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Wireless Power Transmission System Based on Parity Time Symmetry for AUV

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Abstract—One of the main challenges in the application of wireless power transmission systems is to achieve stable power transmission and constant transmission power under dynamically changing coupling conditions. A parity-time symmetric model for AUV (autonomous underwater robot) is proposed. Based on the coupling mode theory, the robustness of the parity-time symmetric wireless transmission system is investigated. The theoretical analysis shows that the AUV wireless power transmission system based on parity time symmetry can automatically obtain constant output power and constant transmission efficiency when the coupling coefficient is varied. Based on this theory, the experimental prototype was built by simulating the effects of relevant parameters using LTspice. And the experiments were conducted in air medium and seawater medium, respectively. The experimental results show that under the condition of parity time symmetry, the underwater wireless energy transmission voltage ratio is close to 1, and the transmission efficiency reaches 15%, in the range of 12.5 cm. The theoretical derivation has been verified.

1. INTRODUCTION

Wireless Power Transmission technology has been developed for more than 100 years since its birth, and people are increasingly aware of its importance. The current research on wireless power transmission technology mainly focuses on the following aspects: First, its implementation, mainly electromagnetic induction type, magnetic coupling resonance type, and ultrasonic type, etc., which have their own advantages according to the different applications of these methods; second, the transmission effect, including the transmission efficiency and transmission power of the system, must solve the problem of system loss and efficiency degradation caused by changes in transmission distance; Third, the study of the principle of wireless power transmission, scientists have modeled the wireless power transmission system in various ways, including the mutual inductive circuit model and coupled mode energy method model, and to improve efficiency by studying its transmission mechanism.

In recent years, the stability of wireless power transfer (WPT) systems has been challenged with the popularity of underwater electronic devices, which puts great demands on the changing conditions of wireless charging coupling. Wireless power transfer of AUV (Autonomous Underwater Vehicles) is one of the typical examples of underwater WPT system applications. The schematic diagram is shown in Figure 1, and the charging of AUVs faces problems such as corrosion of electronics by seawater due to battery disassembly into the water and cumbersome charging process. Compared with the traditional method, the AUV can largely improve its working time and efficiency by completing charging underwater. Since the transmitter and receiver of the non-contact charging system do not come into direct contact with each other when transmitting electrical energy, but transmit the electrical energy from the transmitter to the receiver through the coupling effect of magnetic field, the safety of the system is high, and there is basically no danger of leakage and friction. The transmitter and

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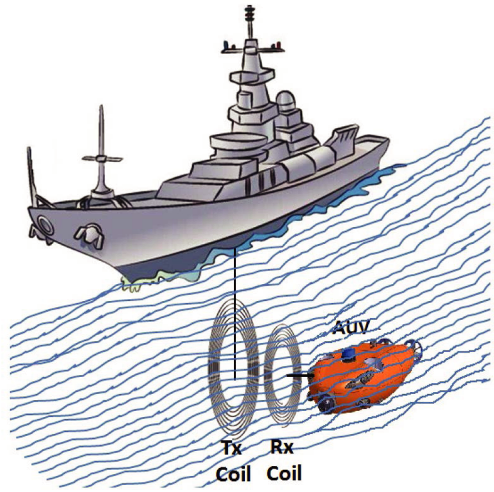

Figure 1. Wireless charging system of AUV [1].

receiver circuits can be simply encapsulated to make the system waterproof, which makes wireless charging popular among many researchers [2]. The seawater with $1 \sim 6\,\text{S/m}$ conductivity has higher conductivity than the air with $0\,\text{S/m}$ conductivity. The high-frequency alternating current in the coil placed in seawater will generate a high-frequency alternating magnetic field, and the resulting high-frequency alternating magnetic field will generate an eddy electric field, and the eddy current generated by the eddy electric field will bring a relatively large eddy current loss, resulting in a decrease in the transmission efficiency and power of the system compared to the transmission efficiency and power in air. Due to the "piezomagnetic effect" generated by the water pressure in the deep sea, the permeability of the ferrite will decrease, so the parameters of the system will change abruptly and make the coupling performance worse; in addition, under the impact of seawater, the axis of the magnetic core will be shifted to a certain extent, which will lead to changes in the coupling performance of the system, and the stability of the system will decrease.

The magnetically coupled resonant radio energy transmission used in this paper is a strong coupling method of near magnetic field, which can transmit electrical energy in the whole near field range, with the near field distance of $c/(2\pi f)$, c and f being the speed of light and resonant frequency, respectively, and when the transmitting system and receiving system are in a strong coupling state with the same vibration frequency, the energy transmission loss and the loss of the vibrating body itself become very small, and the energy transmission of the resonant body efficiency will be greatly improved [3]. By resonating the transmitting coil and receiving coil at the same frequency, one transmitting coil can power multiple receiving coils, and at the same time, magnetically coupled resonance can overcome the influence of some mental obstacles and non-magnetic materials to achieve non-directional transmission, which is a major advantage of magnetically coupled resonance and expands its application range. Magnetically coupled resonant wireless power transmission has high requirements for environmental stability [4]. Due to the change in environment, once the resonance point is shifted, the transmission efficiency will drop sharply, which is an important factor limiting the underwater transmission of magnetically coupled resonant wireless energy [5].

Wireless power transmission by AUVs brings additional challenges to the design of MCR-WPT (Magnetically coupled radio Wireless Power Transmission). AUV usually operates under harsh environmental conditions, thus leading to low transmission power and system efficiency, and circuit fixed operation parameters [6–9] are difficult to regulate. In the literature [10, 11], the system efficiency is unaffected by load variations without any feedback control, and a class E inverter is proposed to regulate the current in the transmitter, but the transmission power and transmission efficiency still fluctuate when the coupling conditions change. By introducing the concept of parity time (PT) symmetry from quantum physics, Assawaworrarit et al. proposed a strongly robust method for wireless power transmission that provides ideas to overcome these problems [12]. When the dynamic model of the WPT system is invariant under joint parity and time reversal transformations (satisfying the PT symmetry condition), the energy stored in the transmitting and receiving resonators will remain equal in the exact PT symmetry region, usually leading to a constant transmission efficiency [13]. In this general model, the nonlinear saturable gain depends only on the energy stored in the transmit resonator and is essential for automatically tracking the PT symmetry condition [14]. The precise PT symmetry region corresponds to a strongly coupled region where the eigenvalues of the PT symmetry model are purely imaginary [15]. Varying within the strongly coupled region, the transmission efficiency remains close to unity without any tuning. This is in contrast to conventional methods, which can only maintain high transmission efficiency by constantly adjusting the frequency or internal coupling parameters, as the transmission distance or the relative orientation of the source and receiver units is varied.

In this paper, we design a parity time transmission model for AUV based on the existing theory of PT symmetry. Firstly, we model the underwater charging process and analyze the feasibility of underwater wireless transmission by coupled mode theory. Then we simulate the magnetic field of the transceiver coil by COMSOL. After that we simulate the transmission model to verify the feasibility of the theory, and finally, we build the transmission system model and conduct experiments respectively in air, freshwater, and seawater media to further analyze the robustness of the underwater transmission state.

2. OVERVIEW OF MAGNETICALLY COUPLED RESONANT WPT AND PT MODEL

The basic framework of the magnetically coupled resonant wireless transmission system (MCR-WPT) is shown in Figure 2. It is generally composed of the following parts: high frequency inverter section, transmitter side, receiver side, compensation network, and load. The coupling of the magnetic field between the primary and secondary coils allows the load side to generate electrical energy. 20 kHz to 200 kHz high-frequency alternating current can generate an alternating magnetic field in the primary coil, and the high-frequency alternating current in the secondary coil is generated because the secondary coil generates a corresponding alternating magnetic field under the action of the primary coil. The received high-frequency alternating current is transformed into direct current by the corresponding rectification circuit and sent to the load. A compensation network is added to reduce the losses due to the leakage inductance caused by the large gap between the primary and secondary coils. The development of magnetically coupled resonant wireless transmission technology still needs to be further explored and studied, and the technology is most widely used in the field of wireless power transmission. In order to better describe the robustness of the WPT system, the concept of robustness coefficient is introduced, and in an ideal state, the robustness coefficient is defined as Equation (1):

$$r_{\text{WPT}} = \frac{d\left(\dfrac{u_2}{u_1}\right)}{dl} \tag{1}$$

where u_1 is the inductive side voltage of the transmitting coil, u_2 the inductive voltage of the receiving coil, and l the distance between the transmitting and receiving coils. Since u_1 is the primary side voltage and is a constant value, Equation (2) can be simplified as follows:

$$r_{\text{WPT}} = \frac{1}{U_1}\frac{du_2}{dl} \tag{2}$$

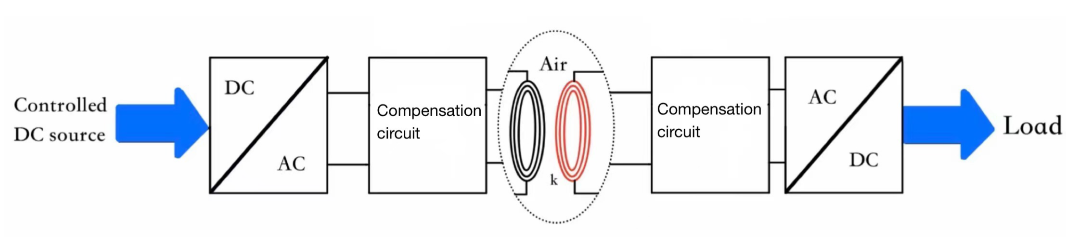

Figure 2. Magnetic coupling resonant wireless power transmission structure.

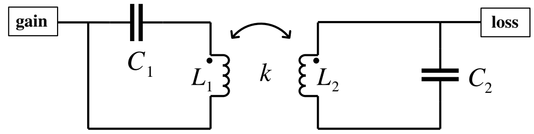

Figure 3. Equivalent circuit diagram of parity time symmetric WPT.

The frequency is affected when the transmission distance or the relative orientation of the source-receiver unit changes, or when the medium between the two receiver coils changes, and the transmission efficiency can only be preserved by constantly tuning the frequency or the internal coupling parameters [16]. The introduction of the parity time circuit is able to counteract the energy attenuation in the receiving coil, transmitting coil, load, and transmission distance by introducing negative resistive elements, thus providing powerful wireless power transmission to mobile devices or vehicles, for example. The parity time equivalent circuit is shown in Figure 3. Typically, coupled mode theory (CMT) is used to analyze the energy transfer between coupled resonant cavities. The general nonlinear PT system CMT model for WPT systems [10] is shown in Equation (3).

$$\frac{d}{dt}\begin{bmatrix} a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} j\omega_1 + g_1 & -j\kappa \\ -j\kappa & j\omega_2 - \gamma_2 \end{bmatrix}\begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \tag{3}$$

where ω_1 and ω_2 are the resonant frequencies of the transmitting and receiving resonators, respectively; a_1 and a_2 are the energy modes of the system, so the energies stored in the transmitting and receiving resonators are $|a_1|^2$ and $|a_2|^2$, respectively; κ is the coupling coefficient between the transmitting and receiving resonators; g_1 is the nonlinear saturable gain rate of the transmitting cavity, while γ_1 is the attenuation rate of the transmitting resonator, and γ_2 is the attenuation rate of the receiving side. γ_2 is equal to the sum of γ_{21} and γ_{22}, with γ_{21} being the attenuation rate of the receiver-side coil and γ_{22} the attenuation rate of the receiver-side load. Because the equivalent resistance of the transmitting and receiving coils is much smaller than the attenuation rate of the receiving side load, it can be neglected.

Assuming that the solutions of a_1 and a_2 are proportional to the case of $e^{j\omega t}$, we can get Equation (4).

$$i\left(\omega_1 - \omega + g_1\right)\left(i\left(\omega_2 - \omega\right) - \gamma k_2^2\right) + k^2 = 0 \tag{4}$$

When g_1 varies, a real solution ω is to be obtained. Set the saturation gain g_1 so that ω is constant to real. Separating the real and imaginary parts yields.

$$\left(\omega_1 - \omega\right)\left(\omega - \omega_2\right)^2 + \gamma_2^2\left(\omega_1 - \omega\right) - \kappa^2\left(\omega - \omega_2\right) = 0 \tag{5}$$

$$g_{1,sat} = \gamma_2 \frac{\omega - \omega_1}{\omega - \omega_2} \tag{6}$$

Equation (5) gives the intrinsic frequency ω for a given decay rate γ_2 and coupling coefficient κ. Then, Equation (6) gives the corresponding saturation gain value at which the system oscillates at frequency ω as steady state. Furthermore, although there are multiple solution possibilities for the steady-state mode frequency, for this simple gain model, the mode requiring the lowest gain makes growth to its steady state and saturates the gain, thus preventing the other modes from obtaining the gain level required to reach steady-state oscillation. Further analysis shows that this steady-state solution is stable. The proposed wireless energy transmission system is oriented to the field of underwater wireless energy transmission. In the case that the transmission medium changes from air to seawater, the transition frequency will be generated because the relative permittivity and conductivity of seawater are different from that of air, and the above analysis shows that the system will enter a steady state within a few cycles, which is faster than the traditional wireless energy charging into the steady state, so it has more advantages in the field of underwater wireless energy transmission.

3. UNDERWATER MEDIA MODEL

Due to the specificity of the working environment, underwater WPT technology is mainly applied in seawater. Compared to air and freshwater, the parameters of seawater produce large changes, and

Table 1. Relevant parameters of different media.

Media	Relative dielectric constant	Electrical conductivity (S/m)
Air	1.0006	0
Water	81	0.01
Seawater	81	4

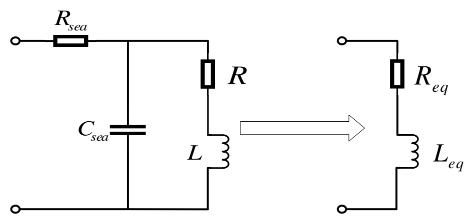

Figure 4. Influence of seawater on the WPT system.

their relevant parameters are shown in Table 1. Compared with the circuit model of air medium, seawater is a non-ferromagnetic conductor; therefore, the real part (resistance) of the impedance of primary and secondary coils in seawater medium increases, and the real part of the increase increases with the increase of frequency. The seawater environment has a relatively high dielectric constant, so a distributed capacitance C_{sea} is generated between two similar conductors in the water. In addition, due to the higher conductivity of seawater, a new loss is generated: eddy current loss, and the eddy current loss resistance is represented by R_{sea}. The parameters of the coil also change accordingly with the influence of seawater parameters, which also cause additional energy loss during the system transmission. The effect of seawater on the system is shown in Figure 4, where ω is the operating frequency of the system.

$$L_{eq} = \frac{L - \omega^2 L^2 C_{sea} - C_{sea} R^2}{(1 - \omega^2 L C_{sea})^2 + \omega^2 C_{sea}^2 R^2} \tag{7}$$

$$R_{eq} = R_{sea} + \frac{R}{(1 - \omega^2 L C_{sea})^2 + \omega^2 C_{sea}^2 R^2} \tag{8}$$

Under the influence of seawater medium, the loss associated with seawater in the coil at this point is defined as γ_{23}, when $\gamma_2 = \gamma_{21}+\gamma_{22}+\gamma_{23}$. In the case of matched resonance ($\omega_1 = \omega_2 = \omega_0$), depending on the relative values of κ and γ_2, there are two regions containing the solutions of Equations (5) and (6). In the strong coupling region ($\kappa/\gamma 2$), the system supports two modes with frequencies, $\omega = \omega_0 \pm \sqrt{k^2 + \gamma^2}$. These two modes have the same saturation gain, which exactly cancels the losses, i.e., $g_{1,sat} = \gamma_2$. In addition, the amplitude distributions of these two modes are equal, i.e., $|a_2/a_1| = 1$. Therefore, these modes satisfy the exact PT symmetry. Unlike the linear eigenmode system, in which the eigenmode symmetry of the eigenmode in the exact phase is achieved by choosing the Hamiltonian quantity of the system with eigenmode symmetry, here the eigenmode symmetry of the eigenmode comes from the nonlinear dynamics of gain saturation: In the steady state, the modes of the system automatically have eigenmode symmetry. We note that although $\omega = \omega_0$ is also a solution of Equation (5) in the strongly coupled region, the mode requires a higher saturation gain as $\kappa < \gamma_2$ increases. In the weak coupling region ($\kappa < \gamma_2$), only one real mode lies at $\omega = \omega_0$, corresponding to the saturation gain $g_{1,sat} = \kappa_2/\gamma_2 < \gamma_2$. However, unlike the linear PT system, in this system the imaginary part of the mode frequency remains zero in both regions. Without any a priori assumptions on the gain saturation mechanism, the gain saturation mechanism only affects the saturation intensity. With small resonant detuning, similar mode frequencies and gain behavior are maintained, although only one mode now has the lowest saturation gain in the strongly coupled region. In the matched resonance case, assuming that the unsaturated gain g_1 is initially set slightly higher than the loss γ_2 in the receiver resonator, the power transfer efficiency at steady state is:

$$\eta = \frac{2\gamma_1 |a_2|^2}{2\gamma_1 |a_1|^2 + 2\gamma_2 |a_2|^2} = \begin{cases} \dfrac{\gamma_1}{\gamma_2} \dfrac{1}{1 + \dfrac{\gamma_1 \gamma_2}{\kappa^2}}, & \kappa < \gamma_2 \\ \dfrac{\gamma_1}{\gamma_2} \dfrac{1}{1 + \dfrac{\gamma_1}{\gamma_2}}, & \kappa > \gamma_2 \end{cases} \tag{9}$$

In the strongly coupled region, the transfer efficiency is independent of the coupling coefficient κ and converges to γ_1 in the limit, $\gamma_{20} \ll \gamma_1$ (resonant detuning reduces the efficiency, but the effect is small for internal detuning $|\omega_1 - \omega_2| < \gamma_2/2$). Therefore, the magnitude of κ is changed, but the efficiency is robust, for fluctuations in the direction, distance, or medium of the two resonators. The efficiency in Equation (9) matches the best efficiency of the conventional wireless transmission scheme at both resonators and assumes frequency tuning for each value of κ. However, no tuning is required here. The nonlinear saturation gain ensures the point symmetry of the steady state in the strongly coupled region and therefore automatically guarantees the best operating frequency for the wireless transmission power. A gain element consisting of an operational amplifier and a feedback adjustable resistor R_2 is shown in Figure 5. The gain element is equivalent to a negative resistor. When the voltage gain $A > 1$, the amplifier and feedback resistor R_2 together act as a negative resistor $R_2/(A-1)$. This negative resistor supplies power to the source resonator, which is magnetically coupled and transmitted to the receiver resonator to supply the load R_L. The saturation in this experiment comes from the power supply limitation of the amplifier. To ensure that the circuit saturates, the unsaturated gain rate is set to be slightly higher than the total loss rate (by choosing a specific R_2 value). The MCR-WPT in seawater medium has three main characteristics: Firstly, the optimal resonant frequency in different states is selected, which can effectively reduce the influence of the marine environment on the transmission performance of the system. Secondly, the conductivity and dielectric constant of the seawater medium are influenced back by the change of seawater temperature. As the temperature increases, the dielectric constant decreases, and the conductivity increases, which in turn affects the transmission of the MCR-WPT system in seawater. The third variation of seawater pressure also has an impact on the performance and stability of the system electrical energy transmission. The MCR-WPT system in seawater is affected by the above three factors though. Fortunately, the impedance matching and maximum power tracking methods [17] used for MCR-WPT systems in air can also be used for MCR-WPT systems in seawater as well. In general, the eddy current loss resistance R_{sea} and the distributed capacitance C_{sea} in seawater medium are affected by various factors and are difficult to calculate, and a certain real value of γ_{23} is assumed in this paper. Figure 6 shows the results of the simulation calculation of the underwater electromagnetic coil using python. The parameters of the wireless charging system are limited during operation due to the influence of the underwater medium, so the operating frequency of the MCR-WPT underwater is generally controlled to a few hundred kHz.

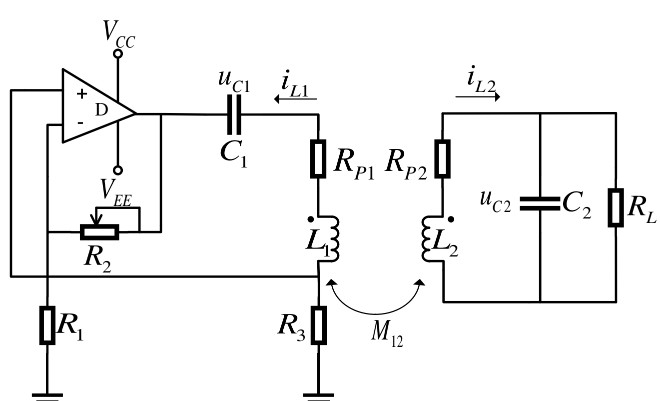

Figure 5. Schematic diagram of SP type parity time circuit.

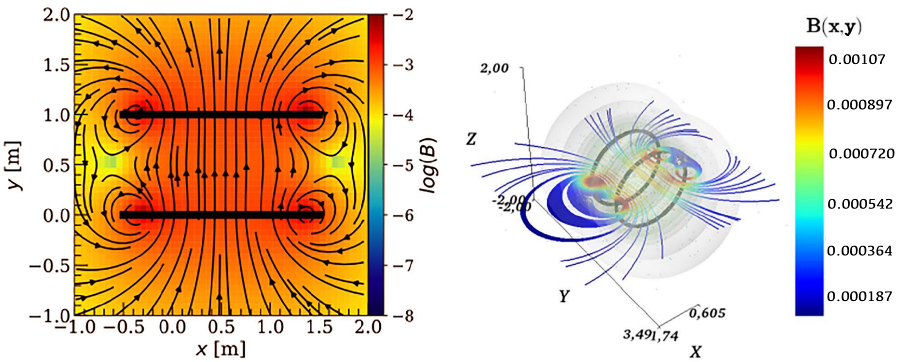

Figure 6. Magnetic field simulation of coil model underwater.

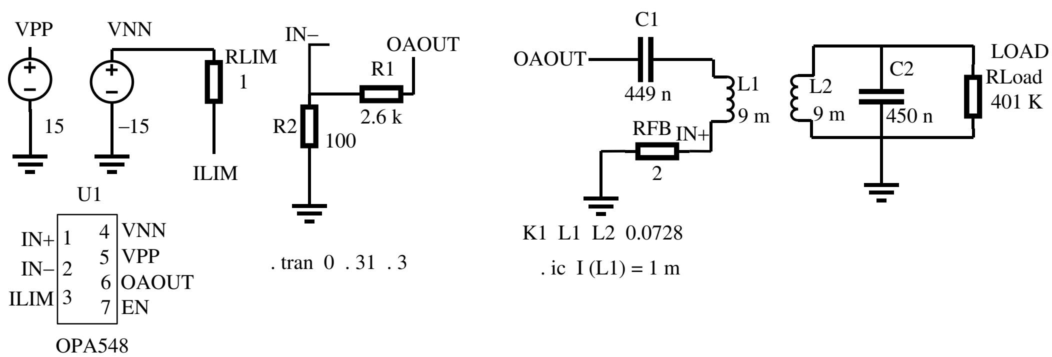

Figure 7. Simulation schematic of the WPT system.

4. SYSTEM SIMULATION AND EXPERIMENTAL VALIDATION

To verify the correctness of the theory, the simulation platform is built in the simulation software LTspice, as shown in Figure 7, with the following simulation parameters: $L_1 = L_2 = 9\,\text{mH}$, $C_1 = 449\,\text{nF}$, $C_2 = 450\,\text{nF}$, $R_L = 2\,\Omega$, and $R_0 = 4.1\,\text{k}\Omega$. The output voltage, current, and voltage of the load of the transmitting resonator of the system with negative resistance (implemented with OPA548) are measured. The waveforms of the transmitting and receiving coil voltages, when the coupling coefficient between the transmitting and receiving coils is set to $\kappa = 0.2$, are shown in Figure 8. It can be seen that when the system enters steady-state operation, by setting different coupling coefficient values (mutual inductance values) in the coupled inductor, the transmission of the system can be simulated when the transmitting resonator and receiving resonator are in different positions, and the coupling coefficient is changed to obtain the change in the transmission efficiency of the system when it is varied in a certain range, as shown in Figure 8. Neglecting the attenuation rate of the two inductor coils, the load attenuation rate is given as

$$\gamma_{22} = \sqrt{L_2/C_2}/2R_L = 0.022$$

When $\kappa > 2\gamma_2 = 0.34$ the system operates in the strongly coupled region. It can be seen from Figure 9 that when the circuit operates in the strongly coupled region, the magnitude of the ratio of the RMS value of the circuit output voltage to the RMS value of the primary circuit input voltage is basically constant. When $\kappa < 0.05$, the ratio of the voltage starts to decrease. The above results are in basic agreement with the theory. Figure 10 shows the relationship between the operating frequency and the coupling coefficient. In the weak coupling region, the operating frequency of the circuit is about 1 (normalized frequency parameter). When the circuit operates in the strongly coupled region, the operating frequency of the system varies with the frequency. As can be seen from the figure, the operating frequency of the circuit jumps around $\kappa = 0.5$, and this jump does not affect the efficiency of

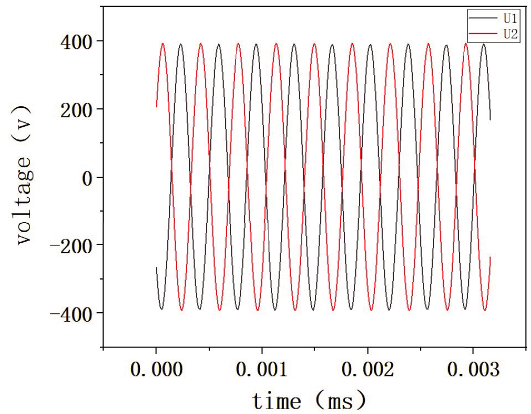

Figure 8. Simulated voltage waveform of load resistance.

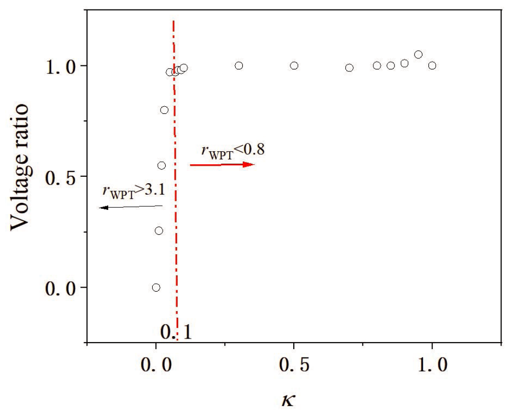

Figure 9. Relationship between voltage ratio and coupling coefficient.

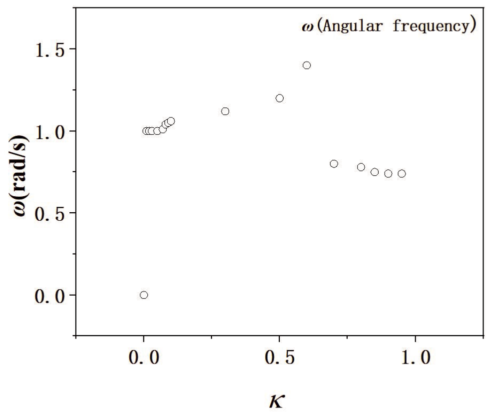

Figure 10. Relationship between frequencies and coupling coefficients.

the system. Then, in the strongly coupled region, the system operating frequency is $\omega = \omega_0 \pm \sqrt{k^2 + \gamma^2}$. This is consistent with the results of the theoretical analysis.

In order to further test the correctness and feasibility of the theory and to verify whether it can be used for underwater wireless power transmission, this paper builds a 15 W wireless power transmission system based on parity time in the laboratory. The experimental platform is shown in Figure 11, and the system parameters are shown in Table 2. The basic SP-type topology is used in the experiment. The transmitting and receiving power coils have the same parameters, and both use Archimedes coils with a diameter of 12 cm. To improve the robustness of wireless charging, it is expected that the receiving coil can be located in a large space with $L = 12\,\mathrm{cm}$, always satisfying $\kappa > g$. Therefore, asymmetric dimensions with large transmitting and small receiving coils can also be used in unmanned underwater vehicle applications.

In addition, the coils should have a quality factor to maximize the free position capacity in space. According to the theoretical analysis, the critical coupling coefficient is $\kappa_c' = \gamma_2$, i.e., $\kappa_c = \gamma_{21} + \gamma_{22} + \gamma_{23}$. Therefore, the two coils can be optimized so that the coupling coefficient is equal to the critical value in the worst case of unalignment. The operational amplifier is chosen instead of the OPA548 chip, a high voltage and high current operational amplifier. Since underwater wireless charging is complex and variable, but mainly affects the coupling coefficient, the coupling coefficient is first measured by changing the distance l between the two coils to change the coupling coefficient realistically corresponding to the mutual inductance coupling coefficient and measuring the relevant data.

Varying the distance between the two coils from 2 cm to 26 cm in order to measure the received-transmitted voltage ratio, we obtain the voltage transmission ratio as shown in Figure 12. When the

Table 2. Parameters of the underwater WPT experiment setup.

Symbolic	Remarks	Value
L_1	Transmitting coil	86 µH
L_2	Receiving coil	86 µH
C_1	Primary side capacitance	500 nF
C_2	Secondary side capacitance	500 nF
R_1	Equivalent resistance of Transmitting coil	4.4 Ω
R_2	Receiving coil equivalent Resistance	4.4 Ω
f_1	Transmitter frequency	25 kHz
f_2	Receiver frequency	25 kHz
R_L	Equivalent load resistance	4.7 kΩ
V_{DC}	DC power supply	15 V

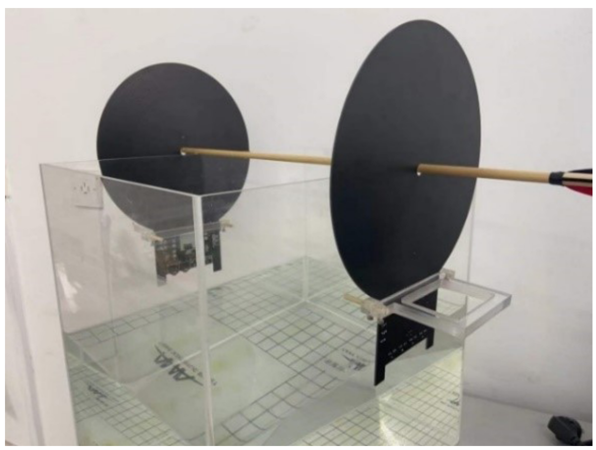

Figure 11. Experimental system for underwater wireless power transmission.

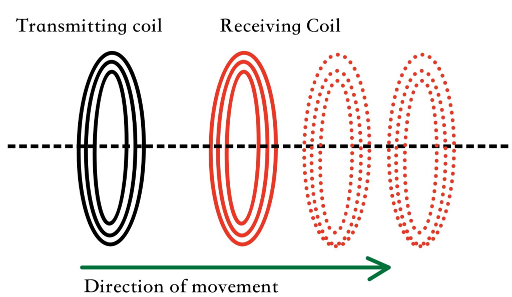

Figure 12. Schematic diagram of coil movement.

distance between the two coils is less than 12.5 cm (strong coupling region), the voltage transmission efficiency is stable at 1. When the distance between the two coils is greater than 12.5 cm (weak coupling region), the voltage transmission efficiency decreases significantly. Within a certain error range, the correctness of the theory is verified. As shown in Figure 13, in the strong coupling region, the operating

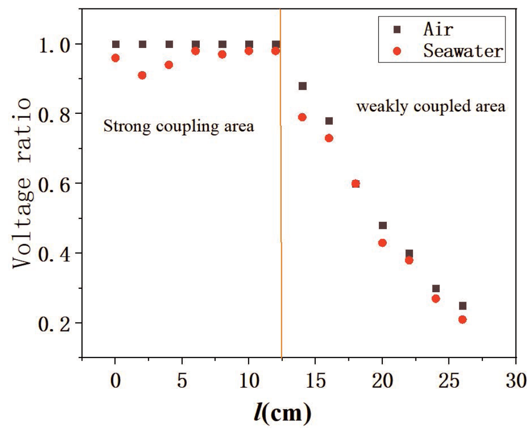

Figure 13. Curves between voltage ratio and the distance.

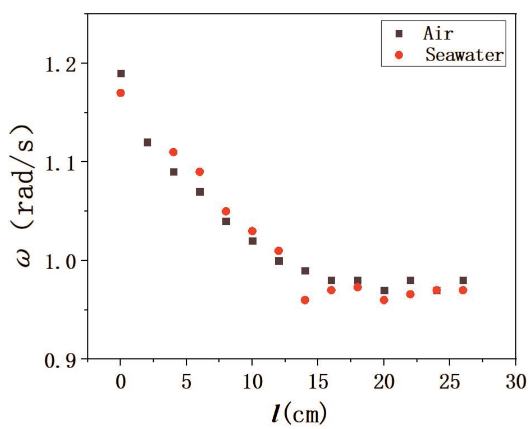

Figure 14. Curves of frequencies and the distance between two coils.

frequency of the circuit decreases as the distance increases. In the weak coupling region, the circuit maintains the inherent resonant frequency, which is also consistent with the simulation results.

The relationship between the distance between the two coils and the robustness and frequency was measured in air and seawater in two cases, respectively. The obtained results are shown in Figure 14.

Also, the specific parameters in the underwater MCR-WPT system were measured at 10 cm, and the experimental parameters are shown in Table 2, yielding an energy transfer efficiency up to 15% for this system in the strongly coupled region.

In a complex underwater environment, PT wireless power transmission has the advantage of being fast and stable with a stabilization time of 2 ms. Figure 15 shows the transient response when the coupling coefficient changes abruptly. The change of the medium and the change in the distance between the primary and secondary coils usually cause the change of the coupling coefficient. The PT symmetrical switching mode WPT system enters the steady state within 1 ms due to the abrupt change in the coupling coefficient. The coupling coefficient changes from 0.4 to 0.1 leading to 1 ms decay, and the coupling coefficient changes from 0.1 to 0.4 leading to 1 ms decay. The MCR-WPT circuit proposed in this paper has a good dynamic response, and this experiment considers the same perturbation and observation process, so no frequency tracking speed or frequency sweep processing based on ant colony algorithm is used [18]. Therefore, the no-load power of the system is small, which reduces the power loss at the transmitter side. PT symmetry can control the time to adjust the frequency within a few switching cycles. Since the underwater wireless energy transmission environment is complex and variable, this fast response time helps the wireless charging technology cope with various complexities in the seawater environment and has a broad application prospect.

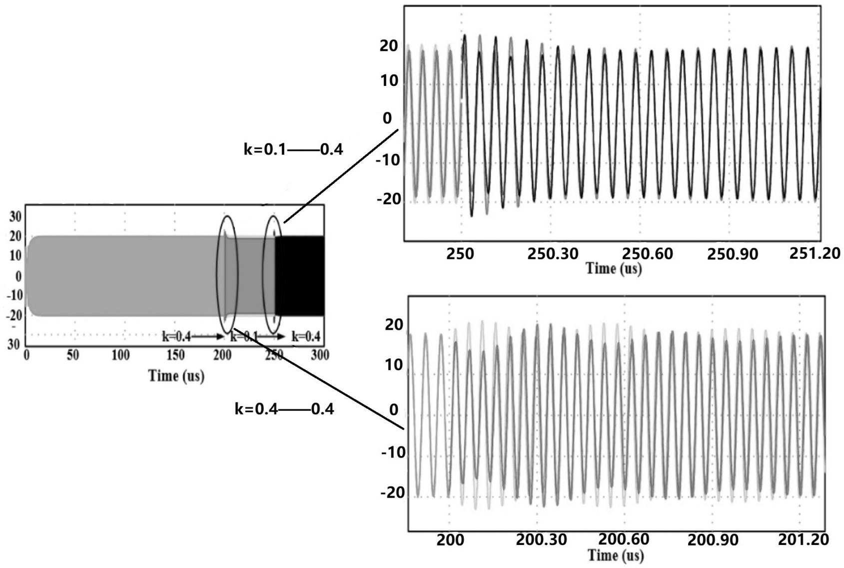

Figure 15. Transient response to sudden change of coupling coefficient.

5. SUMMARY

This paper presents a model of an underwater PT symmetric radio energy transmission system to achieve stable transmission under complex underwater conditions with the advantage of fast response. Stable transmission under complex underwater conditions with the advantage of fast response is achieved. A series-parallel topology is presented to model a PT symmetric radio transmission system that can be used underwater, and an operational amplifier is introduced to construct a negative resistance with nonlinear gain. System simulations are performed with LTspice to analyze its robustness. The experimental results show that the model achieves a transmission wireless close to 1 in the strongly coupled region (12.5 cm) and achieves stable underwater wireless energy transmission. The experimental results agree with the simulation ones within the error tolerance. This verifies the correctness of the analysis and shows that the PT symmetric wireless energy transmission system is suitable for wireless energy transmission with complex environments and has broad application prospects.

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