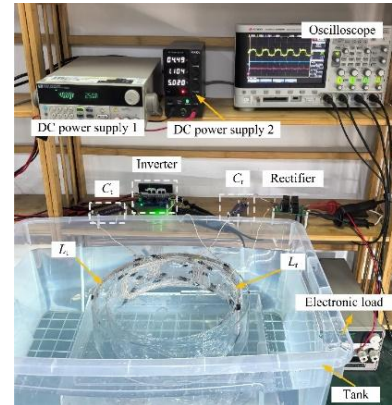


Fig. 16. Experimental prototype diagram

In this section, a design example for underwater wireless power transfer is presented. The specific indicators are as follows. In the wireless power transfer system for AUVs

proposed in this paper, the following four types of misalignment exist.

- 1) The misalignment between coils along the z axis direction.
- 2) The angular misalignment between coils when the z axis misalignment distance is 0 mm.
- 3) The angular misalignment between coils when the z axis misalignment distance is +50 mm.
- 4) The angular misalignment between coils when the z axis misalignment distance is -50 mm.

Due to the structural configuration of the experimental prototype, the transmitter and receiver coils are designed with diameters of 350 mm and 300 mm, respectively. The relatively large overlapping area between the two coils ensures sufficient magnetic coupling under the practical operating conditions. Therefore, the lateral misalignment along the x - y plane is not considered in this experiment, and the misalignment tests mainly focus on the axial displacement along the z -axis and angular deflections, which are more representative of the disturbances caused by underwater AUV motion.

TABLE III
MAIN PARAMETERS OF SYSTEM PROTOTYPE

Symbol	Parameter	Value
U_{DC}	Input DC voltage	48 V
L_t	The inductance of the transmitter coil	49.29 μ H
L_r	The inductance of the receiver coil	49.84 μ H
C_t	The primary compensation capacitance	5 nF
C_r	The secondary compensation capacitance	5 nF
R_t	Parasitic resistance in transmitter coil	0.19 Ω
R_r	Parasitic resistance in receiver coil	0.205 Ω
R_o	Output resistance	20 Ω

First is the first type of misalignment when the distance along the z axis direction changes. The experimental waveforms of the system proposed in this paper under different misalignment distances are illustrated in Fig. 17, where the output voltage and output current of the inverter are in phase. Furthermore, as the transmission distance varies, the operating frequency of the system changes accordingly to ensure that the output characteristics within the strong coupling region remain basically unchanged.

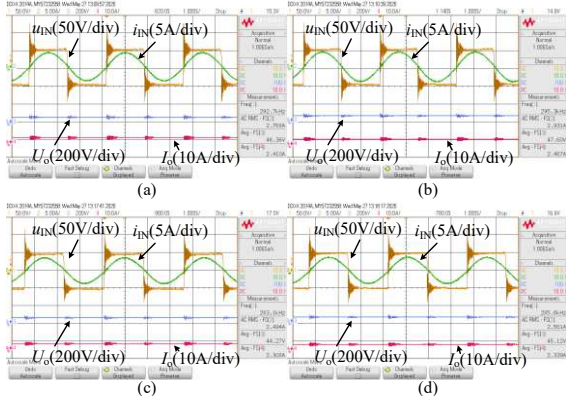


Fig. 17. Experimental waveforms of misalignment along z axis direction
a) air 0mm b) air 40mm c) seawater 0mm d) seawater 40mm

Fig. 18 presents the variation of the transmission efficiency under this circumstance. When completely aligned, the transmission efficiency of the system in air is 91.05%, and that in seawater is 90.86%. Within the range from -80mm to 80mm, the transmission efficiency of the system remains basically unchanged. The maximum fluctuation in air reaches 90.09% with a fluctuation amount of 1.05%, while the maximum fluctuation in seawater reaches 90.12% with a fluctuation amount of 0.82%.

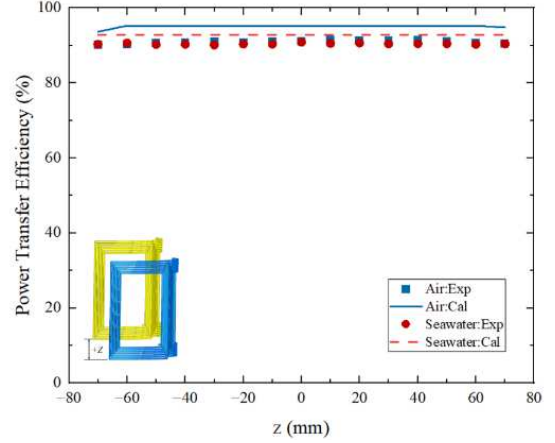


Fig. 18. Transmission efficiency under different transmission distances along z axis

Fig. 19 illustrates the experimentally measured output power as a function of the transmission distance along the z axis. The power at the center position in air is 107.51 W, and as the axial misalignment increases, the power remains stable in stages and then gradually increases, where the experimental values achieve good agreement with the theoretical values. The power at the center position in seawater is 98.57 W, and as the axial misalignment increases, the output power remains nearly constant in the PT symmetric region, while a slight variation appears near the boundary of the weak coupling region, where the experimental values achieve good agreement with the theoretical values.

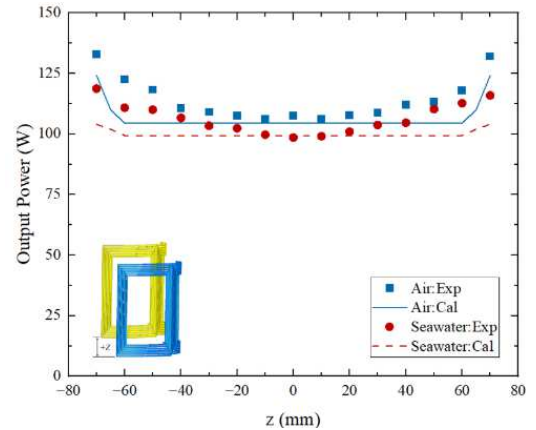


Fig. 19. Output power under different transmission distances along z axis

The second type is the angular misalignment between coils. Due to the inherent characteristics of the AUVs, an excessively large deflection angle is meaningless for practical situations, so several cases with the deflection angle between -30° and 30° are tested. The experimental waveforms are illustrated in Fig. 20.

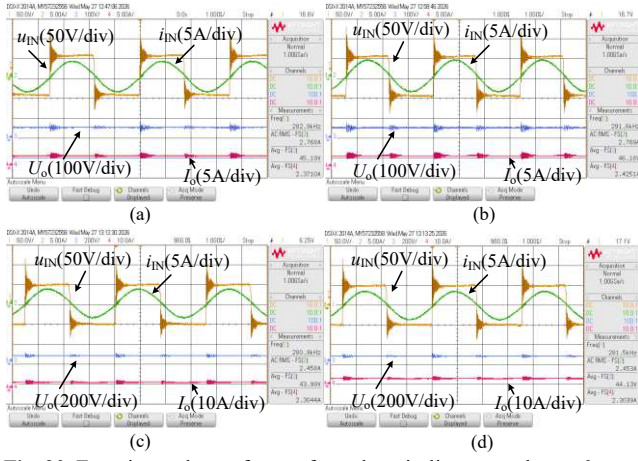


Fig. 20. Experimental waveforms of angular misalignment when $z=0\text{mm}$
a) air 0° b) air 20° c) seawater 0° d) seawater 20°

Fig. 21 and Fig. 22 present the transmission efficiency and output power under different deflection angles in both air and seawater media when $z=0\text{mm}$. It can be observed that the output characteristics of the system can remain basically stable in both media, and the experimental values achieve good agreement with the theoretical values.

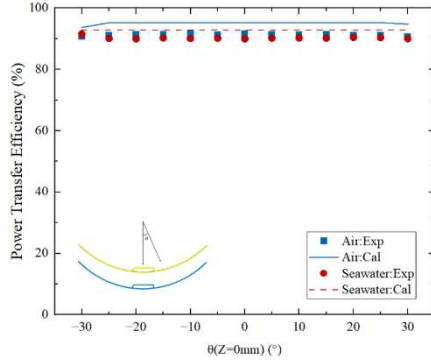


Fig. 21. Variation of transmission efficiency with angular misalignment when $z=0\text{mm}$

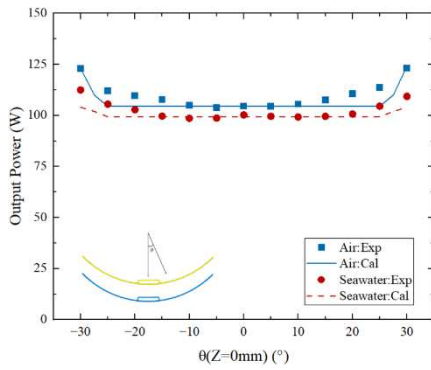


Fig. 22. Variation of output power with angular misalignment when $z=0\text{mm}$

The third and fourth cases are the situations where the deflection angle between -20° and 20° is tested when the z axis misalignment distances are $+50\text{mm}$ and -50mm respectively. The experimental waveforms are illustrated in Fig. 23.

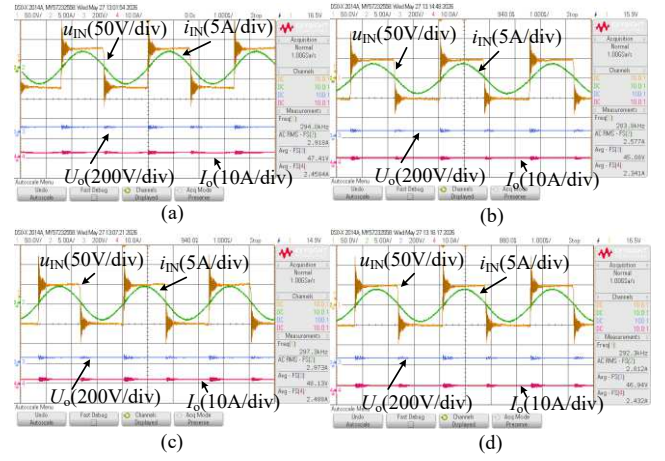


Fig. 23. Output characteristics under angular misalignment a) air 0° ($z=+50\text{mm}$) b) seawater 0° ($z=+50\text{mm}$) c) air 0° ($z=-50\text{mm}$) d) seawater 0° ($z=-50\text{mm}$)

As illustrated in Fig. 24, the output characteristic diagrams with the deflection angle between -20° and 20° under different z axis misalignment conditions are presented. In terms of transmission efficiency, the system efficiency is insensitive to the angular misalignment of $\pm 20^\circ$ in both air and seawater media. The efficiency stabilizes at approximately 92% in air and approximately 90% in seawater, and the theoretical calculations achieve good agreement with the experimental results. In terms of output power, the power level in air is higher than that in seawater, and both experimental results agree well with the theoretical curves. The slight power variation at large angular deflections is attributed to the decrease in coupling coefficient and the approach to the PT broken region. The power curves under the positive and negative axial misalignment positions are symmetrical, demonstrating that the system possesses excellent robustness against angular misalignment.

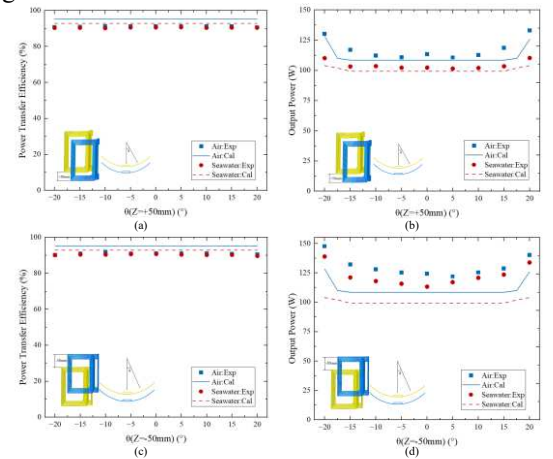


Fig. 24. Output characteristics under angular misalignment a) transmission efficiency 0° ($z=+50\text{mm}$) b) output power 0° ($z=+50\text{mm}$) c) transmission efficiency 0° ($z=-50\text{mm}$) d) output power 0° ($z=-50\text{mm}$)

5 Conclusion

Based on the underwater impedance model, this paper constructs the PT symmetry AUVs wireless power transfer equivalent circuit, and completes the system design and characteristic analysis in combination with DD coupling coils. Relied upon its inherent PT symmetry mechanism, the proposed topology significantly enhances the anti misalignment performance under axial deflection and multi angle tilt working conditions, effectively resisting the AUVs

power transfer misalignment caused by ocean current disturbances. This scheme requires no additional auxiliary control and wireless communication hardware, and can maintain stable power transfer under multi dimensional misalignment conditions by relying solely on the inherent topological characteristic of the inverter equivalent negative resistance.

Verified by prototype experiments in both air and seawater environments, the power transfer efficiency on the air side stabilizes at approximately 91.05% and that on the seawater side stabilizes at approximately 90.86% within the entire axial $\pm 80\text{mm}$ misalignment interval. The maximum efficiency fluctuation in air is only 1.05%, and that in seawater is as low as 0.82%. Under the rated alignment working condition, the output power is 107.51W in air and 98.57W in seawater, and the power can still remain stable after a wide range of axial misalignment. At two axial positions of z equals 0mm and plus or minus 50mm, during the coil $\pm 30^\circ$ and $\pm 20^\circ$ angular deflection tests, the power and efficiency curves in both air and seawater environments change smoothly. The efficiency in the seawater environment stabilizes at around 90%, and that in the air environment is maintained at around 92%, showing that the theoretical simulations and experimental data achieve good agreement. In conclusion, this underwater wireless power transfer system possesses excellent axial and angular anti-misalignment capabilities, adapts to complex seawater working conditions, and can meet the engineering application requirements for routine AUVs autonomous wireless power replenishment at seabed base stations.

Declarations

Competing interests The authors declare that they have no competing interests.

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